Management of Ground and Groundwater Contamination on a Compact Site Constrained by Ongoing Activities – 9073

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ABSTRACT

Sellafield Site is a compact and complex site which since the 1940s has been home to a range of facilities associated with the production and reprocessing of fissile material. The site contains the UK equivalent of the Chicago Pile-1 reactor, Hanford B Reactor, Rocky Flats Buildings 771 and 774, West Valley Main Process Plant Building, Savannah River Vitrification Plant, Savannah River MOX Plant, Savannah River F Canyon, Hanford 222 Analytical Laboratory, Savannah River K-, L-, and P-Basins, and the Fort St. Vrain Reactor all in an area of approximately 1000 acres.

Spent fuel reprocessing is still undertaken on site; however waste management and decommissioning activities are of increasing importance. These include the emptying and removal of fragile ponds and silos containing significant radioactive inventories, the decommissioning of reactors (including the world's first commercial reactor for power generation and the Windscale Piles, the site of a reactor fire in the late 1950s) and the construction of a new generation of vitrification and encapsulation plants.

Leaks, spills and on-site disposals during the site's industrial lifetime have resulted in a legacy of fission products and other radionuclides in the ground and groundwater. Volumes of contaminated ground have been estimated as being as much as 18 million m^3 and an estimated below ground inventory of approximately 1.8 E16 Bq. These have all occurred within close proximity to a range of receptors including farm land and the sea.

The cramped nature of the facilities on site, overlapping source terms and ongoing decommissioning, waste management and operating activities all raise significant challenges in the management and remediation of contaminated land and groundwater. The strategy to address these challenges includes:

1. Data collection, management and interpretation.

The congested nature of the site and the age of some of the monitoring facilities has resulted in particular difficulties. For example the design of a new characterisation project has had to be constantly reworked to ensure fragile plants, site services, current operations and decommissioning projects are not impacted.

2. Assessment of Risk to the public and workforce.

Risks need to be assessed for the short, medium and long term. The main pathways to receptors are through groundwater or excavations. Risks to the public are complicated through the proximity of the site to major receptors such as the sea and a near-by farm. As entry to the site is controlled, excavations into contaminated ground are only possible by members of the workforce whose activities are managed to minimise any risk. This is through a system of excavation permits and authorisations for disposal of excavated material which can add significant time and cost to construction projects on site.

3. Prioritisation of remediation.

Large volumes of impacted ground and groundwater sit beneath fragile buildings with significant inventories. With current decommissioning schedules wholescale remediation of ground and groundwater near or under key buildings cannot commence for at least another 40 plus years. Early remediation and/or containment of groundwater further away from the source terms and remediation of smaller accessible areas of contamination are being considered and will be assessed through a

comprehensive optioneering process. Long term clean-up strategies run into the early part of the 22nd Century, making any predictions as to the end-use of the site and therefore clean-up criteria for current projects difficult to determine.

Management of information and data is key in establishing this strategy and information relevant to contaminated land has been collected in various forms over the 60 year history of the site. This data and information is currently being pulled together by the Land Quality team where it can be put into a form that can be easily assessed, visualised and modelled as well as being managed and stored for future generations.

INTRODUCTION

Sellafield Site is a compact and complex site which since the 1940s has been home to a range of facilities associated with the production and reprocessing of fissile material. The site contains the UK equivalent of the Chicago Pile-1 reactor, Hanford B Reactor, Rocky Flats Buildings 771 and 774, West Valley Main Process Plant Building, Savannah River Vitrification Plant, Savannah River MOX Plant, Savannah River F Canyon, Hanford 222 Analytical Laboratory, Savannah River K-, L-, and P-Basins, and the Fort St. Vrain Reactor all in an area of approximately 1000 acres.

Leaks, spills and on-site disposals during the site's industrial lifetime have resulted in a legacy of fission products and other radionuclides in the ground and groundwater. Volumes of contaminated ground have been estimated as being as much as 18 million m^3 and an estimated below ground inventory of approximately 1.8 E16 Bq. Until recently the focus on site has been to manage the ongoing reprocessing and fuel manufacturing operations. Decommissioning and clean-up activities have only recently grown in importance and with them a growing realisation of the work required to bring the management of contaminated groundwater and ground to modern standards. This process would be daunting on any site with a similar below ground legacy but at Sellafield this legacy sits beneath a congested site with a large number of elderly plants containing considerable inventories.

This paper starts with a summary of the nature of the below ground challenges at Sellafield and then continues to explain the elements of the contaminated land programme that have required improvement. In particular the importance of improving the quality of the underpinning groundwater monitoring data is emphasised. However, the difficulties and cost of undertaking characterisation work means that it is also important to be able to work with old data of varying quality from a wide variety of sources.

BACKGROUND INFORMATION

The Sellafield site is on the north-western coast of England approximately 12 miles south of the coastal town of Whitehaven in West Cumbria. The Irish Sea lies to the west of the Sellafield site and the fells of the Lake District National Park lie to the east. The land generally slopes from the east to the west of the site towards the coast. Two rivers are within or adjacent to site, the River Calder flows through the site from the north-northeast to south-southwest and the River Ehen flows in a south-easterly direction between the site and the coast. The two rivers join to the southwest of the site where they discharge into the Irish Sea. The site is surrounded by farmland and is within close proximity to a range of possible receptors including a dairy farm and the sea.

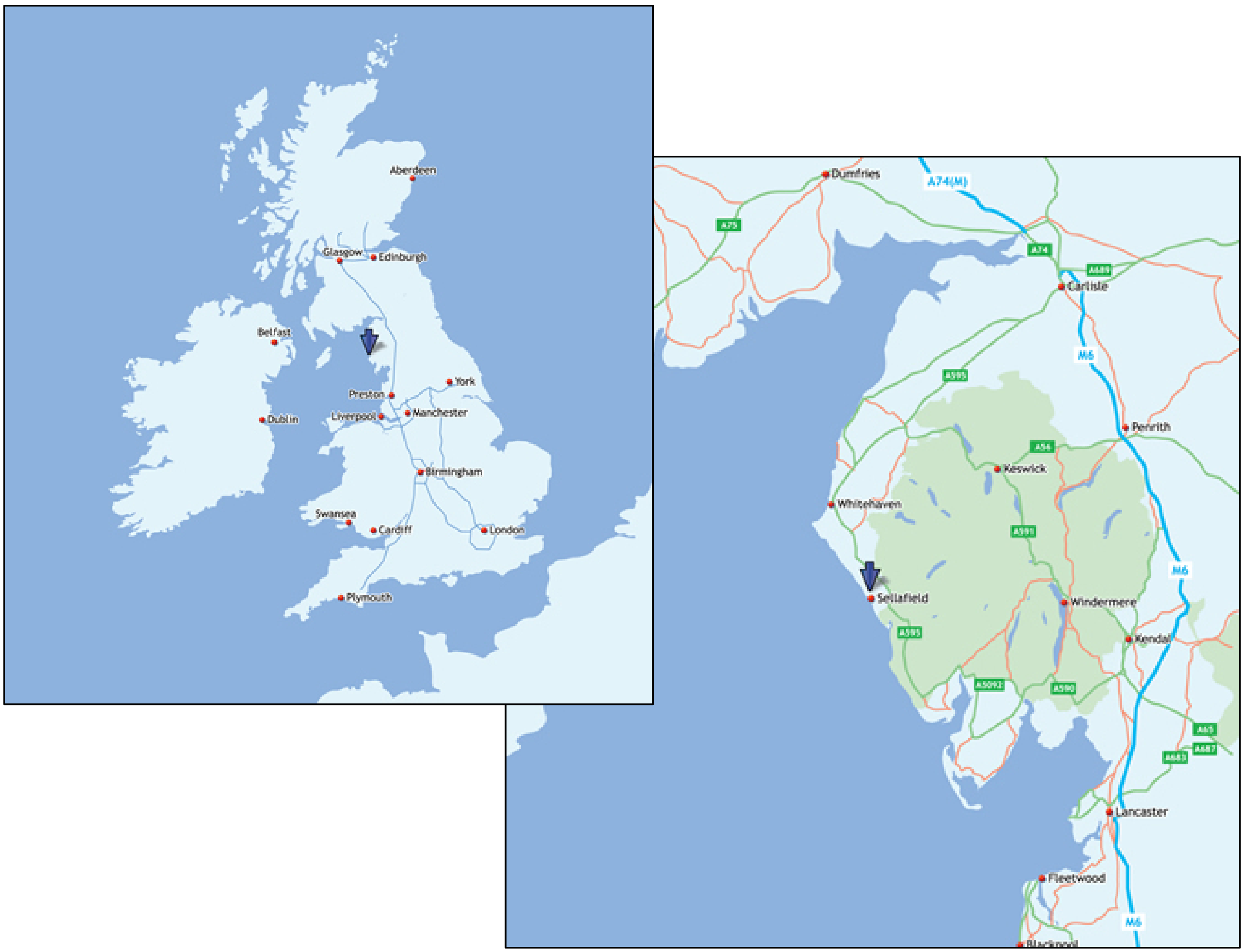

Fig. 1. Location of Sellafield Site

The geology of the site comprises a complex series of glacial deposits (drift) consisting of clays, gravels and sands below which is bedrock sandstone. Groundwater occurs in the glacial deposits and the bedrock sandstone. The glacial geology is complex with several glaciation events, several re-advances, glacial tectonic activity and significant sea-level change. The upper drift aquifer is classified as a minor aquifer and the underlying sandstone aquifer as a major aquifer. Locally, the drift aquifer may comprise two units separated by discontinuous clay bands.

The industrial history of the Sellafield site began in 1941 when it was developed as a Royal Ordnance Factory. TNT production ceased at the end of the Second World War and the site was cleared in 1946. In 1947 the site was chosen as the location for Britain's first atomic reactors and associated reprocessing plant. These reactors and plants were concentrated in the centre of the site in a 80 acre (33 hectare) area known as the 'Separation Area'. In the early 1950's the world's first power generation reactors (Calder Hall) were constructed. With the exception of a prototype reactor built in the 1960's, all of the subsequent construction on site has been for the purpose of reprocessing spent nuclear fuel and the temporary storage of solid and liquid reprocessing wastes prior to vitrification, encapsulation and storage. On-going activities on site are focused on reprocessing of spent nuclear fuel, fuel manufacture, and site decommissioning and clean-up.

Fig. 2.

Over the years a number of leaks and spills, largely confined to 'Separation Area', have led to localised radiological and chemical contamination of the ground beneath the site. Some of this contamination has percolated downward to contaminate the groundwater that flows toward the coast. An initial estimate suggests that this process has resulted in approximately 18 million cubic metres of land being contaminated, mostly at very low activity concentrations.

Weak Beta-emitters, tritium and technetium are found in groundwaters on site, as they not only made up a considerable percentage of the inventory of the leaks and disposals on site, but are also relatively mobile. Annual average concentrations of tritium found in boreholes to the southwest of Separation Area exceed the World Health Organisation drinking water standard (10,000 Bq/l). Annual average concentrations of technetium are also found to have exceeded the World Health Organisation drinking water standard (100 Bq/l) in boreholes in this area of site. Strontium-90 and caesium-137 are also found on site, a significant proportion of boreholes contain groundwaters with total beta activities above the WHO drinking water standard of 1 Bq/l. Analyses for individual alpha-emitting radionuclides indicate that in the few boreholes in the centre of site where alpha contamination is found uranium predominates, with much lesser activities of plutonium, neptunium-237 americium-241 and radium-226.

Non-radiological contamination is also known to be present on site though until recently groundwater samples have not been routinely analysed for non-radiological contamination. Total Petroleum Hydrocarbon (TPH), Volatile Organic Compounds, Semi-Volatile Organic Compounds and dissolved metals are now part of the routine analysis suite on site.

The backbone of the management programme is the groundwater monitoring and characterisation work which provides data and information to drive improvements in our site understanding, risk assessments and plans for remediation work. These programmes of work and how they are challenged and modified by the challenges posed by working on Sellafield site are discussed below.

DATA COLLECTION AND DATA MANAGEMENT

Data is required to:

1. Update conceptualisation (understanding) of the site geology, hydrology, contaminant distribution and transport,
2. Update the understanding of current and future risks to the on site and off site receptors,
3. Provide leak detection,
4. Support remediation planning.

Data sets and information that are useful to the Land Quality team are available from a range of different sources. These have been gathered since the early days of site and are of variable quality and accessibility. The Land Quality team has evaluated these and a data management plan determined not only from the importance and quality of the data but also on its suitability for transfer into an electronic format where it can be easily stored and viewed.

A contaminated land data management system, called IMAGES has been assessed as being the most suitable for use with the Sellafield data. It has been designed specifically for contaminated land data management on nuclear sites in the UK and is currently being modified and adapted for Sellafield data. Work is starting with groundwater monitoring data and other data sources will follow, such as data generated through Site Excavation permits. These datasets will be linked through a Geographical Information System (GIS) platform to allow easy access, interpretation and integration with other datasets such as land use and plant infrastructure. With a site as complex and compact as Sellafield large complex datasets are the norm and the resources required to management them and ensure confidence should not be under estimated. The resources required to collect soil and groundwater samples to send to the analytical laboratories and then to manage the data returned need to be as well trained and qualified as those interpreting the data and building the site conceptual model.

Often it is not a problem with how the data was originally collected or analysed but a lack of retention of documentation and lack of documentation of the management of the database within which the data are stored. In assessing the old data it has been found that it is important to ensure that any conclusions of the quality of the data are fully documented and are available to the people accessing and interpreting the information.

The current conceptualisation, while adequate in assessing current risks to receptors is currently not detailed enough to provide confidence in future risk assessments or to be used on determining the consequences of remediating or isolating contaminated groundwater plumes. Also in the past samples have been collected for regulatory compliance purposes and any use in improving the conceptual understanding has been of secondary importance. This has resulted in not all boreholes being maintained to modern standards or being in optimum locations. Various projects are now in place to provide new and better quality data to rectify these issues. These include:

Refurbishing existing boreholes

A project is now in place to assess the existing borehole network in order to refurbish or decommission the boreholes where appropriate. This will ensure that samples obtained are fit for purpose as well as making sure the boreholes aren't enhancing transport of contamination.

Improving the collection of samples

Currently there is no single method of collecting samples from boreholes on site. Sampling methods are constrained by:

1. The volume of sample required – Low detection limits mean large sample volumes are required,
2. Disposal of waste water – Disposal routes are limited leading to a requirement to minimise the generation of waste water,
3. Dose rates in a few areas mean that working times need to be minimised.

A study is currently assessing the best sampling method for use on the site as well as assessing what the consequence has been of using the different sampling methods on the quality of the groundwater monitoring data.

Characterisation Project

This project started in April 2007 and includes detailed characterisation of the centre of the site (Separation Area) to allow subsequent assessment and updating of the existing Sellafield site conceptual models (geologic, hydrologic, and source term). The work activities entail the drilling and installation of over 100 new groundwater monitoring boreholes, a geophysical evaluation of a disposal trench area and extensive field and laboratory testing. Project progress through the end of June 2008 includes the completion of the geophysical evaluation of the disposal trench area and the completion of approximately 25 percent of borehole drilling and associated sampling.

The site has presented many obstacles to the characterisation project. One of the biggest problems has been the logistics of getting close enough to source terms as these often sit underneath fragile buildings with significant inventories. Another issue has been the avoidance of below ground structures. The density of the buildings, and associated underground services makes the selection of suitable locations to put in boreholes difficult. The result has been that there have been fewer shallow boreholes close to known source terms to characterise the unsaturated zone and more boreholes further away from source terms to characterise the groundwater then envisaged in the original investigation design.

DATA INTERPRETATION

As mentioned above data is being collected to improve understanding (conceptualisation). The term 'conceptual model' can be defined in many ways, but the simplest one is that it is a hypothesis for how a system or process operates.

A description of the conceptual model should include all that is known about a system, any assumptions made for the purpose of a full description, and a discussion of the possibilities for those things which are unknown (if they might be important). There are many possible conceptual models which will be consistent with current evidence, and each one could lead to entirely different predictions. It is crucial for good management to explicitly understand this conceptual uncertainty, as well as the uncertainty arising from system variability and data error.

All aspects of the conceptual model are linked but they can be divided into different areas to aid description.

- History and Geography
- Geology and Hydrology
- Source terms
- Contaminant transport

The current characterisation project is providing the information to improve our conceptualisation in particular it is focussing on resolving issues.

History and Geography

The Sellafield site has been used as an industrial site since the 1940s. It was radically altered after the 2nd World War when the site was flattened and the first generation of reprocessing plants were built. More information on the history and geography of the site can be found in introduction to this paper and on the Sellafield website (http://sellafieldsites.co.uk/land/).

All relevant historical information pertaining to Land Quality it is currently being collected and evaluated. This will take some time as there are many different historical records, one example being the Land Quality photo library, which currently contains over 10,000 photographs. IMAGES should prove invaluable in putting all this information together in one place and GIS will be used to view and analyse it.

One particular aspect of the site history that is currently of particular interest is the location and nature of the services and structures below the site as these can act as both sources of contamination and pathways. We are now undertaking a package of work to go through various sources of site information such as old maps and reports to better understand the location of all the old drains and services. It is increasingly clear that they are extensive, date from throughout the history of the site and are not always well defined.

Geology and Hydrology

Geological and hydrological characterisation of the site and surrounding areas has been extensive. Characterisation of the site was started in the late 1970s by the British Geological Survey and at lot of regional characterisation was undertaken in the 1990s when a nearby site was proposed as a setting for the disposal of Intermediate Level Waste. Important papers on the geology of the Sellafield area are available from NIREX who were responsible for undertaking the characterisation for the siting of a possible repository (1,2).

The geology of the site comprises a complex series of glacial deposits (drift) consisting of clays, gravels and sands below, which is bedrock sandstone. Groundwater occurs in the glacial deposits and the bedrock sandstone. The glacial deposits are heterogeneous and although similar units can be found in different boreholes it is not possible to map units across the site from borehole to borehole with any degree of confidence. The deposits contain fine-grained deposits which have been linked with contaminant retardation and coarser grained sands and gravels which could be acting as pathways for contamination.

Uncertainty in the detailed drift geology and hydrology underneath Separation Area was one of the drivers for the current Characterisation Project, which was discussed in the Data Management Section above. This should provide a better understanding of the extent of clay, sand and gravel units and the potential this has in modifying contaminant transport. The information from the characterisation project will feed into an updated version of the conceptual model, which will update the contaminant fate, and transport models that in turn will form the backbone of an updated Risk Assessment Model for the Site.

The Sellafield site water balance model has been an area identified as a key technical uncertainty. The site water balance is the difference between the amount of water entering and leaving the site via the groundwater and is important in understanding contaminant transport. A major uncertainty is the anthropogenic recharge (e.g. leakage from water mains) that occurs on site. The complexity and age of the mains water system on site coupled with the number of operating plants sitting above the source terms and uncertainties in their water usage make it difficult to resolve uncertainties in this number. In 2008 several tasks are currently underway to provide the basis for updating the Sellafield Site water balance model including desk studies and the positioning of gauges on some key water pipes is also being considered.

Source Terms

Interpretation is hampered by the proximity of the leak events and disposals to each other. There are over 200 recorded leaks and spills on site but the below ground radiological inventory is dominated by a small number of events. These all occurred in an area in the centre of the site called Separation Area, which is approximately the size of 160 soccer pitches (80 acres).

Tracing groundwater contamination found in a borehole to its original source is therefore fraught with uncertainty and difficulties; this is not helped by the difficulties in drilling boreholes near source terms as mentioned above. There is an argument for saying that it is not possible to tell individual source terms apart and treat the whole of separation area as one source term. However this would prevent the use of groundwater monitoring for leak detection as well as making it harder to prioritise remediation of source terms. Also the chemistry of the leaks are different, for example the two largest leaks are thought to have contained roughly the same activities but one leak has been estimated to have a volume between 20- 30m^3 and was a single event while the other has an estimated volume of 9,000 to 10,000m^3 and occurred over a number of years. The radionuclides entering the environment from these leaks will behave differently and there work done to understand the spread and migration of these radionuclides will need to be tailored to the specific leaks.

Characterisation of soils and the interpretation of groundwater results is being done to try and better understand the contribution and behaviour of the different leak specific source terms to the overall source term in Separation Area, This work includes:

1. Understanding the geochemistry of the source terms.

Samples are being collected as close as possible to the source terms to enable geochemical analysis of the soils which have been contaminated, to better understand the potential for the radionuclides to be sorbed onto soils and made ground. This work is particularly important in assessing the fate of the largest source term. In the past it has been estimated, based on modelling of the leak chemistry and the known geology of the leak site, and groundwater monitoring that 90% of the inventory has been retained close to the leak site. The consequence of this material being more mobile than previously thought or becoming mobile is significant and this work should enable an assessment to be made of the current understanding. This information will also be used to assess the viability of future remediation technologies, such as soil washing.

2. Assessment of Groundwater Monitoring Results

More work and care is being taken over the collection, analysis and interpretation of groundwater results. In the past samples have been collected for compliance and any use such as the validation of models have been of secondary importance. There is now a focus on the use of results to improve the site understanding and predictive modelling. As discussed above this has driven an improvement in the groundwater monitoring assets and sampling methods. This in turn will provide greater confidence in the groundwater data and enable more intelligent interpretation of the results which may provide a greater understanding of the contribution of different source terms to groundwater contamination. Work has also been undertaken to establish formal groundwater technical liaison with appropriate Operating Plants/Units to enhance Sellafield Site understanding of the current local groundwater contamination characteristics and the impact of potential plant leaks on the existing land and groundwater contaminant store.

3. Finger printing

The similarity of the radionuclide inventory of the leaks coupled with the heterogeneity of the glacial drift and the ability of the radionuclides to sorb to fine grained material within it makes it difficult to pin point the original of the contamination in the groundwater by looking at the ratio of the major contaminants alone. It may however be possible to look for unique ‘fingerprint’ contaminants that were produced by processes in single source term plants that will allow contamination to be traced back to individual plants.

ASSESSMENT OF RISK TO THE PUBLIC AND WORKFORCE

Risk assessment, using a simplified understanding of groundwater flow, has been carried out using MONDRIAN (an in-house risk modelling code) and GOLDSIM (a general purpose risk simulation tool). These assessments are underpinned by a number of studies of groundwater flow and contaminant transport using MODFLOW (a commercial finite difference code) and TRAFFIC (an in-house finite element code). Detailed geochemical modelling using PHREEQC has also been carried out in the vicinity of the major sources. Work has been done over the last couple of years to manage the use of parameters in the models and a database has been constructed to ensure consistency.

The main possible pathways to receptors are through excavations or groundwater. Risks to the public are complicated through the proximity of the site to major receptors such as the sea and a near-by farm. Risks are currently being assessed for the next 100 years as uncertainties still exist for the final end-uses of the site. In the most recent Risk Assessment work using GoldSim an effort was undertaken to look at the top 38 recorded leaks, spills and disposals on site. An estimate was made of their start and end date, volume leaked and radiological inventory as well as an assessment of the quality of this information. From this information risks were calculated for each source term rather than a total risk for the site and found to be significantly less than 10^{-6} per annum risk of a fatal cancer.

As entry to the site is controlled excavations into contaminated ground are only possible by members of the workforce, and their activities are managed to minimise any risk. This is through a system of excavation permits and authorisations for disposal of excavated material. This can add significant time and cost to construction projects on site.

PRIORITISATION OF REMEDIATION

At Sellafield significant volumes of impacted ground and groundwater sit beneath fragile buildings with significant inventories. With current decommissioning schedules wholescale remediation of ground and groundwater near or under buildings cannot commence for at least another 40 to 50 years. Early remediation and/or containment of groundwater further from the source terms and remediation of smaller accessible areas of contamination are being considered and will be assessed through a comprehensive optioneering process. Long-term clean-up strategies run into the early part of the 22nd Century, making any predictions to the end-use of the site and therefore clean-up criteria for current projects difficult to determine.

Good use of visualisation techniques such, as GIS are important in understanding how the order of decommissioning of buildings and infrastructure can be timed to allow early intervention if required.

When working with such long time periods good records management is again very important. It is necessary to record any decisions made on the quality of any data and to ensure that as much information on the quality and how the data was collected is made available within the database. This will ensure the value of the data to a wide range of current stakeholders as well as future generations.

CONCLUSIONS

Sellafield site is a complex and congested site. 60 years as a nuclear licensed site has left a considerable legacy of contamination in the ground and groundwater. Until recently the focus on site has been to manage the ongoing reprocessing and fuel manufacturing operations. Decommissioning and clean-up activities have only recently grown in importance and the resources to manage the below ground legacy has increased.

In building a team to manage contaminated ground and groundwater on a site as congested and complex as Sellafield it became increasing clear the scale of the resource required to ensure the quality of the groundwater and ground data being generated was greater than originally thought and is equal if not greater than the resource required to interpret the data. In the past this has not been fully appreciated and effort is now required to address the current deficiencies in the programme. Undertaking characterisation work on Sellafield site is difficult due to the need to interface with so many buildings, site services, etc. It is also very expensive and when working close to fragile buildings with considerable inventory has nuclear safety implications. It is therefore worth the effort and cost to make as much use as all available data as possible.

Often it is not a problem with how the data was originally collected or analysed but a lack of retention of documentation and lack of documentation of the management of the database within which the data are stored. In assessing the old data it is important to ensure that any conclusions of the quality of the data are fully documented and are available to the people accessing and interpreting the information. The more information on the quality and how the data was collected that is made available within the database the more it becomes possible to make the data availability to a wider range of stakeholders and ensures that the data is valuable to future generations.

Once the data sit in a good well managed database they need to be easily accessible, viewed and interpreted to provide a robust conceptual model. On a site such as Sellafield this is a complex and difficult task without good visualisation tools such as Geographical Information Systems and statistical packages to trend and contour data. The data need to be viewed alongside not only geological, hydrological which are managed within the team but also with site information such as the location of drains, fragile buildings, location of former buildings, etc. which are managed elsewhere. Considerable work is therefore required to be confident that these external databases are well maintained and fit for our purposes.

Finally, good management of data and information not only means good records management but also relies on the retention of a well-qualified team that allows for easy succession planning.

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