

SCIENCE DESIGN FOR TWO SHAFTS IN PHASE 1A OF THE PROPOSED ROCK CHARACTERISATION FACILITY AT SELLAFIELD, UK

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Abstract

In 1997, United Kingdom Nirex planned to begin construction of an underground Rock Characterisation Facility (RCF) at Sellafield as part of its ongoing assessment of the suitability of the site as a host for a deep radioactive waste repository. The RCF was to have addressed issues relating to the geology, hydrogeology and geomechanical behaviour of the site by collecting data for testing predictive models and acquiring information only available from an underground situation.

In March 1997, the UK Government refused permission for Nirex to begin construction and work at Sellafield was wound down. However, the science design for Phase 1a of the RCF, two vertical access shafts, was completed to provide a set of conceptual designs which address the issues identified by Nirex. By using Sellafield as an example, the designs contribute to a series of reports which demonstrate an approach to validation using an underground facility.

This paper describes the Science Design for data collection during shaft construction, which began with the information requirements specified by Nirex on the basis of its conceptual models and predictive work. It describes the scientific measurements designed to acquire this information and the process of combining the individual measurements into test plans for each shaft.

Measurements were planned in the shafts themselves and in boreholes drilled from the shafts. They were designed to provide data on formation porosity and permeability, the geochemistry of formation water and the nature of the fresh-water salt-water interface, shaft inflow, the influence of geological structures on performance, and geomechanical responses to shaft excavation.

A key element of the design process was the development of test plans, requiring the coordination and integration of the construction and science activities so that both could be carried out in a timely and cost-effective manner.

1 Background

In 1994 United Kingdom Nirex Limited (Nirex), as part of an extensive programme of scientific investigations to determine whether or not the site was suitable for construction of a deep repository for the disposal of intermediate-level radioactive wastes, applied for permission to construct an underground Rock Characterisation Facility (RCF) near Sellafield in west Cumbria, UK.

The application followed an extensive surface-based site investigation during which 29 deep boreholes were drilled and tested to investigate and develop a three-dimensional understanding of the geology and hydrogeology of the subsurface formations in the area. The scientific programme planned for the RCF was designed to follow on from this work and run in parallel with an ongoing surface-based investigation, the Nirex research programme and safety assessment studies.

Assessments of the safety of a potential repository in 1995 identified a number of key issues which needed to be addressed in the RCF before Nirex could have taken a decision on whether to propose a repository at the site. These issues related to aspects of:

- groundwater flow and radionuclide transport;
- the natural and induced changes to the geological barrier; and
- the design and construction of the repository.

These issues were to be addressed in the RCF by collection of data with which to test the predictive models of the site behaviour, with respect to geology, hydrogeology and geomechanics.

2 The Sellafield RCF

The planned RCF was to have comprised a series of horizontal galleries at a depth of approximately 700m, giving access to a reasonably large portion of the potential repository zone and providing sufficient space to carry out experiments in isolation from one another. The galleries were to be accessed by two vertical shafts (the North and South Shafts) in the centre of the facility and separated by approximately 50m.

Construction of the RCF was to have taken place in three phases over about 10 years. Phase 1 was the sinking of the two shafts and their connection by roadways, Phase 2 was construction of galleries within 200m of the shafts, and Phase 3 was extension of these galleries to a total length of 975m. Phase 1 was further subdivided, with Phase 1a being sinking of the shafts alone (i.e no connecting roadway). The Science Design described in this paper applies to Phase 1a.

The two shafts were to be concrete lined through the sedimentary rocks but unlined in the potential host formation, the Borrowdale Volcanic Group, with a finished diameter of 5m.

In recognition of the geological formations to be encountered, the likely construction methods required and the scientific objectives, the shafts were divided into 11 Sectors; Nos. 1 to 7 in the South Shaft and Nos. 8 to 11 in the North Shaft. Sinking of the North Shaft was planned to lag behind that of the South Shaft in terms of depth and the phasing arranged so that inter-shaft testing could be carried out. The planned duration of Phase 1a was approximately 3 years.

3 Information requirements

Two kinds of scientific information were required; data which could only be gained from underground investigations and data to test gross and Sector-specific models of the geology, hydrogeology and geomechanics of the site.

The data only available from underground investigations included specific data requirements for Phase 1a, in particular the nature of fractures and their variability over length scales greater than that available from boreholes, the characteristics of flowing fractures, stress-dependent behaviour of the flow system, the response of the rock mass to the excavation process and certain hydrochemical data.

Thirty-five models were identified for testing during Phase 1a, at a number of scales from local to regional. Eight of the models were geological, four of which were deterministic and four probabilistic to describe spatially variable properties such as structural domains and sedimentary architecture. Eighteen hydrogeological models were developed, using the geological models as a framework. In addition to the normal hydrogeological parameters, these models also included hydrochemical models of the variations of groundwater chemistry within the potential repository zone. Nine geomechanical models were developed to assess the mechanical behaviour of the rock mass during and after construction, four of which were simple hydromechanical models to assess coupled behaviour of discontinuities close to the shafts.

These information requirements were translated into a schedule of measurements to be undertaken during shaft sinking and formed the basis of the Science Design. From this schedule and outline test plans, a series of individual measurement designs and detailed integrated test plans was developed. The measurements, their distribution and key design features are summarised in Table 3-1 and described in the following sections.

4 Geological Measurements

The design for the principal geological measurement, *Geological Mapping*, consisted of the observation and recording of geological, geomechanical, and hydrogeological features seen in the underground excavations, and the sampling of geological materials. Mapping requirements, in terms of type of feature and amount of detail to be recorded, would vary throughout the excavations. A mapping method was required to ensure that no geological features of possible significance would go unnoticed and unrecorded by mappers. The recommended method allowed for high resolution photographic images of all excavated surfaces to be made, together with inspection of all newly excavated faces which would allow decisions to be made about which geological features should be

subsequently recorded by the mappers onto previously prepared hard copy photographic images.

A principal feature of the mapping design was the imaging system. The shaft wall was to be imaged around its circumference with a rigidly mounted digital camera. The camera would be rotated between exposures to give a series of consecutive frames, with horizontal and vertical overlaps of 50% and 10% respectively. This technique provides 'high resolution' images that are at least as 'sharp' as high quality photographs and capable of being enlarged, like photographs, without losing sharpness of relevant detail. In addition, digital images would be stored electronically in the project database. A number of imaging systems were reviewed, and a system was recommended for further investigation. Because potentially significant developments are being made in digital imaging systems, the final choice of system would be made as late as possible in any final design process.

An additional design requirement was that the shaft wall was to be profiled after every blast round. The number of profiles and density of measurements within each profile were designed to vary according to the level of detail of geological information recorded. The design recommended a commercially available downhole scanner, comprising a computer-controlled automatic scanning laser profiler, designed to profile underground cavities.

The mapping process would be undertaken within each shaft sinking cycle and would commence with the Mapping Team being called out and then travelling to the science deck of the sinking stage with their equipment. Digital images would be acquired from beneath the science deck, followed by a profile of the shaft walls. While imaging and profiling was taking place, mappers on the science deck would record geological information on mapping forms and on a mapping template consisting of an image of the shaft walls made during a previous mapping shift. The mappers would take samples as necessary (using a barcode labelling system for sample tracking and control) and then return to surface where they input all the information they have collected into the database.

Core Logging procedures were prepared based upon those developed for the previous surface-based acquisition programme. It was proposed that **Core Orientation** should be carried out by correlation of borehole wall imagery with discontinuities in the core. A slimhole imaging system was proposed comprising an optical logging tool supported by a workstation for derivation of discontinuity orientations. Visual correlations would then be made between specific discontinuities clearly identified in the core and on the imagery. Sticks of core would be oriented using several correlated discontinuities per stick, and apparent discontinuity orientations recorded during core logging would be corrected.

5 Geomechanical Measurements

Selection of the shaft spacing was based on engineering considerations, but was also intended to preclude significant interaction between the stress-strain fields developed around each shaft in response to excavation. Furthermore, the South Shaft was to be sunk in advance of the North Shaft, resulting in both spatial and temporal separations between the excavation-induced responses of the rock mass around each shaft. These responses would have resulted in the development of excavation disturbance zones (EDZs) around each shaft, in which the mechanical and hydraulic properties of the rock mass are expected to change.

The design of the *Response to Excavation* measurement comprised the drilling and instrumenting of boreholes from the North Shaft and the South Shaft, in advance of the North Shaft, into a block of ground through which the North Shaft would later pass. The key design issues for these measurements were therefore; optimisation of the location of instruments with respect to the anticipated *EDZ*; simplification of installations to minimise the risk of instrument failure (i.e. limit multi-instrument installations in single boreholes); and the minimisation of disruption to shaft-sinking operations and programme by planning activities to avoid the programme critical path.

At each measurement location, changes in the selected parameters were to be measured in a plane perpendicular to the axis of the North Shaft. It was assumed that the distribution of excavation-induced changes would be anisotropic but axisymmetric (i.e. with respect to the axis of the North Shaft). Instrument array layouts targeted the specified plane or horizon and, as far as practicable, all instruments were to be installed in this plane. The preferred arrangement of boreholes and instruments consisted of:

- an array of three overcoring stress measurement, stress-change monitoring and *acoustic emission (AE) monitoring* boreholes drilled from the North Shaft. These to be inclined at -70° , separated by 120° intervals in azimuth. This layout was determined in part by the geometrical requirements of the AE system, and by the need for the strain monitoring cells to be within the North Shaft EDZ.
- an array of three extensometer & packer extensometer boreholes drilled from the South Shaft in advance of North Shaft excavation at a nominal inclination of -5° .

Each borehole was to be geologically and geophysically logged to assist in the identification of features of interest. Cross-hole *seismic tomography* carried out between boreholes drilled from the South Shaft would provide data to assist locating individual instruments. Short, sub-horizontal boreholes drilled from the North Shaft at each of the three locations, would allow measurements for *estimation of mechanical rock properties* conducted using a specifically-developed proprietary ultrasonic logging tool. The overcoring stress measurements were to be carried out using CSIRO HI cells, and would provide information on the undisturbed stress tensor prior to excavation of the North Shaft in the zone of interest. On completion of overcoring stress measurements, CSIRO HI cells would be installed to monitor stress changes in response to excavation.

The *acoustic emission monitoring* system design allowed for two sets of sondes. The first (termed the AE system) was designed to monitor high frequency events (around 50 kHz) in the near-field, associated with excavation-induced rock fracturing. These sondes were also capable of transmitting signals to allow seismic interferometry to be conducted in the zone of interest. The second set of sondes (the microseismic or MS system) was designed to monitor lower frequency events (less than 10 kHz) in the near and far-field, associated with redistribution of the *In situ* stress field. Detailed procedures for active AE testing and passive monitoring were developed to allow the development of the EDZ to be assessed during the excavation of the North Shaft through the zones of interest. This involved a quiet period of four hours when sources of external acoustic and electrical noise were to be minimised. The AE system would be removable, whilst the MS system would be left in place for long-term monitoring.

The array of boreholes drilled from the South Shaft consisted of two Borehole Fracture Extensometers (BOF-EXs) and one Packer Extensometer (PAC-EX). The BOF-EXs were to measure strain in the specified plane around the North Shaft, and provide a continuous profile of measurements from the most disturbed areas close to the shaft wall, to essentially undisturbed conditions remote from the shaft. Measurements were to be made in a zone extending from approximately 0.5 to 3 diameters from the shaft.

Because of their arrangement in plan, BOF-EX measurements would include components of both radial and tangential strains which it would not be possible to separate. The measurements were designed in two adjacent quadrants to provide information on strain and stress anisotropy. PAC-EX instruments were to be used to monitor changes in the mechanical aperture of selected fractures as a function of time, hydraulic pressure and radial distance from the North Shaft. Active testing of the instruments could also be carried out and would involve perturbing the system by increasing or decreasing pressure in the test zones, and monitoring displacements, pressure changes and pressure-recovery times.

6 Hydrogeological Measurements

The hydrogeological measurements were designed to determine the *In situ* hydrogeological conditions in the formations penetrated by the shafts and to estimate shaft impact on local hydrogeology. Specifically, the measurements included:

- Quantification of the inflows of groundwater into the shafts during construction;
- Measurement of near-field, and possibly far-field, formation fluid pressures in boreholes drilled from the shafts;
- Collection of groundwater samples for hydrochemical analyses and installation of instrumentation for the *In situ* measurement of Eh, pH, temperature, and chloride;
- Formation hydraulic testing in probe holes in advance of excavation;
- Formation hydraulic testing in boreholes drilled from the shafts; and
- A long-term pumping test to explore the impact of the shaft construction on the Brockram formation, immediately above the potential repository formation.

Inflows of Groundwater into the Shafts were to be quantified by measuring the inflow

and outflow from the shafts and calculating the net groundwater flux. The shafts would have acted as large diameter well(s) for at least part of the construction period and their hydrogeologic impact was to be estimated from the quantities of groundwater flowing into them. The design provided a detailed methodology for flow monitoring of construction water, estimating the inflow from singular hydrogeologic features, and monitoring the water pumped from the shaft sump. The basic monitoring would calculate the net flux to or from the shafts from the construction water, water pumped from the shaft, and the fluid drained from the shaft muck, all recorded daily on the science programme's Automated Data Acquisition System (ADAS). Water garlands installed on the shaft wall below zones of enhanced drainage would provide an additional means to observe the inflow capacity of the formations penetrated by the shafts.

The construction water was also to be tagged with tracers to provide a quantitative estimate of the amount of construction fluid returned to the surface. The tracers would be a mixture of a colorimetric tracer, sodium fluorescein, and a conservative organic tracer, benzoic acid. Sodium fluorescein would provide a field determination of the construction-water dilution which would be confirmed by HPLC analysis of the benzoic acid.

The design for ***Groundwater Pressure*** measurement allowed for the collection of data with which to estimate the long-term fluid-pressure response of the local formations during and after construction. After construction, the formation fluid pressure of formations sealed by the shaft lining would recover while those in the unlined portion of the shafts would depressurise to a steady condition. Groundwater pressures would be observed using single and multiple-packer configurations and long-term monitoring instruments. Boreholes would be set in recesses in the shaft wall to allow for long-term maintenance.

Hydrochemistry of the groundwater in formations penetrated by the shafts was to be determined by collecting and analysing water samples from boreholes and shaft inflows, and from *In situ* hydrochemical monitoring equipment installed in sealed boreholes drilled from the shafts. Analysis would include species sensitive to oxidation state and atmospheric contamination such as Fe species, Eh, pH, alkalinity, ¹⁴C, helium, and dissolved gases. The *In situ* equipment package would have comprised instruments, packers, valves and flow cells. The potential contamination of samples would be evaluated by monitoring tracer concentrations using field fluorometry to determine sampling time. Only groundwater samples with less than 1% tracer concentrations would be collected for analysis. Final assessment of construction water contamination would be based on analysis of benzoic acid tracer concentrations.

Probe-Hole Hydraulic Testing of sequences of up to four probe holes drilled before each segment of shaft excavation was to be used to establish the pressure and flow potential of formation-fluids below the current location. A testing sequence was developed to measure cumulative flow from the probe holes; determine the probe hole with the largest volume of flow; identify significant hydraulic connections among the probe holes, and collect groundwater samples for field and laboratory analysis.

Probe-hole testing equipment would comprise a single expandable packer to divert flow and isolate the probe holes so as to more fully characterise singular hydrogeological features, rather than the entire length of the probe hole.

Hydraulic Testing in Boreholes drilled from the shafts at selected depths were intended to provide estimates of the bulk hydrogeological parameters for the formation, to provide fluid-logging profiles of the distribution of inflow or outflow along the length of boreholes, and to provide pressure versus time data for selected isolated zones. Crosshole testing would be used where possible, to examine the rocks around the shafts and between the boreholes. Testing would comprise sequences of flow and shut-in periods, usually initiated by shutting in boreholes as soon after drilling and geophysical logging as possible to monitor pressure recovery data. The total-flow and pressure-recovery data would be used to estimate bulk-transmissivity, and provide formation-to-formation and borehole-to-borehole comparisons. Full profile evaluation would be obtained using “moving packer” fluid-flow logging to observe salinity contrasts in low-permeability formations.

Boreholes used for testing would also be used for long-term fluid-pressure monitoring, so shaft wall recesses for borehole wellheads were created to allow the installations to be protected from excavation and post-construction activities.

All hydraulic testing would be monitored and controlled with a portable data acquisition system using the real-time data-analysis software GTFM to optimise testing time, account for pre-test borehole-pressure history, optimise estimates of formation parameters, and provide estimates of the confidence in estimated parameters. Active tests would be terminated as soon as performance objectives are met, or if further improvements in confidence levels were not possible.

Long-Term Hydraulic Testing of the Brockram Formation, a key formation above the potential repository host rock, was designed to evaluate the long-term effects of the shafts and determine whether a pressure signal could penetrate into the host rock. One or more boreholes would be drilled from the base of the South Shaft and tested using a constant-pressure production method with an imposed sinusoidal variation in rate or pressure to uniquely identify the test’s pressure response.

Responses would be monitored in the site-wide network of boreholes with multi-packer systems to evaluate regional permeability anisotropy, along with tracer additions. The production borehole would be equipped with a high-pressure control valve, a digital flow meter, a sampling port, a pressure controller to control flow rate variations, all monitored with a smart data acquisition system. The long-term test would be optimised using GTFM real-time analysis software.

7 Integration with construction

The design of the RCF comprised two elements; the engineering construction of the shafts and the scientific programme, which were to be carried out concurrently. These two elements required careful integration both to ensure that the scientific objectives were not compromised by the construction activities and that the construction activities were not unreasonably impacted by the science programme.

In addition to developing individual measurement designs, detailed Sector Test Plans were drawn up showing the locations and interactions of the measurements. These plans demonstrated how the required data collection would be acquired in a cost-effective manner, with the lowest disruption to shaft construction operations, and were a major element in the overall design. Mutual early planning also allowed the Shaft Sinking Contractor to plan scheduled activities, work schedules and crew changes, equipment maintenance and changeover, and safety activities. Regular collaboration meetings were held to anticipate and identify potential activity conflicts and establish working solutions.

Particular problems addressed in this integration process were the timing of tests, working space constraints, protection of equipment from blast damage, sequencing of test installations in sections which had to be lined, management of water inflows, safety and co-operation in the provision of services. Some tasks were duplicated in the construction and science designs and the responsibilities were optimised at this stage.

Scheduled monitoring of construction data jointly managed by the Science and Shaft-Sinking Contractors was also planned, with the objective of ensuring collection and preservation of data relevant to the science activities and their interpretation.

8 Data Management

Data Management procedures were developed in the form of a comprehensive Information Management System (IMS) to ensure that all construction, monitoring, and testing information would be properly collected, archived, and made available for retrieval. This information would consist of either electronically or manually recorded data uniquely identified along with its relationship to other information.

Linkage of the IMS data streams would ensure that the large number of interactive science tests could be tracked accurately and allow real-time decision making regarding test durations and modifications whilst maintaining scientific integrity. The data-collection function was designed for user access and to be flexible enough to allow corrections as needed. The IMS would also have available information such as calibration data to assure data quality.

The science database would be linked to a graphics-and-analysis package to allow data display in multiple graphical formats and performance of basic filtering using specialised data-analysis software including compatible data/software formats.

Information retrieval would be via a graphical user interface allowing a multiplicity of formats to meet the needs of the users, with specific criteria for time, location, type of information, and relationship to other information in the database. The database would operate as a satellite to the Nirex RCF Database, which was to have been the central repository for both construction and science-related information. The IMS would also have been linked to and integrated with the pre-existing site-wide historical database.

9 Summary

The testing plans developed in the science design for the shaft-construction phase of the proposed RCF represented an effort to obtain a body of data to provide a baseline, early-time representation of hydrogeological conditions and geomechanical integrity of the rock mass around and above the RCF before it was fully constructed. The Science Programme was designed interactively with Nirex and the Shaft-Sinking Contractor to ensure timely and cost-efficient data collection without compromising either scientific objectives or construction quality.

Because the state of stress, the hydrodynamic equilibrium, and the local hydrochemistry would change in the months and years following construction, data collected during the construction period would be an important benchmark against which all future changes can be compared.

The Science Design incorporates state-of-the-art technologies such as digital imaging, *In situ* hydrochemical and geomechanical instruments, acoustic emission monitoring techniques, benzoic-acid tracers and real-time test-analysis software. A high-capacity, interactive data-acquisition system was planned as part of a comprehensive data-management system, designed to assure data integrity and accessibility within a defensible Quality-Assurance framework.

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