6.2.2 Site characterisation and site confirmation

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Overview

The domain insight 6.2.2 “Site characterisation and site confirmation” is part of the wider sub-theme that aims to investigate one of several potential sites to demonstrate that they would be suitable from a post-closure safety perspective and other viewpoints (sub-theme 6.2 “Site investigation and confirmation”). This sub-theme is part of theme 6 “Siting and Licensing”.

It relates to the programming and realisation of detailed site characterisation(s), through a complete safety assessment, and preparation of an environmental impact assessment to the level required for construction and operational licence application submission.

The site characterisation and confirmation phase programme are usually called “characterisation or pre-licensing phase” and marks the final stage of the siting process. Due to the financial and human efforts needed to start actual work on site, it is assumed that the site is suitable for construction of a disposal facility and adverse geoscientific features are unlikely.

The site selection process is part of the sub-theme 6.1: ”Establish site selection process and site screening” and will be conducted prior to detailed site characterisation.

The detailed site characterisation phase at one or more sites, starts after the screening and site selection stage. The site characterisation and confirmation phase ends when the licence for construction of a DGR is obtained. However, in consistency with [IAEA, 2023], site investigations activities will last throughout the period of operation and closure activities to support updates of safety reports.

Keywords

Site investigation, site characterisation, siting phase

Key Acronyms

DGR: Deep Geological Repository

EIA: Environmental Impact assessment

SCP: Site Characterisation Programmes

SDM: Site Descriptive Model

1. Site Characterisation and Confirmation domain: overall goals, objectives, activities and strategies

1.1 Goals

The goal of initiating a site characterisation and confirmation phase is to obtain sufficient detailed data from a site to document the safety models, confirm that the selected site is suitable for hosting a geological disposal facility and that no adverse features may jeopardise the licence approval process and the provision of authorisation to construct a repository. The data are synthesised in the site descriptive model (SDM), which is a key document to support the safety assessment, and the environmental impact assessment (EIA) and the design, construction, and operation of the disposal facility. The results and data obtained are presented in the licence application.

The types of datasets collected during site characterisation and confirmation stage are related to a wide range of activities, many of which will be continued from earlier siting phases, or which would extend into further phases of the roadmap for a deep geological repository (DGR), such as:

- Activities undertaken for confirmation that the geoscientific and environmental aspects of the site make it suitable to host a repository from a safety and environmental perspective (additional detailed geological mapping, deep drilling and associated investigations, geophysical surveys, biosphere studies, etc.).
- Activities to collect additional site parameters for detailed design of the facility and associated infrastructure (geotechnical investigations, hydrological and hydrogeological surveys and investigations).
- Activities to define and design monitoring and surveillance programmes for the disposal facility during its construction, operation, and eventually closure phases (seismic network, piezometric networks, environmental networks, etc.),

The above indication of activities to be carried out during site characterisation are not by any means exhaustive and the detailed plan of activities to be implemented at a site will strongly depend on national and local site circumstances. In any event, the detailed site characterisation plan will consist of multiple site survey programmes, some of which could last beyond the construction and operation of the DGR.

Results and data obtained during all the phases serve to strengthen conceptual and numerical models dealing with natural site evolution as well as the disposal facility’s impact on the geosphere, biosphere and safety modelling.

The data also serve to enhance confidence building for construction, emplacement operations, closure, and long-term monitoring of the disposal facility.

This domain insight mainly deals with the planning, technical means (including equipment, tools, methods and their strategy for use), and data management during the site characterisation phase.

6.2.2 Site characterisation and site confirmation

Domain Goal	
6.2.2 Undertake detailed site(s) investigation, confirmation of the site, through a complete safety assessment, and preparation of an environmental impact assessment to the level required for construction and operational license application submission (detailed site characterisation and site confirmation	
Domain Activities	
Phase 1: Programme Initiation	Generic studies to identify the key geoscientific and environmental parameters to acquire during the operation associated with the characterisation programmes to comply with the key safety options. Identification of key parameters to be acquired and key information to be collected from safety guides documents, key geoscientific and environmental domains.
Phase 2: DGR Site Identification	Evaluation of the geographical regions, level of information available and gaps to be filled. This includes the collection of existing information in national geological, meteorological, environmental, administrative and land use databases to prepare the detailed site characterisation programmes. In addition to open sources/national databases, pre-existing oil and mining survey information or desk-based studies form part of the basis for selecting one for detailed characterisation.
Phase 3: DGR Site Characterisation and confirmation	Develop site characterisation programmes (SCP). Definition of the level of detailed information to be acquired in each of the geographical regions and the associated means and tools. Performing the detailed characterisation observation/measurement/sampling specialised activities defined in the SCP consistent with the stage of development of the DGR. Management of the data, synthesis of the observations and preparation of the documentation to be incorporated in the SDM confirming the suitability of the site.
Phase 4: DGR Construction	Site characterisation and confirmation data during phase 3 will provide the framework to set up a monitoring network including all compartments of the geosphere and biosphere to monitor impact of the facility on its environment. It may provide input to objectives and means for the development of post closure requirements for monitoring.
Phase 5: DGR Operation and Closure	Continued monitoring of selected key measures of performance to confirm that the system is performing as expected and to help identify the significance of any observed deviations.

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1.2 Objectives

After selecting potentially suitable sites for a disposal facility, as an earlier part of the siting process, detailed site characterisation programmes should be defined at any remaining sites to fulfil the goal of the siting, which is to submit a license application and receive an authorisation to construct a repository for one of them.

Thus, the detailed characterisation stage aims at:

- Acquisition of geoscientific information on the rock mass and groundwater bodies present at the site. The geological and hydrogeological information will allow the proponent to produce a geoscientific reference document, the SDM that will support the development of more detailed and site-specific design studies and safety assessment (beyond conceptual designs and preliminary safety assessments initiated in previous phases). This geological information should include geometrical aspects to identify a suitable volume of the rock mass to accommodate the volume of waste, as well as rock mass conditions and hydrogeological (including hydrochemical) characteristics to support preliminary computations for safety assessment. This acquisition is carried out through surface investigation, borehole investigation and sampling. If required/necessary, an underground research laboratory (URL) could be constructed to obtain realistic data representative of the selected site conditions. Such a URL might be generic (i.e. not located at the prospective site for disposal), in which case any data collected would be analysed and interpreted as analogue information, or a URL might be site specific (i.e. located at the prospective site for disposal), in which case any data would more likely reflect actual repository conditions at the site, especially if the URL later became an integral component of the repository.
- Data driven production of conceptual and numerical model(s) that will represent the current state of the site as well as its past and future evolution (geological history, geoprospective, climate changes, etc.). This information will serve to justify the phenomenological basis for the evolution of the disposal facility and its environment, including the production of evidence-based scenarios of future conditions.
- Production of technical information to address design and construction issues linked with site preparatory works, surface infrastructure (railways, roads, storage facility, maintenance, and operating building), as well as underground excavation and support structures e.g., ramp, shafts, and drifts. Effects of construction on the environment (surface drainage systems) as well as rock mass behaviour should be studied. Hydraulic parameters involved in surface drainage, as well as connecting water bearing structures through shafts and ramp should be precisely described and evaluated.
- Production of information for supporting communication and dialogue with national and local stakeholders (regulators, scientific community, political community, administrative bodies involved and public). This information should explain the level of scientific understanding and present the preliminary options of the safety case for a disposal facility.

The detailed site characterisation activities require careful planning to provide the necessary data to support the licence application. Most of the techniques and tools to be employed may be obtained from vendors and contractors associated with water supply, geothermal, mining or oil prospecting sectors. However, the strategy for using these tools differs substantially from the prospecting activities of other industrial sectors because the need for identifying the location of exploitable natural resources and maximising their production is fundamentally different from the need for characterising and preserving the natural confinement properties of geological media to be used to host a repository. In addition, specific tools and test procedures have been developed for acquiring data in very low permeability environments, as well as special protocols for sampling cores and minimising groundwater contamination.

1.3 Activities

1.3.1 Building a SDM

A SDM is an integrated multidisciplinary description of a site and its regional environment with respect to the current state and naturally ongoing processes.

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The SDM synthetises a series of site discipline-based site descriptions for the whole site. The descriptive model includes information concerning the site's regional setting. The geology provides the framework for all other models. The descriptions associated with an SDM include the geometry of system components, populated by properties.

The SDM comprehensively describes the site from past to present time and includes the results of any numerical modelling undertaken to better understand the site and its evolution to date.

1.3.2 Analysis of available data

During the conceptual planning stage and area survey and site screening stages, studies include the analysis of all available data. Geophysical, climatic, hydrological, hydrogeological, seismic and other data are collected to produce maps and 3D models established with more or less accuracy depending on the region. This may include information derived from historic hydrocarbon exploratory drilling or seismic campaigns conducted within sedimentary basins or drilling surveys for ore exploration in granitic formations for example.

During the characterisation and confirmation stage, the investigation work is focused on the verification of a wide range of parameter values associated with site properties required for the fulfilment of safety functions and design options for the DGR.

1.3.3 Geological work programme

The geologic information required from the site investigations to create the site descriptive model includes (depending on national regulations), but is not limited to:

- The regional geological setting and description of the spatial heterogeneity of the geological units,
- The topographic form of the site and its surrounding region with a description of the main geomorphological features,
- The nature and properties of the soils and any superficial sediments or any geological layers overlying the host rock,
- The nature and properties of the host rock,
- The nature and characteristics of the structural geological features,
- The nature, extent, and history of exploitation of mineral deposits and other natural resources within the area,
- The geological evolution of the area including the genesis, relative age and nature of fracture-filling materials and studies of displacements and movements along discontinuity surfaces,
- The nature of volcanic activity at the site if any, from a knowledge of Quaternary and earlier volcanism,
- The nature of tectonic activity of the site from knowledge of geologically recent fault movements and the aid of seismological monitoring,
- The nature of geodynamic processes at a site (e.g., erosion, uplift, and subsidence).

1.3.4 Hydrogeological Work Programme

The hydrogeological information required from site investigations to build the hydrogeological and dispersion conceptual and numerical models comprises among other things:

- The extent of the flow system affecting the site and the nature of its boundaries to define the extent of the modelled area,
- The surface water hydrology including the location and extent of water bodies, the recharge and discharge area, the temporal variation in flow, the impact of weather and climate variations and the water balance,
- The geometry of the different hydrogeological units within the overall flow system and any relation to observable geological features,
- The hydraulic and transport properties associated with the hydrogeological units (e.g., transmissivity, hydraulic conductivity, porosity, storativity, flowing fracture frequency, dispersion lengths) to describe flow and solute migration within and between them,
- Flow stream description and properties within and between the hydrogeological units,

- The spatial and temporal variations in groundwater pressures within the groundwater flow system,
- The hydrogeological evolution of the area.

1.3.5 Hydrogeochemical Work Programme

To characterise hydrogeochemical conditions at the site, describing the origin and flux of the water in the rock mass, vertically and horizontally, including also the following,

- The hydrogeochemical compositions of the groundwater from any identified groundwater units,
- The characterisation of rock/water interactions influencing the current and the past groundwater compositions that may have relevance for radionuclide retardation, and evidence of structural or stratigraphic controls on groundwater composition,
- The isotopic composition indicating the ages or 'residence times' of water and solutes in the groundwater system, and evidence of recent flows,
- The composition of groundwater at disposal depth that will re-saturate the backfill,
- The distributions of trace elements, natural radionuclides and related stable nuclides that are analogues for the geochemical behaviour of waste-derived radionuclides,
- The distribution, nature and composition of dissolved gases in any identified groundwater units.

1.3.6 Geotechnical Work Programme

The geotechnical information required from site investigations, to be used in engineering design and construction studies comprises among other things:

- The mechanical properties of the rocks and soils that could influence the design and construction of the facility at all depths of interest,
- The thermal properties that will have direct implication on the distance between deposition holes for canisters. Thus, it will define the suitable volume of rock mass or size of the footprint of the repository,
- The magnitude and orientation of in-situ stress and determination of how stress/strain has changed in the past and might evolve, if this is relevant to safety.

1.3.7 Biosphere Work Programme

The biosphere information required from site investigations to provide data and information on the characteristics of the site and support the EIA are:

- Geographic location, land use and topography,
- Measurements and seasonal variations of local weather conditions including precipitation, wind strength and direction, solar insolation and temperature, actual and potential evaporation, etc. including a description of potential hazards associated with extreme weather conditions,
- Long-term variability in climate,
- The characteristics of the near-surface geology, hydrology, hydrogeochemistry, hydrogeology relevant for biosphere interpretations,
- A description of the soils across the site,
- The extent of terrestrial vegetation across the site including cultivated land and forests,
- A survey of terrestrial fauna and especially endangered and protected species,
- Human habits, behaviours, and characteristics at the site.

Further discussion and information regarding the information required from site investigations and its use may be obtained from [IAEA 2023].

1.4 Survey strategies

1.4.1 Survey areas and boundaries

The boundaries of the investigation areas and depths to be surveyed are to be determined by identifying and evaluating potential radionuclide migration pathways over very long-time scales, considering the occurrence and location of potential discharge zones. Potential future changes to the hydrogeological system must also be assessed.

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In practical terms, regional surveys are likely to be continued in greater detail than in earlier phases of work. The regional context is likely to be defined as an area bounded by topographic features or geological structures and formations that may be used to delineate the location of hydrological and hydrogeological boundaries (water catchment, river, or coastal boundary). These features would be expressed by various types of boundary conditions in regional hydrogeological models.

Typically, a site would be identified as a defined area nested within its regional setting. As such, the site area is influenced by the regional hydrogeological conditions and modelling would be used to establish groundwater flow vectors and flow rates within the site. Natural features, administrative divisions or otherwise specified coordinates may be used to define the boundaries of the area comprising a "site". If the site area is large enough, the repository location (footprint) can be optimised in terms of its location within the site in a zone considered favourable.

1.4.2 Choice of the survey grid and key parameters adapted to this grid

The amount of information to be acquired about a given property within an investigation area is determined according to several criteria. Measured property values must be of appropriate accuracy and precision, but they must also be representative. Most important in this regard is knowledge about the spatial variability associated with the properties found within the geological environment under investigation. This variability arises from various factors associated with the genesis of the lithologies present, as well as their geological and hydrogeological evolution. For example, the spatial variability of properties associated with sedimentary formations will reflect the relationship between different facies making up the depositional units and their subsequent diagenesis and weathering, amongst other factors.

For intrusive crystalline rock types, the petrophysical characteristics of a defined lithology may be relatively homogenous over large length scales. However, structural overprinting and differential movements within a rock mass would induce a degree of complexity and variability in property values. Based on the degree of property value variability in the formations present, as well as the defined data requirements, it is possible to establish survey grids within an area, which are necessary to take samples and representative measurements needed to fulfil characterisation objectives.

1.4.3 Specific features

Detailed studies on specific features present at a site shall be conducted as these may be important for the construction, operation and/or long-term safety of the disposal facility.

These features can be structural objects, such as faults or fracture zones located within or at a distance from the footprint of the disposal facility, or seismic activity and surface elevation modifications linked, for instance, to glacial rebound.

The scope of the characterisation studies will be adapted according to the geological environment of a selected site.

1.5 Site characterisation technologies

Geological characterisation methods fall under three categories: (i) surface methods including satellite-based and airborne system, (ii) survey and characterisation methods undertaken in boreholes, and (iii) methods applied in survey drifts in a URL or the disposal facility. Specific techniques and technologies are associated with each method to describe or measure the characteristics of the surface and underground. These methods have been developed over time through government funded research and development or through commercial innovation and applications, such as within oil or mining exploration companies, by civil engineering companies, and by organisations in charge of the management and protection of hydrogeological or geothermal resources.

The technologies and methods used in the site characterisation stage are generally similar to those employed earlier during site investigation. The difference originates in the need for more, and more detailed and site-specific data, especially from the sub-surface, and in which there is a high level of confidence. Generally, in the later stages of a siting programme, existing investigation methods suitable for relatively high-level evaluation are further developed, improved and adapted to the geological environment of the site and the requirements to be met.

1.5.1 Surface methods

For sedimentary formations, surface based geological methods, such as outcrop mapping and tectonic analyses are used to characterise the sedimentary geological setting with particular attention given to interpreting stratigraphic relationships, geometry and structure (i.e., faults and fracture networks). These methods can be complemented by near surface “light” geophysics data acquisition methods (e.g., electrical recording, radar, etc.) in order to determine specific layer geometry and localise discontinuities in the sub-surface. The geological models supported and derived from these data are used, in part, for the static correction of 2D and 3D seismic data necessary to compensate for velocity variations in overburden.

2D and 3D seismic methods are used primarily to reconstruct the geometric framework of the geological media (bedrock stratigraphy, presence of faults or fractures). Results are available in the form of line data (2D) or blocks of data (3D). At depths commonly considered for a geological waste disposal facility (a few hundred metres to a thousand metres) these methods can reveal the presence of faults a few metres in vertical throw. Technical 3D resolution is better than 2D as it relies on the spatial coherence of datasets and emphasises the identification of low-amplitude discontinuities. Stratigraphic inversion or analysis of seismic data has been used to infer petrophysical attributes such as images of porosity variation in carbonates and siltstones. However, in argillaceous formations, only a qualitative estimate of variability can currently be made based on such data.

In crystalline rock formations, in addition to seismic methods other techniques such as magnetic, electromagnetic and magneto-telluric methods, measurements of electrical resistivity and of gravity are commonly used. For site characterisation in crystalline rocks, examples of the application of site investigation methods can be seen in Finnish and Swedish studies.

Finally, to complete this discussion of surface-based investigation methods, the installation of a seismological monitoring station should be included in this category. This network provides recordings of the natural seismicity and contributes to the general survey of the site.

1.5.2 Survey and characterisation boreholes

Once the geometry of the studied formations and the survey grid are defined, drilling is a rapid means for collecting information on the physical and chemical nature of the in-situ rock and interstitial fluids.

Drilling rigs come in a range of sizes that are rated to drill under different ground conditions to various depths. The power necessary to drill down to a specified depth with a prescribed borehole diameter will vary in relation to the rock type being drilled and this would be reflected in the size and complexity of rig needed.

For hard rock environments, quite small and highly mobile rigs may be used to drill relatively narrow diameter investigation boreholes to depths of several hundred metres.

Conversely, for investigations in weak or friable sedimentary environments prone to instability, such as encountered in poorly indurated cover or clay rocks, larger diameter boreholes are required for obtaining core for rock mechanical testing in a laboratory. These boreholes could be drilled down to 2000 metres depth and require specific drilling muds to ensure borehole stability.

Depending on the characterisation objectives, the boreholes can be vertical, inclined or deviated; vertical boreholes are suited to the study of tabular structures, deviated or inclined boreholes are more appropriate for the study of sub-vertical fractures, and sub-horizontal or directional boreholes are suited to the survey of future drift axes.

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Cored boreholes provide detailed knowledge of the geology underground and permit the direct observation of petrophysical, sedimentological and structural features. In addition, detailed mineralogical characterisation of each horizon can be achieved in a laboratory, as well as various direct measurements such as density, porosity and permeability.

In general, percussion drilling is implemented in any aquifers overlying the host formation and the boreholes are often dedicated to hydro-geochemical characterisation in order to minimise contamination of samples.

The measurement and analysis programme comprises,

- The analysis of the cuttings or cores and the follow-up of the drilling parameters,
- Geophysical wireline logging including hydrogeological logging tools (flow logging, electric conductivity fluid logging, heat flow logging),
- Geochemical sampling with in-situ samplers,
- Packer tests for hydraulic parameters (hydraulic conductivity, specific storage),
- Geomechanical tests for acquisition of a stress profile (HTPF),
- Tracer testing (in suitable formations).

Once the borehole and associated in-situ measurements are completed, borehole instrumentation can be installed. Generally, such completions are installed to observe the stabilisation of formation pressures, which in low permeability sediments may occur over periods of 1 to 2 years. Disturbances causing fluctuations in groundwater pressures may also be observed. Understanding the basis for natural and induced variations in groundwater pressure is important for establishing baseline conditions and interpreting larger scale hydraulic conditions at a site.

Hydrogeological equipment commonly installed in a deep borehole may comprise:

- Pressure or pressure/temperature,
- Multi-packer completions (also for pressure monitoring or for periodic hydrochemical sampling),
- Sophisticated completions to investigate the diffusion of natural radioisotope tracers,
- Optical fibre temperature measuring devices.

1.5.3 Survey and characterisation drifts

After establishing geological conditions based on surface and borehole investigations, the underground research programme has to demonstrate that the construction and operation of a geological disposal will not introduce new pathways for radionuclide migration. 3D characterisation of the rock mass underground may also be necessary to confirm hypotheses or address outstanding geological and hydrogeological uncertainties. Thus, the construction of a URL or the first excavation in the disposal facility itself serves an investigation/confirmation/validation purpose through further data acquisition and the monitoring of excavation effects. A URL also permits the development and optimisation of construction technology.

To achieve the scientific objectives of surveys in underground drifts when construction is underway elsewhere, a specific methodology should be devised for carrying out the experimental programme concurrently with the construction of the shafts and drifts, to ensure that scientific and engineering objectives are coordinated and not in conflict. Key aspects contributing to the formulation of the methodology are: (i) specification of procedures and processes to address all the questions related to the scientific or technical domain, (ii) clarity concerning contractual and organisational processes and obligations and (iii) the in-depth analysis of previous international URL and disposal facility construction experience.

1.6 Environmental characterisation

To assess the impact of construction and operating of the disposal facility on the natural environment, an environmental monitoring programme should be implemented prior to any major construction work.

The monitoring programme should comprise:

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- Soil variability and quality for the main land types present in and around the site area: forest, grassland, and crops. This may include biochemical stations for assessing the biomass budget.
- Meteorological network (wind, temperature, rainfall, air quality survey, greenhouse gases etc.). This information provides baseline understanding and also contributes towards addressing groundwater budget calculations.
- Surface water flow monitoring and geochemical quality for the drainage network contributing towards the groundwater budget.
- Biodiversity monitoring network for flora and fauna
- Land use survey, including surveys of agricultural practices.
- Periodic satellite data and aerial photos to track land cover changes.

1.7 Data Management

The management of high-quality and traceable data throughout the site selection process (all phases and stages) is essential for providing assurance to the regulator and other stakeholders that tasks associated with data acquisition, interpretation and integration have reliably been carried out in conformance with specified procedures. Such assurance is necessary for ensuring confidence in a licence application and public acceptance.

As site characterisation progresses, an ever-increasing amount of data and processed information will be generated. Some data will reflect spatially defined one-time measurements, while others will reflect time-series sampling.

Many of the datasets will be very extensive, reflecting high spatial or temporal resolution and/or large investigation volumes, such as seismic surveys. Data will be collected using a wide range of techniques to investigate a wide range of features and processes. The accuracy, precision and the representativeness of the parameters measured will vary greatly, depending on the technique used and the feature or process being considered. Technical and descriptive metadata providing context for underlying data, will also need to be captured and stored.

Raw data collected in the field or in the laboratory may need to be processed to provide derived data (e.g., field derived parameter values reflecting water table fluctuation or groundwater pressure measurements are necessary for producing ‘hydraulic conductivity’).

A robust quality assurance system should be developed in order to guarantee the preservation of:

- The data flow management, (including responsibilities, etc.),
- The description of data acquisition techniques,
- The metadata associated with all datasets,
- The data control at different steps of their use,
- The information associated with them.

End users, primarily safety assessment modellers and repository design engineers, will take the site derived data and information as well as any elicited information and wider research data (e.g., from natural analogue studies or generally applicable information derived from elsewhere), and use them for the calibration of numerical models.

2. Detail of investigations (during site characterisation and confirmation) to achieve operational and post-closure safety.

This section describes how the domain of site characterisation and confirmation (and its associated information, data, and knowledge) contributes to overall safety demonstration and practical implementation of the DGR.

Considering EURAD Roadmap generic safety and implementation goals (see, domain 7.1.1 Safety Requirements), two main components for a DGR are relevant to this domain insight; the geological barrier and the performance of the disposal system over a long period of time.

6.2.2 Site characterisation and site confirmation

Physical investigations of the natural environment at a site require the acquisition and interpretation of a large volume of data and information to meet requirements. As investigations proceed, more data and information will be gathered which is likely to strengthen or challenge the understanding of the site and its evolution.

Because of the nature of iterative site investigations, site descriptions and conceptual models should be periodically updated to reflect a growing appreciation of the characteristics of a site based on further rounds of data acquisition and interpretation. It is possible that new areas of investigation will be required to assess the significance of newly identified features and processes that might impact the safety or design of the engineered system. This means that it will not be feasible to fully define and fix all the data and information requirements for site investigations at the beginning of the project. Consequently, flexibility in operations is necessary to allow for redefinition of the requirements and modification of site activities in response to new data, information and understanding that is obtained as site investigation proceeds.

Site characterisation drilling and geophysics will provide further information regarding the thickness and properties of formations within the rock mass that will ensure satisfactory waste isolation. Such information would also enhance models used to calculate the location and volume of host rock needed for the disposal facility and for identifying the characteristics of any unfavourable geological features to be avoided.

Borehole measurements, including those obtained from core/fluid/gas sampling, would provide information supporting the second key safety function of a disposal system, containment, which is intended to prevent or limit the transfer of radioactive substances and toxic elements in the waste to the biosphere.

Hydrogeological tests and core and fluid sampling measurements are used to identify aqueous and gaseous pathways, as some of the long-lived radionuclides present in the waste inventory are liable to dissolve in water and potentially migrate to the surface.

Thus, key activities during the site characterisation and confirmation stage will be to verify, through tests in boreholes and sampling, that the host rock possesses intrinsic properties to maintain the integrity of engineered and natural barriers (for isolation), in addition restricting water migration, limiting radionuclide dissolution and promoting the retardation of radionuclides (for containment). These properties must be ensured over long periods of time (from thousands to several hundred thousand years).

Through environmental and groundwater monitoring, using surface and borehole monitoring networks, baseline conditions can be established and diagnostic indicators, such as groundwater pressure fluctuations, may provide information on a site’s evolution prior and after the construction of the disposal facility. Seismic monitoring at the site, as part of a national seismic network, will provide information with which to assess the seismic risks in the region or area.

These monitoring networks will evolve over time to meet the needs for long-term monitoring of the repository facility.

The aim associated with monitoring is to maintain favourable site properties that are conducive to post-closure safety, despite the perturbations caused by construction of the facility (excavation damaged zone, i.e. fractures caused by stress redistribution around the underground structures after excavation).

Detailed investigations during the site characterisation and confirmation stage will provide in-situ stress assessments derived from regional analysis, borehole measurements, core sampling and laboratory measurements of the core samples. Such assessments indicate the expected stability of disposal components within a repository. However, the most reliable data may come from experiments and observations carried out at the real depth of the disposal facility in a URL.

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3. International examples of research programmes

France Andra - Cigéo Project: Since 1991, research has been carried out to examine different strategies for managing the most hazardous radioactive wastes. This research led to a decision in favour of deep geological disposal.

The Nuclear Safety Guide N°1, issued by ASN in 2008, establishes the safety principles for the design and construction of a disposal facility for nuclear waste in a deep geological formation. The guide provides information on how the investigations should be carried out in the geological media, what parameters to measure and detailed specific requirements about quality assurance.

The objectives of the surveys carried out during the first phase of investigation (1994-1999) on the selected sites (at that time, investigations were carried out in three distinct sites) were to confirm that the geological formations proposed were adequate for the installation of an underground research laboratory and to propose a layout for these laboratories.

The essential aspects scrutinised were the site's internal and external geodynamic stability and its hydrogeological characteristics. Other important points concerned the mechanical, thermal and geochemical properties of the rock. A previous study of the available data (boreholes and reflection seismic profiles from hydrocarbon exploration) on the Meuse and Haute Marne Districts focused attention on a single area lying on the boundary of the two districts (called the Meuse/Haute-Marne site, or Bure site).

Surface based investigations were conducted in 1999 and 2000 to characterise the URL site and the wider area in more detail. At the laboratory site, a 3D seismic survey (covering 4.4 km^2) was performed to provide an image of the volume of the rock mass that would contain the laboratory with a greater level of detail than previously known. The survey confirmed that the Callovo-Oxfordian argillaceous layer is regular with a thickness over 130 metres. It revealed no faults in this layer or in the overlying limestone. Some anomalies were identified in the underlying formations, which were subsequently investigated with boreholes between 2003 and 2004.

Cored drilled boreholes were constructed along the axis of the proposed URL shafts to provide greater understanding of the geometry and nature of the geological formations.

On the laboratory site, four additional boreholes were drilled to various depths around the location of two shafts associated with the URL and they allowed geochemical and hydraulic tests to be undertaken. Consequently, it was possible to determine the hydraulic gradients in the three formations overlying the Callovo-Oxfordian (Calcaires du Barrois, Kimmeridgian marls, Oxfordian) and to specify their hydrodynamic characteristics to define the initial hydraulic state at the site before constructing the laboratory.

Additional surface-based investigations were conducted between 2001 and 2005 in the Meuse/Haute-Marne investigation area. Eight boreholes, reaching different depths at five different locations, were constructed in 2003 to measure the hydraulic head in the Oxfordian formations and in the upper levels of the Dogger formation, over a large area around the laboratory. Water samples were taken to analyse radionuclides present naturally (krypton-81 and chlorine-36) and to determine the time since they had infiltrated the rock.

Between 2003 and 2004, eight more boreholes were constructed. Four deviated boreholes were drilled to confirm the homogeneity of the Callovo-Oxfordian formation and the absence of faults. Four vertical boreholes were used to measure various parameters of significance to the consequences of gas generation.

The purpose of the research programmes in the URL is to provide the data and supporting evidence required to understand phenomena identified as important for the design and safety assessment of a disposal facility. Requirements that are more specific were set out in the 1991 Waste Act, which stated that measurements must be carried out in the laboratory to confirm or refine the values of parameters and to appraise anisotropy, spatial distribution, and scale effects.

6.2.2 Site characterisation and site confirmation

The experiments carried out for the URL involved the following:

- A thorough understanding of the relevant aspects of the geological, hydrological, and geochemical settings.
- The determination of the hydraulic properties of the argillaceous rocks over a range of scales using direct hydraulic measurements and inferences from coupled chemical and mechanical behaviours.
- The monitoring of construction and the controlled excavation of underground openings to characterise the EDZ.
- The testing of methodologies for EDZ mitigation and remediation.

Finland – Posiva Oy Okiluoto:

When Posiva's spent fuel repository site selection (see also domain insight 6.2.1) decision-in-principle (DiP) was positively assessed by government, the investigations for the confirmation of the Olkiluoto site commenced in 2000 (the Finnish Parliament ratified the decision-in-principle in 2001). The main objectives of these investigations were verification of the earlier conclusions on site suitability, more detailed characterisation and monitoring of features in the target host rock (such as lithological variation, localisation of brittle fault zones and groundwater flows, groundwater chemistry) and creation of detailed site descriptive models for repository design, safety assessment and planning of construction work, as well as definition and identification of suitable rock volumes for repository space. The characterisation activities were carried out in three partly overlapping stages:

1) Surface-based investigations (2000-2012)

- Drilling of deep and shallow cored holes (with a total of 46 deep drillholes, length varying between 200-1200 m) and extensive borehole investigations.
- Detailed geological mapping of outcrops and investigation trenches.
- Air-borne, surface, single-hole and hole-to-hole geophysical surveys including e.g. magnetism, electrical conductivity, density, seismic velocities and radioactivity; an extensive high-resolution reflection seismic survey.
- Environmental research for monitoring the state of Olkiluoto environment and the effects of ONKALO construction, including e.g. surface water studies, intensive forest research, observations and sampling of flora and fauna.
- Establishment of a local seismic network.

2) Construction of the access tunnel and shafts of the ONKALO underground research facility with parallel underground investigations (2004-2014)

- Pilot holes with extensive hydrological and geophysical surveys.
- Probe holes.
- Geological mapping of the underground openings.
- Hydrogeological mapping of and measurements of inflows in the underground openings.
- Characterisation holes.
- Upgrading the local seismic network.
- Construction of niches for various, typically long-running research projects that aimed at gaining information on specific topics, such as:
    - Sulphate reduction experiment (SURE).
    - Posiva's Olkiluoto spalling experiment (POSE) to establish in situ stress at about -350 m and spalling strength of Olkiluoto migmatitic gneisses.
    - Study of rock matrix retention properties (REPRO).
    - Hydraulic characterization of the rock mass and geochemical characterization of poorly conductive fractures (HYDCO).
    - A detailed study of the characteristics (depth, continuation, and hydraulic properties) of excavation damaged zone (EDZ).

3) Development and testing of rock suitability criteria and a rock suitability classification system with related investigations, and construction of test and demonstration facilities (2007-2014)

- Definition of the target properties of the host rock, related to chemical composition of the groundwater, groundwater flow, groundwater transport properties and thermomechanical stability was started in 2007 and culminated in 2009 in tentative criteria set for the host rock

for the purpose of locating suitable rock volumes for the repository (deposition tunnels and deposition holes).
- Testing of the criteria and development of investigation methods for their validation during construction of the access ramp and demonstration facilities (2009 - 2014) including, for example, two 3D tunnel seismic investigation campaigns as well as two mise-à-la-masse studies to test the efficacy of the methods for identifying local brittle features (small fault zones and significant fractures) in Olkiluoto.
- Development of the classification methodology during construction of the demonstration facilities (2010 – 2014).

The vast set of data collected from the investigations was compiled into the various site descriptive models, both deterministic and numerical (geological and hydrogeological structure models, geochemical model, model for rock mechanical and thermal properties model, geological and hydrogeological discrete fracture network (DFN) models, transportation model), and site descriptions were published in 2004, 2006, 2008 and 2011, the latest as background material for a safety case in support of the Preliminary Safety Analysis Report (PSAR) and application for a construction licence for a spent nuclear fuel repository, which was submitted in 2012.

ONKALO® underground research facility reached its planned extent in 2014, and after Posiva was granted the construction licence in the same year, the ONKALO® underground research facility was integrated into the planned final disposal facility and the construction re-commenced with the excavation of further vehicle access tunnels towards the planned repository. The focus of site investigations shifted from overall site characterisation to detailed characterisation of the repository host rock volume and to obtaining the information needed for the rock suitability classification and for design and construction activities. These investigations have since included geological, geophysical, hydrogeological and hydrogeochemical pilot hole and tunnel investigations during the 2016-2023 construction of a test facility (a test deposition tunnel and a set of test deposition holes) for a full-scale trial run for final disposal that will take place in 2024-2025 and, starting from 2018, during the construction of the first sections of repository central tunnels and the first five deposition tunnels and their deposition holes (ongoing).

The Olkiluoto monitoring programme has continued to cover the entire site, with special focus in monitoring the impacts of construction and operation of the ONKALO® on the hydrogeological, hydrogeochemical, rock mechanical and environmental conditions at the site. The data from monitoring and from the detailed studies of the repository host rock during construction have been used to further update and refine the site descriptive models, perhaps most notably resulting in the state-of-the-art ODFN3 (Olkiluoto discrete fracture network model v.3) in 2017, in support of the latest site description published in 2018. These have provided important information for further safety analysis and Posiva's safety case in support of the Final Safety Analysis Report (FSAR) and application for an operating licence for a spent nuclear fuel repository, submitted in the end of 2021.

Similar investigations are planned to be carried out during the whole operating period (around next 100 years), as the construction of the repository will proceed into rock volumes previously characterised only by surface-based investigations. The investigation methods will be refined along the way, as deemed necessary depending on possibly varying data needs in the future, for example.

4. Critical background information

With respect to site characterisation and confirmation, the key information, processes, data or challenges that have a high impact or are considered most critical for implementing geological disposal are:

- Basic safety guide issued by the Nuclear Regulation Authority (NRA) related to investigation for a geological disposal,
- Basic safety options for the project,
- Basic design and operation options,
- Disposal project strategy and implementation plan,
- Result of the screening relative to the site selection,
- Overall knowledge in geosciences due to previous natural resources survey,

- Existing boreholes or seismic surveys.

5. Integrated information, data or knowledge (from other domains) that impacts understanding of site characterisation and confirmation

With respect to EURAD Roadmap, site characterisation and confirmation refers to the theme 4 "Geoscience".

- Level 1: (4.) Assemble geological information for site selection, facility design and demonstration of safety (Geoscience),
- Level 2: (4.1.) Provide, or confirm a description of the natural barrier and how it contributes to high level safety objectives (Site description),
- Level 3:
  - (4.1.1) Develop a model of the host rock and surrounding geological environment, including distributions of rock types, geometry and properties of structural features, geotechnical properties and the hydrogeological and hydrogeochemical environment (Site descriptive model).
  - (4.1.2) Describe bedrock transport properties (aqueous and gas transport, advection/dispersion, diffusion) including retention (sorption, matrix diffusion) of different geological materials.
  - (4.1.3) Characterise or confirm surface ecosystem properties and their potential evolution in the future (Biosphere model, also part of 4.3).

6. Maturity of knowledge and technology

Site characterisation and confirmation programmes have been carried out for many decades and broad experience has been acquired by the most advanced programmes.

All currently available technologies are mature and probably sufficient to perform necessary exploration work. However, there are definitely questions arising and specific challenges of radwaste disposal that may ask for improved or even new technologies (e.g. application of fibre-based measurements, non-invasive monitoring techniques for specific properties/parameters).

6.2.2 Site characterisation and site confirmation

7. Guidance, Training, Communities of Practice and Capabilities

This section provides links to resources, organisations and networks that can help connect people with people, focussed on the domain of Site investigation.

Guidance
Site survey and site selection for nuclear installations. — Vienna: International Atomic Energy Agency, 2015. (IAEA safety standards series, ISSN 1020–525X; no. SSG-35) STI/PUB/1690 ISBN 978–92–0–102415–2
Training
School of Geological Disposal Siting, site investigations and site characterisation, https://www.skbinternational.se/what-we-offer/courses-and-training/our-courses/school-of-geological-disposal-siting-and-site-investigations/ IAEA Management of Site Investigations Training Course [under publication in 2024]
Active communities of practice and networks
IAEA URF Network https://nucleus.iaea.org/sites/connect/URFpublic/Documents/URF-Network_TOR_2016.pdf

8. Further reading, external Links and references

8.1 Further Reading

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Delay J., Dewonck S., Distinguin M., (2006) Characterisation of a Clay rich rock through development and installation of Specific Hydrogeological and Hydrogeochemical equipment at the Meuse/Haute-Marne Underground Research Laboratory. Physics and Chemistry of the Earth, 32, (2007) 393-407, doi:10.1016/j.pce.2006.01.011

NUCLEAR ENERGY AGENCY OF THE ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT (NEA), Geoscientific Information in the Radioactive Waste Management Safety Case: Main Messages from the AMIGO Project, NEA No. 6395, ISBN 978-92-64-99138-5 (2010).

OTA, K., SAEGUSA, H., KONDO, H., GOTO, J., KUNIMARU, T. and YAMADA, S., Site characterisation and synthesis into SDMs for NUMO Safety Case. Proceedings of ANS 17th International High-Level Radioactive Waste Management Conference (IHLRWM 2019), Knoxville, TN, USA (2019

OPE: Observatoire Pérenne de l’Environnement (Long Term Environmental Observatory), Available at: https://www.andra.fr/lobservatoire-perenne-de- lenvironnement-ope-labellise http://www.andra.fr/

NEA, Preservation of Records, Knowledge and Memory across Generations (RK&M), Monitoring of geological disposal facilities: technical and societal aspects, Radioactive Waste Management NEA/RWM/R (2014).

8.2 External Links

IAEA URF Network - https://nucleus.iaea.org/sites/connect/urfpublic/SitePages/Home.aspx

6.2.2 Site characterisation and site confirmation

8.3 References

[Andra, 2005] AGENCE NATIONALE POUR LA GESTION DES DÉCHETS RADIOACTIFS, Evaluation of the feasibility of a geological repository in an argillaceous formation. Dossier 2005 Argile Synthesis. Meuse/Haute Marne Site. Andra, France (2005).

[IAEA,2001] INTERNATIONAL ATOMIC ENERGY AGENCY, The use of scientific and technical results from underground research laboratory investigations for the geological disposal of radioactive waste, IAEA, IAEA-TECDOC-124 Vienna (2001)

[IAEA, 2015] IAEA Safety Standards Series No. SSG-31 Specific Safety Guides STI/PUB/1640 ¦ 978-92-0-115513-9

[IAEA, 2023] The Management of Site Investigations for Radioactive Waste Disposal Facilities-International Atomic Energy Agency, Title, Series Name Series Number [IAEA Preprint] (2023) - https://preprint.iaea.org/search.aspx?orig_q=reportnumber:IAEA-PC--8805.

[SKB, 2013] ANDERSSON, J., SKAGIUS, K., WINBERG A, LINDBORG, T. and STRÖM, A,.Site-descriptive modelling for a final repository for spent nuclear fuel in Sweden. Environmental Earth Sciences, 69, 1045 (2013)

[SKB, 2000] Integrated account of method, site selection and programme prior to the Site investigation phase, Technical Report TR-01-03, https://skb.se/publication/18341/TR-01-03.pdf

[SKB, 2001] SKB, Site investigations. Investigation methods and general execution programme, SKB Technical report 01-29 (2001)

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