6.2.1 Site Investigation

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Overview

This domain insight 6.2.1 “Site Investigation” is part of the wider sub-theme directed to site investigation and confirmation which aims to investigate one of several sites for a deep geological repository (DGR) to demonstrate that it would be suitable from the safety and other technical, environmental and socioeconomical viewpoints (sub-theme 6.2). This sub-theme is part of theme 6: “Siting and Licensing”.

This document relates to the initiation of a site(s) investigation programme to obtain sufficient data to give assurance that the site(s) is/are likely to be suitable, based on a preliminary safety assessment, and whether the final stage of site confirmation would be likely to result in a license application.

The site selection process, including the establishment of site selection criteria, make a site screening process possible, which are all part of the sub-theme 6.1:” Establishment of the site selection process and the site screening”.

The sub-theme 6.2 has been divided in two domains 6.2.1 site investigation phase and 6.2.2 site characterisation and confirmation phase.

Finally, in accordance with IAEA [IAEA, 2023], site investigation activities will be conducted throughout the entire duration of operation and closure of the repository, to support updates of safety reports.

The terminology “site investigation”, “site characterisation”, “siting”, etc. are often used for describing similar activities. Considering that the way these activities are carried out depends on the national context, the actors of a radioactive waste management programmes may define their terminology in a specific glossary.

Keywords

Siting phase, site investigation, site characterisation,

Key acronyms

DGR: Deep Geological Repository

EIA: Environmental Impact assessment

SDM: Site Descriptive Model

1. Site investigation domain: Overall goals, objectives, activities and strategies

1.1 Goals

The goal of a site investigation in a deep geological repository (DGR) programme is to obtain sufficient data from the candidate areas/sites to give assurance that the areas/site(s) is/are likely to be suitable from a post-closure safety and constructability point of view. The outcome from the site investigations contribute to safety case submitted as an integral component of a licence application.

The nature and scope of site investigations will evolve over the course of a siting process, and indeed will extend beyond siting, as follows:

- Initial investigations at a specific site are undertaken to establish a Site Descriptive Model (SDM) which forms the basis for a safety assessment. In addition, outcomes of the investigations are used to establish an Environmental Impact Assessment (EIA) and for the design and layout of the DGR (see domain insight 4.1.3),
- As the siting phase progresses, more detailed site investigation activities contribute towards optimisation of the design, construction, and associated infrastructures of the facility,
- Continued or new site investigation activities, such as long-term environmental and monitoring activities, may continue during construction and operation phases, to confirm site understanding and contribute to the final post-closure safety case to be used as the basis for an authorisation to seal the repository and ultimately release a site from regulatory control.

Therefore, site investigations are carried out in multiple survey programmes over long time periods, from inception to closure of the DGR.

Data and results obtained during all phases serve to build conceptual and numerical models dealing with natural site evolution as well as the impact of DGR construction and operation on the geosphere and biosphere. Siting goals should be established as precisely as possible for a successful implementation of the programme.

Thus, the key to limiting the potential for unfocussed work during site investigations and to avoid the collection of unnecessary data, is to ensure that site investigation phases are well planned and driven by specific requirements. Henceforth, it is necessary that the implementer has competent and experienced staff or advisors in the domain. The specific requirements developed for a national disposal programme should address not only post closure safety considerations, but also those related to construction, operation, and closure, as well as environmental and stakeholders' concerns associated with the lifetime of the entire disposal programme.

6.2.1 Site Investigation

Domain Goal	
6.2.1 Initiate a site(s) investigation programme to obtain sufficient reliable data to give strong assurance that the site(s) is/are likely to be suitable, based on a preliminary safety assessment, and whether the final stage of site confirmation would be likely to result in a successful license application (site investigation)	
Domain Activities	
Phase 1: Programme Initiation	Generic studies to identify the categories of information required to characterise the site for the type of waste disposal system under consideration. Document the key Safety Disposal Option in the preliminary Safety Assessment, regarding the geological media under consideration that led to the selection of the site(s). Document the preliminary design options for the considered waste disposal system and the required needs for investigation and confirmation. Document the site selection criteria specific to the country and selected area that will be investigated during the subsequent phases. Document the criteria for defining the region, area, and site boundaries.
Phase 2: DGR Site Identification	Evaluation of geographical regions, areas, and candidate sites to identify those that are potentially suitable in terms of post-closure safety, design, and specific local criteria. This would include compilation of existing geological, meteorological, environmental, administrative and land use information. In addition to open sources/national and international databases, pre-existing information from oil and mining surveys or desk-based studies accessing other information sources would provide part of the basis for selecting one or a few sites for detailed characterisation.
Phase 3: DGR Site Characterisation and confirmation	Expand the database of pre-existing information by obtaining additional high-quality data from targeted surface-based and sub-surface investigations. Improved regional and site scale understanding of sub-surface conditions will be achieved through drilling boreholes. Data analysis and interpretation is aimed to generate a multi-disciplinary SDM with high enough confidence that can form basis for a site-specific environmental, operational, and post-closure safety assessment.

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Phase 4: DGR Construction	Site investigations provide the framework to set up a monitoring network including all compartments of the geosphere and biosphere to establish a baseline and monitor the impact of the construction and operation of a facility on its environment. Monitoring surveys and studies will be used for checking and improving conceptual models, as well as populating and calibrating numerical models to support, review and update safety reports during repository operation. They may also provide input to identifying additional requirements and means for the development and implementation of post closure objectives for monitoring.
Phase 5: DGR Operation and Closure	If national programmes choose to continue with post-closure monitoring activities, continued monitoring of selected key measures of performance may be undertaken to confirm that the disposal system is performing as expected and to help identify the significance of any observed deviations.

1.2 Objectives

Siting comprises the establishment of the site selection process (sub-theme 6.1), the selection of prospective sites and site investigation and confirmation at those selected sites (sub-theme 6.2). A siting process begins as soon as a decision is made to investigate a potential region, area, or site(s). Siting ends when the suitability of a site has been confirmed, a licence for construction by a regulatory body is approved and a final decision to construct the DGR at the chosen site is concluded. The goal of the siting phase is therefore to select a suitable site for hosting a DGR and to obtain the necessary authorisations to construct a DGR. Achieving this goal requires the identification of objectives orientated towards the provision of evidence to demonstrate the suitability of the selected site in terms of post-closure safety, environmental impact, constructability, and design.

During the early stages of siting, when the scientific basis and safety case for the facility in an area or at a site are being established, the site investigation programme is typically driven by an applied geoscience research methodology. During later stages as the programme proceeds into advanced phases with the development of a detailed site-specific safety case and design, the programme becomes more tightly focussed, with execution aligned to standardised procedures and industrial processes.

The objectives of the site investigation programme fall into three main categories:

- Production of a geoscientific reference document, the SDM, which will support safety, design, and environmental impact studies. The SDM should provide information at a level of detail adapted to the phase of the project. A SDM, is a multidisciplinary model (geology, hydrogeology, hydrogeochemistry, geomechanics, that includes thermal properties, geomorphology, climatology, ecology, etc.) presenting a coherent picture of the current understanding of the surface and sub-surface conditions (from past to present) at a specific site. This model will present data and information that describe the current state of the site as well as its past evolution and the phenomena at stake (geological history, future geomorphological evolutions, climate changes, etc.). This information will serve to investigate the phenomenological evolution of the DGR and its environment and the sensitivity of the system to various driving forces described through alternative scenarios.
- Production of technical information to address construction issues linked with underground excavation such as ramp, shafts, and drifts. Effects on the rock mass at different distances from the geological structures should be studied as well as impacts on water bearing structures. However, it should be clearly stated that the actual knowledge of the geological structures and behaviour of the rock mass cannot be fully understood without obtaining high-quality data from the underground excavations at the proposed DGR's intended depth.

- Demonstration of scientific understanding and promoting confidence in the safety case for a DGR and for supporting communication and dialogue with national and local stakeholders (regulators, scientific community, political community, involved administrative bodies and public).

Site investigations require careful planning. Exploration activities and techniques differs substantially from standardised water supply, geothermal, mining or oil prospecting activities. Due to the relatively large costs involved, programme management should not consider the investigation activities as “off the shelf” matters that can be requested from many vendors strictly on a commercial basis. Concerns relating to the provision of critical technology and expertise mainly relate to (i) data and information management; (ii) non-intrusive data acquisition tools and techniques and (iii) intrusive data acquisition tools and techniques.

The design and implementation of the siting programme should also address requirements and objectives relating to the development and enhancement of an appropriate safety culture and organisational structure inside the waste management organisation, as well as within partners and contractors.

1.3 Activities

The activities for a site investigation programme are based on:

- The strategy adopted for the management of the siting phase and its development in stages.
- The identification of the scientific disciplines and the associated scopes of work needed to fulfil the requirements regarding EIA, repository design and construction, and post-closure safety.
- The selection of the geographical domains: region/area/sector and site(s) involved in the project considering both environmental and project needs.
- The level of knowledge to be reached in each of the considered/selected geographical domains.
- The level of detail of knowledge to be achieved at each stage of the siting phase.

There should be a close and continuous collaboration from the early stages among and between site investigation and the safety assessment personnel throughout the siting phase, to transfer knowledge and agree on the significance of outstanding uncertainties. Consequently, the data and information obtained from a specific site will be invaluable for safety assessment personnel, as they will use this data for in-depth analysis to assess the potential dose or risk of harm resulting from the release of radionuclides from a DGR.

Safety assessment modellers would also be closely involved with site investigation personnel to agree and refine conceptual models of site evolution and to establish scenarios for the future evolution of a site.

Thus, site investigation activities will be undertaken to verify that the host rock and any surrounding formations possesses intrinsic properties restricting water movement that may facilitate the degradation of engineered barriers and the release of radionuclides from waste packages, as well as promoting the retardation of any radionuclides that may be released from a repository. In addition to demonstrating the containment function of the disposal system, site investigation activities will provide an assurance that the isolation capability of the disposal system at a site is appropriate. These properties must be assessed over long periods of time (from thousands to several hundred thousand years).

Nonetheless, it's imperative to recognise that the scope of investigations in the site selection phase should not be limited to post-closure safety considerations alone. These investigations should also offer a comprehensive portrayal of both the subsurface and surface environment, enabling the early identification of any site-specific characteristics or conditions that could impact the project at various stages, including constructability, repository operation and closure, environmental impact, and post-closure safety.

1.4 Data acquisition strategy

The starting point for a site investigation programme is desktop studies regarding the general setting of the site(s), typically based on an existing literature survey or expert judgement. In addition, it is necessary to consider requirements derived from regulatory bodies together with any additional data requirements related to repository design, environmental impact, and post-closure safety.

Developing a strategy involves the identification of options, followed by the rational selection of an approach outlining the main steps and resources required for the acquisition of site-specific data, as well as assigning responsibilities. Near-surface surveys with mapping and geophysical investigations can be carried out and drilling programmes can be initiated to obtain data from depth. The selected strategy should provide for the maximum amount of efficiency associated with the use of resources (time, finance, expertise, equipment) considering the time frame anticipated for licencing submission and the human and financial resources available.

Then, the data acquisition strategy will be designed for:

- Selecting/outlining the geographical domains (region/area/sector/site),
- Establishing the level of detail to be obtained and the main knowledge gaps to be addressed,
- Selecting strategies for surface and subsurface data acquisition.

Data are typically acquired during site investigations using tools operated by specialised companies working for natural resource prospection and environmental companies. However, the quality and demands of the data for base and precious metals exploration, or for identifying and characterising oil and gas fields by exploration companies, is significantly different from the demands on the data needed for a DGR.

Once acquired, raw data is usually subsequently filtered, processed, and interpreted internally or externally to provide secondary data and information. Process models are employed to address specific questions and evaluate the significance of observations and data as well as uncertainties, and finally to establish a SDM.

1.5 Geographical strategy

According to safety requirements, the boundaries of the region/sector/areas/site of the DGR and depths to be surveyed are determined by the potential locations of a repository and the occurrence and location of potential discharge zones to which radionuclides might migrate over very long timescales. In this regard, potential future changes to the hydrogeological system must be considered, both in terms of the driving forces and processes that might promote change, but also in relation to the location and characteristics of future potential discharge zones. Note that system evolution may be controlled by large scale events and processes (global or regional scale) or by more local changes in hydrogeological system boundaries. Survey zones should be established based on an understanding about how regional impacts might affect a site. The data necessary for carrying out such large-scale analysis may initially be found in scientific or technical literature published by national geological surveys or other organisations.

According to environmental requirements, the EIA should provide data to record the reference state of the surface environment prior starting construction work of the DGR. The EIA aims to assess potential environmental changes that could occur, to identify their origins and to distinguish between changes due to the construction and operating of surface and underground facilities and changes due to other natural or anthropic reasons.

The scale of the survey zone for an EIA should provide data and information on environmental features and dynamics from the local scale up to an area with an extent that depends on national conditions or specific requirements. The objective is to monitor and record responses on the evolving state of the environment at the scale of this area, and for a period that could exceed the operational lifetime of the facility. In the same way as for safety requirements, the wider environmental survey zone will define the geographic limits for more detailed studies.

In practical terms, regional surveys are restricted to a sector limited by faults, outcrops of layers, and hydrological limits (river or coastal boundary) that are or might be affected by a repository development programme. These would constitute the limits of regional scale hydrogeological models within which a repository site would be situated.

If the regional sector is large, an investigation area surrounding a prospective repository location may be defined to focus and optimise the use of resources. The potential site(s) would be nested within this sub-regional scale area and the wider region. The site area may represent the footprint of the DGR within that sub-regional area or it could reflect an otherwise defined extent (such as an established administrative unit, defined by physical features or of a specified shape or area).

In establishing the strategy for defining geographical investigation areas, other factors in addition to post-closure safety are of key importance, in particular socioeconomic factors may play a role. These socioeconomic factors are addressed in impact studies, particularly on subjects related to environmental and territorial integration of the DGR project, such as the water cycle, energy supply, transport infrastructure, spatial planning, and quality of life. All these factors are to be discussed with local stakeholders, sometimes through public consultations.

These impact studies are part of an ongoing iterative process throughout the life of the project. They will be updated as the project progresses. Their content is proportionate to the environmental sensitivity of the area, the scale and nature of the work and any foreseeable impact of the work on the environment and human health.

1.6 Activity planning strategy

The planning strategy would identify the parameters to be measured and processes to be understood. The strategy does not need to identify the methods and tools for collecting the data and information, as this is an essential component of the implementation plan. As already presented, the data/information/parameters required fall into three main domains:

- Geoscientific information for safety assessment and EIA,
- DGR design,
- Stakeholders' information and needs.

Geoscientific information

The broad natural system information required for preparing a safety and environmental assessment of a site includes descriptive models of the following disciplines:

- Geology, hydrogeology, hydrogeochemistry,
- Geomechanics: to include both rock mechanics and thermal aspects.
- Radionuclide transport/migration.
- Surface ecosystem (ecology),
- Quaternary geology (important in areas subjected glacial cycles e. g., Canada, Sweden, Finland etc.), and,
- Geotechnical/soil properties.

These descriptive models define the three-dimensional geometry of a rock mass as well as the parameter values that describe the properties of those units and their spatial variability:

- Geological framework of the site includes:
  - the distribution of geological rock units and structural features, the latter might act as conduits/pathways to radionuclide migration.
- Hydrogeological framework includes:
  - the nature of groundwater flow in terms of flow mechanisms and solute transport retardation processes, potential radionuclide migration pathways, flow velocities and hydraulic gradients,

  - o the nature and distribution of groundwater bodies, their evolution over time and their potential to affect barrier safety functions and potential pathways in the future,
  - o the nature of the driving forces that influence the potential migration of fluids through the geosphere (groundwater, gas) such as topography and groundwater density.
- An understanding of the regional stress and thermal regimes.

Environmental information

The EIA studies will acquire information to address:

- Detection of any serious and irreversible damage to the environment, based on the identification of potential impacts and means for avoiding or mitigating them,
- Natural and economic resources to be used in an efficient way,
- Socio-economic aspects.

The information needed for an EIA encompasses in addition to construction and operational effects:

- Air quality, dust greenhouse gases emissions,
- Noise,
- Soil and land use,
- Topography, visual impact
- Biosphere, fauna, fora,
- Surface water bodies, hydrology, and groundwater.

DGR design information

The information required deals with understanding the effects of repository construction and design on the nature of the rock mass surrounding a repository (i.e., the volume of rock that is damaged or disturbed during excavation, support, and lining (termed as Excavation Damaged Zone (EDZ)) and how the characteristics of the site would limit or constrain design features and/or construction methods and materials.

The mechanical properties of the rock mass being considered for a DGR influence the containment and isolation characteristics of the repository, but also strongly affect the detailed design of the repository, including its dimensions, the disposition of shafts, tunnels and disposal vaults, and the construction methods to be employed. In addition to the geotechnical attributes of the rock mass (e.g., in terms of rock quality, in-situ stress, and other properties), it is critical to evaluate information derived from other disciplines in the context of the engineering design, especially geology and hydrogeology. Finally, groundwater composition may have a bearing on the long-term integrity of engineered materials and barriers that are part of the DGR detailed design.

Stakeholder information and needs

Any data and information from site-specific and generic studies should be readily available in a comprehensive, understandable, and timely manner.

Thus, the implementer needs to provide reports at different levels of detail to address the different needs of different audiences. This will require the development of an appropriate publications strategy that itself should sit within a broader stakeholder engagement and communications strategy.

While stakeholder needs and expectations for confidence building are specific to each country/program/culture/decision-making process they should be carefully evaluated and understood. Confidence relies not just on an acceptance of the robustness of the proposed disposal concept, underpinned by data and information, but confidence also relates to trust in the implementer and trust in the overall decision-making process.

Frequently cited aspects relating to the culture and behaviour of implementers/regulators and political bodies that contribute to stakeholder trust and confidence concern issues relating to the clear definition of roles and the overall decisional process, as well as openness and transparency.

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1.7 Financial and human resources

The availability of financial and human resources dedicated for site investigations are extremely diverse and vary significantly from one national programme to another. They are a function of the inventory, the availability of expertise, ability and will to commit resources.

In all situations, decisions and impacts based on budget constraints should be clearly documented.

1.8 Use of data acquired during Site Investigation

It is emphasised that it is neither sufficient for site investigation personnel to simply data transfer without context, nor for safety assessment personnel to request additional site data without explaining the reasons for a need.

At the beginning of any site investigation programme, conceptual models, sometimes called geosynthesis, are developed first. These models combine geologic understanding, expert knowledge, field data, and natural analogues into a consistent story that explains observed site conditions. Conceptual models are the framework within which site investigation experts assemble data they collect, and through which they identify and justify further data collection needs. Additional data collection and analysis may lead to alternative conceptual models or interpretations for the same site.

Numerical models are used throughout any safety assessment study and are sometimes involved in the geosynthesis stage. Numerical models constrain conceptual models through governing equations or relationships between the inputs and outputs.

Numerical modelling is further subdivided into data analysis models, process models, and performance assessment models.

Consequently, the resulting SDM relies on conceptual models evolving through new acquisition and interpretation and on numerical models that are used for evaluating future site evolutions due to internal or external aspects. Note that for some countries such as France, the site information that is the basis of conceptual models based on existing data are gathered in “Reference Site Document” describing only the current situation and current evolution processes.

2. Contribution to generic safety functions and implementation goals

This section describes how the site investigation stage (and its associated information, data, and knowledge) contributes to an 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 aspects for a DGR are relevant to the domain insight “Site Characterisation”: The geological and the engineered barriers containment and isolation functions over long period of time.

2.1 Isolation - Ensure isolation of waste from people and the accessible biosphere

To meet the fundamental objective of protecting humans and the environment from the risks associated with dissemination of the radioactive substances and toxic elements in the waste, one of the key safety functions of a repository system is the isolation of the waste from surface effects and human actions. At a site with appropriate disposal system properties, construction of disposal cells/vaults deep in the bedrock successfully achieves these objectives, i.e. the repository would provide isolation from societal changes or the direct effects of long-term climate change at the ground surface, as well as uplift and erosion due to isostatic rebound and/or tectonics.

Thus, the site investigation activities will consist primarily of characterising the bedrock to the depth of the DGR. Depending on site conditions, it may be necessary to extend the investigation depth, but the limit will be very dependent on site features and understanding.

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It shall be demonstrated that the host rock is:

- Of sufficient thickness and lateral extent to ensure the long-term confinement of radionuclides and accommodate all the waste inventory and its safety guard zones.
- Deep enough to ensure long-term protection against erosion and impacts resulting from climatic surface phenomena.
- Homogeneous enough with limited tectonic discontinuities and lithological variability to enable confidence in interpretations.

The comprehensive characterisation of a site during investigations must ensure that nothing will interfere with the integrity of the repository or its long-term safety. This relates to, for examples, materials used and the construction and sealing of boreholes used for investigations and monitoring.

2.2 Containment – retention and retardation

Another key safety function is the containment of the radionuclides in the engineered barrier systems (e.g., canister and buffer material) and retention/retardation of the radionuclides (in case an engineered barrier system fails, reflecting the properties of the bedrock itself. This means having a good understanding of the half-life associated with radionuclides in the waste packages, the physicochemical degradation potential of the waste, the packages, and the engineered components. This understanding is required to ensure that any radioactive substances and toxic elements that might be released from a waste package, remain as close to their source as possible. In addition, it will be necessary to have a good understanding of the processes and potential pathways for the radionuclides that could facilitate transport of these elements to the biosphere in the long term.

The natural pathways of concern are:

- Aqueous pathways, as substances may dissolve in water and migrate over time to the surface.
- Gaseous pathways, as certain radionuclides can migrate in this form.

As well as pH, redox conditions and the presence of aggressive species, water is a primary factor in the degradation of waste packages and other engineered barriers, as well as the main transfer medium for radioactive substances and toxic elements away from a repository. Extensive knowledge of the hydrochemistry and aqueous pathways is therefore a key objective of post closure safety. Limiting the transfer of radioactive substances and toxic elements by water is the purpose of the following three safety functions:

- Preventing the circulation of water in the repository that would promote the degradation of engineered barriers that function to prevent and limit groundwater access to the waste form within a waste package.
- Preventing the circulation of water within a repository to delay and limit the solubilisation and release of radionuclides and toxic elements from the waste package to the wider repository environment.
- Preventing the circulation of water to delaying and reducing the migration of radioactive substances and toxic elements from the repository to and through the geosphere.

These three safety functions rely primarily on the favourable characteristics of both the host rock and the engineered barriers around the waste canisters.

These favourable characteristics shall not be jeopardised by the design (architecture, engineered components) of the repository or activities during the construction, operational and closure stages. The packages, the engineered barriers and the repository's engineered components, specifically the underground facility's architecture on completion and the closure structures, also contribute to containment of the waste and to maintaining the conditions for flows of water through the facility to be very low.

2.3 Ensure long term stability with respect to external processes/events

To assess the long-term stability of a DGR for periods of time up to one million years (or beyond if required by regulatory authorities), the following should be assessed:

- the past evolution of the host formation and the wider geosphere to understand the current state and the 3-D distribution of the characteristics of the host geological formation and its overburden,
- the changes that might occur in the future over the lifetime of the repository and their impact on the characteristics of the host and surrounding geological formations in relation to potential radionuclide transfer to the biosphere.

The external events to be taken into consideration include seismic activity and climatic changes as well as associated effects, such as erosion, permafrost development and prolonged periods of drought (inducing modifications both for deep water circulation and surface conditions). Their impact on the long-term geomorphologic evolution, landscape and biosphere changes during climatic cycles are also to be considered (conditioning radionuclide transfers to the biosphere system).

2.4 Ensuring long-term stability in terms of internal process

The aim is to maintain favourable engineered barrier properties despite the perturbations inevitably to be induced by the construction of the facility (e.g. EDZ, i.e., fractures caused by stress redistribution and direct damage around the underground structures during and after excavation).

In addition, the barrier properties of the rock must remain intact despite any effects caused by heat generating waste packages and the degradation of the packages and the engineered barriers.

Surface-based and borehole site investigation will provide valuable data, through groundwater sampling and core lab measurements, for investigating the evolution of engineered and natural barriers. However, the most reliable data may come from experiments and observations carried out in a real DGR, either as part of an underground research facility programme, or as a result of research undertaken as part of underground rock characterisation in tunnels and shafts.

3. International examples of research programmes

France Andra - Cigéo Project:

In 1991, Andra began a major research programme to study disposal in a clay formation, including the study of the Meuse/Haute-Marne site in which an argillaceous rock (clay rock) known as Callovo-Oxfordian, which is approximately 165 million years old, lies at a depth of 400 to 600 m.

The French Nuclear Safety Authority (ASN) issued a basic safety rule (RFS III.2.f) in 1991 that set out the long-term safety expectations for the DGR, the design principles, the criteria to be used to select suitable geological media, and the terms of studies. Furthermore, it defined the fundamental objectives that must guide research on disposal. In 2008, the ASN updated basic safety rule RFS III.2f, replacing it with the safety guide for the final disposal of radioactive waste in a deep geological formation.

Part of the site’s geological, hydrological, hydrogeological, and geophysical surveys, comprising the investigation to be carried out from the surface, were aiming at:

- First determine the lithological, structural, petrographic, hydrogeological, thermo-mechanical, geochemical, and tectonic characteristics to assess the potential host rock’s ability to fulfil the criteria for site selection.
- Gather the information necessary for the modelling of the site with a view to demonstrating its safety.

These objectives could be achieved in a complementary way by surface investigations, by reconnaissance drilling and by the study of the materials extracted from these drillings (water, gas, and rock).

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The reconnaissance drilling aimed to determine:

- The permeabilities and porosities of the host rock and surrounding formations,
- The hydraulic role of major faults, if applicable,
- The field of hydraulic potentials in the host rock and surrounding rock, and
- The natural temperature distribution in the host rock.

Particular attention has been paid to the mechanical parameters of clay and their anisotropy.

The following were measured as part of the recognition program:

- Mechanical parameters (strength, deformability, viscosity),
- Thermal parameters (coefficients of conductivity and expansion, specific heat),
- Porosities, permeabilities and thermo-hydro mechanical coupling coefficients,
- Hydrogeochemical properties of the clay relating to migration of radionuclides.

Finland – Posiva Oy Okiluoto:

The site selection process in Finland was initiated in 1978 with a screening study of the entire area of Finland and identification of potential investigation sites. The work started with a general geological assessment, where the overall suitability of the Finnish crystalline bedrock for deep geologic disposal was recognised. Studies aiming at the selection of a few potential sites for more specific investigations commenced in 1983, when the Finnish government made a decision-in-principle about the plan for carrying out nuclear waste management in Finland with target schedules, and culminated, after a multi-phased process of evaluation and elimination, in the selection of five investigation sites in 1987. During these studies, pre-existing data - such as satellite images, geological and geophysical maps, aerial photography, and base maps - were used to identify suitably large bedrock blocks, to determine the presence of large fracture zones and to define the main geological formations. Some field checks were made to confirm the interpretations. The screening study also included an environmental assessment that considered factors such as population density, transport routes, conservation and groundwater areas, land use plans and ownership.

Preliminary investigations of the five investigation sites (6–9 km^2 bedrock blocks bounded by fracture zones) started in 1987 with area-specific programmes that included air-borne surveys, surface-based geophysics, geological mapping and sampling, deep and shallow core drillings, geophysical and hydrological borehole surveys, and groundwater sampling to confirm the main properties of the sites. Conceptual 3D bedrock and groundwater flow models were created for the sites to describe fracture zones and hydraulic head distribution and flow rates for groundwater in the matrix and the fracture zones.

Based on the preliminary investigations, four sites were selected for detailed site investigations. These commenced in 1993 and were carried out in accordance with the decision in principle by the Finnish government in 1983, aiming at site selection. In 1994, The Nuclear Energy Act stating that nuclear waste must be handled, stored and permanently disposed of in Finland and nuclear waste of other countries cannot be imported into Finland entered into force, and Posiva Oy was founded in 1995 to seek a solution to this issue. The detailed site investigation programme was divided into 1) baseline investigations describing the present conditions in the bedrock, 2) additional characterisation for the acquisition of complementary data, and 3) investigations for testing the earlier results and hypotheses to build confidence in existing understanding. The investigations focused on collecting hydrogeochemical data and making hydrogeological observations, measuring rock stresses in deep boreholes and increasing structural understanding; the site descriptive models were updated using the new data.

Safety analyses carried out based on the detailed site investigations concluded that all four sites investigated would have been suitable for the selected KBS-3 safety concept and as sites for final disposal. However, based on the EIA procedure, the conditions for successful implementation were deemed as more favourable in Eurajoki (Olkiluoto) and Loviisa (the municipalities hosting the Finnish nuclear power plants), with the local consent being highest in those two areas. Taking into account the facts that Eurajoki municipality adopted the final disposal project as an important part of their strategy for the future, that Olkiluoto had a larger area reserved for the repository and that the larger portion of the spent nuclear fuel was located in Olkiluoto resulting in smaller need for transportation, Posiva proposed Olkiluoto as the site for the repository in the application for a decision-in-principle in 1999. The government made a positive decision-in-principle in 2000, concluding that studies could continue based on a KBS-3 type concept with site characterisation activities concentrating at Olkiluoto. The decision was ratified by the parliament in 2001.

Sweden SKB Äspö:

The need for an underground research laboratory (URL) in the Swedish waste management programme was presented in 1986 (R&D programme) in response to requirements imposed by the Nuclear Activities Act. The main aim was to provide an opportunity for research, development, and demonstration to be conducted in a realistic and undisturbed rock environment at depths mimicking the depth of a planned future final repository. During the preconstruction phase between 1986 and 1990, regional geological investigations, surface based geophysical as well as cored borehole investigations were conducted. These investigations formed the basis for predictions and outcome models. The URL construction phase lasted between 1990 and 1995 comprising detailed characterisation of the rock, modelling of the ground water flow and evaluation of predictions from the preconstruction phase. The operational phase started in 1995 and is still ongoing. The main objectives have been to develop and demonstrate methods for construction and operation of the final repository. Further objectives are:

- Testing of alternative technology that can improve and simplify the design of the final repository without compromising quality and safety.
- Increase the scientific understanding of the safety margins and provide realistic data for safety assessments of the post closure safety of the repository system.
- Provide experience and train personnel for various tasks as preparation for the final repository.

The research programme also provides information to the public on technology and methods that are being developed for the final repository.

4. Critical background information

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

- Basic safety guide and any requirements issued by regulatory authorities related to investigation for a geological disposal,
- Selected disposal concept, including safety functions,
- Siting strategy,
- Basic design and operation options,
- Disposal project implementation plan,
- Results of the screening process for site selection,
- Overall knowledge in geosciences due to previous disposal programmes or natural resources surveys,
- Existing boreholes or seismic surveys,
- International requirements from IAEA,
- Implementers/operators requirements,
- Stakeholder requirements and expectations etc.

5. Integrated information, data, or knowledge (from other domains) that impacts understanding of Site Investigation

With respect to the EURAD Roadmap, "Site Investigation" 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 investigation programmes have been carried out for many decades and in a wide range of industrial and research sectors. Specific and broad-based site investigation experience has been acquired by organisations involved in designing and implementing the most advanced geological disposal programmes.

During the last decades, there has been a shift from pure geoscientific academic or "mining type" site investigation approaches to programmes giving an increasing role to environmental, socioeconomical and land use permitting aspects, with a greater degree of national and local stakeholder involvement.

As a result, the decision-making process and trust in the implementing organisation appears of greater importance than the actual characteristics of the preselected sites in terms of gaining stakeholder acceptance, noting however, that site characteristics must nevertheless be suitable to safely host a repository.

7. Guidance, training, communities of practice and capabilities

This section provides links to resources, organisations and networks that can help connect 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

Delay J., Rebours H., Vinsot A., Robin P., (2006) Scientific Investigation in deep wells at the Meuse/Haute-Marne underground research laboratory, Northeastern France. Physics and Chemistry of the Earth, 32 (2007) 42-57, doi:10.1016/j.pce.2005.11.004

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

8.2 External links

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

8.3 References

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[IAEA, 2011] Geological Disposal Facilities for Radioactive Waste Specific Safety Guide No. SSG-14 - International Atomic Energy Agency, https://www-pub.iaea.org/mtcd/publications/pdf/pub1483_web.pdf

[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.

6.2.1 Site Investigation

[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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