Environment Agency

Evidence

The early stages of implementing geological disposal: regulatory use of geoscientific information

Report – SC100011/R

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Doug Wilson

Director of Research, Analysis and Evaluation

Executive summary

This report presents a contractor review of the regulatory use of geoscientific information in various national programmes for the geological disposal of higher activity radioactive waste. The review is presented as a series of case studies. It is intended that this information will help the Environment Agency prepare for its future role as regulator for any geological disposal facility (GDF) developed in England.

This report is structured to reflect the Managing Radioactive Waste Safely (MRWS) siting process current at the time of the review.[1] The review contains sections focused on desk-based studies and surface-based investigations, which were separate, distinct stages in the former MRWS siting process. However, the other national radioactive waste disposal programmes reviewed do not have stages corresponding precisely to those of the former MRWS siting process. Where there are differences, these are pointed out and the consequences discussed. The conclusions presented in the report are relevant to the use of geosciences data in the early phases of developing a GDF and are largely independent of the design of the site selection process.

The case studies were chosen, in agreement with the Environment Agency, on the basis that the national radioactive waste disposal programmes selected for review had similar aims and regulatory environments to the UK, had achieved a degree of progress towards implementation, and encompassed a range of different geological environments. The case studies are based on published material from the appropriate national developers, regulators, governments and other stakeholders. Meetings were held with appropriate staff from the key organisations to ensure that the report is factually accurate, the important stages and decisions within the site selection process are documented, and first-hand insight of the lessons learnt was obtained.

The case studies considered for the review of desk-based studies are the national programmes for Finland, France, Sweden and Switzerland. The case studies relating to surface-based intrusive investigations relate to:

- Meuse/Haute-Marne area of France
- Forsmark and Laxemar-Simpevarp areas in Sweden
- Waste Isolation Pilot Plant (WIPP) in the USA

The information in the case studies represents the position in 2013 and does not take account of any subsequent progress.

Each case study covers the following topics in a consistent structure:

- the framework for radioactive waste management and the roles of the government, developer, regulator and other relevant stakeholders
- the strategy adopted for site selection and the geological setting of the siting areas considered
- the development and application of the criteria used to select and evaluate sites
- a summary of the geoscientific investigations undertaken by the developer

[1] In July 2014, UK Government published a revised approach to selecting a site for a GDF in its White Paper ‘Implementing Geological Disposal’.

- a summary of the development of the safety case by the developer as geoscientific information from investigations became available
- the basis for the regulatory and government decisions that allowed GDF development to proceed to subsequent phases

The case studies explain how desk-based studies and information from site investigations were used to inform regulatory decisions. This includes discussions of:

- planning activities by the developer, relevant to site characterisation, at different stages of the programmes and their assessment by the regulator
- the basis for interim demonstrations of feasibility and the final safety case, and how they were assessed by the regulator;
- the technical challenges of most concern for the disposal facility concept under consideration and how they were assessed by the regulator

The discussions with staff from other national developers and regulators covered clarifications specific to the relevant national programme as well as more general reflections and advice. These more general views are collated in a separate chapter. The report concludes with some lessons that might be drawn from the case studies. Examples of these conclusions are given below.

- **Process of site selection and evaluation**. During desk-based studies, pre-existing geoscientific information is likely to be mainly non-intrusively acquired data with only limited intrusive site-specific data available. For relatively homogeneous and well understood sedimentary host formations, such information may be sufficient to compare sites based on criteria such as depth and thickness of formation, and those relating to long-term stability. In more heterogeneous high strength rocks, making desk-based comparisons of sites is likely to be more difficult because less information about such criteria may be available.
- **Use of geoscientific information**. Safety assessments will be developed progressively through the process for siting and developing a GDF. Before any potential sites are identified, a largely generic safety assessment might be sufficient to guide the definition of site requirements, possibly with variants to address broad differences between available geological environments, for example, higher strength rocks versus lower strength sedimentary rocks. Generic assessments might be used to inform the development of safety functions related to the engineered barrier system, or in the identification of relevant scenarios to be assessed or identifying problematic issues, or for screening the importance of features, events and processes (FEPs). After potential sites become available, site-specific safety assessments will be developed based on available knowledge and understanding of the potential host geology for a GDF including geoscientific information obtained from site investigation studies.
- **Role of the regulator.** In most of the national programmes studied, the developer produces research, development and demonstration plans every 3–5 years. These plans allow the regulator to review the developer's progress, and provide a forum for maintaining international contacts and disseminating information to domestic stakeholders.

This report offers a useful resource for understanding the progress made and lessons learnt in several advanced national radioactive waste disposal programmes across a relevant set of geological environments. It provides examples of how other organisations have dealt with a range of potential issues arising during the siting of a

GDF. In particular, it provides examples of how regulators have assessed geoscientific information early in siting programmes for a range of geological environments and disposal facility concepts.

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Contents

List of tables

List of figures

1. Introduction

The report reviews the regulatory use of geoscientific data in various national programmes for the geological disposal of higher activity radioactive waste. The report is intended to provide information to help the Environment Agency prepare for its role regulating any future development of a geological disposal facility (GDF) in England.

At the time this review was undertaken, in the UK government's policy on the long-term management of higher activity radioactive waste was documented in the White Paper, 'Managing Radioactive Waste Safely: A Framework for Implementing Geological Disposal' (MRWS) (Defra et al. 2008). This set out a staged process for selecting a site for a GDF, referred to in this report as the Managing Radioactive Waste Safely (MRWS) siting process. In July 2014, the UK government published a revised approach to implementing geological disposal[2] (DECC 2014). The report has not been restructured to reflect this revised approach and reflects the former MRWS siting process current at the time of the review. The conclusions within the report are relevant to the use of geosciences data in the early phases of developing a GDF and are largely independent of the design of the site selection process.

The review provides an analysis of the use of geosciences information in the early phases of a siting programme. Non-intrusive (referred to as desk-based) siting studies are examined in Chapter 2, while Chapter 3 looks at intrusive site investigations, with a focus on surface-based techniques. The distinction arises from the different stages set out in MRWS siting process, which is described in more detail in Section 1.2. Chapter 4 collates some experiences and advice offered by the international agencies interviewed during this project. Chapter 5 presents the review's conclusions and some lessons that might be drawn from these international examples of advanced programmes.

As part of the review, a number of case studies were compiled. However, the planned or historical developments of national radioactive waste disposal programmes in other countries do not correspond exactly to the stages of the former MRWS siting process. So although other national programmes include desk-based studies and intrusive investigations along with regulatory decision points, the purpose and scheduling arrangements of these stages might differ between programmes. The details of these differences are noted in the case studies and the consequences discussed.

The case studies were chosen, in agreement with the Environment Agency, on the basis that the radioactive waste disposal programmes had similar aims and regulatory environments to the UK, had achieved progress towards implementation, and encompassed a range of different geological environments.

The case studies considered for the review of desk-based studies relating to disposal of higher activity waste are:

- Finland
- France
- Sweden
- Switzerland

[2] The Scottish Government did not sponsor either the 2008 White Paper or the 2014 White Paper. The Scottish Government's policy for higher activity radioactive waste, as published in January 2011, states that such wastes should be managed in near-surface facilities as near as possible to the site where the wastes were produced.

The case studies considered for the review of surface-based intrusive investigations relating to higher activity wastes are:

- Meuse/Haute-Marne region of France
- Forsmark and Laxemar-Simpevarp areas in Sweden
- Waste Isolation Pilot Plant (WIPP) in the USA

The information contained in the case studies represents the position in 2013 and does not take account of any subsequent progress.

A summary of the international recommendations relating to the use of geoscientific information in siting a GDF, developed by the International Atomic Energy Agency (IAEA), is given in Section 1.3. This generic process provides a wider context to the various national approaches to GDF development.

1.1 Approach to information gathering

The case studies presented in this report are based on published material from the appropriate national developers, regulators, governments and other stakeholders.

Meetings were held with appropriate staff from the main organisations discussed in the case studies to ensure that the report is factually accurate, and that the important stages and decisions within the site selection process had been documented.

Before meetings, the relevant case study was sent to participants along with an outline of the questions that the authors wished to ask. Minutes of the meetings were kept and copied to the interviewee and the Environment Agency. The responses were used to enhance the case studies.

The authors are grateful for the useful discussions they had with staff from various national developers and regulators (Table 1.1). The authors emphasise that any remaining errors or omissions in this report are their responsibility.

Table 1.1 Summary of contacts with developers and regulators

Date	Contact details
22 August 2011	Email response from ASN (France) to a list of questions
19 September 2011	Meeting with Posiva (Finland)
20 September 2011	Meeting with STUK (Finland)
24 October 2011	Meeting with Nagra (Switzerland)
26 October 2011	Meeting with SKB (Sweden)
6 January 2012	Meeting with ENSI (Switzerland)
17 January 2012	Comments from Sandia National Laboratories and DOE (USA) on a draft case study
1 February 2012	Meeting with SSM (Sweden)
8 February 2012	Meeting with Andra (France)

1.2 MRWS siting process

The MRWS White Paper (Defra et al. 2008) describes the policies and plans relating to the long-term management of higher activity radioactive waste in the UK. A crucial aspect of the MRWS siting process is the use of a staged approach towards implementation. The White Paper subdivides the site selection process into 6 broad stages:

- Stage 1: initial expression of interest from a community
- Stage 2: application of subsurface unsuitability tests, relating mainly to avoiding areas with natural resources
- Stage 3: community decision to participate
- Stage 4: desk-based studies in participating areas
- Stage 5: surface-based investigations at candidate sites
- Stage 6: underground operations, part of which involve underground investigations

The staged approach adopted in the MRWS siting process is illustrated in Figure 1.1. Within this siting process the UK Government is responsible for selecting sites for surface-based investigation and for underground operations.

The Environment Agency is the environmental regulator for the nuclear industry in England. It is responsible for making sure that, if a GDF is built, it will meet the required high standards for protecting people and the environment while it is being developed and operated, and after it is closed. In addition, the Environment Agency is the statutory body responsible for the protection and management of groundwater resources in England. It works jointly with the Office for Nuclear Regulation on matters related to geological disposal, together providing advice and comment on matters within their respective regulatory remits to make sure that any future disposal facility meets the required high standards for environmental protection, safety, security, waste management and radioactive waste transportation.

The developer of a geological disposal facility will need the Environment Agency to grant an environmental permit(s) to allow a candidate site or sites to be characterised using boreholes, and for any GDF to be constructed and operated at a preferred site. The Environment Agency will only issue the necessary environmental permits if it is satisfied that the proposals meet their demanding requirements.

The regulatory guidance *Disposal Facilities on Land for Solid Radioactive Wastes: Guidance on Requirements for Authorisation* (GRA) (Environment Agency and NIEA 2009) describes the submissions that a developer will need to provide in support of applications for environmental permits at various stages in developing a GDF. The submissions include an environmental safety case in support of an application for an environmental permit to dispose of radioactive waste.

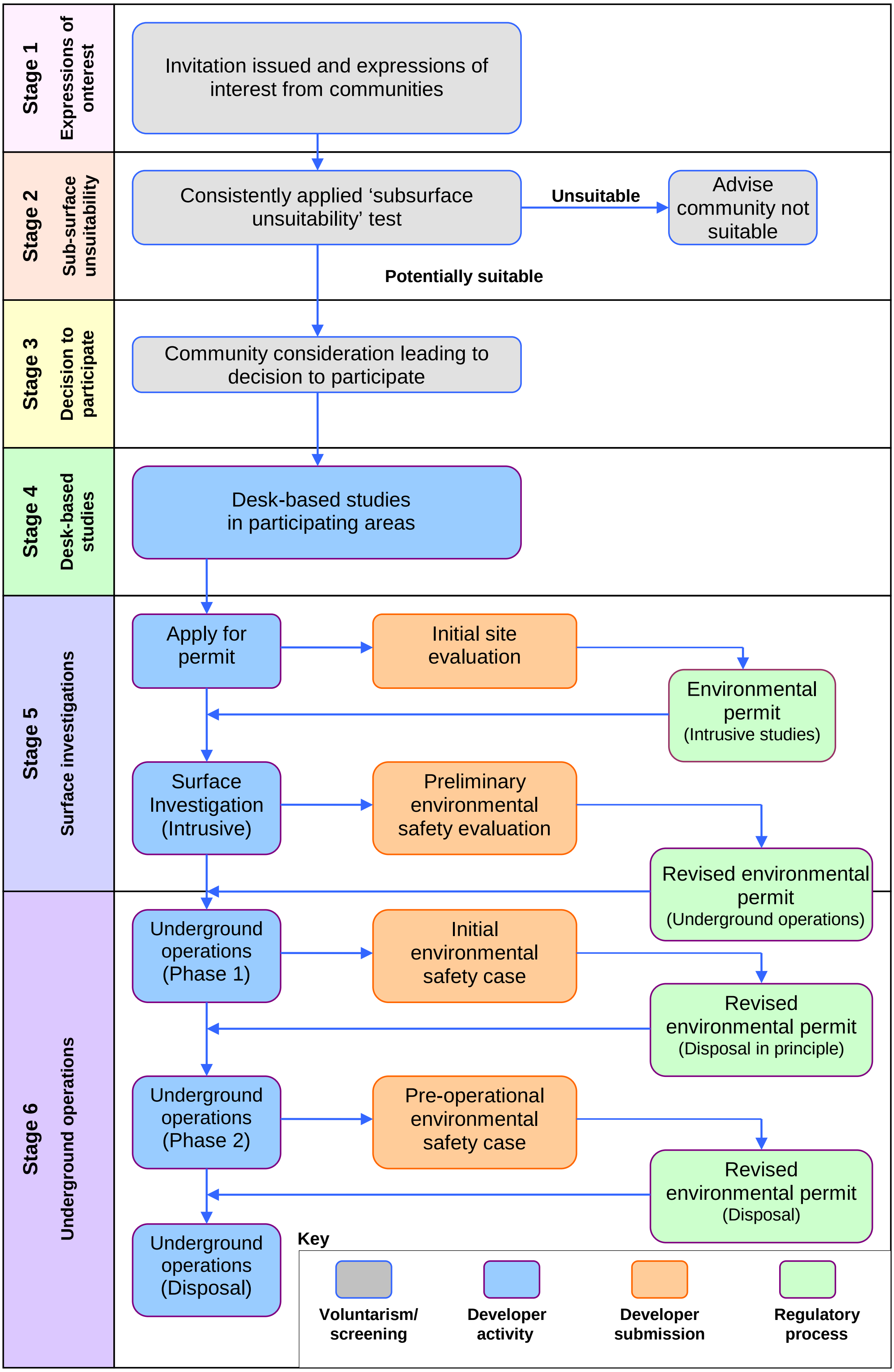


Figure 1.1 Stages and important activities in the MRWS site selection and characterisation process

1.3 An international perspective on site selection

The guidance developed by the International Atomic Energy Agency (IAEA) on the siting of GDFs for radioactive waste disposal (IAEA 2011) is sufficiently generic to apply to different geological environments and disposal concepts. It therefore provides a framework for understanding the case studies presented in this report. These detail how the site selection process and the emphasis placed on different types of geoscientific information at different stages of this process vary between different national radioactive waste disposal programmes.

The IAEA guidance envisages a staged siting process, with the amount of data increasing as the overall siting process progresses. It recommends identification, in the early planning stages of the process, of important siting factors, potential host rocks and a possible siting area. Progressively more detailed investigations and site characterisation activities are then carried out to identify a preferred site. Societal, environmental and legislative issues are evaluated and addressed at each stage of the siting process.

The guidance lists a series of factors affecting the suitability of a site to host a GDF. The data requirements to determine suitability are also listed. It might be possible to obtain some of the geoscientific data requirements during early desk-based studies, while other data will require intrusive surface investigations or potentially data from underground. Other non-geoscientific factors identified as important for the siting of a GDF include transportation, protection of the environment, land use and social impacts. Examples of how these factors were applied to the process of site selection, including indications of the level of detail obtained at different stages, are described in the case studies in this report.

Table 1.2 lists the most important factors recommended by the IAEA relating to geoscientific information, along with the data requirements to assess them.

Table 1.2 IAEA recommended factors relating to geoscientific information

Factor	Notes	Data requirements
Geological setting	The geological setting should be amenable to characterisation, should have geometric, geomechanical, geochemical and hydrogeological characteristics that inhibit radionuclide transport and allow safe disposal facility construction, operation and closure.	(a) Regional and local structural and stratigraphic data of the rocks, sediments and soils (b) Chemical and physical properties, including mechanical and thermal properties
Future natural changes	The host rock and disposal facility containment system should not be adversely affected by future dynamic processes of climate change, neotectonics, seismicity, volcanism, diapirism and so on.	(a) Climatic history (local and regional) and expected future trends at regional and more global scales (b) Tectonic history and framework of the geological setting at a local and regional scale and its historical seismicity (c) Evidence of active (Quaternary and possibly late Tertiary) neotectonic processes such as uplift, subsidence, tilting, folding and faulting (d) Any presence of faults in the geological setting, their location, length, depth and information on the age of latest movement (e) The in situ regional stress field (f) Estimate of the characteristics of the maximum earthquake physically possible at the site on the basis of its seismotectonic context (g) Estimate of the geothermal gradient and evidence of thermal springs (h) Evidence of active (Quaternary and possibly late Tertiary) volcanism (i) Evidence of diapirism (j) Palaeohydrology
Hydrogeology	The hydrogeological environment should tend to restrict groundwater flow and support waste isolation.	a) Hydrogeological evaluation of local and regional geological units; characterisation and identification of aquifers and aquicludes in sufficient detail (b) Identification and characterisation of important hydrogeological units in the region (for example, location, extent and interrelationship) (c) Recharge and discharge of the major local and regional hydrogeological units (location and water budget) (d) Hydrogeological characteristics of the

Factor	Notes	Data requirements
		host rock (distribution of porosity, hydraulic conductivity and hydraulic head gradients) (e) Groundwater flow (average flow rates and prevailing directions) of all aquifers in the geological environment (f) Physical and chemical characteristics of the groundwater and host rock in the geological environment (g) Investigation of the palaeohydrogeological evolution of the site
Geochemistry	The physicochemical and geochemical characteristics should tend to limit radionuclide releases to the accessible environment or least to restrict their migration.	(a) Mineralogical and petrographical composition of the geological media and their geochemical properties (b) Groundwater chemistry
Events resulting from human activities	Potential future human activities should be considered in siting and the likelihood that such activities could adversely affect the isolation capability should be minimised.	(a) Records of past and present drilling and mining operations in the vicinity of the site (b) Information about occurrences of energy and mineral resources in the area around the site (c) Evaluation of actual and potential future use of the surface and groundwater at the site (d) Location of existing and planned surface water bodies
Construction and engineering conditions	Surface and underground characteristics should allow optimised infrastructure construction in compliance with appropriate safety regulations.	(a) Detailed geological and hydrogeological data on the host rock and its overburden (b) Topography of the site and the surrounding area (c) Flood history of the area (d) Specification of areas of landslides, potentially unstable slopes or materials of low bearing strength or of high liquefaction potential (e) Potentially adverse conditions during excavation (high rock temperature, high gas concentration, high rock stress to strength ratio, existing shear zone) (f) Historical seismicity of the region (g) Geochemical and mechanical properties of host rock

Source: IAEA (2011)

2. Case studies of desk-based siting

2.1 Introduction to the case studies

This chapter describes how desk-based studies relating to initial stages of site selection for a GDF have been applied in other national programmes. The role of geoscientific information in this process is emphasised.

The reason for preparing the case studies is to report the experiences of developers and regulators in other national radioactive waste disposal programmes which might be applicable to the Environment Agency in its role as regulators of the radioactive waste disposal programme in England.

The examples of desk-based studies concern disposal of higher activity wastes in Finland, France, Sweden and Switzerland. These national programmes were chosen because they represent instances of site selection processes which have achieved a degree of progress and cover a range of different geological environments.

2.1.1 Case study structure

To help reveal similarities or differences between the different programmes the case studies have a uniform structure with the following main headings:

- **Overview of the process of radioactive waste disposal**. An overview of the roles of the developer, implementer, government and other stakeholders is provided. The disposal facility concepts under consideration and the regulatory framework are summarised.
- **Site selection process.** A summary of the site selection process to date, the schedule for future development and a brief overview of any abandoned siting programmes is presented.
- **Criteria for site selection and evaluation.** The geoscientific criteria used to accept or reject a site, or allow comparisons between different sites, are developed as part of the siting process. These criteria are typically elaborated as more geoscientific data and more types of geoscientific information are obtained and as the disposal facility concept is refined.
- **Role of geoscientific information in the siting process.** This section focuses on the role of geoscientific information in siting and describes briefly how other factors such as transport, land use and the degree of local support were also applied to site selection.
- **Development of safety assessments and environmental impact assessments.** Generic safety assessments can inform or justify the selection criteria used to identify potential sites. Safety assessments can also be used to indicate the feasibility of a site and disposal concept meeting safety requirements.

- **Critical review and its impact.** The interaction between the developer, regulator, government and other stakeholders is described, with an emphasis on the collection and interpretation of geoscientific information.

2.2 Finland

2.2.1 Overview of the process of radioactive waste disposal

The first nuclear power plants in Finland began operation in 1977. In 1978 there was a Decision in Principle (DiP) on how to manage nuclear waste in Finland and to change the Nuclear Energy Act to specify that:

- producers would be responsible for bearing the cost of managing waste using funds accumulated during operation
- an option would be retained to export waste abroad
- a company should be set up to manage nuclear waste
- research and development (R&D) should be increased
- plans would be made which the government would regulate

The disposal siting process started in 1983 when a Decision in Principle was made by the government to build a GDF. The government decided in 1995 that the option to export nuclear waste generated by Teollisuuden Voima Oy (TVO) to Russia should cease and that instead it would be stored until disposed within Finland.

Posiva Oy, established in 1995, is responsible for the construction, operation and eventual closure of a deep GDF for spent nuclear fuel generated by the nuclear utility companies TVO and Fortum Power and Heat (FHP), which jointly own Posiva. The early work on spent fuel disposal was carried out by TVO. Low level waste (LLW) and short-lived intermediate level waste (ILW) are disposed of in near-surface facilities located at each of Finland's 2 nuclear power stations. The deep GDF for spent nuclear fuel is the subject of this case study.

Finland occupies the central part of the Precambrian Fennoscandian Shield. The bedrock is composed mostly of Archean and Proterozoic gneisses and greenstones which have undergone numerous deformations through tectonic activity. The bedrock is typically covered with a thin layer (on average 3–4 metres) of Quaternary deposits. Hence the geological environments available to Finland for a GDF are more limited than is the case in the UK.

It is intended that spent fuel from the Finnish nuclear power reactors will be disposed of in a 'KBS-3' type geological disposal facility. KBS is an abbreviation of the 'kärnbränslesäkerhet' (the Swedish word for 'nuclear fuel safety'). Spent fuel is contained within copper canisters and emplaced in deposition holes surrounded by bentonite clay (KBS 1983). The disposal facility is to be constructed at a depth of between 400 and 600 metres in the crystalline bedrock.

The most important organisations for regulatory functions are:

- the government, which grants licences for nuclear facilities and issues general safety regulations

- the Ministry of Employment and Economy (MEE),[3] which oversees that waste management complies with national policy and, together with the State Nuclear Waste Management Fund, that financial provision for future waste management is adequate
- the Radiation and Nuclear Safety Authority (STUK), which is responsible for the control of radiation and nuclear safety, for issuing detailed safety regulations, and for the technical and safety related review of licence applications

The government specified the goals of the programme, the timescales and defined decision points through the Nuclear Energy Act. TVO and later Posiva were responsible for defining the siting process and disposal facility concept.

The Nuclear Energy Act currently requires the developer to submit a report to STUK every 3 years outlining the current state of R&D into the proposed disposal concept and site. STUK reviews this report, provides statements to government and the local communities involved, and makes recommendations for improvements or additional information. STUK has a role in supporting communities through the application process where they need it.

2.2.2 Site selection process

Site selection was a stepwise process (Richardson 2009), with the timing of specific stages decided in 1983. It was also agreed that the waste producers (that is, TVO and FHP) should provide a R&D report to government on progress every 3 years, and that STUK should review the report and provide a statement. In addition, STUK has provided input to each of the decision points in its role as government adviser and each siting stage had required an assessment of the safety of the proposal. There was contact between the regulator and TVO prior to the first formal review of R&D plans in 1987.

A timeline of the development of the site selection and evaluation process is given below and illustrated in Figure 2.1.

The site screening phase (1983 to 1986) is taken to correspond to the desk-based studies in Stage 4 of the MRWS site selection process. Items in blue are taken to correspond to subsequent stages of the MRWS process (Stages 5 and 6) and are not described in detail in this report.

1983 to 1986	**Site screening.** The whole of Finland was considered a potential siting area. On the basis of mainly geoscientific criteria, 5 areas including Olkiluoto were selected for preliminary investigations. Olkiluoto was added at a late stage of the process, as previous filtering was considered to have excluded it unnecessarily.
1987 to 1992	**Preliminary site investigations.** This involved borehole investigations at each of the 5 sites. Three sites were proposed for further investigations. The main exclusion criterion was geological complexity (McEwen and Äikäs 2000).
1993 to 1999	**Detailed site investigations.** This involved further boreholes and detailed seismic work at 3 sites. Hastolmen (Anttila et al.

[3] Established in 2008 from the Ministry of Trade and Industry, the Ministry of Labour and parts of the Ministry of the Interior.

	1999), next to the Loviisa Nuclear Power Plant, was also investigated (McEwen and Äikäs 2000).
1999 to 2000	**Site selection.** STUK reviewed Posiva's application for a DiP for the Olkiluoto site (STUK 2000). A Decision in Principle by a vote in parliament was required by the Nuclear Energy Act prior to a licence application. This was followed by a Decision in Principle by the relevant local municipality. After this vote the ability of the local community to withdraw ceased. Olkiluoto was selected as the location for a GDR, subject to further confirmation studies.
2001 to 2009	Additional investigations (site confirmation studies) were carried out to supplement the studies conducted during the detailed site investigations (Posiva 2009). Investigations for the underground rock characterisation facility, ONKALO, were undertaken.
2004 to 2010	The ONKALO rock characterisation facility was constructed. It is intended that this facility will later serve as an access route to the disposal facilities.
2012	Posiva plan to submit an application for a construction licence for the disposal facility by the end of 2012.

The programme is regulated in 3 steps:

- Decision in Principle for the disposal concept and Olkiluoto site (2000)
- construction licence application (2012)
- operation licence (around 2020)

The site screening phase had several stages. First 327 'target areas' or 'regional blocks' (~100km^2) were identified. Application of screening criteria reduced this number to 61. From within these remaining target areas, a number of 'investigation areas' (~10km^2) were identified. The number of investigation areas was progressively reduced by geological and other types of screening. The identification of 5 investigation areas in which to conduct preliminary site investigations was influenced by the degree of local support. The role of geoscientific information in this process is described in detail below.

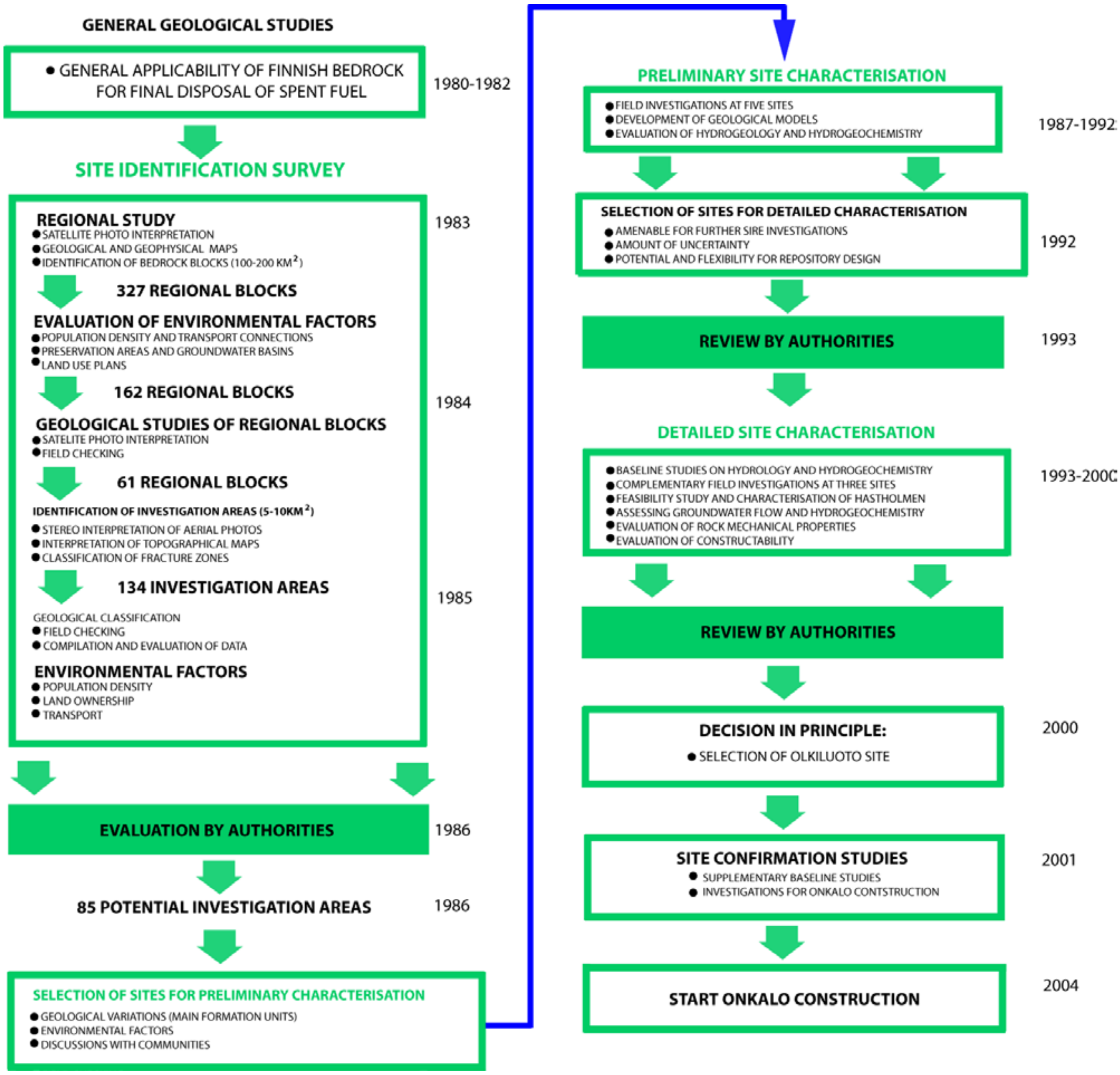


Figure 2.1 Development of the siting programme for Finnish nuclear fuel waste

Notes: From McEwen and Äikäs (2000)
The left-hand column relates to the desk-based studies reviewed in this report.

2.2.3 Criteria for site selection and evaluation

The criteria for the initial stages of the site selection process focused on avoiding fracture zones (zones of increased fracture intensity) as described in Section 2.2.4. Fracture zones were identified by mapping lineaments using topographic maps and geophysical surveys. At the desk-based studies stage, it was assumed that lineaments corresponded to fracture zones. Fracture zones were assumed to be associated with higher groundwater flow rates, future tectonic movement and potential groundwater and mineral resources. The reasoning that led TVO to reach these conclusions, and therefore influence the form of the site selection process, is described in this section.

Before the start of the site selection process, the Geological Survey of Finland (GTK) carried out a review of the geological factors associated with the deep disposal of radioactive waste (Niini 1981, Niini et al. 1982). A classification of the rock mass in Finland, and the factors that influenced its suitability for disposal purposes, was developed with rock masses classified according to their rock types and mineralogy. Geological structures in the rock masses were classified according to whether they were ductile or brittle structures. Ductile structures were not considered in detail, as they were not thought to be of significance. Brittle structures were considered important due to their influence on groundwater flow and were classified in terms of their length, shape and width.

Vuorela and Hakkarainen (1982) considered the geology of Finland with reference to the location of potentially suitable environments for the disposal of spent fuel. They listed the following geological characteristics as being of potential relevance for site selection:

- **Topography.** Local height differences influence the hydraulic gradient and the groundwater recharge, and hence the local and regional flows of groundwater. Finland has predominantly low relief topography, with low topographic gradients. Therefore this factor was not considered an important discriminator in selecting areas. However, Posiva consider sites beneath a hill or slightly elevated region preferable since they offer downward groundwater flow.

- **Bedrock stability.** The Baltic shield was considered tectonically stable, with negligible seismic activity. Bedrock movements related to glaciation were believed to be associated mainly with fracture zones.

- **Size of the formation at the final disposal site**. There were considered to be suitably large, sufficiently homogeneous rock masses in the Finnish bedrock. It was not thought that the expected size of the disposal facility would significantly limit the number of areas that might be suitable.

- **Homogeneity.** Granitic massifs were considered to be normally sufficiently homogeneous. Areas of other rock types were also believed to contain a limited number of sufficiently homogeneous blocks.

- **Rock type.** It was believed that most potential disposal facility locations would be found in areas with granite rock types (for example, porphyritic and fine grained granite, granite gneiss and granodiorite).

- **Faulting and fracturing.** The type and frequency of fractures in the bedrock were considered to be important factors with reference to the stability of the disposal facility and to groundwater flow.

- **Porosity of the bedrock.** The porosity of solid crystalline rock was known to be low, typically less than 10^{-4}, and was thought to be increased with fracturing and weathering. Regions of relatively higher matrix porosity might be preferable since they offer retardation by matrix diffusion.

- **Sorption.** Sorption characteristics of various rock types were discussed. It was expected that basic rocks types (gabbros, amphibolites, some schists) could have better sorption capacities than acidic rock types (granites, quartzites). However, this advantage might be offset by the fact that acidic rocks can have a high content of mica and clay minerals, which have good sorption characteristics. Furthermore, clay minerals and micas are frequently concentrated in and around fractures. In part because of the anticipated variable sorption capacities of different rock types, investigation areas were subsequently chosen to include different rock types.

- **Natural resources.** Certain rock types were known to contain minerals of economic importance. There were also geological features, such as fault zones, within the different rock types that were thought to be associated with ore potential. This is because mineralisation of the rock mass to produce economic natural mineral resources was linked to such zones. Vuorela and Hakkarainen (1982) suggested that the best rock type for disposal should be common and be unlikely to have a specific use in the foreseeable future. Fracture zones were viewed as having potential importance to future water supplies. This was because groundwater yields in these areas might be sufficiently high that groundwater could be pumped from wells.

- **Erosion.** Erosion during the last glacial period was known to be less than 10 metres in Finland. Erosion caused by one or more glaciations was not considered to have any significant impact on the safety of the disposal facility and did not need to be taken into account in site selection.

At the initial stages of the site selection process, hydrogeological data in Finland only existed for depths of less than 200 metres (Salmi et al. 1985). It was thought that the Finnish crystalline bedrock normally had a high mechanical strength, high density and a low porosity. There were, however, known to be areas of the bedrock that have a lower density and strength, such as fracture zones. Fracture zones were considered to be regions of inherent weakness.

Future crustal movements were expected to occur predominantly along the fracture zones and not in what were termed the intervening intact solid blocks or solid bedrock blocks (McEwen and Äikäs 2000). Salmi et al. (1985), however, did warn that although the site selection process aimed at selecting sites away from fracture zones, it would only be after the structure and tectonics of the selected investigation area had been studied in detail that future bedrock movements might be predicted. It was considered that significant fault and fracture zones needed to be avoided for the following reasons (McEwen and Äikäs 2000):

- They provided fast pathways from the disposal facility to the surface
- They were most likely to be associated with future tectonic movements, from any source, including post-glacial rebound faulting
- They potentially provided a source of groundwater
- Mineralisation of the rock mass to produce economic natural mineral resources was likely to be associated with such zones

A large proportion of the geological studies subsequently focused on investigating the location, size and hydraulic properties of fracture zones. At the desk-based studies stage, fracture zones were inferred by mapping lineaments. This mapping was done using topographic and geophysical surveys (see Section 2.2.4). For the purposes of site selection, lineaments were classified into the following classes:

- **Class I –** the width of the lineament is approximately 1km and the corresponding length of the zone is dozens or hundreds of kilometres
- **Class II** – the width of the lineament is hundreds of metres, with the length of the zone varying from 5km to dozens of kilometres
- **Class III –** width ranged from dozens of metres to a hundred metres
- **Class IV** – smaller fractures and lineaments inside a 5–10km^2 investigation area

At subsequent stages of the siting process, additional non-intrusive investigations were performed. Based on this additional information, a set of more refined geological criteria were used to distinguish between different areas (Salmi et al. 1985). These included the fracture density (at outcrop), topography and the level of exposure. These were not absolute criteria, but were used to compare one site relative to another. A system of 5 classes was developed (I to V), with I indicated the most preferable score.

The fracture density was measured using linear profiles on natural bedrock outcrops. Approximately 15km of profiles were measured at a variety of sites and approximately 13,000 fracture measurements carried out (McEwen and Äikäs 2000). A classification system based on the distribution of fracture intensity recorded was developed. According to the classification, over 60% of investigation areas were sparsely fractured, approximately 30% were moderately fractured and fewer than 2% were highly fractured. In sparsely fractured areas, the fracture frequency was typically found to be 0.6–0.8 fractures per metre (Figure 2.2).

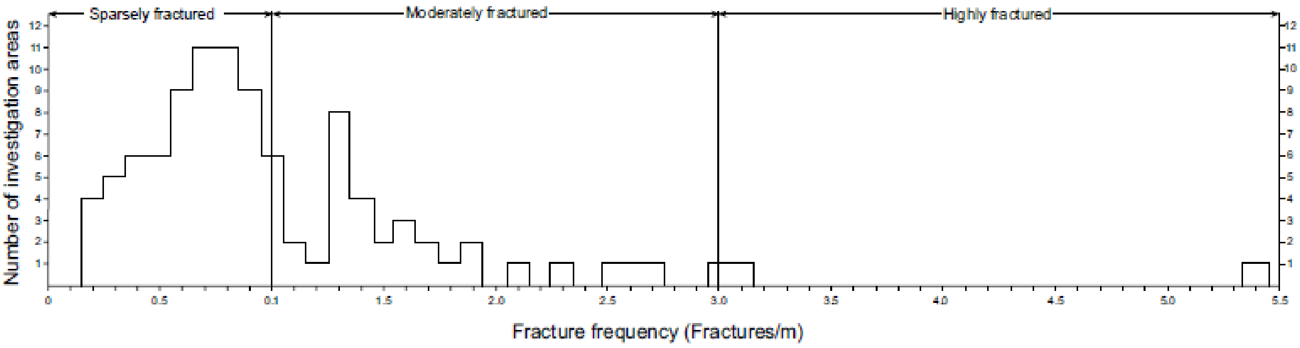


Figure 2.2 Variation of fracture frequency according to a rock classification system based on structural geology (that is, sparsely fractured, moderately fractured and highly fractured)

Source: McEwen and Äikäs (2000)

Topographic variations across the investigation areas were also scored. However, this was not an important factor since Finland has generally low relief. The level of bedrock exposure within an area was believed to be associated with a higher confidence in the properties of the bedrock.

2.2.4 Role of geoscientific information in the siting process

The Finnish site selection programme used a staged approach with repeated instances of screening. The first level of screening was based on the avoidance of significant lineaments. Only later in the desk-based stage of the process were environmental and societal factors such as land use, transport and local support incorporated to help define which sites should be investigated in more detail (Vuorela and Äikäs 1984, McEwen and Äikäs 2000). This process is summarised in Figure 2.3.

The process described below explains the role of geoscientific data in the site selection process up to the point where 5 sites were identified for preliminary site investigations in 1987. The process involved the identification of 327 target areas. This number was selectively reduced to 61 through the application of geological and other criteria. At this point, 134 investigation areas were identified from within the target areas. From these, 5 areas were chosen for the preliminary site investigations.

Identification of, and selection between, target areas

Fracture zones were considered to be the most significant factor in controlling the flow of groundwater at depth (McEwen and Äikäs 2000) and in determining the long-term stability of the disposal facility.

TVO carried out an analysis of the topography of Finland using:

- topographic maps
- satellite images
- aerial photographs;
- maps of lakes and rivers
- regional geophysical, aeromagnetic and gravity maps

TVO used this information to map the location and scales of lineaments, assuming they were all fracture zones. Lineaments were also classified into different types, depending on their length and width. The result of the survey is seen in Figure 2.3 for the whole of Finland. Maps of smaller areas of the country, showing smaller scale lineaments, were produced at a scale of 1:100,000.

It was not considered possible to conduct detailed investigations within all the 327 target areas (with areas greater than 100km^2) identified in Step 2 of the process shown in Figure 2.3. A more limited number of blocks were selected that appeared to be more geologically favourable.

At this stage in the site selection programme, environmental factors were considered relating to:

- population density
- transport-related factors
- land-use planning restrictions
- protected areas
- important groundwater resources

Three classes were used to summarise the environmental factors:

- **Class I** – very low population density, no main roads with heavy traffic but good roads, no homes in close proximity, no cultivated areas
- **Class 2** – no built-up areas, small protected areas, no large cultivated areas, but some cultivation present; some habitation and transport acceptable
- **Class 3** – target area included one of the following: high population density, either heavily used roads or no roads at all, environmentally protected region and groundwater resources

The 327 target areas were reduced to 162 by discarding target areas with Class 3 for environmental factors.

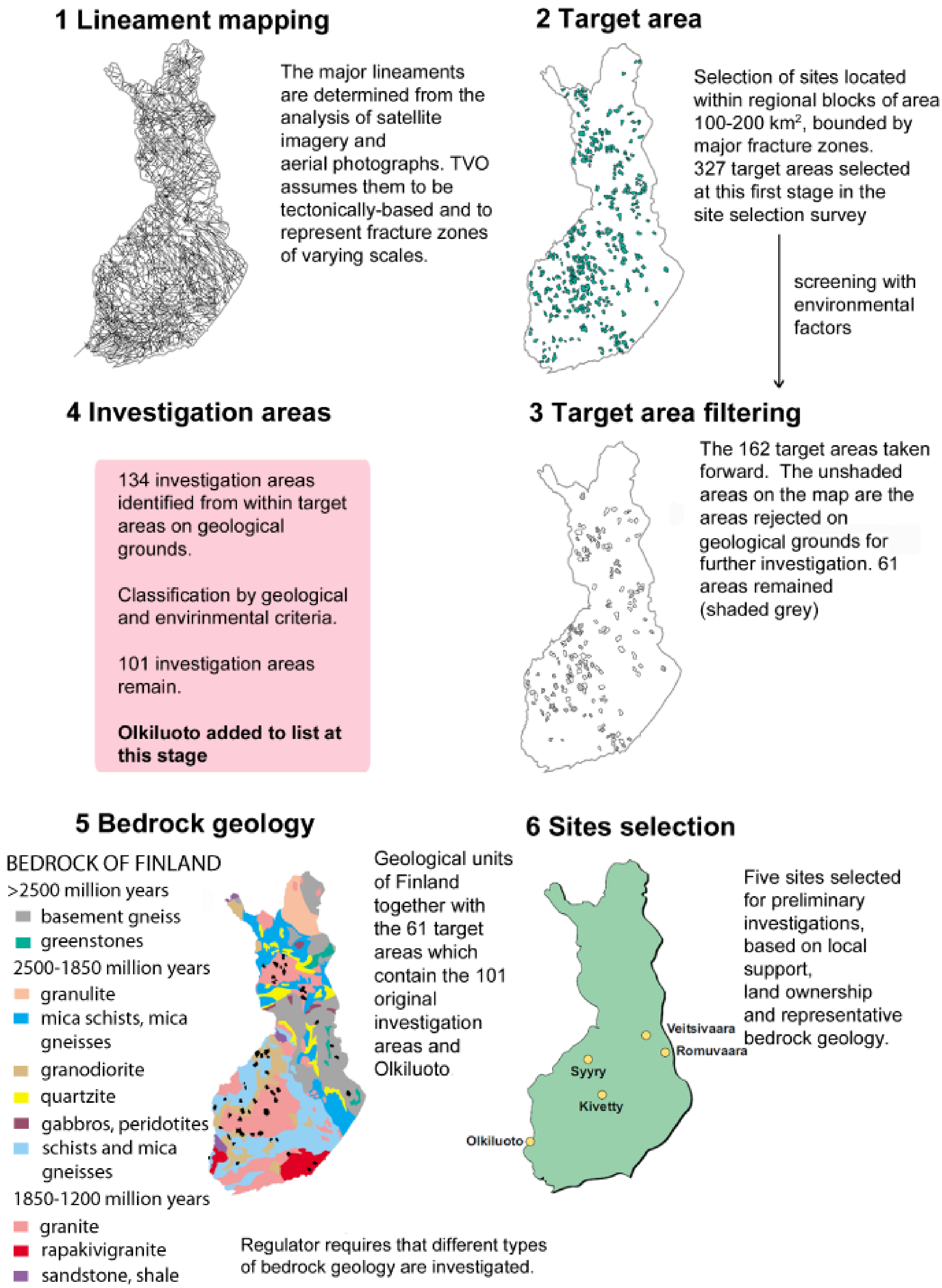


Figure 2.3 Process of selecting sites for preliminary investigations

Notes: Modified from McEwen and Äikäs (2000)

After this initial phase of screening, additional outcrop data were collected and further interpretations made of existing data. The resulting analysis enabled a further classification to be made of the 162 remaining target area into 5 classes (I to V) (Salmi et al 1985), based on the following principal criteria:

- size of the target area
- fracture density at outcrop
- topography
- level of geological exposure (see Section 2.2.3)

A total of 61 target areas, defined as Class I, II or III, were taken forward to the next round of site selection. No target area was placed in Class I, and only 16 were classified as Class II; 8 areas were placed in Class V.

Identification of, and selection between, investigation areas

From the remaining 61 target areas, a total of 134 investigation areas were identified. The investigation areas were smaller blocks, bordered by fracture zones, and lying within the larger target area blocks. It was assumed that an area of at least $5km^2$ would be required to carry out a site characterisation programme, whereas the footprint of the disposal facility would actually be smaller. Data used to locate these investigation areas involved the analysis of aerial photographs, maps and limited field surveys (outcrop mapping).

The investigation areas were provisionally classified according to the factors listed above in a simple manner. The scores given for each attribute (in each case from 1 to 5) were added to generate a final score for each investigation area. No weighting factors were used and no sensitivity analysis was carried out. The geological evaluation was carried out by GTK which placed them into 4 geological suitability classes. Class 4 areas were subsequently excluded from the selection process:

- **Class 1: Primary recommended areas.** This class included 20 areas, the number of which was small enough to allow for reliable reviews to be carried out of their structural properties. The areas were those in which there was the highest level of confidence in their potential suitability, based on outcrop observations.
- **Class 2: Secondary recommended areas.** A total of 38 areas were placed in this class. They were not included in Class 1 because there was greater uncertainty associated with their assessment due to less bedrock exposure; however their number of negative features was not significant.
- **Class 3: Areas recommended but with reservations.** The 43 areas in this class included some that had problematic geological features. These could relate to, for example, the presence of wide fracture zones or higher fracture densities, and the level of exposure could be low or the area small in size. It was concluded, however, that investigation of some of these areas using deep boreholes could demonstrate the fracturing was not significant at depth. Areas were placed in this class because the level of uncertainty concerning their potential suitability was generally high.
- **Class 4: Areas not recommended.** The 33 areas in this class included those with distinctly negative structural features such as significant topographic gradients or small block sizes (that is, unacceptably small areas between fracture zones).

Environmental factors were not considered significant with respect to the long-term safety of the disposal facility. They were concerned with the potential environmental impact of carrying out the site investigations and the construction and operation of a disposal facility in the investigation areas. Because the target areas had been previously selected partly according to environmental factors, the selected investigation areas were also usually sparsely populated and located within a reasonable distance from a road, railway or waterway transport route. The subsequent, more detailed surveys of the environmental factors in the investigation areas, therefore, focused more on population density, transport conditions and land ownership.

Based on surveys, the investigation areas were divided in parallel (with the geological classification) into 3 classes according to population density, transportation conditions and land ownership. The classification indicated the suitability of each investigation area, with Class 1 investigation areas being the most promising, Class 2 areas designated as inferior and Class 3 areas generally unsuitable.

MEE issued advice in 1986 (McEwen and Äikäs 2000) that led to the exclusion of 17 of the investigation areas and the re-classification of 12 others. The reason for this re-classification was the existence of unpublished and incomplete plans for the establishment of conservation areas. This information was not available to TVO during its assessment of environmental factors.

Olkiluoto added to list of investigation areas

As work advanced, it was judged that the method of identifying bedrock blocks from satellite images, aerial photographs and maps was less appropriate on the coast, where the blocks were bounded on one side by the sea. This led to a separate survey being carried out to determine the suitability of the island of Olkiluoto for deep disposal (McEwen and Äikäs 2000). The subsequent analysis concluded that a block of potentially suitable rock of sufficient size could be found and the Olkiluoto site was added to the list of potential investigation areas.

TVO named 102 possible preliminary investigation areas in 1985; 101 from the filtering process described above, together with the island of Olkiluoto. At the Olkiluoto site, there are 2 boiling water reactors, with a European pressurised water reactor under construction. Olkiluoto is also the site of the interim storage facility for TVO’s spent fuel. A Decision in Principle to construct a fourth reactor at the site was taken in 2010.

The differences between the remaining 101 sites considered suitable for investigation were believed to be marginal and it was thought to be inappropriate to distinguish between them without carrying out additional field work.

Selection of sites for preliminary investigations

The Finnish government (Council of State) required the selection of a small, but unspecified, number of investigation areas for preliminary site investigation. The main purpose of these investigations was to ensure that earlier information, which was only based upon surface measurements and observations, could be verified with data from disposal facility depth.

In 1986, STUK and other stakeholders reviewed TVO’s site selection process, as described in Section 2.2.6. While this review was underway, TVO continued with its plans to identify sites for preliminary investigations. It was thought that it was not sensible to consider a community that was opposed at the outset, as it was apparent that the right of a local veto would be included in the new Nuclear Energy Act, which was then in preparation. In addition, the possible complexities associated with the rights of landowners meant that, where possible, TVO only considered sites with one landowner. TVO held a series of meetings with interested communities and their representatives, as well as with experts in municipal affairs. These meetings included discussions on the subject of long-term safety, together with the potential benefits that the host municipality of the GDF could accrue. As a result of this work, TVO received several invitations from municipalities to start investigations at sites identified during the site selection process.

Hence voluntarism and the ease of acquisition of land were important factors in this last stage of the predominantly desk-based phase of site selection. Geoscientific considerations were used to the extent that a representative selection of geological environments (rock types) to study was considered desirable. This was partly influenced by uncertainties in sorption characteristics described in Section 2.2.3.

Five sites were chosen:

- Romuvaara (basement gneiss)
- Veitsivaara (red granite and veined gneiss)
- Syyry (homogeneous tonalite)
- Kivetty (porphyritic granodiorite)
- Olkiluoto (mixed migmatite in which veined and mica gneiss alternates with granite and tonalite)

After detailed site investigations at Romuvaara, Kivetty, Olkiluoto and Hästholmen (added to the list of potential sites at the detailed site investigation phase), it was found that transport analyses of radionuclides did not provide a firm basis on which to rank one site above the others (Vieno and Nordman 1999).

As part of Posiva’s application for a Decision in Principle on a GDF in 1999, it was proposed to locate the facility in the vicinity of Olkiluoto. The site was chosen since no geological factors were evident at the time to support selection of some other site and so other favourable factors (minimisation of transportation risks and existing local infrastructure) justified a focus on Olkiluoto. The only unusual characteristic of Olkiluoto distinct from the other 4 sites considered was the relatively high salinities at depth. At the time of the Decision in Principle, this was considered to be potentially favourable due to providing very stagnant flow conditions. As understanding of the engineered barrier system has developed, high salinities have been found to have potentially detrimental implications for the long-term performance of the bentonite buffer – if such water were to be drawn toward the disposal facility during construction and operation and remain post-closure.

2.2.5 Development of safety assessment and environmental impact assessments

Initial safety assessments to demonstrate the feasibility of geological disposal in the Finnish bedrock were undertaken between 1980 and 1982 (Anttila et al. 1982). A government Decision in Principle to pursue geological disposal in 1983 initiated the site selection process. Safety assessments were subsequently published dealing with normal and disturbed evolution scenarios (Peltononen et al. 1985, Vieno et al. 1985). The disturbed evolution scenarios were dominated by a case where oxidising conditions were assumed to prevail due to glacial melt water following a future glacial event.

After preliminary site investigations were carried out between 1987 and 1992, the TVO-92 Safety Analysis (Vieno et al. 1992) reported that the proposed disposal facility fulfilled the safety requirements and that suitable bedrock was probably available at each of the 5 sites subject to preliminary investigations. The safety assessment was refined in parallel with the subsequent phases of the site investigations with the TILA-96 (Vieno and Nordman 1996) and TILA-99 (Vieno and Nordman 1999) assessments. However, safety analyses performed in the 1990s were based largely on conservative assumptions rather than site-specific factors.

Safety assessments were important in informing decisions. Initially the assessments were largely generic, focused on demonstrating the robustness of safety arguments. TILA-99 was the basis for the 2000 Decision in Principle and considered many model calculation cases, but was largely generic as data were only available from a few boreholes at each site. Generic safety assessments were considered adequate for the 2000 Decision in Principle given the 3 step permitting process.

Since the 2000 Decision in Principle for Olkiluoto, issues specific to the Olkiluoto site have been identified that will need to be addressed as part of the construction licence application. These include:

- possible upwelling of high salinity groundwaters at depth
- the role of dissolved methane in sulphate reduction
- understanding the differences in hydrochemical data from hydrologically conductive fractures and matrix porewater in the context of the natural evolution of the site

2.2.6 Critical review and its impact

The first documented intervention of the regulator in the siting process was STUK's review in 1986 of TVO's site selection programme over the period from 1983 to 1985 (STUK 1987). In this review the importance of selecting different geological environments for the disposal of radioactive waste in Finland was emphasised. The differences between the environments available in Finland are not great compared with the range of the environments present in most other countries. However, even this lower level of geological diversity was considered significant by STUK.

TVO divided the investigation areas under consideration into groups depending on the different types of basement rocks present in Finland, including representatives of acid and basic rock types. TVO/Posiva subsequently included sites with a variety of geological environments in their selection of sites for preliminary investigations.

After the identification of the 5 sites for preliminary investigations, the number of rock types represented was regarded by some reviewers as limited due to the absence of basic (or mafic) rock types. In 1990, the Ministry of Trade and Industry asked TVO to draw up a programme for investigating regions of basic rock. TVO/Posiva subsequently studied these basic formations and issued reports in 1993 and 1996 (McEwen and Äikäs 2000). These studies did not assess any properties of these rock types to be more favourable than the properties of the acidic (that is, granitic) rocks. Moreover, the rather sparse basic rock formations were often associated with mineralisation, which was thought to increase the possibility of human intrusion due to ore exploration purposes.

STUK was required to make statements leading up to the 2000 Decision in Principle. Following the 2000 Decision in Principle, STUK outlined what it expected to be required at the time of the construction licence based on knowledge available at the time. The need for an underground rock laboratory (URL) to confirm the results of the surface-based investigations was made a requirement before the construction licence. The permit for URL construction, known as the ONKALO facility, was given in the 2000 Decision in Principle but it was not envisaged as separate decision point. STUK was responsibility for regulating the construction of ONKALO since it was classified as a nuclear facility.

At the time of the 2000 Decision in Principle, STUK concluded that all the sites considered offered similar potential for long-term safety and that it would be difficult to make general comparisons without more detailed information from each site. The final decision should be made with regard to long-term safety and public acceptance. It was considered that all 5 sites would have been acceptable from the safety point of view.

STUK has progressively developed its requirement as more information becomes available through the submission of Posiva's R&D reports every 3 years. STUK reviews and updates its requirements in response to the R&D reports.

As part of its role to support stakeholder engagement, STUK has helped provide information to communities and surveyed public concerns associated with geological disposal. Concerns tended to be of a practical nature similar to any large construction project and were typically limited to timescales of the next few generations. The impact on the reputation of the local community was also a key concern.

STUK started with 2–3 staff working on the geological disposal project with geoscience or physics backgrounds. It now has more than 15 covering geosciences, material sciences, physics, chemistry and facility design. STUK relies on specialist consultants for support in its review processes.

2.2.7 Summary

What role did geoscientific studies play in the siting programme?

Geoscientific data played an important role in the initial identification of a pool of 327 target areas from which to select sites for preliminary investigations. The initial set of target areas was identified based on the area available between large fracture zones indicated by lineaments.

A systematic approach was then used to eliminate some of the areas remaining to leave potentially suitable areas. This was based partly on environmental factors. An approach to classifying areas based on geoscientific data available from non-intrusive investigations (fracture intensity at outcrop, topography, area available between fracture zones and the extent of bedrock exposure) was also applied to distinguish between investigation areas.

The choice of 5 sites for preliminary investigations was influenced by the requirement to include different representative geologies, as well as societal constraints and land ownership issues. A requirement to investigate sites with different geologies was introduced by STUK.

What decisions were made by (a) the developer, (b) the regulator or (c) any other body, based on information from desk-based studies?

Desk-based studies were used by the developer to identify a pool of potentially suitable areas. A series of filtering stages based on environmental (transport, population density, land use) and geological factors were used to reduce this pool. However, it was recognised that the desk-based approach might exclude viable areas and Olkiluoto was added at a later stage of the screening process because of difficulties in applying the methodology for identifying blocks in proximity to the coast. Furthermore, this approach was understood to have limited utility in distinguishing between different areas regarding final suitability – a large pool of 102 investigation areas remained at the end of the filtering process. Five sites for preliminary investigations were eventually chosen based on local support and the requirement that collectively they encompass a range of different rock types.

The regulator made a recommendation that a variety of rock types be considered for preliminary site investigations to decide if the geology made any difference to sorption properties.

Government also instructed the developer to establish whether basic rocks types could be suitable.

What were the organisations' roles in developing or reviewing desk-based studies?

The developer conducted the desk-based studies. Its work was reviewed by STUK, other stakeholders and MEE. MEE issued advice that led to the exclusion of 17 of the 102 investigation areas and the re-classification of 12 others.

2.3 France

2.3.1 Overview of the process of radioactive waste disposal

In France, high level waste (HLW) and ILW are the radioactive wastes requiring long-term management via geological disposal. Spent fuel is also being considered for disposal, although it is not currently classified as waste as it has the potential to be reprocessed. HLW is the vitrified waste product arising from reprocessing residues of spent fuel. Such wastes are currently stored at the Marcoule and Hague sites. ILW exist in a wide variety of forms, including conditioned in concrete, bitumen or in metal form. Such wastes are currently mainly stored at the Hague, Marcoule and Cadarache sites.

The national radioactive waste management agency, Andra (Agence Nationale pour la Gestion des Déchets Radioactifs) is responsible for the long-term management of all radioactive waste produced in France. It is also responsible for:

- waste acceptance criteria
- R&D relating to radioactive waste
- maintaining an inventory of radioactive waste
- communications with the public and other stakeholders

Andra is regulated by the Nuclear Safety Authority (ASN, Autorité de Sûreté Nucléaire). ASN replaced the former regulator, the Direction Générale de la Sûreté Nucléaire et de la Radioprotection (DGSNR) in 2006. ASN draws on technical advice from the Institute for Radiological Protection and Nuclear Safety (IRSN, Institut de Radioprotection et de Sûreté Nucléaire). IRSN was formed from the merger of the former Institute for Nuclear Safety and Protection (IPSN) and part of the former Office for Radiation Protection

(OPRI) in 2002. The French National Evaluation Commission (CNE, Commission Nationale d'Évaluation) is an independent reviewing body created by the 1991 French Waste Act. It is composed of 12 experts (scientists and non-scientists), including at least 3 international experts (at least 2 in the 1991 Act).

Two important acts were promulgated in 2006:

- Transparency and Security in the Nuclear Field (TSN)
- Planning Act on the sustainable management of radioactive materials and waste

Since 2006, Andra's activities have been guided by a National Radioactive Materials and Waste Management Plan (PNGMDR). The PNGMDR is written by ASN and a multidisciplinary workgroup, chaired by the Directorate-General for Energy and Climate (DGEC), with the involvement of many stakeholders. It is updated every 3 years, and was issued in 2006 and 2010 (Directorate for Energy and Climate 2006, Ministère de l'Écologie et al. 2010). The relationship between these organisations is illustrated in Figure 2.4. Involvement of the general public was also an important part of this process, but this has not been taken into account in this study.

France has a wide variety of potential host rock types for a geological disposal facility. Clay, granite, marl, evaporite and schist have all been considered at some point in the site selection process.

France is currently developing a disposal facility concept for HLW and long-lived intermediate level waste to be emplaced in a clay host rock. The site selection and characterisation work that led to this position, along with studies leading to applications to build URLs at various sites, are the subject of this case study.

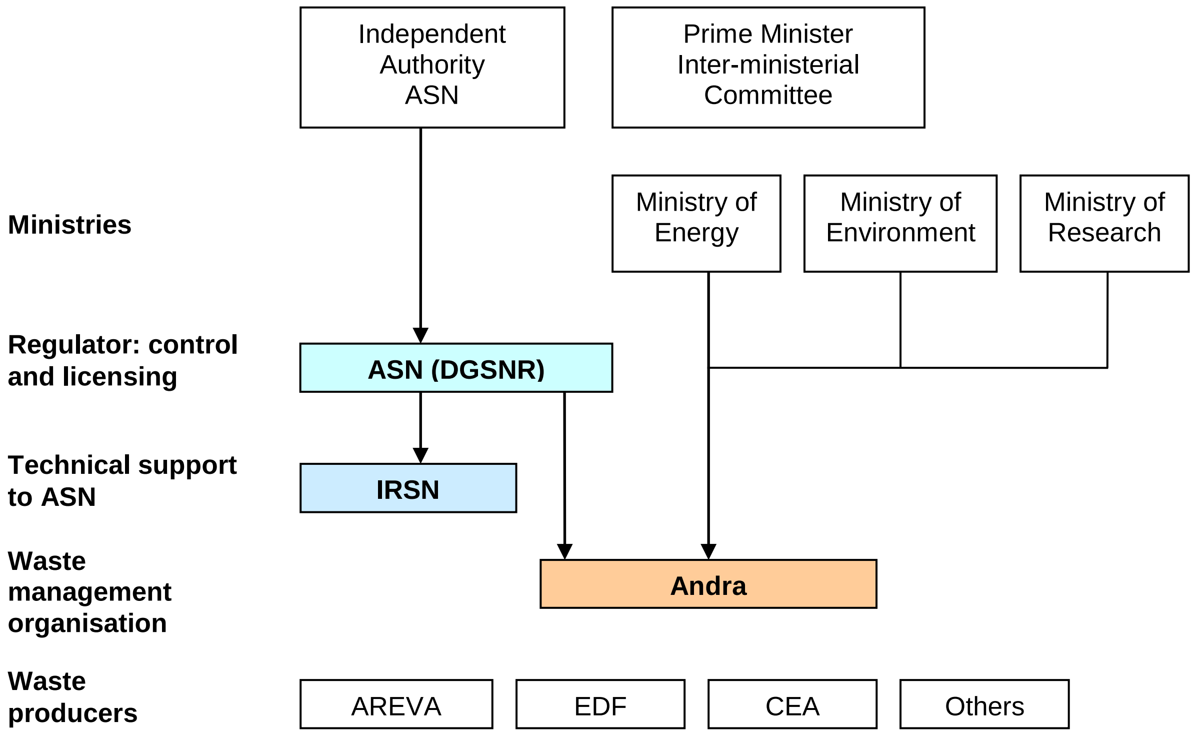


Figure 2.4 Relationship of Andra with the regulatory bodies and its commercial and industrial partners

CEA = French Alternative Energies and Atomic Energy Commission (Commissariat à l'énergie atomique et aux énergies alternatives)

2.3.2 Site selection process

After early studies in 1989 to locate suitable rock formations were abandoned due to anti-nuclear public protest, the French Prime Minister announced a moratorium that led to the 1991 Waste Act. This set out the structure for the management of HLW and long-lived ILW. Andra was created as an independent public body by this act and assigned the task of assessing the feasibility of deep geological disposal by means of the construction and operation of URLs. Using this framework, Andra adopted a phased approach to site selection.

At the time of writing, 4 phases had been completed, with the others in progress or expected in the future. At each phase the acquired geoscientific information was used to refine the disposal design and the information used in the safety assessment:

- **Phase 1**. Three volunteer sites were investigated to assess their suitability to host a URL. Site investigations and preliminary performance assessments resulted in URL licensing applications for clay, marl and granite sites being submitted in 1996. Only the clay site at Meuse/Haute Marne was developed subsequently.
- **Phase 2**. The Dossier 2001 Argile and Dossier 2002 Granite intermediate safety assessments were produced. They described the current state of knowledge in terms of the ability to demonstrate safety of a GDF. The Argile report was based on information from the Meuse/Haute-Marne area, while the Granite report is based on generic environments.
- **Phase 3**. The Dossier 2005 Argile and Dossier 2005 Granite safety assessments for clay and granite rocks were produced, as an update on the 2001 and 2002 reports. Phase 3 culminated in the 2006 Waste Act.
- **Phase 4 (2006 to 2009)**. Planning Act (2006) prescribes specific procedures and deadlines for a deep geological repository. Andra defines a geological area within the ‘transposition zone’ called ZIRA (Zone d’Intérêt pour la Reconnaissance Approfondie, or zone of interest for further investigation) with a view to this area hosting the underground facilities of a future repository.
- **Phase 5 (2009 to 2015**). A licence application for a GDF in a clay host rock is expected in to be submitted in 2015.
- **Phase 6 (2015 to 2025)**. This will involve construction of a GDF for high level and long-lived intermediate-level radioactive waste known as CIGEO (centre industriel de stockage géologique). Operations are expected to continue for at least 100 years, starting in 2025.

The progress achieved to date, relating to each of the geological environments considered as potential host rocks, is indicated in Figure 2.5 and described in more detail below.

In this case study, the focus is on the use of geoscientific information in Phase 1 and in the Phase 2 and 3 Dossier 2002 and 2005 Granite reports; these are thought to correspond most closely to the use of desk-based studies in Stage 4 of the MRWS site selection process. The Dossier 2001 Argile and Dossier 2005 Argile reports are based on data from intrusive investigations at Meuse/Haute Marne.

The division into desk-based and intrusive investigations is not formalised within the French programme; Phase 1 involved drilling some boreholes and the subsequent stages of the process have involved cycles of (intrusive) data collection followed by desk-based analysis. The following subsequent work conducted, is taken to correspond to the surface-based investigations in Stage 5 of the MRWS site selection process and are described in Section 3.2: work leading to the Dossier 2001 Argile in Phase 2; the work leading to the Dossier 2005 Argile in Phase 3; the work leading to the proposal of a zone of interest for thorough reconnaissance; and scenarios of on-surface location in Phase 4, and Phases 5 and 6.

Phase 1: Preliminary performance assessment and URL licensing applications for clay, marl and granite sites.

Following the 1991 Waste Act which set out the framework for managing long lived HLW and ILW, 4 volunteer potential sites were selected for the construction of URLs (granite, marl and 2 clay sites in close proximity to each other). In 1996, licence applications were submitted for URLs for each of the sites. A timeline of events is given below:

- **1993**. Four candidate sites were selected from approximately 30 volunteer communities:
  - a granitic formation located in the Vienne District (central west France), under a sedimentary cover
  - a deep marl formation located in the Gard District, near the Rhone River (south-east France)
  - two sites located in the Callovo-Oxfordian argillite in the Meuse and Haute-Marne Districts respectively – due to their proximity and similarities, the sites were subsequently combined to form the Meuse/Haute Marne Site (north east France)
- **1994 to 1996**. Detailed investigations were conducted from the surface to verify the quality of each of the 4 candidate sites. Borehole drilling operations and geophysical measurement campaigns were performed, including seismic reflection surveys mainly in the clay sites and a gravimetric survey in the granite site.
- **1996**. Andra submitted 3 applications to authorise the implementation of an underground laboratory in the Vienne, Gard and Meuse/Haute Marne Districts. These applications summarised all existing knowledge about the 3 sites, described the work programmes involved with the implementation of underground laboratories, and described the research and experimental programmes intended to complement the existing body of data.

The 3 possible URL sites were reviewed separately by CNE and by IRSN, and a permanent group of experts in 1997 to advise the regulator. In 1997 there was also a public enquiry and consultation with the 3 volunteer communities (Baillet and Ouzounain 2008, Andra 2010a). All candidate communities confirmed their willingness to host an underground laboratory. In 1998, the French government selected the Meuse/Haute-Marne site for the implementation of the URL (Andra 2005a).

The deep marl formation at Gard and the Callovo-Oxfordian argillite at Meuse/Haute-Marne were considered to be of similar general type – indurated clay-rich rocks with low permeability and relatively low porosity. The Callovo-Oxfordian Clay formation at Meuse/Haute-Marne was deemed to be better understood and its geometry considered more suitable than the Gard (marl) site (Baillet and Ouzounain 2008). The structural geology at Gard was also more complex (folded) than at Meuse/Haute-Marne and there was evidence of relatively recent seismicity. Therefore the Gard (marl) site was not developed as a URL.

In 1998, CNE reported unfavourably on the Vienne (granite) site, citing concerns expressed by one member of the board on the risks of groundwater circulating between the granite and the aquifers exploited in the overlying sedimentary formations (Andra 2005d, Andra 2005e).

Therefore, the government decided in 1999 to only licence a URL at the Meuse/Haute-Marne site (at Bure) based on a technical assessment that it had the best prospects for a making a case for long-term safety.

'Dossier 2002 Granite' and 'Dossier 2005 Granite' intermediate safety assessments (Phases 2 and 3)

With the rejection of the Vienne site, the government requested research into a new granite site so as to locate a second URL. A consultation was organised to assess public opinion on 15 granite sites. This consultation met with public opposition and failure of the consultation process was reported in June 2000 (Andra 2005d, Andra 2005e).

With no immediate prospect of developing its own granite URL, Andra set up a new research programme to evaluate the data acquired in foreign underground laboratories (Andra 2005e). Its purpose was to assess the general suitability of granite and to propose generic concepts capable of meeting the long-term safety objectives within the French geological context. The research covered 4 aspects:

- properties of granite
- generic design of a reversible disposal facility system in granite
- disposal facility evolution (thermal, mechanical, chemical and hydraulic)
- long-term safety analyses

This culminated in the publication of the Dossier 2005 Granite, which put forward an assessment of the studies and research into a potential disposal facility in a granite host rock.

'Dossier 2001 Argile' and 'Dossier 2005 Argile' intermediate safety assessments (Phases 2 and 3)

The Dossier 2001 Argile and Dossier 2005 Argile are described in Section 3.2 since they use data from intrusive investigations including from the URL at Meuse/Haute-Marne.

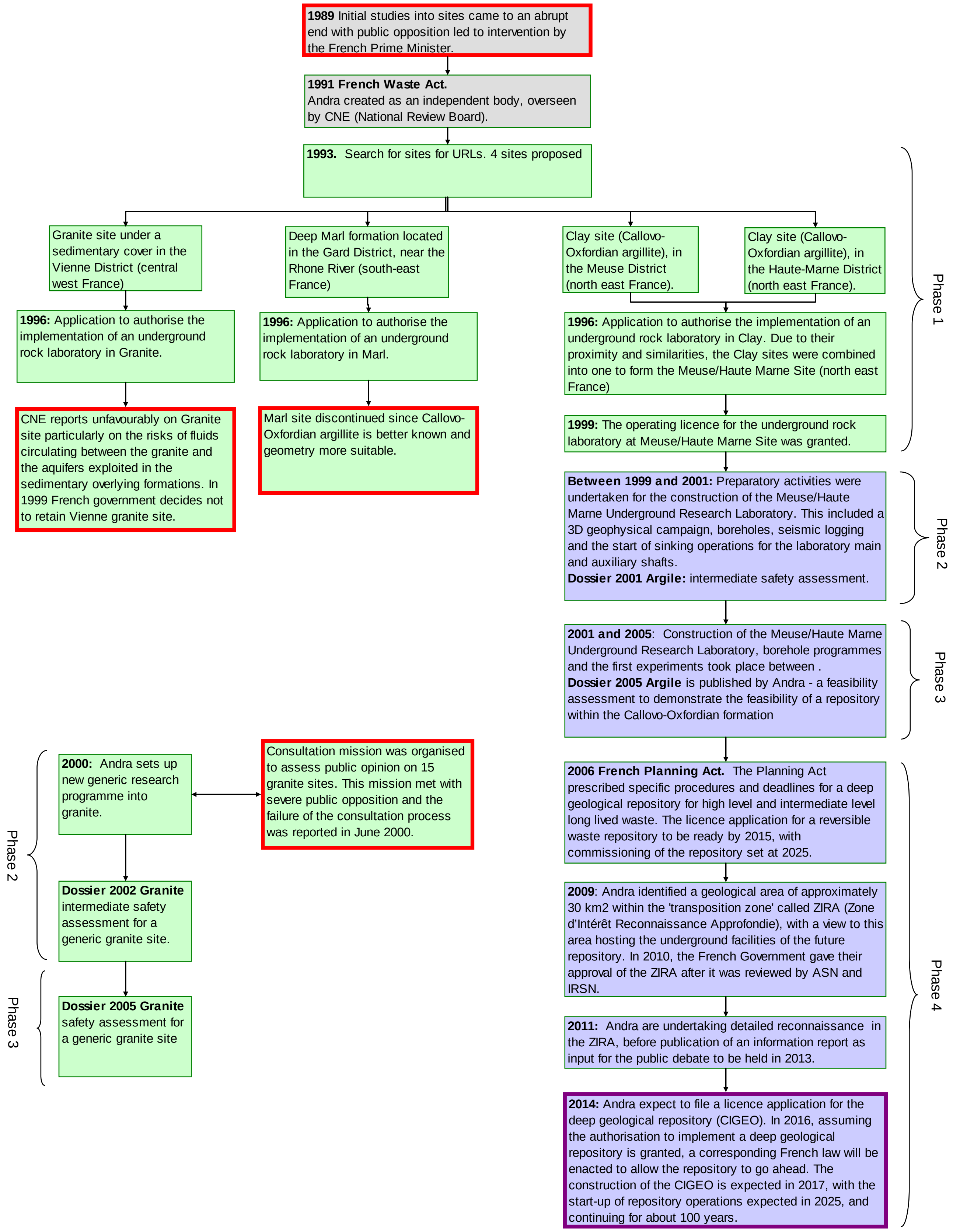


Figure 2.5 Timeline of site selection process indicating the progress attained in each of the geological environments considered

Notes: Red outlined boxes denote break points in the process. Green boxes denote a (mainly) desk-based study (discussed in Section 2.2). Purple boxes denote a study based on (mainly) intrusive investigations (discussed in Section 3.2).

2.3.3 Criteria for site selection and evaluation

The regulator issued the Basic Safety Rule (RFS III.2.f) in 1991 to focus the selection of a design option and the supporting studies after the 1991 Waste Act. This rule sets out the main objectives for a site, which serve as guidelines for the work on geological disposal (Andra 2005d, Andra 2005e, Cahen and Voinis 2008). The objectives are:

- protection of humans and the environment against possible consequences of radioactive waste
- limitation of the radiological impact of a disposal facility to a level as low as reasonably achievable (ALARA)
- the specification of the requirement to use a multi-barrier disposal concept, namely the packages containing the waste, the engineered barrier (components and materials between the package and the geological medium) and the geological medium itself
- the requirement of passive disposal facility evolution without institutional control beyond a given timeframe (500 years)

The Basic Safety Rule indicates the following major objectives with respect to a potential site:

- **Stability**. Site stability should be such that any changes in the initial conditions due to geological phenomena which may occur (glaciation, earthquakes and neotectonic movements) will be acceptable in terms of the safety of the disposal facility. In particular, for a period of not less 10,000 years, stability (covering limited and foreseeable evolution) must be demonstrated.
- **Hydrogeology**. The hydrogeology of the site must be characterised by a very low hydraulic conductivity of the host formation and a low hydraulic head gradient. A low regional hydraulic gradient is also preferable for the formations surrounding the host formation.
- **Mechanical and thermal properties**. Studies, particularly with the assistance of modelling the combined effect of thermal and mechanical phenomena, must be carried out to investigate the influence of the mode and sequence of the emplacement of the waste on mechanical effects in the disposal facility, in particular, the previous cooling time and waste density. These studies should provide the corresponding physical parameters and accurately determine their influence.
- **Geochemical properties**. A quantitative description of the geochemical properties of the system must be made by analysing the transfer conditions of the radionuclides. Mineralogical analyses of host formation materials should be carried out and their geochemical evolution modelled as a function of temperature and irradiation.
- **A minimum depth must be respected.** The site must be chosen so that the planned depth of the disposal facility guarantees that the isolation performance of the geological barrier is not significantly affected by erosion (particularly after a glaciation), by the effects of an earthquake or by human intrusion.
- **Absence of underground resources**. The site must be chosen to avoid areas where there are known or suspected resources of importance.

The development of these generic requirements into specific quantitative criteria is not publicly documented for the early phases of the siting process.

2.3.4 Role of geoscientific information in the siting process

This section summarises the role of geoscientific information used during Phase 1, corresponding to the initial selection and performance assessment of the URLs.

The initial selection of potential URL sites from proposals from volunteer Départments (administrative divisions of government) departments was made in 1993. The selection of sites for a URL was a voluntary process and was led by a member of the French Parliament who co-ordinated a public consultation with the chairperson of each of the 30 volunteer communities; technical advice and information on each of the sites was provided by Andra. Local compensation arrangements were made and it was guaranteed that the storage or disposal of radioactive waste would be prohibited at the URL under the licensing procedure. Four candidate sites were selected from approximately 30 volunteer communities. Although the process was largely one of public engagement, Andra considered that the sites selected for investigations were among the most suitable relative to the other available sites from a geoscientific viewpoint.

Between 1994 and 1996, Andra conducted preliminary surveys at sites in 4 French Départments: the Gard, Vienne, Haute Marne and Meuse (the last 2 were merged into the 'Meuse/Haute-Marne' site) (Lebon and Mouroux 1999). Each site was assessed to confirm that the geological formations proposed were adequate for the installation of a URL. The locations of the URLs are shown in Figure 2.6.

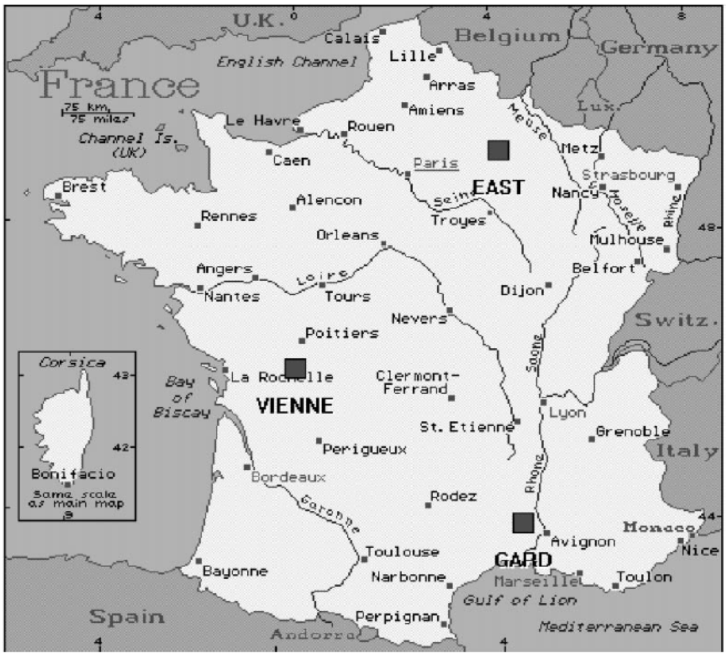


Figure 2.6 Locations of the Gard, Vienne, and Meuse/Haute-Marne (EAST) URL sites

Source: Lebon and Mouroux (1999)

The following types of investigations were carried out (Lebon and Mouroux 1999):

- surface mapping

- cored boreholes with logging and hydraulic tests
- geophysical investigations from the surface

The volume and phasing of activities varied between sites, depending on the initial knowledge available and the geological structure (Table 2.1). Less data were acquired for Meuse/Haute-Marne since it was a relatively simple, straightforward homogenous structure to characterise and since many data from the oil industry were already available (borehole logs, seismic reflexion profiles).

Table 2.1 Summary of 1994 to 1996 preliminary surveys carried out in areas of potential URL sites

Site	Geological mapping (km^2)	Boreholes (m)	Seismic reflection survey (km)	Gravimetry (number of stations)
Meuse/Haute-Marne	750	3,900	15	–
Gard	220	5,400	75	–
Vienne	420	7,200	35	400

Source: Lebon and Mouroux (1999)

The following subsections provide detail on the types of information obtained at each site relating to geodynamic stability, geology, hydrogeology and rock properties. This information was required to demonstrate that each site fulfilled the geotechnical requirements for a potential URL (Lebon and Mouroux 1999). Some of this information came from intrusive (boreholes) investigation.

Meuse/Haute-Marne site

A description of the most important aspects of the geosphere at the Meuse/Haute-Marne site is given below.

- **Geology**. Three boreholes (530–1,100 metres deep) confirmed the location of the Callovo-Oxfordian argillite layer and failed to encounter any faults. The layer is 130 metres thick and lies at a depth of 400–600 metres in the surveyed area. The argillite layer was found to be bounded by 2 limestone formations (Dogger below and Oxfordian above), which are relatively impermeable and in which the hydrostatic heads are relatively similar.
- **Hydraulic conductivity**. The argillite layer was found to be relatively impermeable (10^{-14} to 10^{-12} m s^{-1}).
- **Seismicity**. The area was considered to be located far away from known seismic zones and does not display any geological instability.
- **Mineralogy**. The argillite rock was found to consist of clay minerals, particularly inter-bedded illites/smectites (40–45%), carbonates (30%) and quartz (25%). It has 10–15% porosity and was therefore thought to have good sorption capacity due to the size of the pores (20–40nm).
- **Thermal properties**. The thermal conductivity was measured to show a clear anisotropy due to the sedimentation in fine layers (2–2.2 W m^{-1} per °C within the bedding planes against 1.5 to 2 W m^{-1} per °C vertically).

- **Mechanical properties**. Core samples were taken to measure mechanical properties. When the carbonates content was higher, the compressive strength was found to be around 26MPa. Where their presence decreases, namely at the centre of the formation, it is 19MPa. The test results show that, at the depths considered for the URL, standard civil engineering techniques could be used to excavate and support galleries.

From a geotechnical perspective, the Meuse/Haute-Marne site was considered to contain the argillite formation at an acceptable depth appropriate to host an URL. The rock properties were considered to be representative of a wider volume of rock (Lebon and Mouroux 1999). The physical and chemical properties of the argillite layer were thought to be consistent across a large geographical area due to its formation by deposition of sediment onto a sea bed far from the coast. The location selected near the town of Bure also avoided the karst zones thought to be present to the north of the area investigated.

So as to be able to file the licence application for a URL at the Meuse/Haute Marne site, geological features were analysed against the requirements of the Basic Safety Rule. The advantageous geological properties of the site were listed as:

- a simple and monocline structure (dip: 1–1.5°)
- an area bounded by clearly delimited regional faults
- a sequence not significantly affected by recurrent tectonics during deposition
- tectonics events mainly dated from the Tertiary period
- an absence of natural resources of an obvious economic interest

Andra developed a three-dimensional (3D) geological model around the prospective URL site in 1998 to support the application. The main purpose was to integrate different types of data, 3D seismic surveys and boreholes information.

Gard site (marl or lime-rich mudstone)

Prior to 1994 the geological data were much less abundant at the Gard site than from the Meuse/Haute-Marne site. The surveys began in 1994 with a detailed mapping survey of the geology, a seismic reflection survey, and a borehole at Belvedere de Marcoule. They were supplemented in 1995 with 2 cored boreholes 900 metres deep and with a second reflection seismic survey, followed in 1996 with the drilling of a third cored borehole 1,500 metres deep.

A description of the most important aspects of the geosphere at the Gard site is given below.

- **Geology**. Borehole and seismic surveys showed that the target Cretaceous formation was 200–400 metres thick. Stratigraphic analysis dated the formation as 100 million years old. In view of the geometry of the formation, it was proposed to install the URL at Belvedere de Marcoule with 2 levels to examine the entire layer (Lebon and Mouroux 1999). The marl layer was found to be located between 2 aquifer formations: Cenomanian sandstones above and thin less conductive Albian sandstones below.
- **Hydraulic conductivity**. Very few fractures were found, leading to a low hydraulic conductivity (10^{-15} to 10^{-12} m s^{-1}).

- **Seismicity**. On a regional scale, the Nimes fault, located 10km from the survey sector, was associated with historical earthquakes and palaeo-earthquakes of higher intensity. However, a seismotectonic study of the region suggested that for the past 30 million years, the block lying between the Nimes fault to the south and the Ales fault to the north remained stable. The recorded geothermal gradient of 3°C per 100 metres is indicative of a stabilised geological situation and no indications were observed of recent movements along the local faults.
- **Porosity**. The formation was found to have a highly compact structure with porosity <10%. The texture of the rock (pores 10–20nm in diameter) was thought to give it high sorption capacity.
- **Erosion**. Reflection seismic profiles, as well as the observations on the Mediterranean shoreline, were reported to clarify the erosion history of the valleys of the Ceze and the Rhone, which occurred some 5 million years ago and were caused by a drop in the level of the Mediterranean.
- **Mechanical properties**. The rock was measured to have a very high strength (40–100MPa simple compressive strength), which was considered very favourable.

Although considered favourable, no URL was constructed at Gard. This was due to the opinion that more information was available for the combined Meuse/Haute-Marne site (Baillet and Ouzounain 2008).

Vienne site (granite)

A description of the most important aspects of the geosphere at the Vienne site is given below.

- **Geology**. The first surveys carried out were microgravimetric measurements to identify the contours of a known gravimetric anomaly, corresponding to a granitic massif underlying the surface sedimentary formations. Preliminary geological mapping was carried out using data from 11 boreholes drilled across the whole area to a depth that reached the top of the granite. In 1995, after the reprocessing of an earlier aeromagnetic survey, this map was clarified and the surveys focused on an area to the east of Charroux that corresponded to a granodioritic formation. New boreholes drilled in the area confirmed the initial results, while a reflection seismic survey was carried out to identify the geometry of the sedimentary layers and their contact with the granite. The overlying sedimentary Jurassic deposits are around 150–180 metres thick.
- **Faults**. A surface geological survey and the analysis of satellite images offered some initial insight into the major regional faults.
- **Hydraulic conductivity**. The volumes of rock lying between the major fractures were found to be crossed by small fractures plugged by calcite and clay deposits, resulting in a low hydraulic conductivity (10^{-13} to 10^{-10} m s^{-1}).
- **Groundwater flow**. Systematic hydrostatic tests between inflatable packers were performed on the site. Water inflows in boreholes were encountered at intervals of between 150 and 400 metres. Their transmissivity was considered relatively low for this type of environment (10^{-6} m^2 s^{-1}).

- **Seismicity**. The seismicity of was judged moderate. No traces of palaeoearthquakes are known.
- **Hydrochemistry**. Water samples from the most water-conducting fractures, although reported as difficult to obtain because of low fracture transmissivity, revealed a stratification of groundwater salinity. The water contains 0.5–2 g L^{-1} of dissolved solids between the top of the granite to a depth of 400 metes and around 10 g L^{-1} at greater depth. This salinity was thought to have developed 180–120 million years ago in connection with the tectonic movements that caused the opening of the Bay of Biscay. It was thought that the chemical properties of the waters found at >400 metres' depth demanded a very long contact time with the rock, indicative of a very low groundwater circulation rate.

In summary, the government decided in December 1998 to only licence a URL in Meuse/Haute-Marne (at Bure) based on a technical assessment that it had the best prospects for a making a case for long-term safety. The Gard site had a thicker host formation, but the structure was folded making characterisation and constructability potentially more difficult compared with Bure, where the formation has a gentle near flat inclination. There was also a fault in the region at Gard with evidence of recent seismicity, together with the probability of higher rates of surface erosion due to proximity to the Rhône valley. Hence, the Bure site had clear safety and technical advantages. There were political and societal factors, such as viniculture and tourism, in Gard that also made this area less favourable.

The granite site at Vienne was discarded after technical review by CNE in 1999, citing particularly the risks of water circulating between the granite and the aquifers exploited in the overlying sedimentary formations (Andra 2005d, Andra 2005e).

Dossier 2002 Granite and Dossier 2005 Granite

Since the consultation mission in 2000 had failed to secure suitable volunteer sites, Andra carried out a desk-based research programme (Andra 2005c) using information from international programmes to assess the feasibility of siting a GDF in granite. The geoscientific information used came from URLs at Äspö (Sweden), Grimsel (Switzerland) and Lac du Bonnet (Canada), and investigations at Olkiluoto (Finland). Additionally, some data were available from the preliminary investigations at Vienne. The project also involved studies of granite outcrops in the Massif Central and the Massif Armoricain.

The research programme was made up of 4 fields of studies:

- **Study of the granite**. This research included studies to understand and model the granite, and an analysis of the variability in the characteristics of French granites. The assessment was focused on the Massif Central and the Massif Armoricain, the 2 largest areas of crystalline basement with outcrops on French territory;
- **Generic design of a disposal facility in a granite host rock**. Where appropriate, the study was based on data used for the equivalent study on a disposal facility in a clay host rock. This was especially the case for data on packages and materials;
- **Disposal facility behaviour and its long-term evolution.** Based on the proposed options, studies were made to analyse the long-term disposal facility behaviour to understand and model the thermal, mechanical,

chemical and hydraulic phenomena involved in a disposal facility in a granite medium.

- **Long-term safety analyses**. This is discussed further in Section 2.3.5.

One of the objectives of the Dossier 2005 Granite was to assess the suitability of the granite medium for a disposal facility. After assessing the state of knowledge of relevant data and processes, Andra did not identify any factors which it considered would lead to the conclusion that a granite site was generally unsuitable.

The Dossier 2005 Granite also planned for site characterisation studies in the event that a potential site in France for a granite URL became available. The proposed approach to surveying and characterisation a granite site was based on international experience. Successive surveying stages were designed to gradually improve understanding of geological, hydrogeological, hydrogeochemical and geomechanical aspects, with iteration of the disposal facility design and safety studies. A summary of the surveys envisaged is given in Table 2.2.

Table 2.2 Site surveying methods for a granite site

Main models / Stages	Methods		
	Surface surveying stage	**Underground laboratory stage**	**Repository stage**
Geological: Lithological	Geological mapping and photo-imaging (satellite, aerial and digital terrain model) Airborne geophysics: -Magnetism -Electromagnetism -VLF -Radar -Gamma spectrometry -Transient electromagnetism -Surface geophysics: -Gravimetry -Electrical methods -Electromagnetism -VLF -Seismic refraction -2D seismic reflection -Vertical seismic profile -Seismic tomography -Magnetometry Lithological surveys in boreholes and photo-imaging in boreholes + sampling Borehole geophysics: logging	Detailed geological mapping + trenches and shallow boreholes Surface geophysics: -Electrical methods -Electromagnetism -VLF -2D seismic reflection -Vertical seismic profile -Seismic tomography -Radar tomography Lithological surveys in boreholes and photo-imaging in boreholes + sampling Lithological surveys in drifts Borehole geophysics: logging Geophysics in between boreholes -Seismic tomography -Radar tomography	Lithological surveys in boreholes Lithological surveys in drifts Lithological surveys in disposal cells Geophysics between boreholes -Seismic tomography - Radar tomography
Structural (Fracturing)	Geological mapping Airborne geophysics Surface geophysics Structural surveys in cored boreholes Non-cored boreholes Borehole geophysics: logging, radar	Geological mapping Structural surveys in boreholes and photo-imaging Structural surveys in drifts Geophysics in between boreholes -Seismic tomography -Radar tomography	Structural surveys in boreholes Structural surveys in drifts Structural surveys of disposal cells Borehole geophysics Geophysics in between boreholes -Seismic tomography -Radar tomography

Notes: VLF = very low frequency
Source: Andra (2005c)

2.3.5 Development of safety assessments

The Dossier 2005 Argile and Dossier 2005 Granite were required by the 1991 Waste Act.

For the Dossier 2001 Argile, there was surface-based intrusive data. For the Dossier 2005 Argile, some data from the URL at Bure was becoming available although the planning for the Dossier 2005 Argile had to be modified after an accident delayed construction of the URL to use some generic data from, for example, Mont Terri. The Dossier 2001 Argile and Dossier 2005 Argile are described in Section 3.2 since they made use of intrusive data.

A generic safety assessment for a granite site is reported in the Dossier 2005 Granite (Andra 2005b). The biosphere is not considered in this study and dose calculations were not performed. The purpose of the calculations was to assess the performance of the disposal facility concepts and not to assess whether a given site meets radiological protection targets. The calculations were therefore used to estimate various safety indicators, principally radionuclide flow through different barriers, including:

- Indicators relating to the quantities of water passing through various parts of the disposal facility
- the quantity of radionuclides at certain critical points of the disposal facility at different phases of its evolution

The calculations were based on hydrogeological models of 3 different areas. Although the models are called generic, certain attributes were assigned to them from real sites. In particular, they were based on configurations present in the Massif Central and the Massif Armoricain. This was to ensure that the models were geologically consistent and reflected configurations that are representative of the French geological context.

To take into account the variability of the properties of the French granite massifs, 3 geological site models were used based on a synthesis of the knowledge of French granites. This was intended to make it possible to examine the role of the different characteristics on hydrogeology and radionuclide transfer in safety analyses.

Data to justify the choice of parameters used in the models came from international URLs at Äspö (Sweden), Grimsel (Switzerland) and Lac du Bonnet (Canada), and investigations at Olkiluoto (Finland). Additionally, some data from the French investigations at Vienne was also used such as fracture transmissivity statistics.

The lessons learnt through the study were presented in accordance with 3 safety functions relating to radionuclide transfer in groundwater.

- **Limiting water circulation**
  - Positioning of a disposal facility in a certain location within the massif might allow a favourable location in terms of long hydraulic paths, slow transfer times or low water flow rates.
  - In the tunnels, radionuclide transport is determined by the hydraulic conductivity of the backfill, the transmissivity of the fractures in the granite walls and the hydraulic gradient.
  - The robustness of the results to properties of the engineering disturbed zone (EDZ) was assessed.
- **Restricting the release of radionuclides and immobilising them in the disposal facility**
  - Transfer from HLW packages is diffusion-dominated. The most influential parameters contributing to maintaining this regime are the presence of the engineered barrier and the transmissivity of minor fractures around the deposition cell.

- For the ILW packages, the flow of water passing through disposal tunnels depends mainly on the transmissivity of minor fractures in the granite wall.

- **Delaying and reducing the migration of radionuclides**. Several parameters were identified as being important in delaying the migration of radionuclides in the granite fractures and in attenuating flows:
  - hydraulic properties of the fractures and their connectivity
  - retentive properties (sorption) of the fractures and of the granite rock on the edge of the fracture*
  - topographical and structural layout of the granite massifs in the far-field

  * Retention in fractures is the result of both the diffusion properties in the rock around the fractures and the sorption properties of the radionuclides. The calculations showed that flows of radionuclides are very sensitive to the sorption properties in the fractures. These properties depend on the mineralogical nature of the rock and subsequently of the fracture coating. This was interpreted as underlining the importance of specific characterisation of the radionuclide sorption properties for a site.

2.3.6 Critical review and its Impact

The 3 URL applications were reviewed by CNE, IRSN and a group of experts (GP) in 1997 to advise the regulator. The underlying technical documentation that describes the critical review process is not in the public domain. Lebon (2008) summarised the crucial areas where improved understanding was required based on the experience of the 1996 Preliminary Performance Assessment:

- More information is needed on the influence of the EDZ around the disposal drifts and potential to change the radionuclide transport pathway.
- Confidence in the finding that transport in the Callovo-Oxfordian argillite is diffusion-dominated would be enhanced if the permeability of discrete fractures in the formation could be determined.

The granite site at Vienne was discarded after technical review by CNE in 1999. CNE reported unfavourably on the granite site, citing particularly the risks of water circulating between the granite and the aquifers exploited in the sedimentary overlying formations (Andra 2005d, Andra 2005e). It underlined an interest in ‘outcropping’ granites, which would have more favourable characteristics in this respect. In 1999 the French government decided not to progress with the Vienne granite site.

The Gard marl site was not licensed as a URL because of the opinion that the combined Meuse/Haute-Marne site was more promising (Baillet and Ouzounain 2008).

2.3.7 Summary

What role did geoscientific studies play in the siting programme?

After the 1991 French Waste Act several sites were chosen for preliminary feasibility studies regarding hosting a URL. The selection of sites for a URL was a voluntary process which included a public consultation with each of 30 volunteer communities, with technical advice and information on each of the sites provided by Andra. Although the process was largely one of public engagement, Andra considered that the sites selected for preliminary investigations were among the most suitable relative to the other available sites from a geoscientific viewpoint.

Geoscientific studies were used to assess areas at Gard, Vienne and Meuse Haute-Marne for their suitability as location for URLs. The 3 areas contained different host rock formations: marl, granite and clay respectively. These studies involved boreholes, which are not strictly comparable with the desk-based studies in Stage 4 of the MRWS site selection process.

Eventually only the clay formation at Meuse/Haute-Marne was chosen for the development of a URL, based on a view that it was most suitable from a geoscientific and societal view. The granite site at Vienne was considered by the review body CNE as potentially unsuitable. In the absence of a suitable volunteer site to host a granite URL, Andra continued to research this host rock through desk-based studies using data from URLs at Äspö (Sweden), Grimsel (Switzerland) and Lac du Bonnet (Canada), and investigations at Olkiluoto (Finland). This information was supplemented with non-intrusive studies of the French granite formations.

What were the organisations' roles in developing or reviewing desk-based studies?

Andra was responsible for the preliminary feasibility studies at Gard, Vienne and Meuse/Haute-Marne. The selection of these sites was based on community volunteerism and was mediated by a member of the French Parliament. The 3 potential sites for URL developments were reviewed by both CNE and IRSN and the GP in 1997 to advise the safety authority. CNE's opinion was an important factor in the decision not to construct a URL at Vienne.

2.4 Sweden

2.4.1 Overview of the process of radioactive waste disposal

The Swedish Nuclear Fuel and Waste Management Company (SKB) is responsible for the final disposal of all nuclear waste types in Sweden, although this account focuses on the disposal of spent nuclear fuel.

Prior to 1992, the regulators responsible for reviewing the programmes were the National Board for Spent Nuclear Fuel (SKN) and the Swedish Radiation Protection Institute (SSI). Between 1992 and 2008, there were SSI and the Swedish Nuclear Power Inspectorate (SKI). In 2008, SKI and SSI were amalgamated into a single authority, the Swedish Radiation Safety Authority (SSM).

The Ministry of the Environment is the responsible department in government. It is advised on matters relating to nuclear waste and decommissioning by the government-appointed Swedish National Council for Nuclear Waste (KASAM). KASAM was set up in 1985 and is made up of independent experts in technical issues as well as in social sciences, ethics and humanities.

The bedrock in Sweden has 3 principal components. The oldest component is the Fennoscandian Shield (Archean and Proterozoic crystalline basement, predominantly gneisses and granites). This is overlain in some areas by the remains of a younger

Cambro-Silurian sedimentary rock cover consisting of rocks such as sandstones, limestone and clay shales. The youngest component is rocks formed during the Caledonian orogeny, which occurred about 510–400 million years ago. Bedrock outcrops are common in Sweden and the thickness of the superficial cover is therefore limited, normally a few metres to some tens of metres.

The waste disposal concept in Sweden has focused on the KBS-3 method, which is based on placing spent nuclear fuel in a disposal facility at a depth of approximately 500 metres (KBS 1983). Before emplacement, spent fuel rods are placed in a copper canister, which is itself surrounded by bentonite clay. In Sweden, short-lived operational ILW and LLW from nuclear power stations are disposed of in the Swedish Final Repository (SFR), a disposal facility near Forsmark built 50 metres beneath the Baltic Sea.

Every 3 years, SKB is obliged under the Nuclear Activities Act to submit a report describing its proposed activities relating to the disposal of radioactive waste. SKB has fulfilled its obligations under the Act on Nuclear Activities by publishing a series of research, development and demonstration (RD&D) reports. SKI had responsibility for evaluating and reviewing the programme for the period from 1992 to 2008. SKI also submitted the programme reports to a wide range of external bodies for review. These included universities and institutes of technology as well as environmental organisations. The decision on fulfilment of the obligations is taken by the government on advice from the regulators. The government has the option to issue conditions for SKB's future RD&D activity. The licences for the reactor operations are tied to the fulfilment of the requirements on RD&D according to the Nuclear Activities Act.

Decisions relating to radioactive waste disposal are taken by the Environmental Court or by government on advice from the regulator. The RD&D reports, the associated reviews by the regulator, and SKB's response to government decisions or regulatory criticism – published as 'supplements' to RD&D reports – document the formal regulatory and governmental decision-making process.

A government decision in response to RD&D 1992 supplement (Government of Sweden 1995) stipulated that applications for permits to build a geological disposal facility must contain evidence that site-specific feasibility studies have been conducted on 5–10 sites in the country and that site investigations have been conducted on at least 2 sites.

2.4.2 Site selection process

A timeline of the development of the site selection and evaluation process is given below. Items in blue are the subject of a Section 3 case study.

1977 to 1985	The KBS-3 concept was developed and subsequently widely reviewed. Several geological investigations were performed, called the 'Study Sites Investigations'. When the programme ended in 1985, investigations at 10 different sites had been conducted.
1986 to 1995	SKB's site selection process evolved through the RD&D programmes, with reports issued every 3 years (in 1986, 1989, 1992 and 1995). Critical review of the siting strategy was performed by SKN/SKI and included the views of the Swedish Geological Survey (SGU). SKB conducted surveys in 5 municipalities in 1995.
1996 to 2002	Feasibility studies in 8 municipalities were initiated by SKB. SKB carried out the 'Siting Factors and Criteria for Site Evaluation' project. Safety assessment SR-97 was reported.

2002 to 2007 Surface-based investigations were carried out at 2 sites in the Östhammar and Oskarshamn municipalities. The SR-Can safety assessment considered both sites. SKI and SSI performed a review of this safety assessment.

2009 to 2011 SKB selected Forsmark as the site for the GDF for spent nuclear fuel. SKB conducted a final safety assessment (SR-Site Forsmark) and submitted a licence application according to the Nuclear Activities Act and the Environmental Code. Reviews were conducted by SSM and the Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development (OECD).[4]

Between 1977 and 1985, preliminary work relevant to siting was performed at several 'Study Sites' by different organisations and to different levels of detail. This work included drilling many cored deep boreholes (~1km depth). It provided a large body of geoscientific information for conditions at depth and formed the basis for the development of the KBS-3 disposal concept. It also informed more general and systematic siting studies carried out in the 1990s. Opposition grew due to deficiencies in dialogue with local stakeholders and the programme was suspended in 1985.

SKB's siting process also benefitted from data and knowledge gained through long-term underground research projects. The Stripa Project was the first, large international research project in the nuclear waste field and ran from 1977 to 1992. The project tested how canisters and backfill materials perform at disposal facility depth and developed methods for investigating and modelling fracture zones and groundwater flow. The Äspö Hard Rock Laboratory (HRL) opened in 1986 and is still operational. Its purpose was to test methods for site investigations, develop technology for the deep disposal facility and train personnel.

A systematic site selection strategy started in 1992 (SKB 1994), including details of technical and other requirements for a KBS-3 type disposal facility. This represented a step change in the siting programme, with the introduction of voluntarism and essential engagement with communities at an early stage. As part of its review of the Supplement to the 1992 RD&D programme, the regulator proposed that siting studies should be considered on a national scale. Regional studies were considered necessary to provide reassurance that voluntarism was not leading to an evident restriction in siting options relative to long-term safety factors. The General Siting Study began in 1995 (SKB 1995). This discussed what the possibilities and limitations are when it comes to judging siting prospects based on investigations on different scales (countrywide, regional, county and municipality). At the same time, SKB carried out feasibility studies on the municipality scale in 8 areas between 1995 and 2001. These were desk-based studies aimed at identifying favourable areas for carrying out detailed studies of suitability for a GDF. During the same period, work on defining a set of geoscientific suitability indicators, criteria and requirements continued. A guide to documentation of the early stages is provided by Milnes (2002).

The programme of works to support the site selection process can be divided into the following categories:

- **Early studies** – the intrusive site investigations conducted between 1977 and 1985
- **General studies** – systematic studies covering the whole country with the aim of identifying potentially suitable or unsuitable areas

[4] NEA published its review in 2012 (NEA 2012).

- **Focused studies** – more detailed studies focused on specific areas which had been previously identified as potentially favourable for geological or other reasons
- **Intrusive investigations** – the site investigations phase (2002 to 2009)

The more important aspects of each of these stages are illustrated in Figure 2.7.

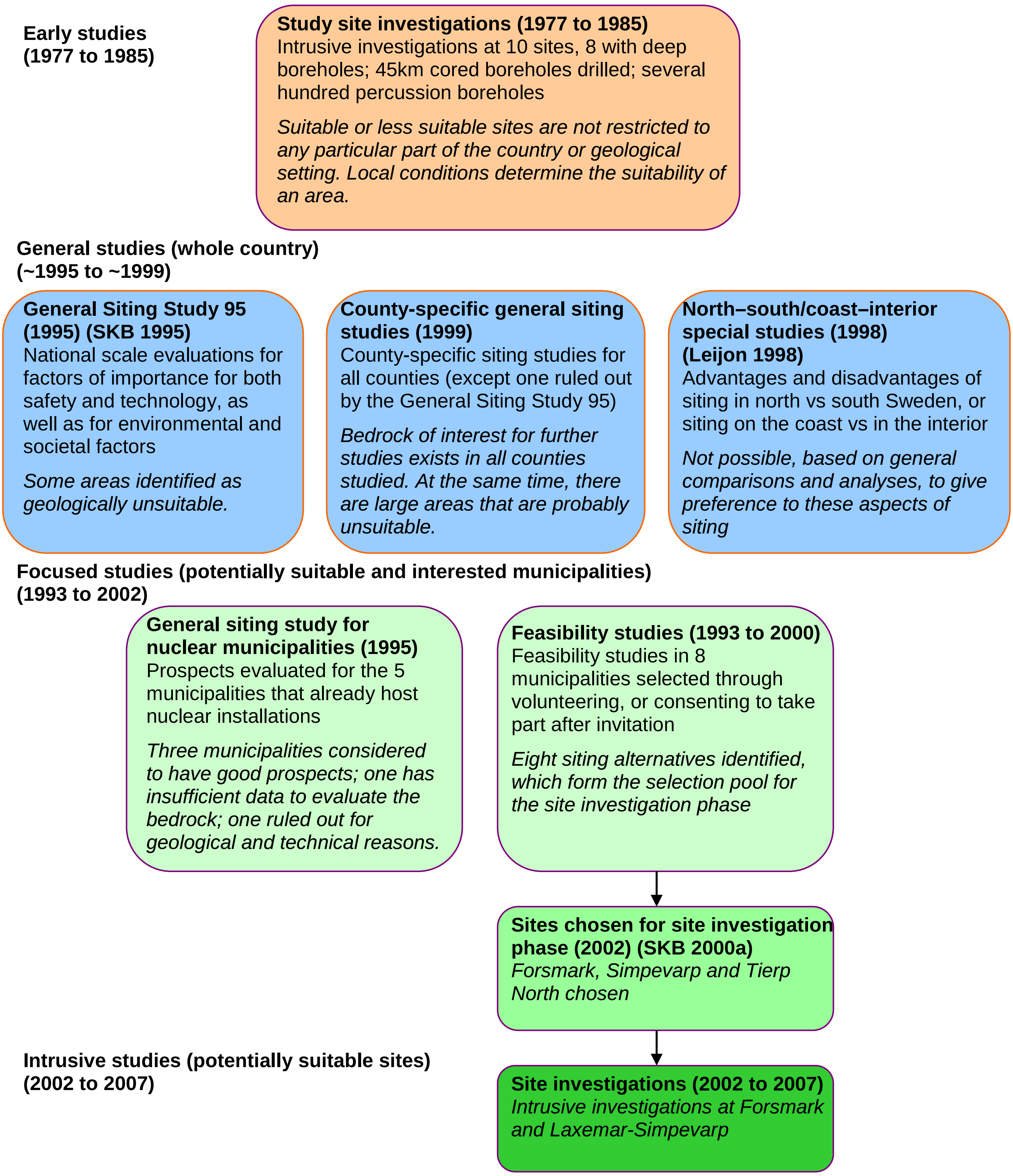


Figure 2.7 Schematic representation of the work to support SKB's site selection process

Notes: The general and focused studies were conducted at the same time.
A summary of the conclusions of each study is indicated in italics.

The desk studies conducted during the period 1994 to 2002 are therefore of primary interest to this case study, that is, the general and focused studies. These are most analogous to Stage 4 of the MRWS site selection process, although SKB was building on knowledge from intrusive investigations and underground facilities from the study sites that strictly would be part of MRWS Stage 5.

General studies

Evaluation on the national scale identified the following areas as being less favourable (SKB 1995):

- areas in which the basement was covered by thick sedimentary sequences (Gotland, Skåne)
- areas subject to intensive, especially geologically young, faulting (Skåne)
- areas dominated by Caledonian nappes (Fjällregionen)

This left the Precambrian basement complex of the Baltic Shield, an extensive area of crystalline rocks, as potentially suitable for a GDF. Within the Precambrian basement, additional criteria were suggested to avoid major deformation zones and areas of high ore content. Otherwise it was considered that the relative suitability of areas could not be generally determined without local investigations, that is, feasibility studies.

2.4.3 County-specific general siting studies

A more detailed screening process was carried out for all parts of the Precambrian basement to determine the relative merits of different parts of each county (except Gotland). Areas were categorised as either 'favourable for further investigation' or 'less favourable for further investigation' within each county. These were desk-studies based on bedrock maps, Quaternary deposits maps, hydrogeological maps and explanatory texts. Although the studies incorporated non-geoscientific conditions, the main geological factors determining relative suitability were bedrock composition, ore potential and occurrence of deformations zones. This identified large areas that were probably unsuitable, although there were remaining areas probably suitable for further investigations within each county.

North–south and coast–interior special studies

SKB conducted a study on the relative suitability of inland versus coastal locations and north versus south Sweden (Leijon 1998). This study assessed whether the general trends that exist with respect to siting on the coast compared with inland, or in the north compared with the south, are of importance in relation to the local variations in groundwater conditions.

The study indicated certain general differences. One example is that the climatic difference between north and south could influence conditions at disposal facility depth, particularly during future glaciations. Comparisons between the conditions on the coast and inland mainly highlighted differences in groundwater conditions. For example, it was found that the occurrence of saline groundwater is common in coastal areas, while areas above the highest shoreline during the Holocene period (marine transgressions have occurred as a result of post-glacial rebound and changes in sea level) could be expected to have fresh groundwater to greater depth.

The conclusion that SKB drew from this study was that:

- it was not possible, based on such general comparisons, to recommend either of these national categorisations as the basis for site selection
- suitability should be judged on studies of particular local areas

The regulator queried this conclusion, as discussed in Section 2.4.7.

Focused studies

From 1993, SKB conducted feasibility studies in 8 municipalities: Storuman, Malå, Östhammar, Nyköping, Oskarshamn, Tierp, Älvkarleby and Hultsfred. Municipalities were chosen as a suitable definition of study area because they are the formal administrative unit that represents the local populace. They are also sufficiently large, typically of the order of 1,000km^2, that they were judged to provide good opportunities for finding an area approximately 2km^2 in size with suitable bedrock for a GDF.

An important component of the feasibility studies consisted of a compilation of all available geoscientific information for the municipality in question and its interpretation in terms of favourable areas for carrying out further investigations. The feasibility studies also considered political, demographic and economic factors affecting the siting of a disposal facility.

In keeping with subsequent results of local referendums, both Storuman and Malå declined further participation in the siting process. So even though the feasibility studies revealed good prospects, no siting alternatives from these municipalities were taken further in the site selection process.

The conclusion drawn from the feasibility studies was that potentially suitable bedrock existed in all but one of the municipalities (SKB 2000a). The studies considered wider societal, practical and environmental factors in concluding there were good possibilities for siting a deep disposal facility in the geologically favourable areas, and suggested 8 'Siting Alternatives', which made up the pool from which a subset of sites would be selected for the site investigation phase. The number of Siting Alternatives was presumably based on a stipulation from the government (Government of Sweden 1995) that applications for permits to build a GDF should contain material that shows that site-specific feasibility studies had been conducted on 5–10 sites in the country.

From the pool of 8 Siting Alternatives, Forsmark (in Östhammar municipality) and Laxemar-Simpevarp (in Oskarshamn municipality) were chosen as areas for intrusive site investigations.

2.4.4 Criteria for site selection and evaluation

The regulators criticised the RD&D Programme 92 (SKI 1995) for not being more systematic in documenting siting criteria and methods. SKI requested a supplementary report be prepared describing the criteria and methods that formed the basis for selection of sites suitable for a final disposal facility. SKB responded with documentation of relevant siting factors (SKB 1995). The siting factors were grouped as follows:

- **Safety** – siting factors of importance for the long-term safety of the deep disposal facility
- **Technology** – siting factors of importance for the construction, performance and safe operation of the deep disposal facility
- **Land and environment** – siting factors of importance for land use and general environmental impact
- **Societal** – siting factors connected to political considerations and community impact

It is largely the first 2 groups of siting factors that relate to the use of geoscientific information. In the site selection process, requirements and preferences for a site were defined initially in terms of broadly favourable and unfavourable conditions. No specific weightings were applied to different siting factors. For the site investigations, however, SKB planned the systematic characterisation of properties relating to geology, mechanical state, thermal, groundwater flow, groundwater chemistry and transport properties. Hence the requirements and preferences for a site were developed during the siting programme, becoming more quantitative as the process progressed. Therefore, it is of interest to differentiate selection criteria applied in the initial phases relating to site screening processes from later criteria that were developed in preparation for the site investigations.

The criteria used to evaluate different sites were based on the functional requirements of the disposal facility and its components (the protective barriers), with consideration of the overall safety and technological requirements. The functional requirements were gradually refined based on knowledge of how different conditions and processes in the rock affect the properties and function of the engineered barrier system. In some cases, these conditions and processes were broken down into values of individual physical or chemical parameters that could be measured at the investigation stage.

SKB developed a series of initial criteria (SKB 1994). Evaluation of geoscientific information focused on identifying unsuitable or unfavourable conditions based on publicly available information. Conditions that should be avoided were identified as:

- abnormal groundwater chemistry (for Swedish bedrock)
- highly heterogeneous and difficult-to-interpret bedrock
- known deformation zones and postglacial faults
- pronounced discharge areas for groundwater
- rock types that might be of interest for prospecting

SKB identified a number of problems in applying siting factors at different scales. A fundamental issue was that a disposal facility will typically occupy an area of a few square kilometres; hence a limited number of factors was appropriate to assessing geoscientific information at scales much larger than this scale of interest, for example, on a national or county scale. A process of successive exclusion of areas based on consideration of factors at increasing levels of spatial resolution was problematic because decisions made on the basis of general geoscientific factors as assessed on a particular scale might not have reflected underlying variability in these geoscientific factors on the actual scale of interest. In consequence, areas might be marked as unfavourable on consideration of geoscientific information at a low resolution that would be classified as favourable on a higher resolution. Other problems noted by SKB relating to applying geoscientific factors on different scales were as follows.

- Surface-based information that can be collated on a national scale primarily reflects conditions at the surface, which do not necessarily reflect conditions at depth.
- A number of geoscientific factors related to information that can only be obtained by field investigations, such as groundwater chemistry in the bedrock. Such information is limited, unevenly distributed, and may reflect specific conditions that are difficult to put in general context.
- Different investigations provide incomplete or indirect information because techniques, interpretation and focus are unlikely to be consistent between regions.

The development of site evaluation criteria is described in 2 SKB reports (Andersson et al. 1998, Andersson et al. 2000). The development of the functional requirements relating to safety came, in part, through understanding gained through a series of safety assessments (see Section 3.3.3). Several of the siting criteria anticipate the site investigations (Andersson et al. 2000) and are based on geoscientific data that is only obtainable through intrusive investigations. Andersson et al. (2000) considers:

- the requirements and preferences made on the bedrock on the site for the deep disposal facility
- how these requirements and preferences can be translated into measurable parameters and criteria that provide guidance for site selection or evaluation

The geoscientific criteria applied during the feasibility studies are listed in Table 2.3. Table 2.4 shows an example from Andersson et al. (2000) of how knowledge about various geoscientific data might change as the programme progresses from feasibility studies, to site investigations and detailed characterisation.

Table 2.3 Geoscientific factors that are studied in Feasibility Studies, based on requirements and preferences formulated for the rock

Factor	Relevant requirements	How requirements and preferences or preferences are taken into account in feasibility studies
Rock types, development interests and homogeneity of bedrock	The rock may not have ore potential.	Further studies and investigations only of areas not judged to have any potential for occurrence of ore or valuable industrial minerals
	It is an advantage if it is a common and homogeneous rock.	Areas with highly heterogeneous or difficult-to-interpret bedrock are avoided. Areas deemed to be homogeneous and consist of ordinary rocks are advantageous
	Suitable thermal properties	An ordinary rock type satisfies the preference of suitable thermal properties.
	Low radon potential	Areas with high radon potential are avoided.
Deformation zones and stability	Regional plastic shear zones and large fracture zones may not be present in the deposition area.	Areas that are chosen for further studies shall be such that the disposal facility can be expected to fit with good margin between known plastic shear zones and large fracture zones. This means that a large area with few major fracture zones is advantageous. Known neotectonic faults are avoided.

Factor	Relevant requirements	How requirements and preferences or preferences are taken into account in feasibility studies
	It is good if the frequency of fractures and local minor fracture zones is low.	Areas where the fracture frequency is low in outcrops are deemed to be advantageous.
Soil cover	A high proportion of exposed rock and otherwise thin soil cover is a preference.	Areas with a high proportion of exposed rock and/or thin soil cover are favourable. Areas with a low proportion of exposed rock are also considered if the geological and geophysical conditions are such that they are easy to interpret.
Groundwater flow	The hydraulic gradient at disposal facility level should be less than 1%.	Areas with a high topographical gradient (1%) on a regional scale are avoided. Pronounced discharge areas are avoided.
Groundwater chemistry	Groundwater at disposal facility level must have a salinity TDS <100 g L^{-1} and be free from dissolved oxygen. A normal groundwater chemistry is desirable.	Areas with indications of a groundwater chemistry that is abnormal for Swedish bedrock are avoided.

Notes: TDS = total dissolved solids
Source: SKB (2000a)

Table 2.4 Example of how knowledge of a geoscientific parameter changes as siting work progresses

Geoscientific parameter	Knowledge during feasibility study	Knowledge during site investigation	Knowledge during detailed characterisation
TDS	Generic	Site-specific information from deep boreholes, sufficient to characterise the disposal facility area.	May contribute new knowledge on TDS in the low hydraulic permeability rock, but also entails a risk of disturbances.
Topography	Full knowledge on regional scale	Full knowledge	Full knowledge
Location, size and direction of fracture zones and fractures	Location of regional zones on surface can be judged	Reasonable precision for regional and local major fracture zones. Stochastic information on local minor fracture zones and fractures	High precision for regional and local major fracture zones in the disposal facility area; fair for local, small fracture zones. Stochastic information on fractures Knowledge of location of fracture zones and fractures at tunnels
Hydraulic permeability of rock mass	Generic for selected geology	Spatial distribution and mean values	Direct knowledge near tunnels

Notes: Of the parameters in the table, only for topography is full knowledge achieved during a feasibility study.

2.4.5 Role of geoscientific information in the siting process

This section provides a more detailed review of how geoscientific data were used in the siting studies. The role of geoscientific data in the identification of Siting Alternatives and the choice of sites to take forward to the site investigation phase is also discussed.

General Siting Study 95

A discussion on the generalisation of geoscientific factors on different scales took place as part of the General Siting Study 95 (SKB 1995). This addressed several problems concerning the use of geoscientific data at the national or regional scale. The problems identified were that:

- the bedrock conditions at a local scale cannot be adequately described in a national scale study
- surface-based studies might have little relevance to conditions at disposal facility depth
- the available data at depth are available at a very limited number of sites (often derived through the site investigation studies) and cannot be generalised to cover an entire region
- some geoscientific data require additional assumptions in their interpretation, which entails an additional uncertainty

The issues identified were applied to different aspects affecting site characterisation, including fracture zones, bedrock geology and ore potential, and illustrated with examples. The examples concerned specific sites for which detailed local geoscientific data were available. SKB compared the conclusions which might be reached using regional scale geoscientific data with those that might be reached if the more detailed local data, with higher spatial resolution, were used.

For fracture zones, the examples considered were the Kamlunge study of the Baltic-Bothnian fracture zone and fracture zones around the Äspö HRL. Fracture zone information was available around Kamlunge because it was part of the Study Sites Investigations. These examples drew a conclusion that regional scale lineament studies (for example, as inferred from topographic mapping with 50 metres resolution) are important to obtain an indication of the occurrence of fracture zones, and hence identify locations of large blocks of bedrock free of fracture zones. It was concluded that caution was necessary when correlating any lineament apparent from geophysical mapping with its significance for safety or construction, which might only become apparent after more intensive studies.

The difference in the understanding of bedrock geology derived through regional scale data compared with that derived through more detailed local scale data was assessed using the Äspö HRL as an example. This was achieved by comparing the bedrock geology maps available in 1987, before the start of site investigations, with more recent detailed mapping undertaken as part of the Äspö HRL site characterisation. It was concluded that areas that appeared homogeneous at the regional scale were in fact significantly more heterogeneous.

Scale issues affecting assignment of ore potential to an area was assessed using an example from Malå municipality. This example was taken as further evidence that siting factors are affected by the scale at which a study is conducted, due to the resolution at which geoscientific data are available.

Scale issues relating to geoscientific data led to the conclusion that whether an area is suitable or not cannot be determined in a general siting study and that more detailed information is necessary for such an evaluation. Nevertheless it was considered possible to identify areas which could be reasonably neglected in further siting work, and other areas which might be prioritised for further study. It was also considered valuable to have a national context to provide background information for subsequent, focused, site selection work.

The General Siting Study 95 gave a summary of the state of knowledge on a national scale with respect to:

- bedrock geology
- chemical composition of the groundwater
- possible changes to the chemical composition of groundwater due to shoreline displacement or sea level change
- topographic gradients as proxies to hydraulic gradients
- hydraulic conductivity of the bedrock
- deformation zones and lineaments
- effects of glaciations
- seismicity
- potential for intrusion
- groundwater discharge areas

SKB identified the following areas where the bedrock was considered unsuitable.

- The Caledonides mountain range consists of a complex structure of mainly sedimentary rock types.
- Skåne and Gotland were identified as regions of high hydraulic permeability sedimentary rock types, with low mechanical strength and a higher content of organic material.

Around 65% of the Swedish bedrock was considered to be of potential interest for further siting studies after this classification. It was concluded that the potential for locating suitable bedrock was good throughout Sweden, with the exception of Gotland, as shown in Figure 2.8.

SKB requires groundwater conditions which are reducing and which avoid areas of high salinity (SKB 2000a). Based on the Study Sites Investigations and other field and laboratory experiments, around 900 sampling points (SKB 1995) in deep groundwater indicated favourable conditions at most of the locations considered.

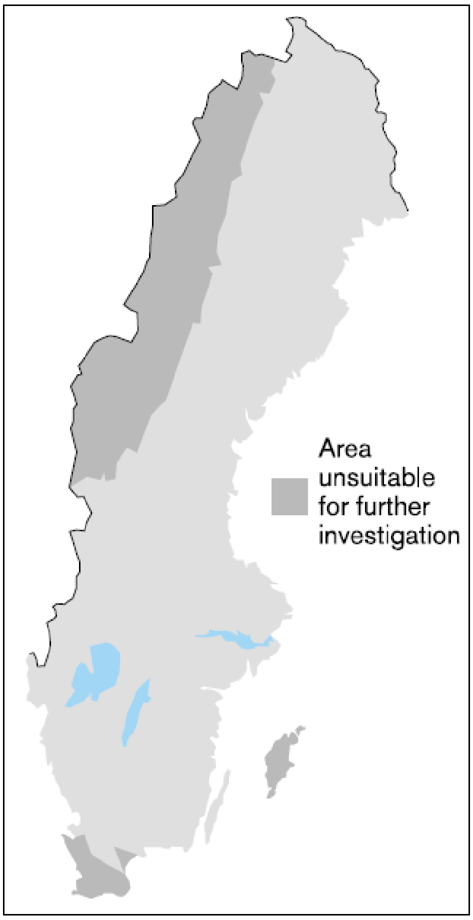


Figure 2.8 General Siting Study 95 showed that the Caledonides, Gotland and parts of Skåne were unsuitable for further investigation based on the properties of their bedrock

Source: SKB (2000a)

Topographic gradients as proxies to hydraulic gradients were considered as a possible method of identifying areas with potentially suitable or unsuitable groundwater flow regimes. The amount of groundwater flow is the product of hydraulic gradient and hydraulic conductivity. In general, low hydraulic gradients occur when the terrain is flat. Analysis of topographic maps led to the conclusion that differences in topography (the difference between the highest and lowest points within an area) at a scale of 25km should not be used to exclude regions as potential sites. This was because the differences revealed by this method are not as significant as other factors, such as hydraulic conductivity, which might vary by several orders of magnitude.

The hydraulic conductivity of the bedrock throughout Sweden was assessed using SGU's well archive. The data collected through the Study Site Investigations did not have sufficient geographic distribution over the country to assess variations in hydraulic conductivity. Hydraulic conductivity was estimated from the measured specific capacity of wells. Wells were screened to ensure they were representative of the typically near-surface bedrock. The number of wells used in the analysis was 124,228. Although trends in specific capacity were apparent, and might be used to find areas of interest, it was concluded that areas associated with high specific capacity should not be excluded. This was because:

- local variations in hydraulic conditions imply that low flow regions may exist within areas of generally high specific capacity

- the near-surface bedrock properties might be significantly affected by glaciation and unrepresentative of conditions at disposal facility depth

It was concluded that maps of lineaments (available at 1:2,000,000 scale) or deformations zones did not provide a sufficient basis to prefer or exclude areas on a regional scale. This was because such studies did not reveal enough about the properties of such structures. The example of a study near Alvesta was cited, where boreholes near the Protogine deformation zone indicated very low fracture intensities and therefore potentially suitable rock. It was thought the local scale studies would be required to site the disposal facility to avoid significant fracture zones.

The potential for human intrusion was thought to be mainly associated with mining activity. Mining and mineral rights in Sweden were collated. However, they were often found to be associated with acid volcanic rock types which were not of interest for further siting investigations. The issue of the potential for intrusion due to extraction of groundwater was deferred to local scale studies.

County scale general siting studies

To provide greater detail on the prospects for siting a GDF in different parts of the country, SKB conducted county-specific siting studies for all counties during the period 1998 to 1999 apart from Gotland, which was considered unsuitable based on the findings on the General Siting Study 95.

The county-specific general siting studies focused primarily on conditions in the bedrock. As well as surveys of geological conditions, the studies included general surveys of natural protection areas, existing industry and transport facilities. In the overall geological assessment of which areas are suitable or unsuitable for further studies, bedrock composition, ore potential and occurrence of deformation zones were considered to be the most important factors. The assessments were acknowledged to vary in reliability, since the quality of the available geological information was uneven.

Data used in county scale general siting studies included:

- an up-to-date geological map and maps of the area covered by aerial geophysical surveys
- the definition of areas of high ore potential – areas to be avoided because of conflicts of interest and the possibility of future human intrusion
- a structural map showing the extent of brittle and ductile deformation zones – to be avoided because of presumed adverse underground conditions
- a synthesis of hydrological data from wells penetrating bedrock, the data stored in SGU’s well archive, showing variations in bedrock hydraulic permeability
- compilations of available data on the thickness of the Quaternary deposits in each county (that is, depth to bedrock), and on the chemistry of bedrock groundwaters

The main conclusion reached was that bedrock of interest for further studies on the siting of the deep disposal facility exists in all the counties studied. At the same time, there were large areas that were considered to be probably unsuitable (SKB 2000a).

The Forsmark area, subsequently selected as the potential disposal facility site, is located within an ore province, Bergslagen, and ore-bearing lithologies occur nearby (Antal et al. 1998). Although the granitoids in the central part of the Forsmark area have no known minerals of economic interest, this was not apparent on the scale of the initial surveys.

North–south and coast–interior special studies (1998)

A disposal facility could be located inland, near the coast or beneath the sea. Each alternative might have advantages and disadvantages with respect to transportation, construction and site characterisation. However, there could also be advantages or disadvantages from the view point of long-term safety. This could be because the hydrochemical environments tend to differ, for example, with saline groundwater occurring at higher elevations near to, or under, the coast compared with inland locations. Other differences include the potential for generally longer or shorter transport paths, travel times and flow path volumes depending on whether the disposal facility is sited in an area with overall recharge (typically inland or island locations) or discharge (typically coastal locations).

SKB considered these issues (Leijon 1998) and concluded that it was not possible, based on the general comparisons and analyses made in the study, to recommend either the northern or the southern parts of the country with regard to prospects for siting. Instead, assessments of suitability must be based on studies of particular areas. The same conclusion applies to the comparative evaluations of siting prospects near the coast versus in the interior (SKB 2000a).

In its review of the RD&D 98 Supplement, SKI noted that SKB had chosen not to place any significant emphasis on the importance of regional recharge or discharge conditions (SKI 2001b). SKI commissioned its own modelling study, which indicated that siting in regional recharge areas could result in significant advantages with long transport routes to the biosphere as well as greater depths to the saline groundwater (Voss and Provost 2001). Consequently, SKI recommended that SKB did not exclude the Hultsfred site (located inland) until issues concerning recharge or discharge, and salinity had been further investigated. A series of modelling reports followed, commissioned by both SKB and SSM, but the issue of the importance of regional recharge areas on disposal facility performance remains unresolved. This is described in detail in Section 2.4.7.

Feasibility studies

The feasibility studies focused on the compilation and analysis of existing data at the municipality scale (~1,000km^2), although some supplementary geological field studies were performed to increase confidence at specific areas. In all of the feasibility studies, geoscientific investigations suggesting potentially unsuitable geological conditions led to the dismissal of parts of the municipality from further investigation.

The reasons for the inclusion of each of the 8 municipalities in the feasibility studies were as follows.

- Storuman and Malå volunteered to take part.
- A general siting study had been performed previously for the 5 municipalities with nuclear facilities. This was because these municipalities had access to nuclear competence and a suitable infrastructure, which justified a study of the geological prospects there. The result was that 4 of the 5 municipalities were judged to have suitable bedrock. For Kävlinge, it was SKB’s assessment that a feasibility study was not justified by due geological conditions, with the area composed of young sedimentary rocks

(Eng 1995). Three of the municipalities – Östhammar, Nyköping, and Oskarshamn – agreed to allow feasibility studies to be conducted.

- SKB contacted the municipality of Tierp because it wanted to investigate the prospects of siting a disposal facility around Forsmark.
- A feasibility study was undertaken in Älvkarleby Municipality because shipments to a GDF in the municipality of Tierp might involve the municipality of Älvkarleby, via the harbour in Skutskär and the rail line through the municipality.

The general siting study indicated potentially suitable conditions in Tierp and Älvkarleby, and both municipalities agreed to take part.

Hence the selection of municipalities for inclusion in the feasibility studies was based on voluntarism (Storuman and Malå) and focused voluntarism (Östhammar, Nyköping, Oskarshamn, Tierp, Älvkarleby and Hultsfred), with SKB identifying municipalities with nuclear competence and/or a suitable infrastructure. Geoscientific data appear to have only been used in this aspect of the selection process to the extent that the national and county scale studies did not rule out any of these municipalities.

How different types of geoscientific information were used at the feasibility study stage of the site selection process are summarised below, based on the example of Östhammar Municipality (SKB 2000b). Geoscientific data of particular interest for the feasibility studies in Östhammar municipality came from studies at Finnsjön in Tierp municipality, near the border with Östhammar, and studies in the area around the Forsmark nuclear power plant.

Finnsjön is one of the study sites investigated by SKB in the late 1970s and early 1980s. At this location, different types of land surveys and borehole surveys in 11 deep boreholes and 20 percussion boreholes were performed. In the area around the Forsmark nuclear power plant, detailed studies for the construction of the 3 reactors and the construction of the SFR disposal facility were made. The area around the Forsmark nuclear power plant also has 2 deep boreholes, with depths of around 500 metres.

Figure 2.9 shows a map of the municipalities of Östhammar, Tierp and Älvkarleby showing the locations of Finnsjön and the Forsmark nuclear power plant, as well as the areas which were dismissed from further investigation, field checked areas (subject to outcrop mapping) and areas of interest for further study.

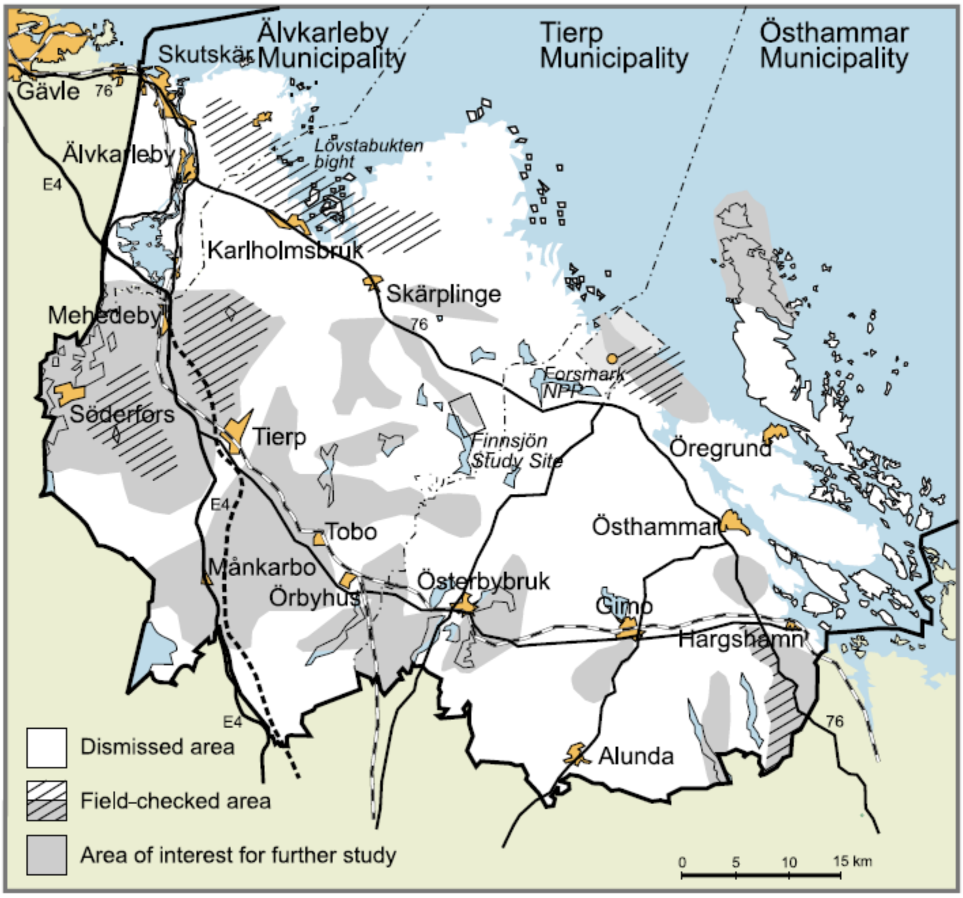


Figure 2.9 Feasibility studies assessment of areas in the municipalities of Östhammar, Tierp and Älvkarleby

Source: SKB (2000a)

Bedrock geology

Östhammar Municipality was covered almost entirely by a comprehensive set of recent geological maps. For a reliable study of the geological conditions, it was considered necessary to consider a slightly larger area than the actual area of interest. Direct bedrock geological observations were missing for the bedrock beneath the sea However, there were data from the islands and indirect information in the form of results from airborne geophysical measurements and bathymetric data.

Geophysical mapping

Geophysical data and topographical data were considered an important complement to the bedrock geological maps and field observations. This was especially true for the compilation and interpretation of deformation zones and the assessment of bedrock radium content. The geophysical data used came from airborne measurements of variations in the Earth's magnetic field, electrical properties and natural gamma radiation. Digital information from the magnetic measurements as well as from radiation measurements were available covering virtually the entire study area. Elevation data provided information which, among other things, could indicate lineaments. In the preliminary study, elevation data of 50 metres resolution were used.

Bedrock radium content

Radium concentrations in the bedrock below 50 Bq kg^{-1} were considered normal, while levels above can be classified as anomalous. High concentrations of radon within the disposal facility do not affect long-term safety, but represents a health and safety problem during the construction and operation period. This might lead to additional requirements for the disposal facility ventilation capacity.

Soil thickness

The long-term safety of a geological disposal facility should not be affected by the superficial soil cover. However, a high proportional area of outcropping bedrock or thin soil cover facilitates geological surveys. This makes assessments of the suitability of the bedrock more confident when intrusive investigations are not used. The whole municipality (Östhammar) was covered by modern digitalised soil maps, with mapping performed during the period from 1981 to 1988.

Hydraulic data

The number of boreholes for which some hydraulic data were available was considered sufficient for an overall statistical analysis of large-scale variation in hydraulic permeability between different rock types. A total of 1,447 wells with specific capacity data were available, with an average depth of 57 metres. Data on hydraulic conductivity at disposal facility depth were only available at Finnsjön.

Hydro-chemical data

Data on groundwater chemical composition of the near-surface bedrock were taken from SGU well archives. Since groundwater conditions change with depth, it was considered important to also consider data from greater depths, to the extent they were available. The most important data came from the Finnsjön area at depths of around 700 metres.

Exploitation interests

Information on ore deposits, mines and ore exploration was obtained from SGU. Information on the current and historical mining claims was provided by the Mining Inspectorate. In addition, the geological descriptions of known ore fields, as well as maps and textbooks, were used in the assessment of ore potential. Potential to develop near-surface quarries (for example, for aggregates) was also considered.

Hydrology

Information on river basins and groundwater recharge or discharge from the Swedish Meteorological and Hydrological Institute was used to identify areas of discharge.

Information density, assumptions and uncertainties

SKB provided a discussion of the quality and quantity of the existing information in the survey areas. Areas with less satisfactory data coverage were identified and conclusions relating to them acknowledged as being uncertain. Assumptions were required to interpret the geoscientific data. For example, fracture zones identified through geophysical surveys were assumed to be sub-vertical unless there was contradicting information from previous surveys. For parts of the municipality, assessments of the suitability of bedrock were based on the assumption that the bedrock at disposal facility depth is reflected by the bedrock at the surface.

Field verification

Field checks were identified as a method of increasing the reliability of the geological assessments. They were generally applied in areas which indicated potential as a disposal facility site. Field verification in Östhammar Municipality included documentation of approximately 180 outcrops with respect to outcropping fractures. At most observation points, the rock magnetic properties were also measured to allow better correlation between observed rock types and the magnetic anomaly map.

Siting alternatives

The conclusion of the feasibility study work was the identification of 8 Siting Alternatives, which made up the pool from which a subset of sites would be selected for the site investigation phase. The number of siting alternatives was presumably based on a government stipulation that permit applications to build a GDF should contain evidence that site-specific feasibility studies had been conducted on 5–10 sites in the country. Areas identified in the feasibility studies as probably unsuitable were excluded from consideration as Siting Alternatives. However, the areas identified as potentially suitable, and therefore of interest for further study, required a further selection process to reduce the number of areas under consideration for Siting Alternatives.

The identification of Siting Alternatives from within the areas identified as being of interest for further studies was based primarily on societal, political and transport considerations (SKB 2000a). Geoscientific data thus allowed areas to be screened out within a municipality, but the identification of Siting Alternatives from within the potentially suitable areas appears to have been based primarily on other factors. However, several of the Siting Alternatives identified were near areas with greater availability of geoscientific data, for example, because they are near to existing nuclear facilities which required surveys for their construction (for example, Forsmark) or they are near to areas considered in the Study Site Investigation programme (for example, Fjällveden) or existing underground laboratories (for example, Simpevarp or Äspö HRL). This suggests increased confidence in the understanding of the bedrock might have influenced the location of Siting Alternatives.

Selection of Sites for Site Investigations

The reasoning which led to the selection of Forsmark and Laxemar-Simpevarp from the pool of 8 Siting Alternatives is described in SKB (2000a). The selection of sites for site investigations was reported within a framework with 3 considerations:

- bedrock
- industrial establishment
- societal aspects

The decision making process was not based on quantitative scoring against criteria, but on qualitative arguments. The bedrock category potentially relates to the use of geoscientific data. Within the bedrock category each Siting Alternative was evaluated in terms of distinguishing characteristics, available data and important uncertainties.

During the 1990s, it was thought that 2 URLs would be constructed and hence the need for at least 2 sites for detailed investigations. It was also considered that evaluating at least 2 sites was good practice so as to compare bedrock conditions. There were potentially 4 sites at which site investigations could have been performed: Fjällveden (Nyköping), Forsmark (Östhammar), Laxemar-Simpevarp (Oskarshamn) and Tierp. Tierp withdrew after a vote in the community. The nearby Älvkarleby Municipality, neighbouring Tierp, also volunteered but was declined by SKB as it was thought too small on its own to find appropriate siting areas. Fjällveden had been studied as part of the feasibility studies. Nyköping eventually withdrew as SKB focused available resources on investigations on new sites in the municipalities of Östhammar and Oskarshamn.

SKB rejected the possibility of trying to rank sites based on what was known at the time, for example, by formulating geological factors for all areas and weighting them with respect to their importance in a safety assessment. Examples of factors that could be used in this phase are soil cover, homogeneity of the bedrock and fracture frequency on outcrops. SKB considered that this approach risked leading to unclear or misleading results, since the factors that distinguish the areas are all of little direct consequence to safety. Furthermore, SKB considered that the available information was determined by the thickness of the soil cover and the proportion of exposed rock, which could make comparisons between areas misleading. For example, the data from the feasibility studies may indicate more fracture zones in an area with a high proportion of exposed rock compared with a soil-covered area. It was also considered difficult to see how the weighting of the factors with respect to their importance in a safety assessment could be justified (SKB 2000a). The regulator disputed this argument (see Section 3.3.7), but nevertheless recommended the selection of Forsmark and Laxemar-Simpevarp as areas for site investigations (SKI 2001b).

2.4.6 Development of safety assessment and environmental impact assessments

The development of safety assessment methodology started in the 1980s with generic assessments based on data from the study sites.

SKI identified safety assessments as having an important role in directing R&D and as a basis for decision-making (SKI 1995). SKI proposed that the government should impose a condition that, before SKB initiated site investigations, SKB should present an in-depth and comprehensive safety assessment of the proposed main system alternative (SKI 1995). SKI also proposed that SKB should commission and present an independent peer review of the safety assessment by national and international experts. These proposals were accepted by the government and implemented by SKB as the SR-97 Safety Assessment (SKB 1999).

The aims of the SR-97 Safety Assessment were to:

- show that KBS-3 would have good prospects of meeting long-term safety and radiation protection requirements, and to demonstrate the feasibility of finding a site in Sweden that meets the requirements
- demonstrate safety assessment methodology
- provide data for measurement programmes for geoscientific site investigations and to evaluate the measurement results
- provide data for the specification of requirements with respect to the canister and other barrier functions
- contribute to specifying the factors that serve as a basis for the selection of sites for site investigations

For the feasibility aspect, it was important to use site data – here using proxy sites: Aberg (Äspö), Beberg (Finnsjön) and Ceberg (Gideå). The sites differed mainly in terms of hydrogeological conditions (island, coastal, inland) rather than different geologies and rock properties.

SKB performed Environmental Impact Assessments (EIAs) as part of its application for permission to start intrusive site investigations at Forsmark (SKB 2001a) and Laxemar (SKB 2001b). These reports give an overview of the planned site investigation phase. They also describe the impact on the local communities and environment that might result from the investigations, along with the protective actions SKB intended to take. A later report (SKB 2002) gives a preliminary EIA for the final disposal facility and associated surface facilities.

The reviews of the 1998 RD&D programme collated by the regulator advised on the safety assessment methodology and its presentation to a wide range of audiences. It also urged attention to alternative disposal methods.

2.4.7 Critical review and its Impact

The regulator, SSM, receives a research grant to follow the main technical areas involved in the disposal programme, which allows it to develop detailed understanding in selected areas. SSM has developed its own programme and maintains the capability to advise on technical areas and to perform independent safety analyses. It is required to review and comment on SKB's submissions, including the formal 3-year review cycle (see Section 2.4.1), where SKB is required to submit to the regulator a report describing its proposed activities for the next review period. The RD&D programmes have a role in providing information to the public, one of the intentions of the requirements of the Nuclear Activities Act. SSM also compiles comments from stakeholders on the RD&D programmes and uses these as additional information when making its recommendation to the government, which decides on the matter.

Thegerström et al. (2006) describes the following additional reviews of SKB's work.

- **Frequent reviews.** These were carried out by the regulator through its staff or its consultants. Regular meetings were held where the regulator scrutinised the progress made by SKB, particularly on the issues raised in its review of SKB's RD&D programme.
- **Internal reviews**. Procedures for internal reviews were developed within the SKB RD&D programme. For many projects, special reference or advisory groups were organised with participation of experts with limited involvement in the SKB programme. These experts were engaged to provide a wider perspective on the scientific issues at hand. Workshops on specific topics were organised with participation of both internal SKB and external experts. Before publication, SKB reports are submitted to internal expert review and where appropriate, review by external experts.
- **International cooperation.** This was identified by SKB as a means of promoting the scientific quality of its work by allowing studies and results to be reviewed by a broader range of experts than would normally be the case in a national programme. Major international co-operation projects such as the Stripa Project and the Äspö HRL were set up with a managerial committee with representatives from the participating (funding) organisations and a scientific advisory committee. The role of the scientific committees was to review and evaluate the work performed and to provide advice to the managerial committee on the future direction of work.

Critical review has been identified by SKB as having an impact on the programme by raising new issues, helping to focus on weak points and modifying certain aspects of the programme or the technical design of the concept (Thegerström et al. 2006). Some examples of relevance to the use of geoscientific information on how the programme and the concept have been influenced by critical review are given below. These examples relate to the siting process, and the documentation and justification of decisions. They therefore tend to be related to the presentation of geoscientific data in developing a clear argument to justify the approach adopted, rather than the actual collection and interpretation of such data.

Stepwise implementation

Initially SKB planned to proceed directly from R&D work and site investigations to construction of an operational GDF. However, comments from KASAM based on ethical considerations concerning the rights and responsibilities of present and future generations prompted a more stepwise approach to the development and implementation plans. KASAM proposed a demonstration disposal facility and SKB adopted this basic idea of demonstration, but in a modified fashion in RD&D Programme 92 (SKB 1992). Full-scale demonstration of important technical issues were to be take place at the Äspö HRL and the canister laboratory, while at the same time plans for siting and implementation of deep disposal were structured in a stepwise fashion.

Site selection process and criteria

The siting process proposed by SKB has been subject to requests for improved documentation and justification as part of the regulatory review of RD&D Programme 1992 and subsequently. The following issues were raised.

- A more detailed description of the process and the site selection criteria to be used was requested during the review of RD&D Programme 98 (SKI 1999).
- A justification of the criteria used for the evaluation of potential sites was requested during the review of RD&D Programme 92 (SKB 1992).
- A report on geological overview studies, and their use as a basis for judging where in Sweden there would be areas suitable for feasibility studies, was requested as a result of the review of RD&D Programme 92 (SKB 1992).
- Evidence of research on the consequences of siting near the coast versus inland and the consequences of siting in southern versus northern Sweden was requested during the review of RD&D Programme 92 (SKB 1992) (see below)

The feasibility studies were guided by the regulatory review of RD&D and government decisions.

Local and regional groundwater flow related to coastal or inland siting

The relative advantages and disadvantages of inland versus coastal disposal facility sites (potentially relating to areas of regional-scale recharge and discharge respectively) were discussed early in the siting process and there has been a debate on this issue since then. The conclusion initially drawn by SKB (Leijon 1998) was that no general recommendations with respect to siting a disposal facility inland or close to the coast could be made. Instead it was recommended that assessments of suitability should be based on studies of particular local areas.

Based on a modelling study that it commissioned (Voss and Provost 2001), SKI challenged these conclusions in its review of SKB's integrated account of method, site selection and programme prior to the site investigations phase (SKI 2002). Voss and Provost (2001) modelled the discharge paths from potential disposal facility sites in south-east Sweden. Results indicated that potential disposal facility sites at Hultsfred and another comparison site might be preferable in terms of the hydrogeological safety margin because of longer travel times and path length, and larger path volume. The modelling (Voss and Provost 2001) made use of various geoscientific data, principally topographic maps and groundwater chemistry data.

Voss and Provost (2001) list 3 issues which complicate the picture concerning the possibility of locating a disposal facility in an upstream portion of a regional-scale groundwater flow system.

- **Heterogeneity within the bedrock**, which contains variable lithology as well as fractures and fracture zones at all spatial scales, was highlighted as an issue. This means that permeable structures in the rock may gather flows and discharge them locally, near to their recharge areas. This possibility means that primary recharge areas, those with long paths, may be more difficult to locate in such bedrock. Despite this, primary recharge areas do exist somewhere within the groundwater system, although their spatial uniformity, continuity and lateral extent may not be sufficient to site a disposal facility (Voss and Provost 2001).
- **Small scale variation in ground height** could lead to undulations in the topography of the water table, leading to small, closed, shallow flow systems. These may occur even in the vicinity of a major recharge area at the upstream end of a regional flow system. If the disposal facility were placed inadvertently within the local system in this area rather than within the regional system, flow paths would be relatively short.
- **Climate changes**, such as permafrost and glaciation, as well as isostatic rebound of the crust and sea level regression, will strongly affect the groundwater flow fields. Therefore recharge and discharge areas will not necessarily remain stationary throughout the glacial cycle and the transport of subsurface contaminants may be significantly affected by the transient flow patterns.

The regulator recommended that SKB make further assessments of differences in groundwater conditions between inland and coastal locations, and the possible consequences for a disposal facility. SKB conducted 2 modelling studies – one for eastern Götaland (Follin and Svensson 2003) and one for northern Uppland (Holmén et al. 2003). SKB also presented a report where it discusses the importance of groundwater flow conditions and salinity for disposal facility siting (SKB 2003).

Follin and Svensson (2003) considered the same model domain as Voss and Provost (2001). They rejected the reasoning that regional scale topography is a major mechanism for groundwater flow from the interior of eastern Götaland. In fact, they found most recharge and discharge areas to be fairly close together regardless of the distance to the coast, which was taken to imply that it is the local scale topography and the hydrogeological properties at each site that will by and large determine the transport times. SKB concluded that groundwater flow cells both inland and at the coast are mainly local and that locations inland, for example at Hultsfred, provide no advantage with respect to safety.

The issue of siting with respect to regional recharge and discharge areas was discussed by SKI in its review of the RD&D 2004 programme (SKI 2005). SKI acknowledged that the SKB reports (Follin and Svensson 2003, Holmén et al. 2003) address some of the concerns raised, but request additional work. SKB responded with a further study (Ericsson et al. 2006), which concluded that increased conceptual complexity results in an increased tendency towards the development of more local flow cells. SKB maintained that the modelling work did not show that an inland disposal facility would have any advantages over a near-coastal one, as more realistic hydraulic and geochemical conditions are included in the calculations.

SSM commissioned further reviews of this work (Dverstorp 2007) and considered that the evaluation of the modelling results was not complete enough to support SKB's conclusion that super-regional flow conditions can be dismissed as a siting factor. A 2010 review by the INSITE expert group (SSM 2010) used by SSM to review SKB's work during the site investigations concluded that endeavouring to make super-regional flow a high-level consideration in the process of identifying a suitable disposal facility site was inappropriate. SSM plans to assess if SKB has made sufficient analysis of all the essential factors that form the basis for making a fair overall evaluation of siting alternatives as part of its review of the 2011 licence application.

The debate surrounding regional recharge or discharge areas and their importance for disposal facility siting took place while the intrusive site investigations were being performed.

Safety assessment methodology

In response to a request from SKI, the OECD's NEA appointed an international review team to conduct an international peer review of SR-97. Experts were selected by NEA on the basis of certain criteria established by SKI. These criteria included exclusion of experts who had worked on major projects on behalf of SKB over the past 6 years and a need for a reasonable balance between representatives from the nuclear industry and from the regulators.

In the regulator's opinion (SKI 2001a), the SR-97 safety assessment provided SKB with a basis for further work on the site investigation and function requirements. However, the regulators found that SR-97 did not contain any in-depth discussion of what the results of the safety assessment would mean for the site investigation programme or the function requirements for the engineered barriers. Instead, SKB stated that the results from SR-97 would be dealt with in separate projects including:

- the project to develop the site investigation programme
- the formulation of requirements and preferences with respect to the bedrock
- the review of functional requirements and design basis requirements for the canister and the other barriers

Thus the regulators intended to return to these issues in connection with the regulatory review of SKB's supplement to RD&D Programme 98 and, at a later stage, in connection with the review of SKB's RD&D Programme 2001. The regulator stated that SKB should conduct a more comprehensive analyses of uncertainties in the assumptions used for the canister and buffer performance to better determine the importance of the rock barrier to safety and thereby identify which parameters it is important to study in a site investigation.

Alternative disposal facility concepts

Following SKI's review of the 1998 RD&D programme, SKB was asked by the government to complement its analysis on concepts other than the KBS-3 design for a disposal facility. It was thought that the government might stipulate the KBS-3 method as a planning prerequisite for SKB's choice of sites for site investigations. To do this, the government would need background material in the form of a supplementary analysis of alternative system designs. However, the final examination of the choice of method is made in conjunction with an application for a permit under the Environmental Code and the Nuclear Activities Act.

Permission for the intrusive site investigations

The government stated in its decision relating to the review of RD&D 98 Supplement that it had no objections to intrusive investigations at Forsmark, Simpevarp and Tierp. SKI's review concluded that SKB had presented an adequate basis for selecting potential sites for hosting a disposal facility.

However, SKI did criticise some aspects of the siting process. SKI considered that there were other factors besides bedrock geology that could provide geoscientific breadth to the selection decisions. For example, it considered that experience from safety assessments showed that the hydrogeological and geochemical conditions have considerable importance for long-term safety. In SKI's opinion (SKI 2001b), SKB should have also attempted to achieve a more systematic compilation and evaluation of more or less favourable conditions for the selected areas on the basis of the available geological information.

One of the most important absolute requirements on an area hosting a disposal facility is that no ore potential should be present. It was SKI's opinion that SKB should formulate this requirement more clearly. For example, it was considered inadequate that only the disposal facility deposition area should be included. It would be reasonable for the requirement to also include a well-defined area around the selected deposition area.

The regulator and other reviewers noted that SKB's change to new siting factors categories (to bedrock, industrial establishment and societal aspects from safety, technology, land and environment and societal) should have been dealt with earlier in the siting process. SSI also considered that SKB's arguments for the changed classification of siting factors were unclear.

SKI thought that SKB, in its selection of areas, had attempted to spread the risks of possible site deficiencies (which would lead to the abandonment of a site) to different geological environments in different regions. The areas that host nuclear power plants, Forsmark and Simpevarp, were understood to have been prioritised, taking into account the fact that there are deep geological data from nearby areas that indicate that there is a possibility of finding suitable bedrock in these locations.

2.4.8 Summary

What role did geoscientific studies play in the siting programme?

Geoscientific data related to bedrock geology were used to rule out some areas of Sweden as a suitable area for further investigations as part of the General Siting Study 95. This report also considered environmental and societal factors.

In parallel with national and county scale studies, the developer undertook studies on specific limited areas. The choice of municipalities (with areas of the order 1,000 km^2) for these more focused feasibility studies was based on volunteerism, along with identification of municipalities with existing nuclear facilities.

Geoscientific data were used during feasibility studies to identify areas – called Siting Alternatives – which might be appropriate subjects for intrusive investigations. Geoscientific data from deep boreholes constructed from earlier Study Sites Investigations were important in estimating conditions at disposal facility depth. At this stage, additional surface-based geological surveys were carried out to supplement to pre-existing data. The identification of Siting Alternatives considered political, demographic and economic factors affecting the siting of a disposal facility, as well as geoscientific data.

The choice of 2 areas for intrusive site investigations was based on industrial infrastructure and societal considerations, as it was judged that it was not appropriate to try and rank the bedrock properties; each of the Siting Alternatives was considered to have potentially suitable bedrock.

Hence geoscientific data were used in conjunction with other factors (societal, Industrial and transport related) at every stage of the siting process.

The form of the site selection process was strongly influenced by a government decision that site-specific feasibility studies should be conducted on 5–10 sites and that site investigations should be conducted on at least 2 sites.

What decisions were made by (a) the developer, (b) the regulator or (c) any other body, based on information from desk-based studies?

On the basis of desk-based studies, the developer (SKB) decided which municipalities to conduct feasibility studies in, which areas should be considered Siting Alternatives, and which areas should be subject to intrusive site investigations. However, some data on hydraulic conductivity and groundwater chemistry at disposal facility depth at a number of sites around Sweden were available from an earlier investigation programme.

The decisions made by SKB were reviewed by the regulator (SKI), which recommended the decisions to the government. The decision not to object to intrusive site investigations at Simpevarp and Forsmark was made by the government on advice from SKI.

What were the organisations' roles in developing or reviewing desk-based studies?

The developer, SKB, conducted the desk-based studies. The regulator, SKI, through its reviews of the RD&D reports, can be seen as consistently requiring SKB to document its decisions and justify them more rigorously. Examples of this include:

- a series of reports commissioned with respect to the potential benefits of an inland versus a coastal disposal facility
- documentation of the criteria and methods applied to site selection
- the General Siting Study 95 and county scale general siting studies as a means of putting the more focused feasibility studies within a national context

Did the regulator use any criteria when deciding whether the desk-based geoscientific studies were adequate?

The regulator formally reviewed SKB's work programme every 3 years during the period when desk-based studies were being carried out. These reviews also incorporated the opinions of other stakeholders, including universities and institutes of technology as well as environmental organisations.

2.5 Switzerland

2.5.1 Overview of the process of radioactive waste disposal

In Switzerland, radioactive wastes arise mainly from electricity production at 5 nuclear power plants. The definition of HLW includes both spent nuclear fuel and vitrified fission product solutions from reprocessing of spent fuel (SFOE 2008). Assuming a 50-year operating lifetime for the existing power plants, the total waste volume for disposal is estimated at 2,700m^3 long-lived ILW and 7,300m^3 HLW (Nagra 2008a). This case study examines the plans for disposal of HLW in a deep GDF; some long-lived LLW and ILW, and spent fuel might also be included in such a facility.

Nagra was established in 1972 as a co-operative of the radioactive waste producers and the Swiss Federation. It has responsibility for preparing the scientific and technical basis for waste management and for performing site investigations, and constructing and operating disposal facilities. In Switzerland, the regulator is the Federal Nuclear Safety Inspectorate (ENSI). In the past, legal requirements were detailed in regulatory guidelines issued by the Swiss Federal Nuclear Safety Inspectorate (HSK), which was also responsible for all aspects of facility inspection. ENSI became the successor body to HSK in 2009.

The responsible government body is the Swiss Federal Office of Energy (SFOE), which is part of the Federal Department of the Environment, Transport, Energy and Communication (DETEC). The government and the regulator are also advised by a number of commissions and expert groups, including ESchT representing interests in neighbouring Germany. The Swiss Federal Nuclear Safety Commission (KSA) advises ENSI and DETEC on fundamental aspects of safety and reviews the evaluations made by ENSI. The Commission for Radioactive Waste Disposal (CRW) conducts reviews of Nagra's reports and advises ENSI on geological disposal.

Prior to 2008, Nagra undertook site investigations in both higher strength crystalline rocks and in lower strength sedimentary rocks. These rock types were considered as potential host formations for a geological disposal facility for LLW and ILW. As described below, these siting efforts were unsuccessful. Consequently, in 2008, a new site selection process – the Sectoral Planning Procedure (SFOE 2008) – was put in place. From 2008, the search for a suitable site has been carried out in accordance with this siting process. This siting process represented a step change in the decision making process for selecting suitable geological formations and sites, although the development of an understanding of what options and conditions offer favourable conditions for demonstrating long-term safety has been a longer term and consistent process.

The Sectoral Planning Procedure describes a process; it is not specific to a particular geological environment. However, the Swiss programme is currently focused on the concept of disposing of HLW in Opalinus Clay, a lower strength sedimentary rock. Several of the diagrams used to illustrate the site selection process in Section 2.5.2 have been produced by Nagra based on this disposal concept.

The federal government leads the process, treating it as a national infrastructure project necessary to meet its land use planning obligations and integrate its sectoral strategies and plans as a whole. SFOE owns the process, interactions and issues centrally. Technical advice is provided by ENSI, the Commission on Nuclear Disposal (KNE) and others.

The geology of Switzerland is varied. Southern Switzerland is dominated by the Alps, a geologically young mountain range formed around 50 million years ago. The plains in northern Switzerland, the Molasse Basin, were formed as a sedimentary sequence of conglomerates, sandstones and clays. In the north of Switzerland the crystalline basement has been exposed in the Tabular Jura, FaltenJura (Folded Jura) and the northern part of the Molasse Basin. In the Tabular Jura, a thin sequence of Mesozoic-Tertiary sediments rests on the basement. There are also some evaporite units in the FaltenJura (see Figure 2.11).

2.5.2 Site selection process

Nagra began site evaluation of crystalline basement rocks first to follow the momentum gained in the Swedish programme rather than a predilection for this geological environment. It also began investigations of suitable sedimentary formations as required by the Federal Council. It was aware of the merits of Opalinus Clay from an early stage, although there had been mixed experience with tunnelling in this geology. Knowledge of how to deal with these geotechnical issues has improved in the intervening time.

Pre-2008 investigations in crystalline rock

In 1979 an application was submitted for a licence to construct a rock laboratory in the crystalline formations of the Grimsel region. Between 1982 and 1985, Nagra carried out seismic surveys and drilled exploratory boreholes at 6 sites in northern Switzerland. In 1985, Project Gewähr (Project Guarantee), which considered the feasibility of HLW disposal in crystalline rock, was submitted to the authorities. In 1988, the Federal Council accepted that it was feasible to construct a disposal facility in crystalline rock with the required level of long-term safety. However, it found that there was insufficient proof that sufficiently extensive bodies of rock with the required properties could be found (SFOE 2008).

The investigations in the crystalline basement of northern Switzerland concluded in 1994 with the Kristallin-I safety analysis (Nagra 1994). Following a review of this project, HSK concluded in 2004 that the safety of a GDF for HLW could be assured if a sufficiently large body of rock with the properties described in Kristallin-I could be found. However, the prospects of finding such a body of rock and demonstrating conclusively that it had the required properties had not improved since Project Gewähr (HSK 2005).

Pre-2008 investigations in sedimentary rock

Since 1987 Nagra has conducted investigations relating to sedimentary rocks and crystalline rocks in parallel. In 1988, 7 potential sedimentary host rocks were identified and 2 options, Lower Freshwater Molasse and Opalinus Clay, were selected for further investigation. In 1994, after a regional geophysical survey, Nagra applied for a licence to establish an investigation borehole at Benken to obtain underground data. The application was granted in 1996 and the borehole was drilled in 1998. A long-term observation system was established. In 1996, an international research project was initiated in the Opalinus Clay of the Mont Terri Rock Laboratory. The rock laboratory was constructed off the service tunnel of the 4km long Mont Terri motorway tunnel.

Nagra submitted a report to demonstrate the feasibility of disposal of HLW in Opalinus Clay to the federal government at the end of 2002 (Nagra 2002a). Following a comprehensive review and a positive evaluation of the project by the federal authorities

(HSK 2004) and international experts (NEA 2004), the Federal Council approved the report demonstrating the feasibility of disposal (Nagra 2005) in 2006.

The 2008 Sectoral Plan

In 2008, the government published its ‘Sectoral Plan for Deep Geological Repositories’. All subsequent work by Nagra and the authorities has been carried out within the framework of the 2008 Sectoral Plan. The conceptual part of the Sectoral Plan (SFOE 2008) sets out the federal government’s goals, and the procedures and criteria applying to the site selection procedure for geological disposal facilities for all categories of waste in Switzerland. The focus of the site selection procedure is on safety criteria, with land-use planning and socioeconomic criteria playing a secondary role.

The Sectoral Plan was developed by working groups. Different options were discussed through a series of iterations in open meetings involving various stakeholders during 2005. The final decision was made by SFOE and the Sectoral Plan was approved and issued by the federal government.

The Sectoral Plan requires a site selection process with stepwise narrowing down of potentially suitable areas through the application of criteria predominantly based on long-term safety. The conceptual part of the Sectoral Plan defines 3 stages, which will lead to the identification of sites for the GDFs. This process is led by SFOE. Where necessary, geoscientific knowledge might be increased by additional investigations.

The aims of the 3 stages of the Sectoral Plan are as follows:

- **Stage 1: Selection of geological siting areas**. The main focus is on identifying suitable siting areas based on safety and geological criteria. The developer (Nagra) proposes geologically suitable siting areas and justifies this selection in a report addressed to the federal government.
- **Stage 2: Selection of at least 2 sites.** A spatial planning assessment of the siting areas proposed in Stage 1 will be made and socioeconomic studies prepared. With input from the siting areas, Nagra will also draw up proposals for the configuration and design of the surface infrastructure and select at least one site for each siting area. This will involve carrying out provisional quantitative safety analyses and a safety-based comparison before identifying at least 2 siting areas – one for HLW disposal and one for LLW and ILW disposal. Co-disposal of higher activity and lower activity wastes might be considered.
- **Stage 3: Site selection and general licence procedure.** The sites remaining after Stage 2 will be investigated with a view to site selection and submission of an application for a general licence. If necessary, the site-specific geological information required for these steps will be supplemented by performing additional geological investigations. The siting regions (cantons) will propose projects for regional development and prepare the background information for deciding on any compensation measures and for monitoring socioeconomic and environmental impacts. Compensation measures will be negotiated and made transparent in Stage 3. The waste producers will finally submit applications for a general licence – one for HLW disposal and one for LLW and ILW disposal, or one for a combined disposal facility.

At the end of each stage, a review will be conducted by the responsible federal authorities. This will be followed by a 3-month consultation phase before the Federal

Council makes its decision. The eventual licence application at the end of Stage 3 needs to review the siting process, justify the choice of site and design concept, as well as making a safety case for the chosen site. The general licence granted in Stage 3 has to be approved by both chambers of the Swiss parliament and is subject to an optional national referendum.

On 1 December 2011, the Federal Council decided to approve Stage 1 and accept Nagra's suggested potential locations. Prior to the decision, ENSI performed a review of Nagra's proposed siting areas based on aspects of safety and engineering feasibility, and in conclusion supported the proposed geological siting areas. Stage 1 is therefore now complete.

The Sectoral Plan 2008 envisages a significantly different siting strategy compared with MRWS siting process and analogies are therefore limited. The differences are particularly due to:

- the availability of considerable amounts of geoscientific data from earlier, intrusive, investigations
- the form of the siting process, which starts as a national scale search, with areas discarded in a stepwise manner

2.5.3 Criteria for site selection and evaluation

A main premise of the Swiss programme is that long-term safety should be the over-riding concern for making siting decisions. This is an ethical position that a sound long-term solution should be sought on a national scale free from short-term economic or societal factors. Hence, siting has been considered from a national perspective from the beginning. The Sectoral Plan was therefore devised as a search for sites considering the whole of Switzerland as a potential siting region (in Stage 1). The structured application of siting criteria (described below) was used to progressively reduce the area under consideration.

The evaluation was carried out in terms of long-term safety and technical feasibility. The selection of suitable geological siting areas (that is, Stage 1 of the Sectoral Plan) was carried out in 5 steps, as specified in the Sectoral Plan. Steps 1 and 2 require Nagra to quantify its waste inventory, propose a disposal facility concept, and then justify the specific requirements that the disposal facility makes on the geological environment, with reference to the framework defined by SFOE. Steps 3 to 5 relate to the use of these evaluation methods to identify geological siting areas, and are described in Section 2.5.4.

In the Sectoral Plan, SFOE specified the framework for site selection. HSK defined 13 individual criteria, which address the specific requirements that the disposal facility makes on the geological environment. These criteria are grouped in 4 'Criteria Groups' (see Table 2.5 and SFOE 2008).

- The criteria in Group 1 address the barrier effect of the host rock.
- The criteria in Group 2 ensure that the barrier effect is maintained for the required time period.
- The criteria in Group 3 assess the reliability of the geological findings in terms of the ability to characterise, explore and predict geological conditions, and to understand the temporal evolution of the site.
- Group 4 relates exclusively to the suitability of the host rock in terms of engineering requirements and the possibility for underground access.

The specification of criteria for the Sectoral Plan were developed on the basis of a previous feasibility study of Opalinus Clay in Zürcher Weinland in 2002 (Nagra 2002a, Nagra 2002c, Nagra 2002d).

Nagra is responsible for deciding how to evaluate the suitability of an area or site against each of the specified criteria (Nagra 2008a). Nagra's approach is then reviewed by ENSI (ENSI 2010a). It is noteworthy that many of the criteria in Table 2.5 relate to geoscientific data that can only be obtained through intrusive investigations. That is, even at Stage 1 of site selection, an extensive resource of geoscientific information at depth is assumed.

Appendix I of the Sectoral Plan (SFOE 2008) specifies the use of indicators as measurable attributes of the geosphere. Nagra adopted this approach for specifying 'indicators' for each of the 13 siting criteria. For some indicators, minimum requirements were specified (for example, the spatial extent of suitable host rock). Other indicators are defined by a qualitative or quantitative scale, where the attributes of a particular area or site are graded on a scale from 'very favourable' to 'unfavourable'. This grading scale is used for ranking areas by preference. Nagra, with input from SFOE, identified a total of 49 indicators relevant to the 13 siting criteria in Table 2.5.

Table 2.5 Criteria for site evaluation from the viewpoint of safety and technical feasibility

Criteria for site evaluation from the viewpoint of safety and technical feasibility

Criteria group	Criteria
1. Properties of the host rock and the effective containment zone	1.1 Spatial extent 1.2 Hydraulic barrier effect 1.3 Geochemical conditions 1.4 Release pathways
2. Long-term stability	2.1 Stability of the site and rock properties 2.2 Erosion 2.3 Repository-induced influences 2.4 Conflicts of use
3. Reliability of geological findings	3.1 Ease of characterisation of the rock 3.2 Explorability of spatial conditions 3.3 Predictability of long-term changes
4. Engineering suitability	4.1 Rock mechanical properties and conditions 4.2 Underground access and drainage

Source: SFOE (2008)

The development of quantitative requirements and evaluation criteria for each of the indicators was supported by:

- **Safety assessment (dose) calculations.** These used experience from earlier safety assessment studies: Kristallin-I (Nagra 1994) and the feasibility demonstration project Opalinus Clay (Nagra 2002a). The results of such calculations were found to be particularly suitable in constraining indicator values for 'thickness of the host rock formation', 'length of release pathways', 'hydraulic conductivity' and 'transmissivity of preferential pathways'.

- **Quantitative models concerning the behaviour of individual processes or barriers.** Such model calculations were used when understanding of the behaviour of individual processes or specific barriers was required. These models were used for indicators that are important in terms of:
  - geometric aspects of siting, such as depth below ground (in terms of engineering feasibility), or lateral extent
  - geochemical aspects related to mineralogy, pH, redox conditions and salinity
  - other indicators, especially chemical interactions, behaviour of the host rock with respect to gas, and behaviour of the host rock with temperature
- **Other observations and experiences.** Examples included evidence presented in Nagra technical reports or documented in the literature. This approach was used for indicators which are important in terms of:
  - land use conflicts (natural resources within the host rock, natural resources beneath the host rock, mineral resources above the host rock, mineral springs and spas, geothermal)
  - reliability of geological understanding (variability of the rock properties, independent evidence of long-term isolation, predictability of future evolution)
  - other indicators, especially clay content and self-sealing capacity, potential for the formation of new groundwater pathways (karstification), distance to regional fault zones, seismic and large-scale erosion.

In following the Sectoral Plan, Nagra has applied a system of objectively selecting areas, based on 49 indicators that can be assessed against defined targets according to their potential suitability to host a deep GDF. In Switzerland, this approach is possible at an early, desk-based, stage of siting investigations because Nagra has a large resource of geoscientific information, including data from intrusive investigations.

The following paragraphs summarise the requirements applied to some of the criteria that are more relevant in the context of desk-based investigations (see Table 2.5). Note that the descriptions or quantities associated with some indicators are to be refined as Stage 1 progresses from Step 3 to Step 4 or Step 5. More stringent criteria can also be set as Stage 1 progresses – either between steps or within an individual step. Additional indicators are used for some criteria in later steps of Stage 1 and these aspects are highlighted below. More detailed information on siting criteria and requirements for a GDF for higher activity waste can be found elsewhere (for example, Table 2.5-2 of Nagra 2008c).

Spatial extent (Criteria 1.1)

The selection of large-scale geotectonic units (Step 3 of Stage 1) is based on the potential lateral extent of areas that show little faulting. The minimum requirement is ≥4km^2 with a useable width of ≥1.5km.

For the selection of suitable host rocks and effective containment zones (Step 4), indicators are refined as follows:

- Thickness: ≥100 metres for sedimentary rocks (or ≥50 metres in sedimentary environments with future deposition potential) and ≥200 metres for crystalline rocks;

- Depth with regards to engineering feasibility: ≤900 metres for sedimentary rocks and ≤1,200 metres for crystalline rocks;
- Depth with regards large-scale erosion: ≥400 metres

Further refinement is made for the selection of suitable rock configurations (Step 5).

Hydraulic barrier effect (Criteria 1.2)

For the selection of suitable host rocks and effective containment zones (Step 4) the following indicators are used:

- Hydraulic conductivity: $K_v \leq 10^{-10}$ m s^{-1} – if no data are available then this can be based on the clay content indicator
- Clay content: If no data are available for the hydraulic conductivity then the minimum requirement for the occurrence of clay is ≥25% for sedimentary rocks other than evaporites – alternatively, a detailed geological description of the rock units and expert interpretation can be presented
- Independent evidence of long-term isolation (residence time of deep groundwater, isotopic signatures and so on). There is no minimum requirement:
  - ‘very favourable’: there is clear evidence of long-term isolation
  - ‘favourable’ there is at least one piece of evidence of long-term isolation
  - ‘limited favourable’: there is some information that can be interpreted as evidence of long-term isolation

For the selection of suitable rock configurations (Step 5), additional indicators are used as follows:

- Aquifers:
  - ‘very favourable’ or ‘favourable’: aquifers above and below the host rocks form independent flow systems
  - ‘unfavourable’ to ‘limited favourable’: there are signs (hydraulically or hydrochemically) that aquifers above and below are connected

Stability of the site and rock properties (Criteria 2.1)

For the selection of large-scale geotectonic units (Step 3) the following indicators are used:

- Model representation of the geodynamics and neotectonics: there must be no serious threat to the large-scale geological stability due to geodynamics and neotectonics within an assessment period of 1 million years
- Rare geological events (volcanism: no volcanic activity is expected within the 1 million year observation period

For the selection of suitable host rocks and effective containment zones (Step 4), additional indicators are used as follows:

- Formation of new water routes (karstification): there must be no significant potential for the formation of new water routes through karstification

- Self-sealing capacity: there are no minimum requirements. The self-sealing capacity is to be evaluated taking into account in situ conditions and expected processes (closure of fractures or discontinuities by elastic or plastic deformations and swelling or disintegration of the rock matrix):
    - ‘very favourable’ is assigned where there is high sealing capacity
    - ‘favourable’ is assigned where there is significant self-sealing capacity

For the selection of suitable rock configurations (Step 5) the following additional indicators are used:

- **Seismicity**. There are no minimum requirements: ‘very favourable’ to ‘favourable’: no general risk to the geological stability of the rock configuration within the 1 million year observation period
- **Distance to regional fault zones**. A distance of 200 metres is specified – this is increased where supported by geological data (for example, by mapped secondary fractures, thickened or distorted areas in seismic profiles, increased inclination on contour maps)

Erosion (Criteria 2.2)

For the selection of large-scale geotectonic units (Step 3), the large-scale erosion over the time period considered is evaluated based on the uplift rate of the land. The minimum requirement is ≤0.4mm per year. Where the local topography is more complex, the potential for local erosion is covered by other indicators.

For the selection of suitable rock configurations (Step 5), indicators are refined as follows:

- Depth below ground in terms of the general erosion of the area: ≥400 metres
- Depth below surface rocks in terms of deep glacial erosion: ≥400 metres in the area of deep valleys

Stage 2

Stage 2 is ongoing at the time of writing. However, detailed requirements for the safety evaluations needed in Stage 2 are documented in ENSI (2010a), and Nagra has evaluated the suitability of existing data for Stage 2 (Nagra 2010).

As the siting process proceeds, safety assessment calculations are likely to become more detailed and site-specific. However, it is ENSI’s view that it will remain important to relate decisions on site selection and evaluation at all stages to the framework of criteria and indicators so as to inform stakeholder understanding.

2.5.4 Role of geoscientific information in the siting process

Nagra has completed Stage 1 of the Sectoral Plan, which concerned the identification of geological siting areas. The use of geoscientific information in this process is the main focus of this section. Nagra has started on Stage 2, as also described in this section. Finally, the planned role of geoscientific information in Stages 2 and 3 of the Sectoral Plan is summarised.

Stages 1 and 2 of the Sectoral Plan do not involve any additional intrusive investigations of potential sites, although Nagra used boreholes constructed by other organisations to obtain data, and is therefore considered to be a desk-based study in this report. However, Nagra has a large amount of geoscientific data acquired from earlier (intrusive) studies, shown in Figure 2.10, on which to base its decisions relating to siting. This information was obtained from deep boreholes, geophysical surveys, geological syntheses and investigations in 2 rock laboratories.

There are limited numbers of seismic lines in the central part of Switzerland due to the presence of the Alps. In these areas, however, there is mapping data from exposures, and hence seismic surveys were considered unnecessary for identifying structures. Nagra benefitted from existing intrusive investigations from tunnels constructed through the Alps and Jura as most tunnels are mapped and photographed, accurately and extensively.

Nagra has made use of seismic re-processing techniques (arising from improvements in software and hardware) to extract more information from the available raw data. In Stage 1 of the Sectoral Plan, all the existing seismic data was reinterpreted so as to be consistent in processing, for example, consistent interpretation where seismic lines cross.

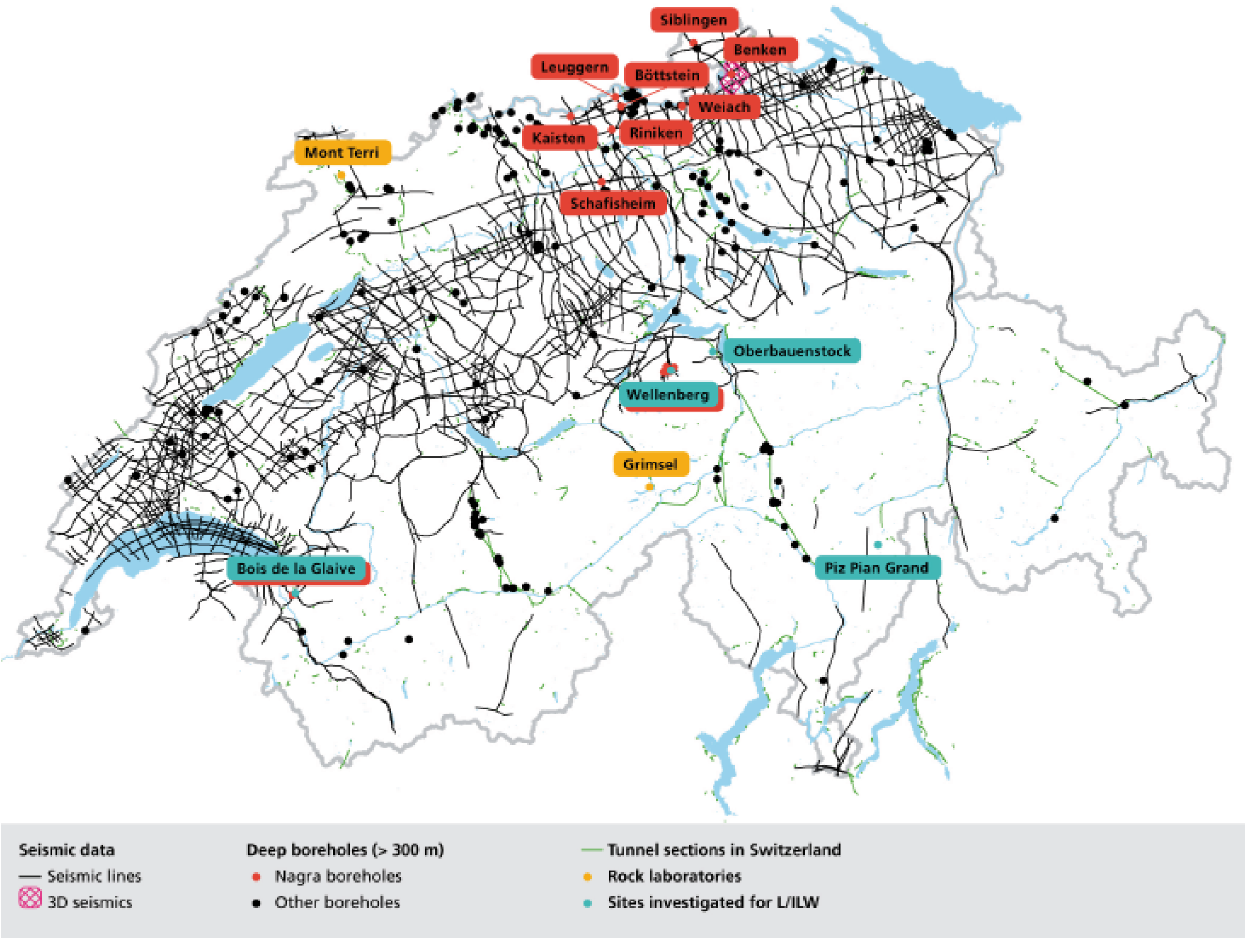


Figure 2.10 Geological investigations in Switzerland up to 2008

Source: SFOE (2008)

Gravimetric surveys have been used to identify structural features such as carboniferous troughs and deep glacial valleys as well as checking for resource conflicts. LiDAR (light detection and ranging) information was used in combination with mapping to identify regional and local structures.

Nagra has utilised the national seismicity network as well as providing support for new national stations to provide information on neotectonics. Nagra is also involved in monitoring long-term ground movement, both vertical and horizontal to inform uplift, erosion and stability.

As well as acquiring non-intrusive information, Nagra has sought opportunities to acquire intrusive information from boreholes and tunnels permitted for other purposes. For example, existing deep water wells have been sampled to provide geochemical information. Literature-based studies have involved expert engagement with universities and the scientific community, analogue studies, and contact with the oil and gas industry which has a large database from studying cap rocks analogous to the Opalinus Clay (for example, for clay content). There is also an extensive resource of geoscientific information from the rock laboratories at Mont Terri and Grimsel. The high density of geoscientific information available in Stage 1 gave confidence that an objective national scale siting process could be performed.

Planning for additional data acquisition in Stage 2 includes extra 2D seismics. The cantons have requested additional two-dimensional (2D) seismic surveys be performed across the siting regions as part of Stage 2. ENSI requested that Nagra confirm the interpreted structures within the regions. Boreholes are thought to be required in Stage 3, together with focused 3D seismic surveys to confirm earlier seismic interpretations and that underground conditions are consistent with expectations. Porewater samples will be taken, as well as groundwater samples from the overlying or underlying formations.

A site-specific rock laboratory is planned as an integral part of the underground construction to provide a research and demonstration facility, for example, to demonstrate swelling capacity of the host rock and the sealing of the engineering disturbed zone.

Role of geoscientific information in Stage 1 of the 2008 Sectoral Plan

The selection of suitable geological siting areas (Stage 1) was carried out in 5 steps, as defined by the Sectoral Plan. The first step was to quantify the waste inventory. The second step was to define the disposal facility concept and define the requirements (as they relate to the 49 indicators) this disposal facility concept makes on the geological environment, as summarised in Section 2.5.3.

The last 3 steps relate directly to the use of geoscientific information.

- In the third step, the large-scale geological and tectonic situation was assessed and large-scale areas that remain under consideration were defined.
- The fourth step involves selecting the preferred host rock formations within the large-scale areas still under consideration.
- The fifth step involved taking into account the presence of regional geological features – regional fault zones, over-deepened valleys resulting from glacial erosion, zones with indications of small-scale faulting, and other zones to be avoided for neotectonic reasons. Preferred areas were identified within which the preferred host rocks can be found at a suitable depth and with sufficient thickness and lateral extent. The preferred areas were used as the basis for delimiting the geological siting areas (Nagra 2008a).

This process is illustrated in Figure 2.11. Within each of Steps 3 to 5, the approach to narrowing down the area under consideration was made by application of the following sequence of filters:

- identification of potentially possible areas by application of minimum requirements for selected indicators
- selection of preferred areas (further narrowing) by applying more stringent requirements for selected indicators
- characterisation and evaluation of the remaining areas to identify preferred areas

The quantitative requirements for the indicators associated with areas, and the scales for rating preferable areas, were developed in Step 2 of Stage 1 of the Sectoral Plan, as described in Section 2.5.3.

Step 3: Identification of suitable large-scale geotectonic units

The criteria used in this step of site selection (as specified by SFOE 2008) are listed in

Table 2.6. These criteria were addressed by considering Switzerland in terms of seismicity, land uplift, and geological and tectonic complexity.

Seismicity data from the Swiss Seismological Service were collated and interpreted to indicate significantly increased seismicity in parts of the Valais and Basel regions, and slight increases in parts of the Alps. Areas with relatively low seismic activity could be found in the central Molasse Basin.

It was assumed that future erosion rates would be related to land uplift rates. There are clear regional differences in uplift rates, with significantly increased rates of uplift in the Alps of up to 1.5mm per year. Although these values were considered to represent only one snapshot in time, they were thought to be compatible with more general geodynamic models and studies of erosion rates based on alluvial deposits over the past 500–10,000 years. Based on these land uplift estimates, the erosion in the Alpine region could be up to 1,000–2,000 metres over a period of 1 million years. Nagra therefore concluded that negative effects on a GDF could not be avoided at the construction depths under consideration.

Regarding geological and tectonic complexity, the Alps were considered to be highly deformed and faulted, and the predictability of long-term changes over an assessment period of 1 million years was considered insufficient. The Faltenjura and the Western Jura were eliminated on the basis of poor prospects relating to regional fault and deformation patterns, continuity of suitable areas, geodynamics and neotectonics.

The areas which remained after this analysis were the Molasse Basin and the eastern Tabular Jura. In the western Molasse, the geological conditions were identified as being more complex. Therefore, the western Molasse Basin was classified as less favourable.

Table 2.6 Overview of relevant indicators for identification of suitable large-scale geotectonic units (step 3).

Aspects to be evaluated	Allocated criteria according to Table 2.5	Relevant indicators for implementation
Influence of erosion	2.2 Erosion	Large-scale erosion over the time period considered
Long-term stability: differential movements, neotectonic activity and seismicity; predictability of potential long-term geological changes	2.1 Stability of site and rock properties 3.3 Predictability of long term changes	Measured data and model concepts for geodynamics, neotectonics (including seismicity), geochemical processes or rare geological events
Geotectonic complexity and explorability	3.2 Explorability of spatial conditions	Regional fault pattern, bedding conditions and continuity of rock strata of interest

Source: SFOE (2008)

Step 4: Identification of suitable host rocks and effective containment zones

The criteria used at this step of site selection are listed in Table 2.7. The evaluation of the host rocks was divided into several sub-steps, with various rock types discarded at each stage. In a first sub-step, the minimum requirements concerning host rock thickness (relating to the criteria spatial extent) and hydraulic conductivity (relating to the criteria hydraulic barrier) led to a significant reduction of the possibilities: All carbonate rocks and sandstones, as well as all low conductivity rocks with insufficient thickness, were excluded.

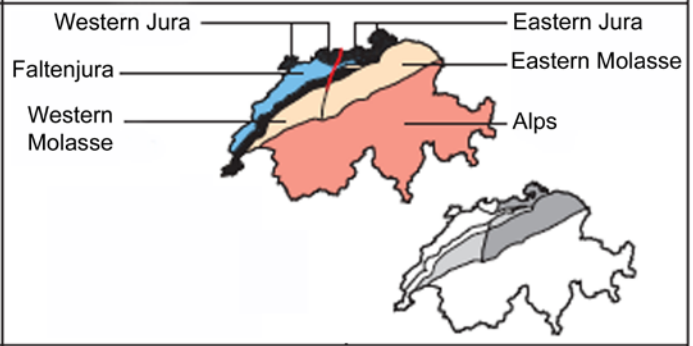
Rock types found in the eastern and western Molasse Basin and eastern Jura were considered. Six potential host rocks for HLW were evaluated:

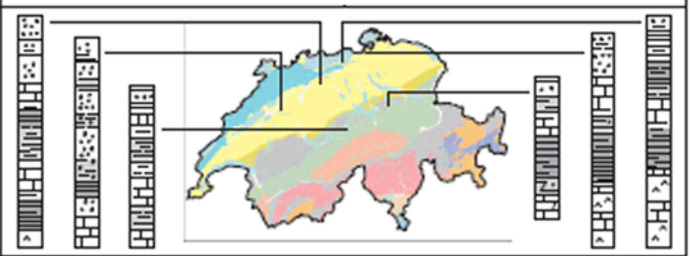
- Opalinus Clay
- Brauner Dogger
- the Effinger beds
- Lower Freshwater Molasse
- Upper Freshwater Molasse
- the crystalline basement of northern Switzerland

Opalinus Clay emerged from a comparison exercise as the preferred host rock, based on consideration of hydraulic conductivity, homogeneity of the rock structure and variability of the rock properties with regard to ease of characterisation; see Table 2.8 for a summary. It was considered that smaller faults and fractures in the crystalline rocks available in northern Switzerland might impair the rock's barrier effect and make such rocks difficult to characterise.

Opalinus Clay is a widespread rock formation in the Jura and Molasse regions. There was thought to be good geoscientific knowledge of this rock type obtained through construction projects such as rail and road tunnels, oil and gas drilling, exploratory drilling for construction, its use as a raw material for the brick industry, landfill and waste disposal projects. Favourable characteristics of the Opalinus Clay were identified as small variations in layer thickness across large distances. The Opalinus Clay was characterised as having a very good barrier efficiency for radionuclide transport, with capacity for self-sealing of fractures, low hydraulic conductivity and good sorption properties.

<table>
<tr><th>Step</th><th></th></tr>
<tr><td>Steps 1 and 2: Waste inventory, Requirements and specifications</td><td>Determining the inventory of waste, the concept and the barriers. Requirements or eveluation scales regarding size, host rock properties, uplift / erosion, etc.</td></tr>
<tr><td>Step 3: Identification and review of large scale geological-tectonic units. Evaluation of large scale conditions regarding uplift / erosion, geodynamics and geological complexity

Evaluation results:
good to very good (dark grey)
possibly suitable (light grey)
inadequate (white)</td><td>
</td></tr>
<tr><td>Step 4: Selecting the preferred host rock formations within the large scale areas still under consideration. This is done in several sun-steps.

The Opalinus clay with its confining units is proposed as the preferred host formation</td><td></td></tr>
<tr><td>Step 5: The configurations of the preferred host rocks within the large scale areas under consideration are evaluated

Taking into account the presence of regional geological features (regional fault zones, over-deepened valleys resulting from glacial erosion and other zones to be avoided for reasons of neotectonics), preferred areas are identified, within which the preferred host rocks can be found at suitable depth and with sufficient thickness and lateral extent.

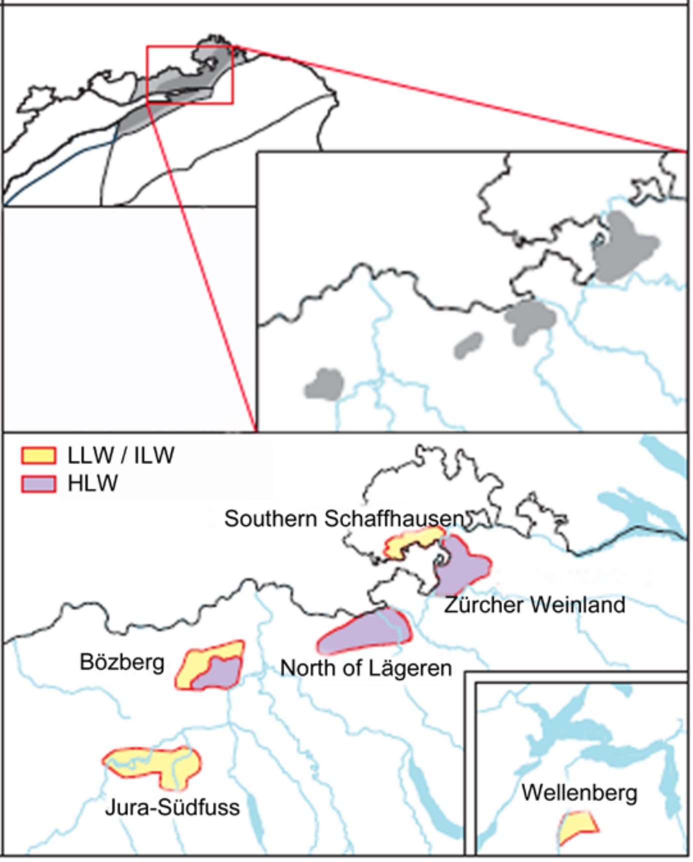
The preferred areas are used as the basis for delimiting the geological siting reions.</td><td>
</td></tr>
</table>

Figure 2.11 Proposals for geological siting areas for the LLW/ILW and HLW storage facility, according to the 5 steps of Stage 1 of the Sectoral Plan

Table 2.7 Overview of relevant indicators for identification of suitable host rocks and effective containment zones (Step 4)

Aspects to be evaluated	Allocated criteria according to Table 2.5	Relevant indicators for implementation
Spatial potential	1.1 Spatial extent	Thickness, lateral extent and distribution at suitable depth
Water flow and material transport	1.2 Hydraulic barrier effect	Hydraulic conductivity (taking into account expected hydraulic gradient), dominant transport processes (advection, diffusion), residence times of deep groundwaters (for example, isotope signatures)
Geochemistry	1.3 Geochemical conditions	Mineralogy, pH, redox conditions, salinity, sorption properties, microbial processes
Preferential transport pathways and their properties	1.4 Release pathways	Type of transport pathway (fracture network vs. porous medium), nature of pore space, transmissivity of preferential release pathways, clay content, self-sealing capacity of fractures or faults
Long-term rock behaviour	2.1 Stability of site and rock properties	Long-term changes, potential for formation of new water flow paths, karstification, self-sealing capacity
Repository-induced influences	2.3 Repository-induced influences	Engineering disturbed zone adjacent to underground structures, gas production and transport, chemical interactions, heat production and conductivity, self-sealing of new fractures
Rock mechanical properties and conditions	4.1 Rock mechanical properties and conditions	Depth and expected rock stresses, rock strength, deformation behaviour
Ease of characterisation and explorability	3.1 Ease of rock characterisation	Homogeneity of rock properties (including architectural elements), experience
	3.2 Explorability of spatial conditions	Geotectonic situation, complexity, exploration conditions

Source: SFOE (2008)

Table 2.8 Selection of preferred host rock formations and areas following application of more stringent requirements: summary of the evaluation for the HLW disposal facility

		Indicator		
Rock formation or sequence	**Distribution**	**Hydraulic conductivity**	**Homogeneity of the rock structure**	**Variability of the rock properties with regards to ease of characterisation**
Opalinus Clay	East Jura, East Sub-Jurassic Zone			
Clay rock sequence 'Brown Dogger'	East Jura			
Effinger beds	East Jura, East Sub-Jurassic Zone			
Lower Freshwater Molasse	Western Molasse Basin			
Upper Freshwater Molasse	Eastern Molasse Basin			
Crystalline rock formations	Northern Switzerland			

Legend:

blue: preferred host rock formation

grey: potentially feasible rock formation

orange: highly probable that more stringent requirements cannot be met

Source: Nagra (2008a)

Step 5: Identification of suitable geological siting areas

The criteria used in Step 5 are listed in Table 2.9. Three sub-steps were defined. First, areas of Opalinus Clay within the eastern Molasse and eastern Tabular Jura with a thickness of at least 100 metres, at a depth of between 400 and 900 metres, were identified. These requirements were motivated by specifications relating to the hydraulic barrier, the threat of erosion, and feasibility of construction respectively.

In the next sub-step, additional indicators were applied. The most important of these was the avoidance of regional fault zones. Regional faults had lengths in the kilometre range and were interpreted from surface mapping and/or seismic data. A 200 metre avoidance distance was used initially. If further information was available, for example, from geophysical surveys, this distance was reduced. Minimum requirements relating to the indicators – redox conditions, potential for karstification, natural resources below the host rock, mineral springs and spas, and gas flow (in the host rock) – were found to yield no further restriction on the potentially suitable areas.

Having established a set of areas that were thought to meet the minimum requirements, selection of preferred areas was made on the basis of the indicators 'thickness' and 'depth below rock surface in terms of deep glacial erosion'. The data to conduct these assessments came from deep boreholes and seismic surveys. Subsequently, the remaining areas were assessed with regard to their size therefore ability to encompass the disposal facility volume.

Table 2.9 Overview of relevant indicators for identification of suitable rock configurations (step 5)

Aspects to be evaluated	Allocated criteria according to Table 2.5	Relevant indicators for implementation
Depth, thickness and lateral extent, space requirement/availability	1.1 Spatial extent	Depth, thickness and lateral extent taking into account geotectonic conditions (regional fault zones, glacial scouring of valleys, foreign rock inclusions), space available, flexibility or reserves
Water flow, hydrogeological conditions	1.2 Hydraulic barrier effect	Hydraulic conductivity and expected hydraulic gradients, transport processes (advection or diffusion), groundwater levels
Preferential transport pathways and their properties	1.4 Release pathways	Nature of transport pathways (fracture network vs. porous medium), nature of pore space, length and transmissivity of preferential release pathways
Influence of erosion	2.2 Erosion	Depth, uplift rate, erosion rate, over deepened valley with Quaternary deposits (glacial erosion)
Natural resources and conflicts of use	2.4 Conflicts of use	Raw materials deposits, geothermal resources, mineral springs, hot springs
Rock mechanical properties and conditions	4.1 Rock mechanical properties and conditions	Depth and expected rock stresses, rock strength, deformation properties
Conditions for accessing disposal caverns and tunnels	4.2 Underground access and drainage	Accessibility of underground structures, geotechnical and hydrogeological conditions (including aquifers, karst, natural gas flow)
Long-term stability, differential movements and neotectonics	2.1 Stability of site and rock properties	Model concepts for climate evolution and geodynamics, indications of differential movements (geomorphology, seismicity), distance to potentially active faults or faults capable of reactivation
	3.3 Predictability of long term changes	Long-term changes, potential for formation of new water flow paths, karstification potential, self-sealing capacity
		Independent evidence of long-term isolation
Ease of characterisation and explorability	3.1 Ease of rock characterisation 3.2 Explorability of spatial conditions	Geotectonic situation, small-scale faults, homogeneity or heterogeneity of rock composition and variability of rock properties (including architectural elements, frequency of fractures or faults), possibilities for 3D seismics, boreholes

Source: SFOE (2008)

Conclusion to Stage 1

Nagra has proposed 3 siting areas for an HLW geological disposal facility with an Opalinus Clay host rock:

- Zürich Nord-Ost
- Nördlich Lägern
- Jura-Ost

Each of these 3 siting areas (~50 km^2) is also considered potentially suitable for disposal of LLW and ILW (Nagra 2008a). This process is illustrated in Figure 2.11, which also shows the locations of the areas selected as siting areas.

Nagra's Stage 1 submission has been evaluated by ENSI in detail. At the end of the review process, ENSI approved the proposed geological siting areas (ENSI 2010a). A consultation exercise was undertaken in autumn 2010, during which the public and stakeholders (such as the Federal Office of Topography, KNE and the cantons) were invited to submit comments. The Federal Council has announced the definitive geological siting areas at the end of Stage 1 of the Sectoral Plan process.

Role of geoscientific information in Stage 2 of the Sectoral Plan

In Stage 2, Nagra will identify potential locations within the siting areas approved in Stage 1. Nagra is required to select at least 2 potential sites for the HLW disposal facility at this stage. An approach for site comparisons is prescribed in the Sectoral Plan, but details will be defined and discussed with the cantons. Nagra is required to take account of safety and technical feasibility, spatial planning requirements and economic aspects. In Stage 2, Nagra may not propose any sites that are clearly less suitable than the others in terms of safety. Also in Stage 2, Nagra is not allowed to exclude sites for which the level of understanding is insufficient to allow suitability to be properly assessed.

Stage 2 of the Sectoral Plan is divided into the following main steps:

- Designate sites in the selected siting areas
- Comparative evaluation and proposal of at least 2 sites: Nagra is to complete a provisional quantitative safety analysis for each of the designated sites; the resulting report must include the methodology, the results of the comparison and a justification of the site selections
- Review of safety and engineering feasibility: ENSI and the technical commissions (KSA, CRW) will review and evaluate the sites designated by Nagra

After submittal of the siting proposals for Stage 1, Nagra began preparations for Stage 2. As of writing, this included producing a report detailing the state of knowledge of the geological conditions at the geological siting areas identified in Stage 1 and concluding whether this knowledge is sufficient to perform provisional safety analyses (Nagra 2010). For the purpose of evaluating safety, it was considered that the state of knowledge was sufficiently clear that unambiguous statements concerning the suitability of sites could be made despite the fact that the parameter ranges are conservative to allow for existing uncertainties. It was thought that these statements would not change if the uncertainties and associated parameter ranges are reduced through future investigations.

The state of knowledge report (Nagra 2010) also describes the work already initiated and planned by Nagra for Stage 2 of the Sectoral Plan. It is envisaged that this work will contribute to reducing uncertainties relating to the geometry (including faults) of the host rocks and will provide information on deposits of natural resources, the properties of the host rocks and the surrounding formations (including sorption measurements), hydrogeological conditions and long-term evolution.

Some of the work under Stage 2 is focused on common regional scale issues such as neotectonics. Site-specific aspects include geometry of the rocks; depth is factored in terms of overburden or stress and may consider depth trends in properties (for example, porosity). Where appropriate, parameters consider site-specific aspects. However, inherent uncertainties may be greater than differences between sites. Some site-specific data may be obtained from third parties involved in drilling (for example, for groundwater supply) and 2D seismic surveys across the sites.

Stage 2 will include plans being submitted for the intrusive investigations to be carried out in Stage 3. It is expected to be about a 2-year process to obtain consent for the boreholes.

Role of geoscientific information in Stage 3 of the 2008 Sectoral Plan

At this stage, additional intrusive geoscientific investigations might be required to allow a comparison of the sites to be made based on verified site-specific data. This stage might therefore be taken to correspond to Stage 5 of the MRWS site selection process. Economic, environmental and societal factors will also be considered in detail at this stage. This stage culminates with the submission of an application for a licence to begin construction of the GDF.

Quality assurance

Nagra has a certified quality management system dating from about 2005. However, the main principles were defined in Appendix 8 of Nagra (2002b) which covers all processes, starting with a specification of a project plan, risk management, definition of interfaces and quality measures. It also stressed the importance of recording additional quality processes beyond those planned. Data clearance is a critical process with data being released for a specific project, never released generally.

2.5.5 Development of safety assessments

Nagra is required to report safety analyses for the following steps:

- demonstrating disposal feasibility
- as part of the site selection process (Stages 1 and 2)
- licensing of the disposal facilities (Stage 3)

Nagra submitted a feasibility study for a geological disposal facility in Opalinus Clay (Nagra 2002a) which included a detailed safety analysis. This study was approved by the Federal Council in 2006, based on advice from the regulator (HSK 2004).

The site selection process for LLW/ILW and HLW disposal facilities is currently ongoing, with Stage 1 completed. The role of safety assessment at each stage of the Sectoral Plan is outlined below.

Stage 1: Generic safety assessment

The generic safety assessment is intended to derive quantitative requirements and objectives for the geological barrier and to quantify the indicators relating to criteria in Table 2.5 as far as possible. This assessment is reported in Nagra (2008b) and summarised in Section 2.5.3.

For the geological barrier, generic properties that could be demonstrated by existing knowledge were used. The assessment was intended to demonstrate the contributions of the different elements of the barrier system and the quantitative requirements placed on the properties of the geological barrier. To derive the quantitative requirements on the geological barrier such as depth, thickness, lateral extent and hydraulic conductivity, a dose protection objective of 0.1mSv per year was applied based on ENSI Guideline G03 (ENSI 2009).

Stage 2: Provisional safety analysis

The provisional safety analysis aims to provide information on the individual barriers at specific sites and to demonstrate that the calculated doses lie below the protection objective. These studies will use the available technical and scientific data for each of the proposed sites. Additional aspects of system behaviour and robustness are to be taken into account by undertaking sensitivity studies to understand the significance of:

- variability and uncertainties in the parameters used in the modelling
- system behaviour that deviates from expectations
- reliability of spatial and temporal predictions (explorability, predictability and reliability of data)

Stage 2: Comparison of sites

At this stage, provisional safety assessments – along with qualitative evaluations – will be used to compare different proposed sites. Based on the provisional safety analysis, no site will be taken forward in the process which would be evaluated as clearly less suitable than the others (SFOE 2008). At the same time, sites may not be ruled out because of differences in the calculated doses arising only from uncertainties in the underlying data. The methodology to achieve these 2 aims is outlined in ENSI (2010b) and summarised below.

For each site, the characteristic dose interval is used as a measure of suitability in terms of safety. A dose interval is defined as the largest interval between the peak doses (calculated over 1 million years) for a reference case compared with peak doses calculated for model variants which account for uncertainty in the model parameters. The reference scenario describes the likely evolution of the whole system – disposal facility, near-field, geosphere and radionuclide transport to the biosphere. Sites might then be compared with each other and the dose limit, using the dose interval for each site.

- Siting areas with a dose interval completely above the protection objective of 0.1mSv per year are excluded.
- No distinction in terms of safety is made among siting areas if their dose interval is completely below 0.01mSv per year. They are considered to be equivalent in terms of safety.
- A siting area for which part of the dose interval lies between 0.01mSv per year and 0.1mSv per year remains in the selection if its dose interval overlaps with the dose interval for the siting area with the smallest dose maximum in the reference case. This criterion of dose interval is used to prevent a potentially suitable site from being excluded too early on the basis of a possibly incomplete database.

At the time of writing, the Stage 2 safety assessment had not been reported, but a preliminary assessment had been made (Nagra 2010) to test the methodology and the availability and quality of data.

Nagra's proposals on locating surface access facilities are expected to be available in 2012. The siting regions are considered to be small enough that the disposal facility volumes can be reached from virtually anywhere on the surface within the provisional planning perimeter. There will be a need to assess any long-term safety consequences associated with the choice of location of surface access points, as well as technical and cost considerations.

Stage 3: Safety analysis with a view to the general licence procedure

The objective of the safety analysis at Stage 3 is to make the safety case as part of general licence application in accordance with the Nuclear Energy Act. The provisional safety analysis of the site is expected to be consolidated and supplemented with a comprehensive scenario and risk analysis.

2.5.6 Critical review and its impact

ENSI completed a review of the geological siting areas put forward by Nagra in 2010 (ENSI 2010a). As part of its review, ENSI was required to answer a series of questions listed in the Sectoral Plan concerning the sufficiency and transparency of Nagra's work. ENSI's main conclusions were that the geoscientific data considered by Nagra for Stage 1 were sufficient and that Nagra had taken into account all the criteria specified in Appendix I of the Sectoral Plan (SFOE 2008) and applied them correctly (ENSI 2010a). ENSI considered all siting areas to be suitable and recommended that all should be considered further in Stage 2 of the Sectoral Plan.

In carrying out its review, ENSI also ran public seminars on topical scientific issues such as deep glacial erosion and neotectonics or earthquakes to solicit responses from a broad audience. In addition, external experts were commissioned to review specific aspects. They came from KNE, the Federal Office of Topography and a selection of geological and engineering consultancies. During the review, Nagra was invited to answer questions and comments by ENSI, some of which were also discussed by both parties in public forums and in meetings of the Nuclear Waste Management Advisory Board. A technical forum on safety was also managed by ENSI. Its function was to discuss and answer technical and scientific questions on safety and geology from the public, the communes, the siting regions, organisations, cantons and public bodies of affected neighbouring countries (SFOE 2008, p. 82). For example, deep glacial evolution was discussed in response to interest from the cantons.

The quantitative requirements on the host rock and geological disposal areas were derived from generic safety assessments and other models of specific processes. ENSI made its own calculations to verify the quantitative and qualitative requirements for each of Steps 3, 4 and 5. ENSI reviewed Nagra's methodology in detail and was able to reproduce the dose results obtained by Nagra. ENSI, citing recent research, disagreed with the sorption coefficient value (K_d) for iodine in Opalinus Clay and bentonite used by Nagra. ENSI found, however, that using its preferred values did not impact on the quantitative requirements on the host rock and geological disposal areas. It recommended that the new values should be considered in future safety analyses.

Having concluded that the safety assessment methodology was sound, ENSI went on to consider the specific quantitative requirements on the host rock and geological disposal areas. Nagra had identified 49 indicators associated with 13 criteria. ENSI went through the indicators individually, commenting on their appropriateness.

ENSI considered that by the choice of rocks with significant clay mineral content and a vertical hydraulic conductivity of less than 10^{-10} m s^{-1} meant that the geosphere would be an effective barrier for the transport of most safety-relevant radionuclides as a consequence of the low diffusive and advective transport velocities and the effect of sorption. ENSI made its own dose calculations to understand the importance of hydraulic conductivity. It considered that the application of more stringent requirements for hydraulic conductivity made by Nagra in the horizontal direction was justified.

ENSI noted that some indicators (for example, rare geological events such as volcanoes) do not differentiate between different areas and therefore cannot influence the outcome of site selection. ENSI recommended ongoing research by Nagra on deep glacial erosion.

For Step 3 of Stage 1, ENSI came to the conclusion that Nagra had identified appropriate geological areas and assessed them correctly. ENSI raised some concerns over large-scale erosion and model concepts for the geodynamics of the Alps and their foothills. This did not affect the conclusions of the siting study, however, as these areas would be unsuitable for other reasons such as faulting.

The choice of Opalinus Clay as the preferred host rock was recommended by ENSI and ESchT. The Opalinus Clay is also, in ENSI's view, the only host rock that meets all the more stringent requirements; the crystalline rocks of northern Switzerland, the Upper and Lower marine Molasse, the Effinger layers and 'Brown Dogger' formations are either too permeable or too heterogeneous.

Step 5 of Stage 1 involved identifying geological siting areas. Figure 2.12 shows the result of the assessments by Nagra and ENSI of the 3 siting areas identified by Nagra. The first 6 criteria involve optimisation of site selection against long-term safety and hence the importance of ensuring these is evaluated as being 'very good'. The others may be improved by optimisation of the disposal facility concept, design or institutional controls, at least in the short term. In some cases, the ENSI suitability rating is lower than the Nagra rating. The following paragraphs comment on some instances where sites were rated differently by Nagra and ENSI.

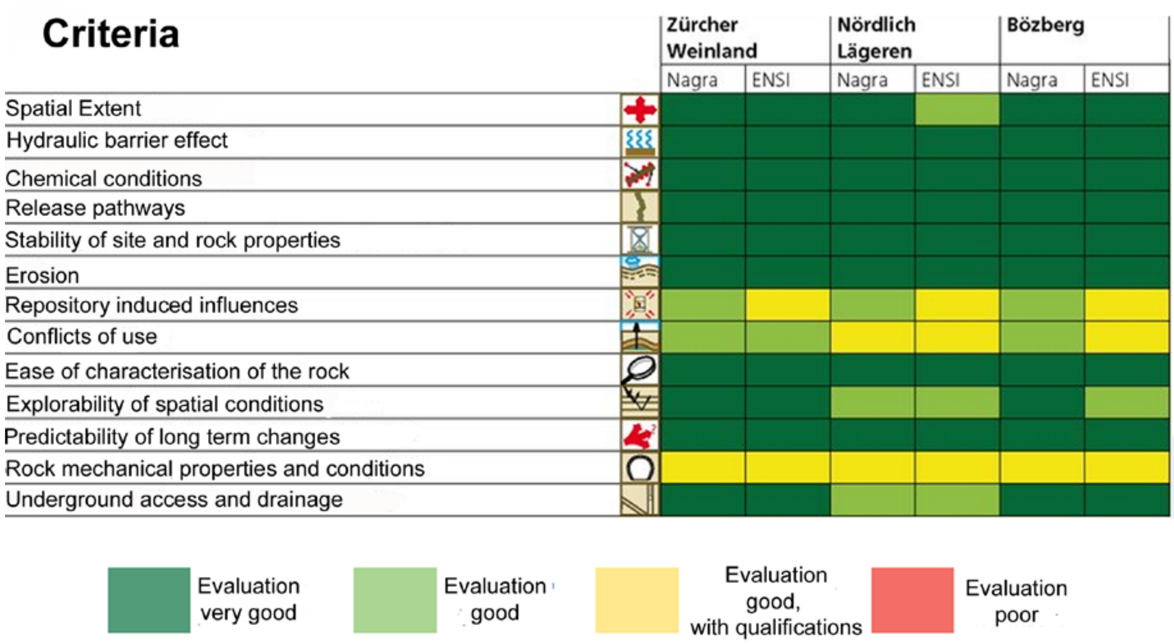


Figure 2.12 Summary of ENSI's assessment of the 3 geological siting areas identified by Nagra

Notes: Modified from ENSI (2010a.

ENSI made the following observations in its evaluation of the siting factors:

- **Spatial extent.** In the Nördlich Lägern siting area, ENSI considered that there are uncertainties regarding the extent of local faulting and hence the available space.
- **Repository-induced influences.** Rocks rich in clay were considered to have some advantages, but also some disadvantages compared with other host rocks such as granite. Disadvantages are the development of engineering distrubed zones around underground structures and the behaviour of clay-rich rocks in terms of temperature, gas and higher pH values. As a result, ENSI gave a lower rating to clay-rich host rocks in all siting areas than Nagra. However, the disadvantages could be resolved by technical measures.
- **Conflicts of use.** Drilling for natural gas is taking place near the siting area of Nördlich Lägern. There are plans to extract raw materials for cement manufacture close to Bözberg. There could, therefore, be the potential for the exploitation of natural resources in the long term. ENSI took account of this possibility in its evaluation.
- **Explorability of spatial conditions.** The hilly relief on the Bözberg makes seismic investigations more difficult and so ENSI reduced its rating for explorability.

Nagra prepared a state of geoscientific knowledge report in 2010 as part of the preparatory work for Stage 2 (Nagra 2010). This report was also reviewed by ENSI (ENSI 2011). ENSI broadly agreed with Nagra's conclusions. However, ENSI included 41 specific requirements which it expects Nagra to address during Stage 2. Those requirements relevant to the geoscientific data included:

- **Requirement 12.** The hydraulic gradient applied in the hydrogeological models of each site should reflect site-specific conditions.

- **Requirement 14**: Nagra should take account of the characteristics of the confining units when extrapolating measured data;
- **Requirement 22**: The aquifer in the Bözberg area needs to be characterised more fully as part of the planned hydrogeological desk study.
- **Requirement 28**: The potential effect of salinity needs to be detailed and considered.
- **Requirement 30**: Nagra should test its experimental method for determining sorption on the Opalinus Clay and document the results in a report.
- **Requirement 36**: Nagra should perform an analysis of regional flow conditions in the geological areas based on large-scale hydrogeological models.
- **Requirement 37**: The groundwater characteristics in Quaternary deposits in typical large and small valleys in northern Switzerland should be defined from existing data.

Hence ENSI's influence in the site selection process to date has been as a reviewer, making specific detailed technical recommendations.

Further on in the programme, progressive licences will be needed to begin construction, non-nuclear operations, nuclear operations and closure.

Nagra prepares RD&D plans about every 5 years, although this is not prescribed by law. The most recent of such was in 2008 (see Nagra 2009). ENSI reviews these documents, and records the important issues and Nagra's responses (Nagra 2011). The next RD&D plans will be prepared around 2016 to co-ordinate with decommissioning plans due then. The timing will also coincide approximately with the Stage 2 submission for review; the RD&D plans are also likely to reflect needs identified during Stage 2.

2.5.7 Summary

What role did geoscientific studies play in the siting programme?

Switzerland is searching for a site for a GDF through its 2008 Sectoral Plan (SFOE 2008). For Stage 1 of the Sectoral Plan (identification of geological siting areas), geoscientific information was the only basis for the decisions. Geoscientific information was used to select areas on the basis of their ability to provide long-term isolation and containment of the waste, and their feasibility regarding construction of a disposal facility. Important considerations were the decision to choose the Opalinus Clay as a host rock, and identification of locations where this formation is at sufficient thickness and appropriate depth to avoid erosion while still being technically feasible. Factors such as infrastructure and environmental considerations are to be accounted for in Stages 2 and 3 of the Sectoral Plan.

Switzerland has an extensive amount of geoscientific information available from earlier investigations covering large areas of the country, including data from deep boreholes and underground laboratories. This information provided the basis for decision making in Stage 1.

What decisions were made by (a) the developer, (b) the regulator or (c) any other body, based on information from desk-based studies?

The structure of the siting process was decided by government through the SFOE in the 2008 Sectoral Plan (SFOE 2008). This outline of the siting process is more prescriptive than, for example, the MRWS White Paper (Defra et al. 2008). Stage 1 of the Sectoral Plan, the only part completed to date, required the developer to propose a disposal facility concept, quantify the requirements the disposal facility makes on the geological environment, and apply these requirements in a national scale search for siting areas. The regulator is responsible for reviewing the developer's submission.

What were the organisations' roles in developing or reviewing desk-based studies?

Nagra has developed the geological basis for site selection and submitted proposals for the geological siting areas. The review of this work is led by the regulator, ENSI. ENSI has conducted its own safety assessment modelling to confirm the conclusions reached by Nagra. ENSI is supported by a number of expert organisations. In addition there are several independent stakeholders (such as KNE, ESchT and expert groups appointed by the cantons), which are also invited to review Nagra's and ENSI's studies.

Did the regulator use any criteria when deciding whether the desk-based geoscientific studies were adequate?

ENSI has reviewed Nagra's submission for Stage 1 of the Sectoral Plan. The framework within which ENSI conducted its review was determined by the SFOE (SFOE 2008). SFOE posed specific questions which ENSI was to address in its review. ENSI used the indicators developed by Nagra to perform an independent assessment of the geological siting areas proposed by Nagra.

ENSI was supported in its review by KNE, the Federal Office of Topography, the Swiss Federal Institute of Technology Zurich and a number of specialised private engineering and geology support offices.

2.6 Summary

2.6.1 Overview of the desk-based stage of the site selection process

Each of the 4 national programmes required work to address similar issues relating to siting at the stage of investigations where geoscientific information, particularly at depth, is limited. A generic list of geoscientific factors influencing the suitability of the geological environment for hosting a GDF is provided in IAEA guidance (IAEA 1994; IAEA 2011). These factors relate to demonstrating suitability with respect to:

- geological setting
- future natural changes
- hydrogeology

- geochemistry
- events resulting from human activities
- construction and engineering conditions

One observation on the use of geoscientific information at the early stages of disposal facility development is the approaches taken in the 4 countries were significantly different. Each of the site selection processes considered the factors identified by the IAEA (or postponed assessment of certain aspects until the intrusive investigations) but the way this was done has varied.

To be able to draw more general conclusions applicable to the UK, it is useful to consider why different approaches were adopted. The differences between the site-selection processes described in the case studies can be understood in terms of:

- role of geoscientific information compared with other factors that affected site selection such as local support or land use
- aims of the desk-based studies within the context of the overall siting strategy
- specific characteristics of the geological environments available in each country
- general availability of geoscientific data, particularly data at the depth of the disposal facility[5]

The influence of each of these factors is discussed below.

Role of geoscientific information in the siting process

All the site selection programmes described in the case studies considered a number of factors which might be categorised as geoscientific factors (relating to long-term safety, rock stability, natural resources and so on), environmental factors (transport, land use and so on) and societal factors (local support, local employment and so on). Each national programme has developed similar concepts, but used slightly different terminology to express them. Site selection for a GDF might be understood as the application of various criteria relating to these factors so as to obtain a site acceptable to government and other stakeholders from all 3 points of view.

Each of the case studies uses a stepwise or staged selection process. Differences between national siting programmes can be understood in terms of the sequence and emphasis placed on each of the different factors during various stages of the process.

In the Swiss programme, for example, Stage 1 of the siting process resulted in the consideration of only geoscientific factors influencing long-term safety and engineering feasibility. Environmental and societal factors, called ‘spatial planning’ in the Swiss programme, are to be considered in Stage 2. In Finland and Sweden, geoscientific, societal and environmental factors were each considered at several different stages in the siting process. The emphasis put on geoscientific factors, relative to environmental or societal factors in other national programmes, is summarised in Section 2.6.2.

[5] The current availability of data relevant to the deep geology in the UK is described in Shaw (2005).

Aims of desk-based studies in the siting process

One interpretation of the aims of desk-based studies might be to identify a siting area (or areas) which exhibits the potential to emerge from a full intrusive site characterisation programme with enough confidence in its suitability that it can be licensed as a GDF. For this interpretation, the most important issue is how much potential should a siting area exhibit, that is, what minimum criteria should it satisfy, at the desk-based studies stage, before further intrusive studies are justified.

However, other interpretations are possible. For example, all the siting programmes considered in the case studies evaluated alternative sites, and in some way demonstrated that alternative geological formations or sites do not offer clear advantages with respect to long-term safety over the sites selected, based on the geoscientific information available. Hence, although the implementing organisations could not claim to have found the ‘best’ site nationally, they might argue there is no indication that a clearly better geological solution exists.

The suitability of a site is determined by environmental and societal concerns as well as the properties of the disposal facility and geological environment. There is a consensus that the technical aspects of suitability will only be determined with confidence after extensive site investigations.

Geological setting and the site selection process

The types of bedrock potentially available as a disposal facility host rock are different in the case studies considered. The geological setting in each country has determined the emphasis placed on different aspects of site selection and characterisation.

The host rock potentially suitable for a GDF in Finland and Sweden is limited to the crystalline basement. In Switzerland, a range of potentially suitable host rocks are available and hence the siting programme in this country has placed more emphasis on choosing a host rock.

In Sweden and Finland, there was a preference for areas with high bedrock exposure as this was thought to reduce uncertainty about the properties of the subsurface bedrock. In both countries, screening for exploitable resources allowed discrimination between areas. Comparative studies focused more on different hydrogeological and hydrochemical settings in Sweden and on sorption properties of the bedrock in Finland.

The Swiss and French implementers selected clay formations for further investigations. The focus of their desk-based selection or characterisation studies was subsequently on the thickness, lateral extent, homogeneity and presence of faulting within the clay and surrounding formations.

The requirements on the host rock and siting areas at the desk-based stage of site selection may be specific to the type of geological environment considered. For example, Switzerland developed some criteria specific to particular geologic media, while other criteria were generic to any geology. Examples of requirements (called ‘indicators’ is the Swiss programme) which were media specific include the host rock thickness and the depth at which engineering is feasible.

The usefulness of some characterisation methods, such as the outcrop mapping used in the Finnish and Swedish programmes, relies on the availability of areas of exposure of the host formation.

Availability of geoscientific data and the site selection process

The type and quantity of geoscientific information available has a bearing on the form of the desk-based studies carried out. More geoscientific information, and particularly the availability of certain types of geoscientific information at disposal facility depth (relating to groundwater chemistry, hydraulic conductivity, evidence of fracturing and so on), leads to more confidence in the understanding of the site. If such information is available, the requirements on the site at the desk-based phase of investigations might be more rigorous than would otherwise be the case. This is because specific data for quantitative comparisons with crucial parameters or assessments would be available.

For example, in the Swiss programme the availability of geoscientific information, particularly at disposal facility depth led to the development of specific criteria and an elaborate screening and site comparison methodology. The methodology is motivated by safety assessment and other calculations.

In contrast, Finland had very little geoscientific information at disposal facility depth when the desk-based studies were undertaken. These identified a large pool of potential sites from which the Finnish developer could not distinguish preferred areas using geoscientific arguments informed by only non-intrusive surface-based data. The Finnish implementing organisation chose to subject 5 sites to preliminary site characterisation. The degree of local support and the requirement to consider a variety of bedrock types were used to select these.

2.6.2 Use of geoscientific information in desk-based studies

The desk-based stage of a site selection process might involve some of the following types of study:

- **National scale studies.** This type involves the application of geoscientific and other types of criteria, on a national scale, to eliminate areas from further consideration or identify areas likely to be most suitable for further investigation.
- **Comparative studies.** Studies to compare different areas, or different geological environments, on the basis of geoscientific criteria associated with long-term safety are made. The aim of such studies is to select the most suitable areas for further investigations. The method of comparison might be qualitative or quantitative.
- **Identification of a site for further characterisation.** The problem of identifying a site (~5–10km^2) from a local administrative area, ‘target area’ or ‘geological siting area’ and so on (~50–1,000km^2) is considered.
- **Safety assessment and site suitability.** This type of study may involve safety assessments leading to dose estimates or radionuclide fluxes, or arguments to support the view that a particular disposal facility concept or site is adequate.

The use of geoscientific information in each of these 4 types of study, within the case studies considered, is summarised in Table 2.10 and discussed below.

National scale studies

Within their desk-based studies, the implementing organisations in the case studies used different types of geoscientific screening to start at the national scale, and either rule out areas as probably unsuitable for a geological disposal facility, or select preferential areas for further investigation. This national scale screening approach was used early in each of the siting programmes considered.

The importance of such screening studies within the overall context of a siting programme varies. National scale screening was most significant in Switzerland where it was used to identify 3 'geological siting areas' (~50km^2), from which sites will be chosen for further investigations. In Sweden, national scale screening studies were less significant, as only around 35% of the country's area was identified as probably unsuitable. In the French programme, no national scale screening studies have been published, but a voluntary process has resulted in a set of different geological environments being considered. The implementer in Finland chose 5 sites for preliminary intrusive investigations based on a national scale search.

The limitation of a national scale screening approach, from a geoscientific view, is that its usefulness in identifying potentially suitable siting areas is restricted by the resolution of the available data. The national scale availability of geoscientific information at disposal facility depth relating to groundwater chemistry, hydraulic conductivity and the presence of fracture zones is typically relatively sparse. Assessing geoscientific data based on average properties on a low resolution risks screening out suitable sites, or focusing on areas that are not necessarily appropriate. These issues are illustrated in Figure 2.13.

This raises the issue of what types of geoscientific information is it sensible to use to screen out areas on a national scale. In each of the case studies, bedrock geology was used to screen out areas considered to be probably unsuitable (Finland and Sweden) or identify potentially suitable formations (France and Switzerland), based on considerations of long-term safety and ease of characterisation.

Switzerland has relied on national scale screening to the greatest extent in the 4 case studies. In this case the most important steps were:

- ruling out the Alps due to concerns about erosion and other factors
- selection of a preferred host formation (Opalinus Clay)
- identification of areas where this formation is present with the greatest thickness within a feasible depth interval

Table 2.10 Examples of different types of desk-based study as part of site selection and how different site selection factors were used

	National scale studies	Comparative studies	Identification of a site for further characterisation	Safety assessment and site suitability
Finland	Lineament mapping was used to delineate blocks of bedrock (~100km^2) called 'target areas'.	Target areas were rated based on geoscientific criteria such as bedrock exposure and fracture intensity at outcrop. Screening of target areas on environmental factors was also used. Sites with different types of bedrock were chosen for preliminary (intrusive) site investigations.	Smaller lineaments used to delineate 'investigation areas' (~5km^2) within target areas. Investigation areas were rated according to geoscientific and environmental factors. The degree of public support was taken into account when choosing sites for preliminary (intrusive) site investigations.	The Decision in Principle to pursue GDF development was based on a safety assessment.
France	Suitable geological formations were identified.	Clay, marl and granite formations were investigated with preliminary (intrusive) investigations at Meuse/Haute-Marne, Gard and Vienne, respectively.	Societal factors meant that only the clay option was taken forward to an underground rock laboratory.	The *Dossier 2005 Granite* safety assessment, considered the feasibility of disposal in granite, was based on data from URLs at Äspö (Sweden), Grimsel (Switzerland), Lac du Bonnet (Canada) and investigations at Olkiluoto (Finland).
Sweden	*General Siting Study 95* considered a national scale search for potential siting areas. Some areas were rejected on geological grounds. Topography, lineaments, well yields and exploitation interests were considered as methods of screening.	A series of studies addressed potential benefits to siting in the north versus the south, or the coast versus the interior. Alternative disposal facility concepts were considered.	The 'feasibility studies' in 8 municipalities (~1,000km^2) led to the selection of 8 'Siting Alternatives' based on screening by geoscientific factors, followed by societal and environmental factors.	The SR-97 Safety Assessment showed that the KBS-3 disposal facility concept would have good prospects of meeting safety requirements. It demonstrated the feasibility of finding a site in Sweden that meets the requirements.
Switzerland	A detailed methodology was developed by the SFOE (the conceptual part of the Sectoral Plan) to screen out areas of the country as probably unsuitable. The crucial factors were potential for erosion and geological complexity.	Different host rocks were compared in terms of suitability including Opalinus Clay, 'Brauner Dogger', the Effinger layer, Lower Freshwater Molasse, Upper Freshwater Molasse and the crystalline basement of northern Switzerland Safety assessments will be used to compare potential sites in Stage 2 of the Sectoral Plan.	Areas where Opalinus Clay formations are present at the required depth, in the greatest thickness, were identified.	Quantitative criteria (called 'indicators') used to select areas in Stage 1 were derived using generic safety assessments. In Stage 2 safety assessments will be used to compare proposed sites.

In Sweden, national scale and regional scale studies were performed at the same time as studies to identify sites for intrusive investigations from within municipalities with nuclear facilities – these were called feasibility studies. The national scale and regional scale studies were made at the request of the regulator to provide a wider context to the feasibility studies, which were focused on much smaller areas.

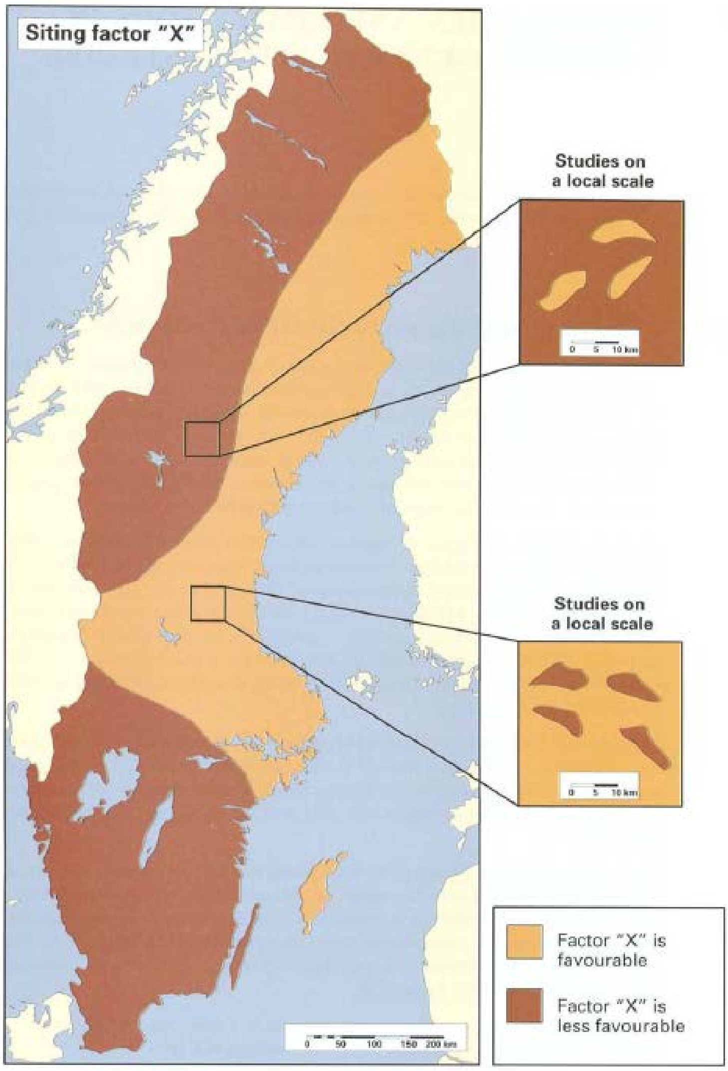


Figure 2.13 An example from Sweden showing how, as data resolution increases, areas which would have been considered unfavourable are found to be favourable and vice-versa

Source: SKB (1995)

Comparative studies

These types of study considered preference for further investigations should be given to any particular sites (~5–10km^2), areas (~100km^2), regions (~1,000km^2) or types of geological environment by comparing them among a set of possible alternatives. Examples of this type of study are described below.

In Finland, 'target areas' (~100km^2) were ranked based on geoscientific information such as:

- level of bedrock exposure – related to ease of characterisation

- fracture intensity – related to the potential for groundwater flow in the bedrock
- topographic gradient – used as a proxy for hydraulic gradient

This ranking was used to discard certain unfavourably ranked target areas. At the conclusion of the desk-based phase of the Finnish programme, sites were chosen for preliminary site investigations with the intention that a number of different types of crystalline rock should be represented to decide if such contrasts were significant, for example, different sorption properties).

In Sweden, consideration was given to the issue of whether regional recharge areas (typically inland locations) had any benefit to long-term safety compared with regional discharge areas (typically coastal).

Stage 1 of the Swiss site selection programme relied on an elaborate system of ranking different areas based on geoscientific indicators. Stage 2 of the Swiss site selection is planned to include a quantitative site comparison exercise, with the aim that no site will be taken forward in the process which would be evaluated as clearly less suitable than the others (SFOE 2008). A methodology has been defined to try and ensure that sites are not ruled out because of differences in the calculated doses arising only from uncertainties in the underlying data.

Identification of a site for further characterisation

The task of identifying a site (~5–10km^2) from a larger area is described in the case studies. In Sweden, the larger area considered was the municipality (~1,000km^2). In Finland, it was 'target areas' (~100km^2) and in Switzerland it will be 'geological siting areas' (~50km^2).

In Sweden, geoscientific data relating to bedrock geology, bedrock radium content, soil thickness, hydraulic data, hydrochemical data, exploitable resources and hydrology were used during 'feasibility studies' to identify areas which might be appropriate subjects for intrusive investigations from within municipalities hosting nuclear facilities. These areas where called 'Siting Alternatives'. Geoscientific data from deep boreholes constructed from earlier investigations were important in estimating conditions at disposal facility depth. Additional surface-based geological surveys were carried out to supplement pre-existing data. The identification of Siting Alternatives considered political, demographic and economic factors affecting the siting of a disposal facility, as well as geoscientific data.

In Finland, this phase of site selection was based around identifying smaller blocks of bedrock, called 'investigation areas', bordered by lineaments and lying within the larger 'target area' (~100km^2). It was assumed that an area of at least 5km^2 would be required to carry out a site characterisation programme. Obtaining the data used to locate these investigation areas involved the analysis of aerial photographs, maps and limited field surveys (outcrop mapping). Because the 'target areas' had been previously selected partly according to environmental factors, the 'investigation areas' were also usually sparsely populated and located within a reasonable distance from a road, railway or waterway transport route. The set of investigation areas were subsequently subjected to further phases of screening on geoscientific and environmental factors.

In Switzerland, this phase of selection is driven by environmental factors – 'spatial planning' in the terminology of the Swiss government, involving issues such as land use. However, the Swiss implementing organisation is not allowed to propose any sites that are clearly less suitable than the others in terms of safety. It must also not exclude sites for which the level of understanding is insufficient to allow suitability to be properly assessed.

Safety assessment and site suitability

Safety assessments have been used within the desk-based stages of siting work to:

- demonstrate feasibility in principle of a disposal concept, provided an adequate geological environment can be located
- quantify the properties of a host rock and geological environment that would be necessary to ensure safety, with the aim of using the derived criteria as part of the site selection process
- use geoscientific data from specific sites to show they have the potential to meet safety requirements, prior to full characterisation
- use geoscientific data from specific sites to calculate doses and then use these as a method of discriminating between different sites

The approach adopted depends partly on the availability of geoscientific information at the desk-based stage. Of the case studies considered, only Switzerland has used, or plans to use, all of these approaches.

In the absence of significant amounts of geoscientific data from disposal facility depth, Finland has developed generic safety assessments to support a Decision in Principle to develop a GDF. Site-specific safety assessments were subsequently developed after data from preliminary (intrusive) site investigations were available.

During the desk-based studies phase, the French implementer developed aspects of a safety assessment methodology (although doses were not calculated) using generic properties for granite host rocks. Because the French programme did not have its own URL in granite, data were used from URLs at Äspö (Sweden), Grimsel (Switzerland) and Lac du Bonnet (Canada), and investigations at Olkiluoto (Finland). In addition, some broad geographical and geological structural data from the French investigations at Vienne were also used.

The Swedish implementing organisation conducted the SR-97 Safety Assessment within the desk-based phase of its siting programme. The aims of that assessment included:

- showing that a KBS-3 disposal facility concept would have good prospects of meeting long-term safety requirements
- demonstrating the feasibility of finding a site in Sweden that meets the requirements
- contributing to specifying the factors that serve as a basis for the selection of sites for site investigations

2.6.3 Roles of the government and the regulator

Defining the siting process

Responsibilities for defining and controlling the site selection process and regulating its implementation vary between countries. In each of the 4 countries considered in the case studies, the government has stipulated requirements on the site selection process. At the desk-based phase of siting studies, the requirements for a staged approach which considers several possible areas before deciding on specific sites for detailed evaluation are common to the case studies reviewed.

The aims of the desk-based studies within the context of the overall siting process are ultimately set by government.

- The Swedish government decided that site-specific feasibility studies should be conducted on 5–10 sites in the country, and that 2 or 3 sites should be investigated with intrusive investigations.
- The Finnish government specified that preliminary site investigations should be conducted in a number of potentially suitable bedrock areas, followed by detailed site investigations in a small number of areas which, on the basis of the preliminary investigations, were considered to be the most suitable.
- The French government developed a strategy of trying to find sites for URLs so as to gather the information necessary to eventually develop a GDF.
- The Swiss Federal Office of Energy (SFOE) developed a prescriptive methodology for the implementing organisation to follow. It specified the identification of siting areas, followed by selection of 2 sites from within those areas. This is to be followed by site-specific safety assessments used to discriminate between which sites could be chosen for development.

The decisions made within some national programmes indicate a search for the most promising areas, in terms of technical suitability, on a national scale. Focusing on such areas potentially gives the benefit of reducing the chance that a full site characterisation programme will not be able to demonstrate technical suitability for a GDF. The role in emphasising this comparative aspect to site selection might be driven by the government, the implementing organisation or the regulator. Three examples of this are outlined below.

- Where the government specifies a number of sites to be investigated there is a clear opportunity to compare them against one another. This is the case even if the decision to investigate more than one site was primarily motivated by project planning or other considerations. The Swiss Sectoral Plan specifies a national scale search for suitable areas, which includes examples of selecting areas with preferable characteristics based on geoscientific considerations.
- The implementing organisation might develop a comparative approach, such as in Finland, where a large number of potential sites were considered and ranked according to a number of geoscientific indicators such as fracture intensity on outcrops.
- Comparative studies relating to site selection might be instigated by the regulator. The Swedish regulator requested reports on national scale and regional scale prospects for disposal facility siting to place the more local investigations being made in nuclear municipalities in a wider context. The regulator also requested studies related to the potential benefits of an inland location relative to a coastal location.

Providing review and independent analysis

The experience of the regulators within the case studies suggests the need to maintain an independent technical capability to perform reviews of the implementing organisation's work and sometimes to test reproducibility. Involvement in technical forums and international organisations is also highlighted.

The involvement of the regulator in the siting process has not always been limited to pre-specified regulatory decision points, such as the decision to allow intrusive investigations. The following text summarises the ways the regulators in the case studies approached the regulation of site selection and characterisation. In some examples, the organisations or groups described were set up after the desk-based phase of site selection. That is, this section anticipates some of the developments in regulatory capability that arose at the intrusive investigations phase of siting.

In Finland, the authorities reviewed steps in the site selection process formally in 1986, 1993 and 1999. The implementing organisation has prepared an outline of the research and development programme every 3 years, which was reviewed by the regulator along with important safety reports. Technical capability was enhanced though a Public Sector Research Programme aimed at supporting regulatory activities and maintaining expertise. This involves research centres and universities, and is steered by the government department responsible for nuclear waste disposal, the regulator, the implementer and the waste producing utility companies. The regulator also relies on external or foreign experts for support to regulatory activities. During the detailed site characterisation phases, the regulator developed independent assessment capabilities.

In France, regulation is performed by ASN (previously DGSN), supported by IRSN for technical reviews. The National Review Board (CNE) also evaluates and reviews various programmes and, although required to be impartial, has proved essential to the progress of the GDF project. IRSN maintains its own laboratory and experimental facilities, as well as numerical tools for assessing a broad range of technical issues.

In Sweden, the regulator reviewed triennial RD&D programmes, as well as important safety assessment documents and licence applications. The implementer held regular meetings to brief the regulators on progress against issues raised in the reviews of the RD&D programmes and the site investigations. The implementer also developed internal review procedures within its RD&D programme. The regulator uses international experts to support their technical reviews, and performs independent assessment calculations. The Environmental Court reviews the environmental impact statements.

In Switzerland, the regulator (ENSI) will perform technical reviews at the end of each stage of the Sectoral Plan. In Stage 1, ENSI was required to answer a series of predefined questions regarding transparency and sufficiency of the implementer's site evaluations. ENSI ran public seminars on topical scientific issues to gain a broader range of opinion. In addition, external experts were commissioned to review specific aspects and ENSI performed independent safety analyses.

Regulatory involvement in site evaluation

In most of the case studies, critical review affected the course of the site selection process. Examples of regulatory involvement in the evaluation of potential siting areas include the following.

- In Finland, the regulator requested that sites with different types of bedrock be subjected to preliminary investigations to determine if this factor had any influence on long-term safety by affected sorption properties.

- In Sweden, the regulator requested in 1992 and 1998 more systematic development of site selection criteria. The regulator also commissioned independent evaluation of an inland site as an alternative to those considered by the implementer.
- In Switzerland in Stage 1 of the Sectoral Plan, the regulator independently assessed the suitability of 3 geological siting areas using the same criteria agreed with the implementer. The regulator considered all the identified siting areas to be suitable and recommended that all should be considered further in Stage 2.
- In France an expert group, CNE, which advises government but is not a regulator, has influenced the siting process. CNE reported unfavourably on the granite site at Vienne which was proposed as a location for an URL. This was due to the granite being located beneath a sedimentary aquifer. CNE proposed areas where the granite outcrops as potentially more suitable in this respect.

3. Case studies of surface-based investigations

3.1 Introduction to the case studies

This chapter describes how surface-based investigations were applied in other national programmes to characterise a site for a GDF. The role of the regulator in this process is emphasised. The examples considered relate to surface-based investigations of the Meuse/Haute-Marne area in France, the Forsmark and Laxemar-Simpevarp areas in Sweden and the area around the Waste Isolation Pilot Plant (WIPP) near Carlsbad, USA. These investigation programmes were chosen because they encompass a range of different geological environments.

- The proposed disposal facility in the Meuse/Haute-Marne area would be in a lower strength sedimentary host rock (Callovo-Oxfordian Clay).
- The Forsmark and Laxemar-Simpevarp investigations were located in areas of higher strength crystalline rock.
- WIPP is located in an evaporite host rock.

Some of these programmes have benefitted from information and understanding gained from URLs at locations either within the area also covered by surface-based investigations or from other national facilities used by analogy. Since they have been integral to the strategy for site evaluation developed in the countries considered, their role is described here alongside the descriptions of surface-based investigations, which is the main focus of this chapter.

The case studies have a uniform structure to help reveal similarities or differences between the different programmes. This structure has the following main headings.

- **Introduction and overview.** An overview of the regulatory framework applicable to the surface-based intrusive investigations is provided, together with a summary of the site investigation programme in the context of the overall process of GDF development.
- **Stages of site identification, characterisation and regulation.** The investigation stages used to characterise the site and any corresponding regulatory decision points are summarised.
- **Geoscientific information acquired for site characterisation.** This section focuses on how different types of geoscientific information were used to characterise a site and inform disposal facility design.
- **Refinement of the disposal facility concept and design.** A summary is given of how the disposal facility concept or design is refined as more site-specific information is available.
- **Criteria for site selection and/or evaluation.** These are the geoscientific criteria used to accept or reject a site, or to allow comparisons between different areas (if applicable to the particular programme). These criteria are typically elaborated as more geoscientific data and more types of geoscientific information are obtained, and as the disposal facility concept is refined.

- **Development of safety assessments and environmental impact assessments.** The role of safety assessments in indicating the feasibility of disposal, justifing the evaluation criteria used to assess potential sites, and directing further investigations is explained. The relationship between the geoscientific understanding of the site and assumptions required for safety assessments are described.
- **Critical review and its influence.** The interaction between the developer, regulator, government and other stakeholders is described, with emphasis on the collection, interpretation and use of geoscientific information.

3.2 France (Meuse/Haute-Marne)

3.2.1 Introduction and overview

In 1999, the French government authorised Andra to build and operate a URL at the border of the Meuse and Haute-Marne districts on the eastern boundary of the Paris Basin. This case study focuses on the regulatory use of geoscientific information in the development of the URL at Meuse/Haute-Marne and subsequent decisions regarding siting a GDF nearby.

The purpose of the URL, as defined by the Waste Act 1991, is to study the feasibility of the disposal of HLW and long-lived ILW in a geological formation. The Meuse/Haute-Marne URL is located at the border of the Champagne-Ardenne and Lorraine regions, near the town of Bure, in the Callovo-Oxfordian (Jurassic) clay-rich rock. At the URL site, the Callovo-Oxfordian layer is about 130 metres thick and lies at a depth of 420–550 metres. The laboratory consists of 2 levels of experimental drifts at depths of 445 and 490 metres. The lithological succession directly above the Meuse/Haute-Marne site is shown in Figure 3.1.

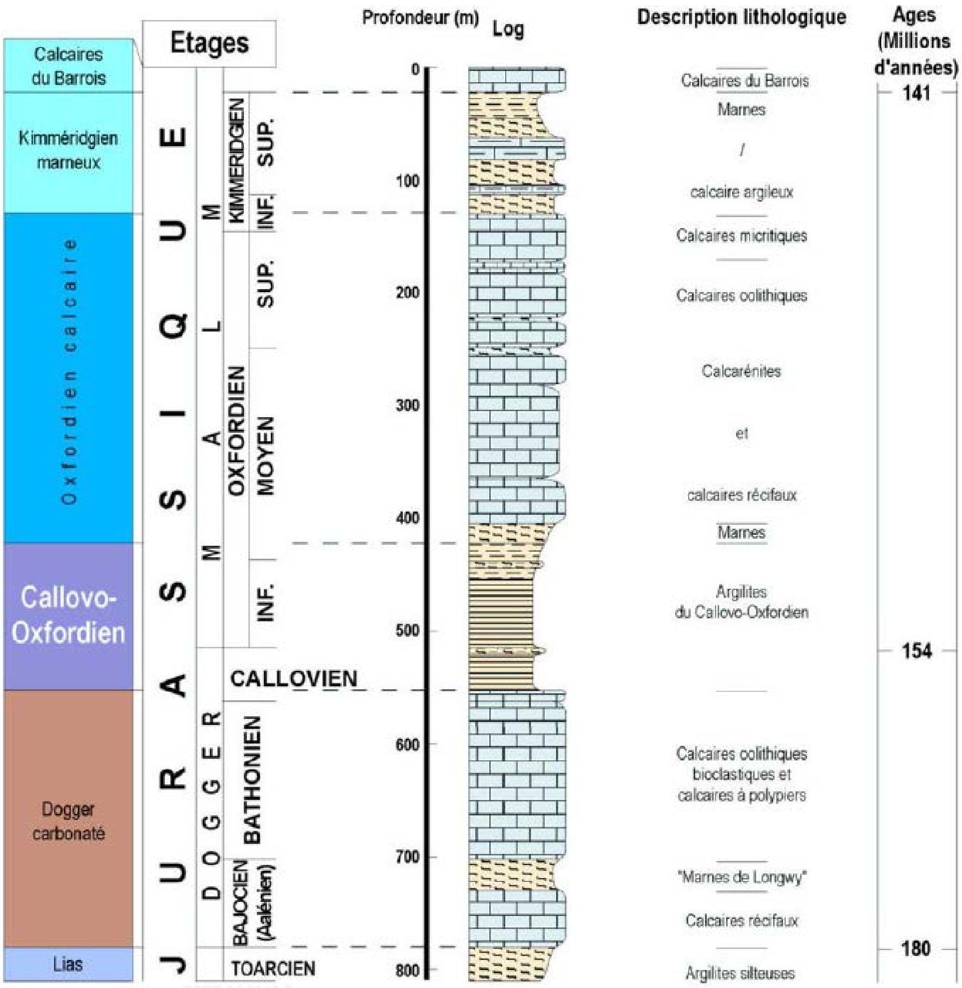


Figure 3.1 Lithological succession directly above the Meuse/Haute-Marne site

Source: ANDRA, 2005a

A 2006 law (Andra 2006) on the management of radioactive waste specified a 10-year research period to establish the authorisation of a GDF. Work after 2006 can be considered in 2 programmes:

- a **surveying programme**, conducted from the surface, which aimed to provide the scientific information to support the choice of a site for the disposal facility
- a **scientific programme**, conducted in the laboratory dedicated to the design and construction of representative elements of a disposal facility such as drifts, disposal vaults and sealing systems

The surveying programme involved defining a geographic domain (~250km^2), which is considered to be equivalent to the URL site with respect to the confining properties of the formation. This area is called the 'transposition zone'. In defining the transposition zone, the main concern was to investigate the homogeneity of the Callovo-Oxfordian layer. Faults were considered liable to break the continuity of the sedimentary layers or to alter their (bulk) properties. Therefore, the extent of the transposition zone did not include any identified faults.

An area of about 37km^2 within the 250km^2 of the transposition zone was defined, which is known as the ZIRA (Zone d'Intérêt pour la Reconnaissance Approfondie, or zone of interest for further investigation). The ZIRA's perimeter was determined partly on geological criteria (depth and thickness of the clay formation, hydraulic pressure and so on). It is intended that a site for the GDF, called 'CIGÉO', will be within the ZIRA.

CLIS (Comité Local d'Information et de Suivi, or Committee for Local Information and Monitoring) was created in 1999, in accordance with 1991 Waste Act, with the mission of informing its members and local people about the activities in the URL, and monitoring and research results. Its role was further defined in the 2006 Planning Act. The primary area for engagement corresponds to a circle of 10km radius centred on the Bure URL. CLIS has 91 members, including democratic representatives of the 2 regions of Lorraine and Champagne-Ardenne and the 2 departments of the Meuse and Haute-Marne. It also includes independent technically qualified individuals to interpret Andra's work.

There is a CLIS at each nuclear site in France (not just in Bure). ASN provides CLIS with financial support; in 2010, CLIS throughout France received a total of about €600,000. ASN also supports CLIS by providing regular updates about what it is doing. Andra is required to respond to CLIS enquiries.

3.2.2 Stages of site identification, characterisation and regulation

The 1991 Waste Act formed the framework for developing a URL at Meuse/Haute-Marne. The Radioactive Materials and Waste Planning Act 2006 specifies the framework for deep geological disposal (Andra 2006).

The French government, in consultation with ASN, develops a plan every 3 years which is the basis for radioactive waste policy. This plan is called the National Radioactive Materials and Waste Management Plan (PNGMDR) (see, for example, DGEC 2006). The purpose of the PNGMDR is to clarify this management framework and improve it. To this end, it assesses the management policy, evaluates the needs and determines the objectives to be attained in the future.

Article 6 of the Radioactive Materials and Waste Planning Act 2006, which is related to the sustainable management of radioactive materials and waste, provides a more precise definition of PNGMDR's objectives.

> '[The PNGMDR] draws up the assessment of the existing management methods for radioactive materials and waste, reports on the estimated needs of storage and disposal facilities, specifies the capacities necessary for these facilities and the storage times, and determines the objectives to be attained for radioactive waste for which there is still no final management method available' (Andra 2006).

Article 6 also states that:

> 'the national plan organises the implementation of research and studies on the management of radioactive materials and waste by setting timetables for the implementation of new management methods, creating facilities or modifying existing facilities'.

A summary of the achievements and research conducted in foreign countries is given in an annex to the PNGMDR since Article 6 states:

> 'The National Plan shall also include an annex consisting of a summary of the achievements and investigations conducted abroad'.

Progress towards implementing the plan is assessed every year by CNE.

Important events since the decision to site a URL at Meuse/Haute-Marne up to the proposed operation of the disposal facility are summarised below. Events in blue relate to the future schedule of development.

1998	Selection of Meuse/Haute-Marne site to host a URL by government, after preliminary (intrusive) surveys at 3 sites (Gard, Vienne and Meuse/Haute-Marne)
1999 to 2001	Acquisition of further knowledge on the Callovo-Oxfordian layer and start of URL shaft construction
2001	Dossier 2001 Argile (Andra 2001) published to provide an intermediate summary of the knowledge acquired
2002	Based on the Dossier 2001 Argile, revision of scientific programme for 2002 to 2005 and selection of disposal facility concepts (waste packages and disposal cells)
2003 to 2005	Borehole drilling around the laboratory site, and construction of experimental drifts in the URL
2005	Dossier 2005 Argile (Andra 2005a) published to provide an intermediate summary of the knowledge acquired
2005	Identification of the transposition zone; an area (~250km^2) with geologically similar properties to those investigated at the Meuse/Haute-Marne URL
2006	Radioactive materials and Waste Planning Act 2006 specifies the framework for subsequent GDF development programmes
2009	Identification of the ZIRA (~37km^2)
2010 to 2011	Further surveys of the ZIRA, leading to identification of a proposed site
2012	Presentation to the National Commission on Public Debate (CNDP)
2013	Choice of the disposal facility site by French government
2015	Submission of licence application (called 'DAC'), which will be reviewed by ASN and CNE
2017	Start of construction of disposal facility.
2025	Disposal facility begins operation

As required by environmental law, the 2012 public debate will be conducted through CNDP so as to communicate to the public the analysis of the environmental consequences of the project. The 2015 licence application will be for construction of the disposal facility. Further licences will be required for its operation and closure. A local consultation process is required as part of the 2015 application.

During the time period considered in this review, the regulatory authorities ASN and IRSN have reviewed Andra's work following publication of Dossier 2001 Argile (Andra 2001), Dossier 2005 Argile (Andra 2005a) and after the delineation of the ZIRA. CNE reviews progress against the National Radioactive Materials and Waste Management Plan every year; this review encompasses a wider remit than GDF development.

The NEA conducted international peer reviews of Dossier 2001 Argile and Dossier 2005 Argile. CLIS commissioned the Institute for Energy and Environmental Research (IEER) to review aspects of Andra's work. IEER is an independent consultancy based in the USA specialising in the review of nuclear industry projects for a wide audience.

The most important activities of the developer, regulators and other stakeholders are summarised in Figure 3.2.

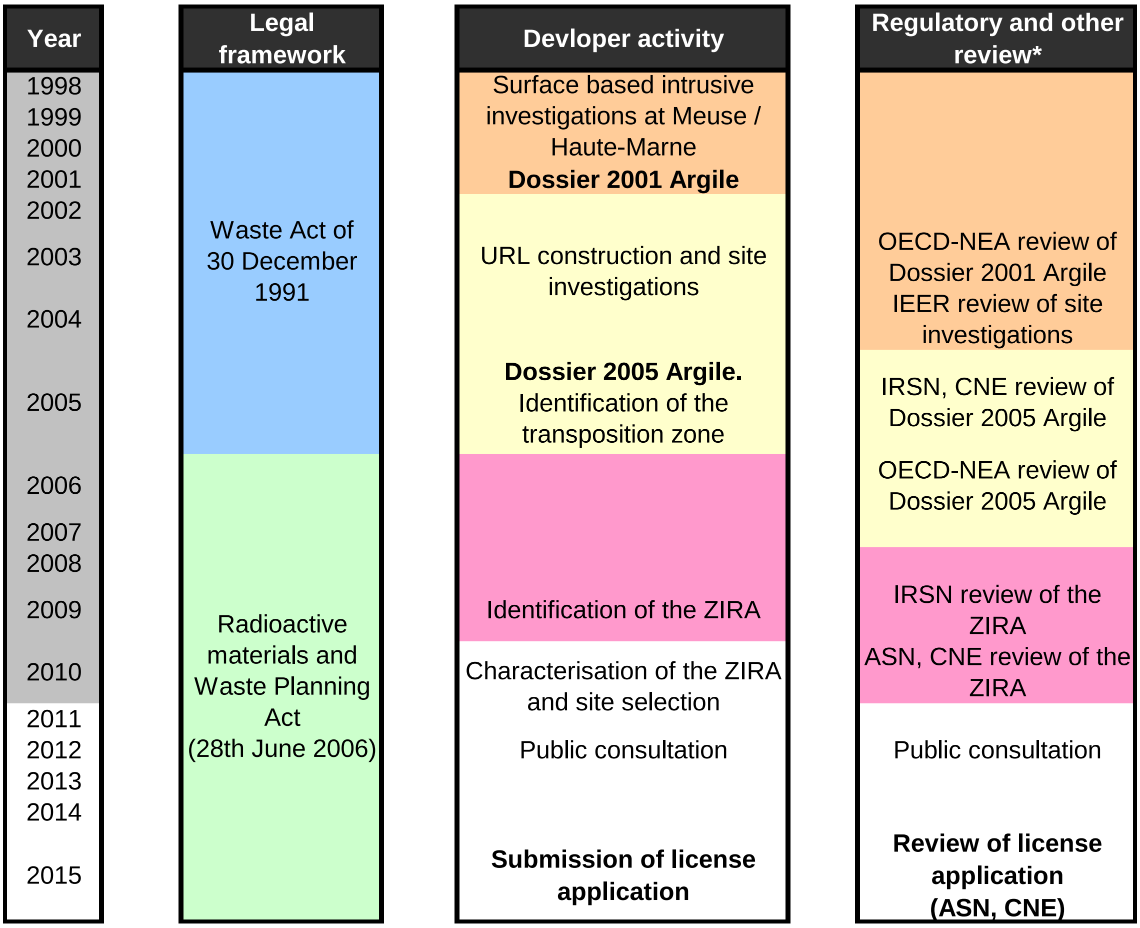


Figure 3.2 Important developer activities and associated reviews by regulators and other stakeholders during site characterisation at Meuse/Haute-Marne

Notes: * CNE has a statutory requirement to assess every year the progress of investigations and studies relating to the management of radioactive waste.

3.2.3 Geoscientific information acquired for site characterisation

Andra’s activities in the Meuse/Haute-Marne can be divided into those relating to the characterisation of the area using surface-based investigations and those involving experiments in the URL. Both types of investigations have developed in stages over time, with some stages subject to regulatory and other critical review. The following sections summarise the aims of various investigations, and the types and quantities of geoscientific information available, under the following section headings:

- Investigations prior to Dossier 2001 Argile
- Surface-based investigations prior to Dossier 2005 Argile
- Research in the URL
- Surface-based investigations after 2005: characterising the transposition zone and ZIRA
- Plans for future investigations

Investigations prior to Dossier 2001 Argile

The preliminary siting studies between 1994 and 1997 (see Section 2.3) involved 15km of 2D seismic surveys and 3 boreholes 530–1100 metres deep, with measurements of the bedrock geology, hydraulic conductivity, mechanical and thermal properties and mineralogy (Lebon and Mouroux 1999). These investigations were considered sufficient to conclude that the properties of the clay formation did not rule out a disposal facility and to select the Meuse/Haute-Marne site for the installation of the URL (Andra 2005a).

Additional investigations were conducted in 1999 and 2000 to characterise the URL site and the wider area in more detail (Andra 2005a).

At the laboratory site, a 3D seismic survey (covering 4km^2) was performed to provide an image of the volume of the laboratory site with a greater level of detail. 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 of the geological formations. Mechanical tests in these boreholes allowed the development of models to predict damage associated with construction of the underground installations.

On the laboratory site, 4 additional boreholes were drilled to various depths around the location of 2 shafts associated with the URL and allowed geochemical and hydraulic tests. Consequently, it was possible to determine the hydraulic gradients in the 3 formations overlying the Callovo-Oxfordian (calcaires du Barrois, Kimméridgien marls, Oxfordian) and to specify their hydrodynamic characteristics to define the initial state before constructing the laboratory.

Because the Meuse/Haute-Marne laboratory was at an early stage of construction in 2001, data from Mont Terri Laboratory in Switzerland was used to support Dossier 2001 Argile (Andra 2001). The Opalinus Clay at Mont Terri was considered to have characteristics comparable with the Callovo-Oxfordian Clay: it has a similar mineralogical composition (clay, quartz and carbonates) to that of the Callovo-Oxfordian, although it is slightly less carbonated. Like the Callovo-Oxfordian argilites, the Opalinus clay was thought to be a reducing medium, with low permeability and small pore size. The radionuclide transport properties of the 2 formations were considered similar with diffusion dominant, as were their mechanical properties (Andra 2005a).

Surface-based investigations prior to Dossier 2005 Argile

Additional surface-based investigations were conducted between 2001 and 2005 in the Meuse/Haute-Marne area (Andra 2005a). Eight boreholes, reaching different depths at 5 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. The hydraulic conductivity of the limestone formations was also measured to allow assessment of the water flow rates. 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. The geological observations made in the boreholes and the core samples allowed consolidation of the geological model.

Between 2003 and 2004, 8 more boreholes were constructed. Four direction-deviated boreholes were reported 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.

One of the direction-deviated boreholes was used to investigate the structures identified by the 3D seismic surveys conducted in 2000 in the Dogger limestones. They were not found to correspond to faults, but had sedimentological characteristics of fossil coral massifs also observed on regional outcrops. Additional seismic surveys in the borehole confirmed their extent and it was concluded that the hydraulic conductivity of the upper part of the Dogger formation would not be affected. This work led Andra to rule out the possible presence of tectonic structures in the Dogger formation at this site.

One of the direction-deviated boreholes cored the Callovo-Oxfordian formation for 400 metres above the structures observed in the Dogger. No discontinuities were intercepted and only few micro-fractures were noted.

Two direction-deviated boreholes intercepted the argilites over a length within the Callovo-Oxfordian formation. Approximately 1,300 metres of core samples were obtained from the Callovo-Oxfordian formation and 300 metres of core samples from the Dogger formation. These boreholes allowed a comparison of the sedimentological and petrophysical characteristics at the scale of the laboratory footprint with the data from the 3D seismic survey conducted in 2000. They indicated that there were no fractures and very few micro-fissures in the Callovo-Oxfordian on the laboratory site and that these micro-fractures were not hydraulically connected, and were generally at the top and bottom of the layer, several meters apart from each other. In situ hydraulic tests reportedly confirmed the very low hydraulic conductivity of the clay.

Two of the boreholes were also used to carry out in situ stress measurements to specify the natural stress field in the Callovo-Oxfordian clay.

The 4 vertical boreholes were used for gas injection tests to specify the pressure above which the transfer of gas into the Callovo-Oxfordian argilites occurs either when combined with water flow or by the opening up of fractures in the formation (specifically the gas entry pressure and the fracturing pressures in the argilites were assessed). In the latter case it was noted that the fractures seal themselves after gas migration and that the hydraulic conductivity of the rock is not modified. These data were complemented by continuous pressure measurements.

In one borehole, a diffusion test was carried out at a depth of 500 metres, similar to those conducted from the experimental underground drifts.

Research in the URL

The purpose of the research programmes in the URL is to provide the data and supporting evidence required to understand the phenomena identified as important for the design and safety assessment of a disposal facility. More specific requirements were set out in the 1991 Waste Act (RFS III.2.f), 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.

The investigations required under the 1991 Waste Act (RFS III.2.f) (Andra 2005a) included:

- assessing the average bulk permeability of the medium
- specifying the hydraulic role of the faults or fractures which may be encountered

- determining and monitoring over time the geochemical properties of water and gas encountered while excavating drifts and drilling boreholes to determine connections between the more or less permeable intercepted zones
- assessing the initial stress tensor
- appraising the feasibility of rock excavation and also its behaviour at the walls
- measuring the deferred mechanical effects (relaxation, creep)
- specifying the geochemical properties which may affect the migration of radionuclides

The URL programme at Meuse/Haute-Marne was suspended between May 2002 and September 2003 following a fatality during construction of the URL. At this point the URL had only reached a depth of ~40 metres. The suspension led to delays in information being available for the 2005 Dossier and the use of some generic data for this assessment.

The following list summarises the experiments Andra has performed in the URL up to the submission of Dossier 2005 Argile (Andra 2005a). Many of the experiments involved long observation periods of several years and were scheduled to continue after 2005.

- **Geological observations in the shafts.** A description of intercepted layers including a survey of fractures and geological objects encountered while constructing the URL shafts was recorded.
- **Measurement of water flow rates in the shafts.** Measurements of water flowing from the shaft walls at different levels in the Oxfordian formations were made. The hydrogeological disturbances caused by shaft sinking in the overlying formations were monitored continuously in the boreholes drilled near to the shafts.
- **Geotechnical measurements in the shafts.** Measurements of deformation in shaft walls and argillite were recorded.
- **Response of the rock to shaft sinking.** Instrumentation was added to a volume of rock intercepted by the main shaft to measure the state of the rock before shaft construction, the disturbances during and after construction, and any deferred effects.
- **Geotechnical measurements in the drifts.** Oblique boreholes were drilled at the intersection between the shaft and the drift roof. Seismic measurements were also carried out before and after excavation. They were reported to show that damage was limited to a thickness of 20–40cm in the walls, where the argillite was micro-fissured. During the excavation, an extensometer was installed in the drift axis to monitor deformations. A measurement section transversal to the experimental drift was installed after excavation, and stress and deformation sensors were emplaced. Boreholes drilled in different directions in the wall of the drift were injected with resin and then over-cored. A fluorescence technique was used to detect any fracture which may have been induced by the excavation; none were detected.
- **Hydraulic conductivity and pressure.** Measurements were made in 2 horizontal and one vertical boreholes to confirm the hydraulic conductivity of the argillite combined with additional hydraulic head measurements.

Most of the measurements indicated hydraulic conductivities of between 5×10^{-13} m s^{-1} and 5×10^{-14} m s^{-1} (Delay et al. 2010).

- **Geochemical analyses and partial gas pressure.** Two boreholes were equipped to sample water and gases dissolved in the argillite to make in situ measurements of chemical parameters and to specify the interstitial water chemical composition. Two methods were implemented: the first based on gas circulation in a borehole to sample and analyse the gases dissolved in the interstitial fluids; and the second based on water circulation in a borehole to monitor how its chemical composition evolved as it reached equilibrium with the interstitial water.

- **Diffusion and retention.** Three boreholes were equipped to carry out diffusion and retention experiments that compared the in situ diffusion experiment results with those of the models built from work on core samples using the same tracers including tritium, iodine-125, chlorine-36, sodium-22 and caesium-134. Monitoring of these in situ diffusion tests by recording the decay of the tracer concentration in the solution injected into the test chambers for 6 months was reported to show that the rock appeared to display a diffusive behaviour consistent with the diffusion parameters established in the laboratory from samples for tritiated water, anionic (chorine-36 and iodine-135) and cationic (sodium-22) species. Investigations were performed by Andra to determine the effects of the clay on ion retention of solutes diffusing through the Callovo-Oxfordian. This work was conducted partly to understand the observed hydraulic overpressure in the Callovo-Oxfordian and partly to examine the processes of ion exchange – particularly anion exclusion, a process by which anions are rejected from small pores due to interaction with the negatively charged clay surfaces.

- **Tests on the EDZ.** These experiments tested the possibility of cutting off any groundwater circulations in the EDZ using grooves about 2 metres deep filled with bentonite. Full-scale tests were conducted that involved creating cut-off grooves in the damaged zone, filling them with bentonite clay and then measuring their performance levels. The feasibility of groove excavation methods were demonstrated, together with the stability of the argillite walls during the groove sawing operations. The hydraulic performance of the groove system was tested by filling 2 grooves with waterproof resin to simulate the hydraulic characteristics of hydrated bentonite. The grooves were filled with compacted bentonite bricks and a hydration system installed. The effects of hydration were observed with various sensors. It was planned to monitor the measurements for several years.

- **Geomechanical in situ creep measurements in the drifts.** Measurements were carried out in boreholes drilled from the drift using instruments monitoring the pressure at the borehole wall and deformation. This experiment was expected to last for several years.

- **Thermal conductivity measurement of the argillite.** To measure the thermal conductivity, a heating appliance (based on that used in the Mont Terri laboratory, Switzerland) was installed in a borehole. Pore pressure, temperature and displacement sensors measure the thermal conductivity parameters of the argillite around this borehole and also provide data on the thermo-hydro-mechanical effects in the rock.

Surface-based investigations after 2005: characterising the transposition zone and ZIRA

In 2005 Andra defined a transposition zone, that is, the area in which it considered the conditions for a disposal facility would be analogous to those encountered at the URL (Andra 2005a). The delineation of this area is described in Section 3.2.5.

Between 2007 and 2008 Andra implemented a further programme of borehole drilling and geophysical surveys in the investigation area to confirm the transposition zone and inform the definition of the ZIRA (IRSN 2009). This involved 14 new boreholes (10 of them in the transposition zone) and 11 seismic lines totalling 185 km (Delay et al. 2010).

The data acquired in 2007 and 2008 enabled Andra to update the assumed thickness of the Callovo-Oxfordian formation. This was reported to confirm the existence of a sufficient thickness of the formation in the transposition zone, except for a band located along the south-west limit of the zone. This band was therefore excluded from the transposition area. One of the boreholes drilled through the Triassic formations to confirm the absence of potential exploitable geothermal resources. The surveys did not change the geometric understanding of the major faults of Gondrecourt and the Marne.

The investigations revealed that the depth of the centre of the host formation exceeds 630 metres along the western edge of the transposition area chosen in 2005; Andra changed the perimeter of the transposition zone to ensure that a maximum depth of 600 metres was respected. Andra claims that the investigations in 2007 to 2008 clarified the limits of Callovo-Oxfordian and confirmed its lithological homogeneity (IRSN 2009). Three-dimensional seismic surveys were carried out for the ZIRA in 2010. No boreholes are planned inside the ZIRA because of the homogeneity of the Callovo-Oxfordian formation, as confirmed by the results of the 2010 3D seismic survey.

Plans for further investigations

Andra identified the following aspects which will require a better understanding in preparation for a licence application in 2015 (Cahen and Voisin 2008, Landais and Labalette 2008):

- gas migration pathways
- chemical perturbations undergone by the host formation due to the exogenous materials placed within it
- impact of the duration of the operating phase on the properties of the formation
- effects of complexants in waste packages on radionuclide transport
- uncertainties on thermal and hydraulic transients and on coupled phenomena, including a more detailed modelling of the transients
- consolidation of the thermal, hydrogeological, mechanical and chemical (THMC) data acquired within the Meuse/Haute-Marne laboratory (through diffusion, thermal and retention experiments)
- full-scale technological tests (for example, sealing of tunnels) to support design and safety demonstration; long-term experiments on disposal facility seals will start in 2013 to investigate technical feasibility and define the manufacturing acceptance criteria

- flow directions in the Dogger formation to be established in greater detail, including specifying the role of regional faults and their environment in the hydrogeological model
- sedimentation history of the site – in Dossier 2005 Argile, the interpretations of well logs suggested the possible occurrence of a sedimentation hiatus, with potential consequences for continuity of the formation
- a more comprehensive model for ion diffusion and representation of retention processes at pore scale
- long-term behaviour of disposal packages and their contents

3.2.4 Refinement of the disposal facility concept and design

Preliminary disposal facility concepts were selected in 1999 to provide a basis for research into the disposal facility and to enable the range of design options to be analysed. They were subsequently elaborated in Dossier 2001 Argile (Andra 2001) and Dossier 2005 Argile (Andra 2005a).

The concept of reversibility appeared in French law with the Waste Act 1991, which mentions the possibility for disposal of being reversible or not. Following research at Meuse/Haute-Marne URL, Andra aimed to demonstrate in the Dossier 2005 the feasibility of a disposal concept in which reversibility is possible for a period of at least 100 years. As a result of the public debate on radioactive waste held in late 2005, the reversibility rationale has become an important part of acceptance of deep disposal. The Planning Act 2006 establishes reversibility as a governance principle (Andra 2010b).

Dossier 2001 Argile (Andra 2005a) envisaged a disposal facility designed in zones assigned to each category of waste:

- B waste (equivalent to ILW)
- vitrified C waste (equivalent to HLW)
- spent fuel

The disposal facility zones would be created independently from each other, and spaced apart to minimise physical and chemical interactions. Each zone would be designed as a series of about 10 modules, constructed as the disposal facility progresses. Zoning the disposal facility was considered to have the advantage of separating the analysis of issues specific to each category of waste (Andra 2001).

Several types of disposal facility design and disposal configuration were considered initially for each type of waste (for example, horizontal or vertical deposition of C waste), along with different construction techniques.

In 2002, Andra adopted a limited number of concepts which formed the basis of the studies carried out until 2005 and allowed a more detailed analysis to be conducted of the disposal facility design. These concepts aimed to identify specific proposals to have a design available for each type of waste package so that the feasibility of their disposal in the Callovo-Oxfordian argillite of the Meuse/Haute-Marne site could be assessed.

Type B waste covers a wide range of primary packages with different packaging, geometries, and radiological and chemical contents (Andra 2005f). To simplify the disposal facility operation, it is envisaged that primary packages will be emplaced in standardised concrete containers, with sides of length approximately 3 metres. The design is intended to provide durability over the century timescale required for reversibility. The containers are dimensioned so that they can be stacked up to 4 high.

Type C waste packages are to be placed in a canister made of non-alloyed steel, with the thickness (55mm) chosen to withstand corrosion during the thermal phase.

The disposal of spent fuel was studied encase it is not reprocessed. Spent fuel would be emplaced in a cylindrical steel canister containing 1 or 4 assemblies depending on the fuel type. The thickness of this canister (110mm) was intended to provide water-tightness for at least 10,000 years.

The disposal cell proposed by Andra for B waste is a dead-end horizontal tunnel with a useable length of 250 metres and an excavated diameter of 12 metres. The cell would be aligned parallel to the principal geomechanical stress to minimise damage to the rock during excavation.

The C waste and spent fuel disposal cell proposed by Andra is a dead-end tunnel with a metallic sleeve. The sleeve allows waste packages to slide in and maintains the reversibility requirement. The tunnels would be 0.7 or 3.3 metres in diameter for C waste and spent fuel respectively, and approximately 40 metres long. The length was limited to make excavation and package emplacement more reliable. The disposal cell would contain 6–20 packages depending on their thermal output. To reduce the areas of rock liable to be fractured by construction work, the cells are to be laid out parallel to the major principal geomechanical stress. They would be spaced so as to limit the temperature in the rock to under 90°C.

3.2.5 Criteria for site selection and/or evaluation

The Meuse/Haute Marne URL cannot be incorporated into a final disposal facility, as specified in the 1991 Waste Act. Therefore, Andra developed an approach which aimed to define a domain that could be considered as being equivalent to that at the URL site from the viewpoints of the confinement properties of the formation and of the disturbance characteristics that a disposal facility would generate. The identification of the ‘transposition zone’ was described in Dossier 2005 Argile (Andra 2005a).

Defining the transposition zone

To define the transposition zone, various characteristics of the Callovo-Oxfordian layer that contribute to its confinement capability were taken into account. These characteristics included the geometry (thickness) of the layer and factors that might adversely affect its homogeneity such as sedimentary gaps or transmissive faults.

Previously collected information (2D seismic profiles, oil and gas exploration boreholes, boreholes drilled between 1994 and 1996, and the 2003 borehole drilling campaign and surface mapping operations) provided coverage of a geographical zone covering approximately 700km^2. These studies were considered sufficient to determine the transposition zone without further investigations (Andra 2005a). The transportation zone defined by Andra is shown in Figure 3.3.

Apart from the major tectonic structures bordering the investigated area (the Marne faults, Gondrecourt graben), no major vertical displacement fault was found in the Callovo-Oxfordian formation, in the overlying Oxfordian horizons, or in the upper part of the underlying Dogger in the northern half of the investigated area.

Comparison between seismic surveys on the URL site and others recorded in the investigation area were reported to show good correlation of various Callovo-Oxfordian sequences. Mapping of the Callovo-Oxfordian formation by seismic surveys defined the upper and lower limits of this formation. Various boreholes were used to confirm this mapping. Starting from the URL site, the thickness of the Callovo-Oxfordian formation increases as one moves towards the northeast of the area studied, due to the argillite deposition conditions. This was considered to enhance the confinement capability.

The median depth of the formation reduces slightly in a small area to the east and south of the URL and increases in the remainder of the area investigated. It was considered that there would be acceptable changes in the mechanical properties of the rock, as long as the depth remains less than 630 metres.

Logs recorded from borehole cores have been reported to show the same sedimentation sequences in the formation as at the URL, which confirmed that the URL is representative of a large geographical zone. They are also reported to show that the various depths of the Callovo-Oxfordian formation are correlated over large distances (several tens of kilometres) and that their layout is not disturbed by facies variations or sedimentation gaps liable to modify their hydraulic properties.

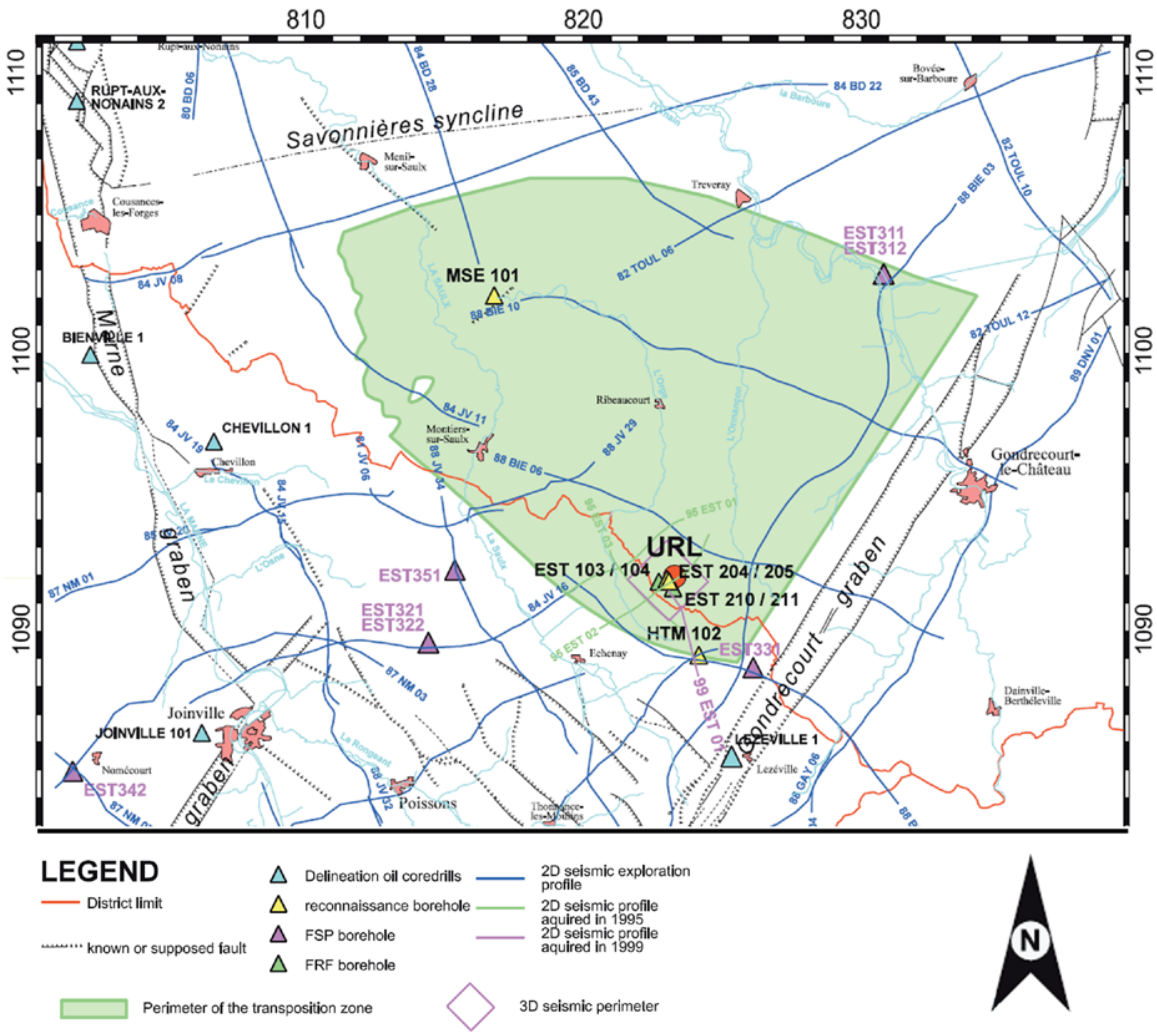


Figure 3.3 Transposition zone at Meuse/Haute-Marne, showing locations of geoscientific data used to characterise the area

Notes: Modified after Andra (2005a)

Defining the ZIRA

An area of about $37km^2$ within the $250km^2$ of the transposition zone has been defined as the ZIRA. The ZIRA was determined on the basis of geoscientific criteria relating to long-term safety. The criteria included (IRSN 2009):

- the thickness of the host formation should be over 140 metres
- the hydraulic gradient should be less than 0.2 metres per metre (m/m)
- depth in the middle of the layer should not exceed 600 metres (because of construction issues arising at greater depths)
- the possibility of implementing underground infrastructure perpendicular to the dip of the host layer

Additional ZIRA criteria relate to surface features such as surface water and location of surface installations near villages.

Andra proposed 5 alternative areas for the ZIRA within the north-eastern and eastern parts of the transposition zone. The local community were involved in the final selection, which was chosen to be away from habitation. The ZIRA defined by Andra is shown in Figure 3.4. Other issues such as land use, transport links and a requirement to ensure that economic benefits are equitably distributed are being considered in regard to the potential sites for the surface facilities. Some of the surface facilities could be sited a few kilometres away from the disposal facility. Potential areas for surface facilities have been identified.

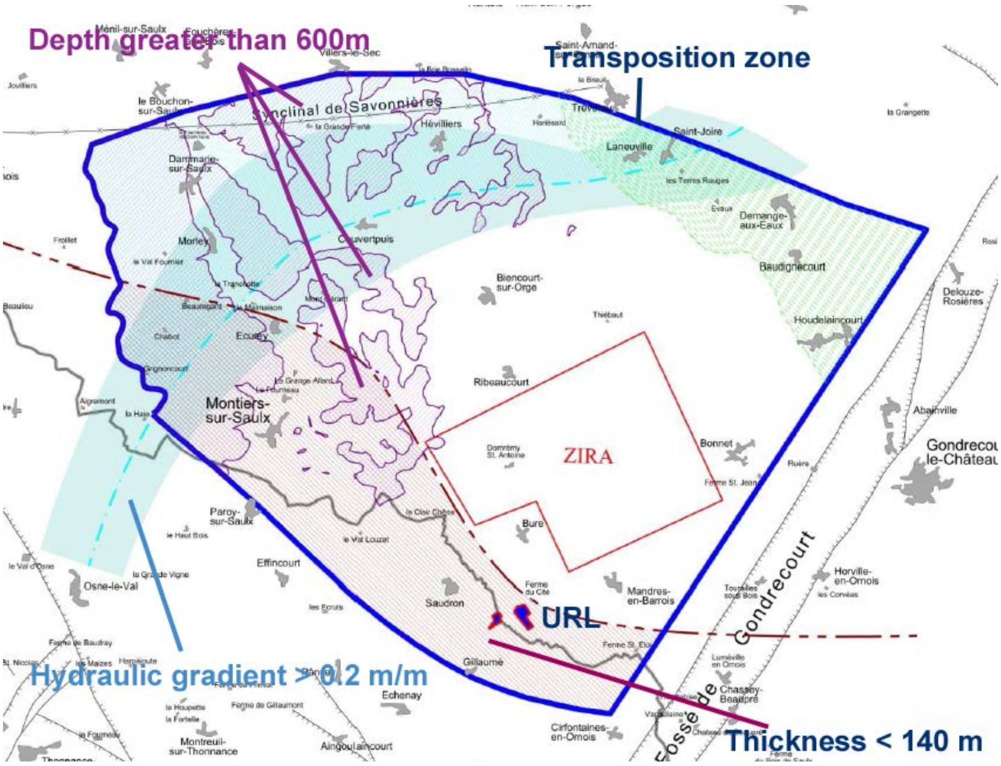


Figure 3.4 The ZIRA at Meuse/Haute-Marne

Notes: Modified after IRSN (2009)

3.2.6 Development of safety assessment and environmental impact assessments

Andra has performed 2 preliminary safety assessments within the time period considered in this review. These form part of Dossier 2001 Argile and Dossier 2005 Argile. They are not site-specific assessments, but rather feasibility studies for a GDF to be constructed in the Callovo-Oxfordian. However, they are based on information obtained from the Meuse/Haute-Marne and the URL.

Dossier 2001 Argile

The safety calculations presented in the dossier (Andra 2001) are indicative. They are not claimed to be a faithful reflection of a physical reality as they are based on systematically pessimistic and conservative hypotheses. The dose values calculated were therefore claimed to be approximate, allowing Andra to identify the important components of the disposal facility system and to direct the analysis towards the most sensitive issues. The safety assessment in Dossier 2001 Argile is based on preliminary disposal facility design information which was revised in 2002 in the light of this work.

The 1991 Waste Act (RFS III.2.f) stated that the study of the disposal facility must take into account 2 different scenarios:

- scenarios described as 'normal evolution', corresponding to the way the disposal facility and surrounding environment changes over time when operating without external disturbance
- 'altered scenarios', meaning that the development of the disposal facility and/or the surrounding environment is disturbed by either natural phenomena (such as certain climate events) or human intervention (such as intrusion into the disposal facility)

This approach resulted in 83 scenarios being defined. For each scenario considered, the thermal, hydraulic, mechanical, chemical and radiological phenomena were described, including coupled effects. This was reflected in a conceptual model of the state of the disposal facility. The possibilities for release of radionuclides from the packages were then identified and the transfer paths defined.

For the altered scenarios, the following events were selected for evaluation:

- deep water well
- borehole intercepting a drift
- glaciation developing from the Alps
- temperature increase due to climate change
- maximum physically possible earthquake
- exploitation of geothermal resources

For the normal evolution scenario, the radiological impacts were found to result mainly from iodine-129 and chlorine-36. In the case of iodine-129 (from spent fuel), the impact may be close to the limit set by Fundamental Safety Rule RFS III.2.f. For the other elements, they are very significantly below the limits. The impacts, where they exist, only occur after several hundred thousand years. The results were interpreted by Andra to indicate that the doses would fall within the regulatory limits as they are based on conservative hypotheses.

In the altered scenarios, the calculations are interpreted to have revealed the important role played by the shaft seals and the role of the EDZ. The results were reported to indicate the performance levels that need to be guaranteed to ensure safety, as well as indicating possible avenues of progress in terms of positioning the disposal facility in zones with low hydraulic gradient and in improved characterisation of the EDZ. The radiological impacts, assessed on the basis of hypotheses considered pessimistic by Andra, were in the milli-Sievert (mS) range. It was judged that these impacts could be reduced by a set of disposal facility design measures which would be the subject of future research. It was thought that the impact of an altered evolution scenario could be brought down to acceptable values comparable with the regulatory limits in the normal evolution scenario.

Dossier 2005 Argile

The safety assessment (Andra 2005a) is based on the more complete understanding of the site enabled by scientific knowledge acquired during the site characterisation and URL experimental programmes. It is structured in terms of 'safety functions' and the disposal facility is expected to:

- prevent water circulation – the geological medium contributes to this, as well as the design of the disposal facility structures
- immobilise the radionuclides within the package – the waste contributes to this objective, as well as the containers and the chemical conditions in the disposal cells
- delay and attenuate the migration of the radionuclides which would have been released outside of the disposal cells

These functions are ensured over time by several different and independent components. The objective of the safety assessment is to analyse how each of the natural and engineered components ensure the long-term safety objectives. This involved evaluating the radiological impact to a critical group.

Dossier 2005 Argile (Andra 2005a) pursued the strategy of defining normal evolution and altered scenarios. It also introduced the terminology of phenomenological, conservative and pessimistic models.

- **Phenomenological (or best estimate) model**: the model that, all other parameters being fixed, is deemed to yield results fitting at best those obtained by experiments and/or observations
- **Conservative model**: a model used to obtain a calculated impact that falls within a range of high values (with all other parameters fixed elsewhere). In the simplest case, where the impact increases as a parameter value increases (or decreases), a value is chosen from the upper (or lower) range of available values
- **Pessimistic model**: a model not based on phenomenological knowledge, chosen to obtain an impact greater than one calculated using values from the expected range (for example, to provide bounding calculations)

The normal evolution scenario and its sensitivity studies are considered as a suite of calculations.

- A 'reference calculation' sets out Andra's current knowledge of the disposal facility's foreseeable evolution. The purpose of this calculation is to assess factors that would increase the impact of creating a disposal facility. To this end, it includes a series of parameters and models. It chooses those based on the best available scientific knowledge and incorporating a degree of conservatism that varies according to the uncertainties, being less conservative where the parameters or models have been validated in detail, and more conservative where substantial questions remain outstanding.

- A series of single- or multi-parameter sensitivity analyses set out to rank the parameters and models by determining the ones that, if they were to vary, would have the greatest consequences for the overall assessment.

The disposal facility seals were identified in Dossier 2001 Argile as being of importance for safety. Subsequent work, especially the more precise definition of the design of these structures (development of hydraulic cut-offs, more detailed definition of the installation conditions) were reported to demonstrate that the failure of the seals does not appear to be a very damaging event for the disposal facility's safety. The lengths of the drifts, the low gradients, the low quantity of water provided by the geological environment and the dead-end design are reported to limit the impact of such a situation.

Andra concluded that Dossier 2005 Argile demonstrates the feasibility of the disposal facility with a reasonable degree of confidence. In particular, Andra concluded that the safety assessment shows that the radiological protection objectives assigned to the disposal facility are complied with. A few altered evolution situations emerged from the analysis by Andra, but they did not lead to a significantly higher radiological impact than that of the normal evolution scenario.

From the conclusions of the safety analysis, Andra identified areas to prioritise for future work. These focused on several areas:

- consolidation of the data acquired within the Meuse/Haute-Marne laboratory
- full-scale technological tests to support more detailed engineering studies
- work to explore the transposition zone

Environmental impact

To develop an EIA for the proposed disposal facility, Andra set up a permanent Observatory of the Environment at Meuse/Haute-Marne (Ouzounain et al. 2008). It is intended that the observatory will track the evolution of the local environment for over a century (that is, the period of operation of the disposal facility). Once the site is selected (late 2013), Andra will summarise the data available to establish the initial state of the disposal facility environment. The initial state will describe natural resources and natural areas of agriculture, forestry, forestry or recreation, as well as material assets and cultural heritage likely to be impacted by the project.

3.2.7 Critical review and its influence

During the period after 1999 when the government decided to develop a URL at Meuse/Haute-Marne, regulatory reviews have been made by ASN, supported by IRSN, of the Dossier 2005 Argile and the subsequent delineation of the ZIRA. NEA was asked by the French government to review Dossier 2001 Argile and Dossier 2005 Argile. In addition CNE has reviewed Dossier 2001 Argile, Dossier 2005 Argile and the delineation of the ZIRA as part of its annual appraisal of progress in the government's waste management plan. The CLIS at Bure commissioned reviews of Andra's work by IEER in 2004, and with respect to the delineation of the ZIRA. The more important aspects of these reviews are described below.

Review of Dossier 2001 Argile

The French government asked NEA to review Dossier 2001 Argile (NEA 2003). The terms of reference set for the review concerned consistency with:

- other national disposal programmes, in particular the ones considering argillaceous formations
- international practices

NEA was asked to assess:

- the clarity of the documentation
- the consistency of the methodologies for assessing the long-term safety
- the internal consistency between the scientific and technical knowledge base and the assumptions used in the report at different levels
- the pertinence of the conclusions, in particular those linked with the main objectives of the Dossier 2001 Argile

The NEA International Review Team (IRT) made the following observations and recommendations within the above framework:

- The documents underpinning the report were recommended to be more complete in terms of not being reliant upon context and information documented elsewhere, and again there should be more extensive referencing to underlying information. The NEA IRT recommended that the Dossier 2005 documents should be written with a hierarchical structure.
- Andra was recommended to develop procedures for making the subjective elements of the safety case more transparent and traceable, and to address the issue of taking the temporal evolution of the system into account. The NEA IRT found that the consistency between the elements of the safety analysis was generally adequate, but recommended that the propagation of uncertainties needed improvement. It was considered that this could be partly met by an analysis of a more comprehensive set of scenarios.
- Although the choice of 'pessimistic' parameters was subjective, the NEA IRT considered them to be consistent with scientific and technical knowledge. The only significant research and development omission they identified related to gas issues.

The NEA IRT considered that Andra's scientific programme for 2002 to 2005 was well-informed by the Dossier 2001 Argile, with all significant research requirements identified in the Dossier 2001 Argile being addressed by proposed work programmes.

CNE reviewed the Dossier 2001 Argile in the annual review of waste management activities under the 1991 Waste Act (CNE 2002). It made a series of detailed recommendations, which included the following.

- The importance of the quality of the disposal facility seals was noted and taken to indicate the importance of the tunnel sealing tests that should be performed in the underground laboratory.
- Recommendations were made concerning the structure of the Dossier 2005 Argile to improve the clarity of the presentation.
- Concern was raised that not all types of fracturing in the clay, of significance for radionuclide transport, would be detected through geophysical surveys. The existence of such fractures would need to be established through other methods.
- It was noted that the reported transmissivities in the Dogger and Oxfordian limestones were significantly lower than those estimated regionally by about a factor 100 (Oxfordian) to 1000 (Dogger). The extent of these lower transmissivity areas was unknown and CNE considered that the method of modelling these features used by Andra was unjustified.
- CNE raised issues about the scale dependence of hydraulic conductivity, citing studies by the Belgian Agency for Radioactive Waste and Fissile Materials (ONDRAF/NIRAS) in Boom Clay carried out as part of the Safety Assessment and Feasibility Interim Report 2 (SAFIR 2) where the issue was found to be significant.

Review by IEER 2004

The local information and monitoring committee (CLIS) chose to commission the IEER to evaluate Andra's research programme and to make recommendations in areas where improvements may be needed (IEER 2004).

IEER considered that Andra's research programme was not sufficiently transparent to allow independent advice on many aspects of this programme to be issued. It recommended that the detailed results, current projects, the research schedule, modelling and performance evaluations should be easily accessible to the public.

IEER noted that, in Dossier 2001 Argile, the importance of the disposal facility seals was highlighted, with 'altered scenarios' in which the seals were assumed to have failed resulting in doses above the regulatory value.

IEER considered that important aspects of the necessary research had not been started such as:

- research on the seals within the host rock after in-situ characterisation of the rock
- characterisation of small-scale fractures and bedding planes that could be important for creating a realistic assessment of the EDZ
- research on gas production and migration

Review of Dossier 2005 Argile

In 2005, the Dossier 2005 Argile was the subject of a triple critical assessment. This involved:

- a scientific and technical assessment conducted by CNE

- a review performed by ASN, which was informed by IRSN
- a peer review by an NEA IRT to verify the soundness of approach and results in relation to international standards

The conclusions are given below (CNE 2005, Baillet and Ouzounain 2008). Although favourable, the review of the assessment by CNE and the safety authority (ASN 2006) also identified the need for:

- **More realistic modelling of the re-saturation of the disposal facility in future assessments**. CNE thought that re-saturation would happen at different rates in different parts of the disposal facility and that the various factors of influence were subject to uncertainties in timing and spatial homogeneity (CNE 2005). CNE raised concerns that differences in the re-saturation could lead to temporarily enhanced groundwater flows, with potential consequences for safety.
- **Better understanding of gas generation and the effects of gas on the disposal facility.** CNE noted that gas production will influence re-saturation and the development of an EDZ (CNE 2005). CNE noted that Andra believed that the dissolution of hydrogen gas in the pore water of the Callovo-Oxfordian and its subsequent diffusion would prevent an excessive rise in pressure in the disposal facility. CNE considered that this analysis would need further verification by experiments. It noted that Andra had begun experiments relating to gas entry pressure into the pores of the argillite, multiphase flows and gas–water interactions. CNE considered that these topics had not yet reached a sufficient level of maturity to assess whether the problem gas should lead to reconsideration of, for example, the volume and nature of exogenous materials brought into storage, so as to limit gas production.
- **More realistic modelling of the migration properties of the engineering disturbed zone (EDZ).** CNE (2006) discussed the importance of understanding the potential for flow in the EDZ to short circuit the geological barrier. However, CME acknowledged that Andra had started experiments in this area and had prioritised it for future studies.

IRSN considered that a GDF in the Callovo-Oxfordian Clay at Meuse/Haute-Marne was feasible to the extent that there were no issues identified which would preclude establishment in the future of a demonstration of the safety of such a facility (IRSN 2005). IRSN considered that there would be no obstacle to finding a GDF site in the transposition zone defined by Andra.

IRSN supported its review with its own hydrogeological modelling of the area, modelling of clay/concrete interactions, simulations of radionuclide transport, calculations related to disposal facility seal performance and statistical analyses of fractures measured in the investigation area.

IRSN found that the consistency of its hydrogeological model with available hydraulic head and salinity measurements required the explicit representation of water-conducting features in the model (Rocher et al. 2008). In view of the uncertainties in this study, IRSN concluded that improvements in detection techniques for such features would improve confidence in a safety case.

IRSN tested various methods to detect hydrogeologically active faults in limestone at its Tournemire laboratory which are complementary to the more standard methods of geological and geophysical surveys for example, electrical resistivity tomography, ERT (Rocher et al. 2008). IRSN considered that, as part of a forward programme, it would be necessary to:

- define a strategy for the recognition of possible fracturing in the host formation and the geological layers that surround it
- improve the hydrogeological knowledge, in particular to decide whether or not fractures might call into question the generally homogeneous flows in formations flanking the host layer

IRSN also requested an improved understanding of the mechanical behaviour of the rock, and knowledge of the physical and chemical properties of concrete in their original state and as they evolve (IRSN 2005).

IRSN considered that the assumptions describing the hydrogeological system and the biosphere to be sources of significant uncertainty. Improving the knowledge in these 2 areas was considered to be an important issue to address in the future. It was noted that the doses predicted were highly dependent on choice of assumptions used to describe the critical group and the transport pathways. IRSN emphasised that these choices are not purely technical and it would be useful to define them wherever possible based on a consensus from different stakeholders (IRSN 2005).

The review by an NEA IRT of Dossier 2005 Argile was generally positive (NEA 2006). It stated that Andra had successfully established confidence in the feasibility of constructing a disposal facility in the Callovo-Oxfordian argilites in the region of the Meuse/Haute-Marne URL. In particular NEA considered there to be great confidence in the crucial safety function of the Callovo-Oxfordian, that is, diffusion-controlled transport and radionuclide retention.

The terms of reference for the review included:

- whether the approach was consistent with international practices and with other national disposal programmes, in particular those considering argillaceous formations
- whether the future research needs were consistent with the available knowledge basis and priorities well-identified – the French authorities were particularly interested in receiving detailed recommendations for specific improvements, notably if the decision-making process led to a site-selection phase
- the appropriateness of specific technical aspects, for example, the approach to gas production and its transfer

The review team found Andra’s scientific and technical programme to be fully consistent with international best practice and commended the approaches used in several areas.

The NEA IRT (NEA 2006) made the observation that some of the boreholes drilled by Andra could not, under licensing conditions, be preserved as long-term monitoring wells, but instead had to be plugged and abandoned. The NEA IRT considered that:

- development of a long-term monitoring network on the sector scale will most likely be required for any future disposal facility
- information which could have been obtained in the period leading up to site selection and development, if these boreholes had been allowed to be retained as monitoring wells, would have been valuable

The NEA IRT noted that the analysis of gas production and transport issues appeared to have been done after the design was completed to confirm that gas would not lead to significant issues in long-term safety. Results from the analysis had not been fed back into the design process and there was thus a need to integrate gas issues into the design principles. The NEA IRT suggested that, to increase confidence in modelling results, more data would be required to confirm the expected gas migration pathways though the emplacement cell liners and EDZ into the tunnels adjacent to the cells and then into the host rock.

The NEA IRT commented that, although the Dossier 2005 Argile was presented as having a hierarchical document structure, the different levels of documents did not form a strict hierarchy and information in higher level documents was not always detailed in the immediate lower level documents. It considered that detail of referencing could also be improved.

In addition, the NEA IRT made the following observations and criticisms.

- In addition to planned experiments, the NEA IRT thought it might be of interest (to further support diffusion-controlled transport through the Callovo-Oxfordian formation) to carry out long-term (>10 years) large-scale (decimetre to metre scale) in situ tracer experiments.
- The NEA IRT thought Andra should seek to obtain a better understanding of the cause of the over-pressurisation observed in the Callovo-Oxfordian formation. It noted that, although Andra's 2006 to 2010 Scientific and Technical Programme mentioned osmosis in general as a topic of future research, no specific plans were given.
- The NEA IRT noted that most international radioactive waste disposal programmes search out natural analogues to support and provide confidence in disposal at a particular site. The present and future use of natural analogues to support Andra's case was not greatly visible.
- The NEA IRT thought that, while Andra's hydrogeological model was adequate to demonstrate that any radionuclide releases to the environment would be below levels of regulatory concern, confidence in the modelling could be enhanced by making it more realistic.
- The NEA IRT emphasised the need for Andra to increase further the understanding of retention processes in the Callovo-Oxfordian formation. In particular, the potential influence of naturally occurring organic matter in the overall migration behaviour was highlighted as an issue that needed to be investigated and clarified.

As a result of the issues raised from the critical evaluation of Dossier 2005 Argile, a research programme was set up by Andra in early 2007 to address the progress from the feasibility studies of Dossier 2005 to studies supporting a licence application (Cahen and Voinis 2008). The various internal and external reviews led Andra to plan additional work, as described in Section 3.2.3.

Review of the ZIRA

In 2010, after consulting the various stakeholders and based on ASN opinion, the State approved the choice of a 30km^2 area for implementing the deep geological repository.

IRSN considered that the technical criteria adopted by Andra when choosing the ZIRA were relevant to safety (IRSN 2009). IRSN noted that the value of the dip of the host formation, although relatively high in the ZIRA compared with those in the transposition zone, remained sufficiently low (about 2%) to allow the construction of underground structures preferentially oriented in the direction perpendicular to the Callovo-Oxfordian dipping layer.

Over much of the ZIRA, the depth of the mid-point of the Callovo-Oxfordian exceeds 490 metres – the median depth layer studied in the laboratory of Meuse/Haute-Marne. IRSN noted that, due to a higher lithostatic pressure, damage caused by disposal facility construction may increase with the depth of the structures. It also noted that Andra had chosen to place the ZIRA in one sector of the transposition zone where the depth of this layer was deepest.

ASN considered that the ZIRA location proposed by the Andra was satisfactory from the standpoint of safety and had no objection to Andra's planned surveying work (ASN 2010). ASN raised the issue of the ability of 2D seismic method to detect certain fractures in clay formations, but considered it satisfactory that Andra proposed to use a 3D seismic survey of the ZIRA, supplement if necessary by boreholes. ASN also noted that prior recognition of karst pockets in the Barrois limestone (for example, through electrical resistivity profiles and boreholes) would prevent the risk of flooding associated with these pockets during excavation of disposal facility drifts.

CNE had previously stated that the decisive criterion for the choice of ZIRA should be based on geological considerations (CNE 2010) and that the approach adopted by Andra was consistent with the use of geological and engineering criteria which would be necessary for the eventual establishment of a geological disposal. CNE recommended that future investigations should address:

- the possibility of extrapolating observations on the mechanical behaviour of tunnels at 500 metres depth in the URL to depths of 600 metres for a disposal facility
- the need to present an accurate description of surface facilities to support the public debate that would precede the licence application
- the opportunity to clarify the geological and hydrogeological conditions prevailing during excavation access ramps and to verify that the completion of this work would not alter the conditions within the ZIRA

IEER was commissioned by the CLIS to review Andra's approach to defining the ZIRA (IEER 2011). It commended some aspects of Andra's research such as the modular disposal facility design and the investigations of thermal properties, but had a number of criticisms.

IEER considered the most serious concern to be optimism in the interpretation of complex phenomena with regard to disposal facility performance. It felt Andra's performance analysis used a limited sensitivity analysis to explore the effect of the range in parameter values on performance. For example, the potential for both advective and diffusive transport in the vertical pathways was not considered. IEER commented that Andra had not carried out a full probabilistic analysis using the appropriate ranges of parameters. A simplified probabilistic safety analysis performed by IEER, with parameter ranges consistent with the ones defined by Andra, was claimed to indicate that uncertainties in the input parameters result in a higher uncertainty in the total doses than reported by Andra.

Andra had relied on the homogeneity and isotropy of the Callovo-Oxfordian formation in its evaluation of the long-term disposal facility performance. However, Andra's approach was not considered by IEER to adequately represent the range of possibilities. It was thought that, in some cases, the experimental data were excluded in a way that biased mean values and resulted in an underestimation of the actual observed range in the parameter values.

The official timetable for the disposal facility project was considered by IEER to be too rushed, given the amount of R&D on solutions for handling future waste types arising from new reactor designs that IEER considered remained to be achieved.

IEER thought that there were important advantages to a horizontal emplacement design for waste. However, it also thought that given the difficulties of making the deposition boreholes in this type of sedimentary rock, as evidenced by fractures and deformations in several boreholes drilled in the underground laboratory, the possibility for waste emplacement in vertical boreholes should be revisited, especially for spent fuel disposal. The borehole requirements for spent fuel disposal are different and more difficult than for disposal of vitrified HLW. IEER considered that drilling a 3.3 metre diameter borehole for spent fuel disposal would present severe challenges in view of the difficulties already encountered in a 0.7 metre diameter borehole.

Finally, IEER thought that Andra should provide documentation of its results that were more accessible and easier to review.

3.2.8 Summary

What was the regulator's role in judging the suitability of proposals for surface-based characterisation?

ASN and, prior to 2006, DGSN have been responsible for:

- consulting with the government to develop a plan every 3 years (the National Radioactive Materials and Waste Management Plan) which is the basis for French radioactive waste policy
- consulting with the government to produce the 2006 Radioactive Materials and Waste Planning Act, superseding the 1991 Waste Act which allowed development of the URL and specifying the framework for deep geological disposal
- reviewing the developer's progress in 2001 and 2005, after publication of the Dossier 2001 Argile and Dossier 2005 Argile respectively
- reviewing the developer's definition of the ZIRA

Regulatory reviews were supported by IRSN, which provided technical advice. IRSN has the capability to perform groundwater modelling and safety assessment calculations, and runs an experimental facility at Tournemire.

CNE provides advice to the government by evaluating, every year, the research conducted for HLW management. Although it is not a regulator, it is able to influence the French GDF programme.

What decisions were made by the developer, the regulator and any other body (for example, government) based wholly or partly on information from surface-based site investigation?

Under the 1991 law, the developer was to construct a URL to assess the feasibility of developing a GDF. The GDF would be located in a region where the conditions important for safety and construction would be analogous to those studied in the URL. Hence, the French programme emphasised URL development as a crucial method of demonstrating feasibility, with surface-based site investigations used to identify areas where conditions are analogous to those at the URL site.

Since experiments in the URL were at a relatively early stage in 2005, the Dossier 2001 Argile and Dossier 2005 Argile, and regulatory decisions relating to them, were based on data from surface-based investigations.

How were data from desk-based studies and non-intrusive studies used to determine the purpose and location of the initial boreholes? How were the data from the evolving characterisation programme then used to determine the purpose and location of further sets of boreholes?

The French investigations at Meuse/Haute-Marne initially (in 1999) combined non-intrusive and intrusive surface-based investigations with data acquired from desk-studies, such as oil industry survey data. After 1999, non-intrusive and intrusive surface-based investigations were conducted along with observations made during URL construction and subsequent experiments within the URL.

At the URL site, geophysical surveys were followed by borehole investigations. These in turn were followed by shaft sinking and URL construction. Boreholes were constructed along the axis of the proposed URL shafts to provide greater understanding of the mechanical and geological conditions. Mechanical tests in these boreholes allowed the development of models to predict damage associated with construction of the underground installations.

A major concern was how reliably geophysical surveys of the URL site, the transposition zone and the ZIRA could detect fractures which were associated with advective flow conditions. This was done by following geophysical surveys with borehole investigations to confirm the absence of fracturing or to clarify any detected anomalies.

What criteria did the regulator use to allow development of a radioactive waste disposal facility to proceed to the subsequent stage?

In taking its decisions, ASN called on outside technical expertise of IRSN, and requested opinions and recommendations from an advisory committee of experts working in the subject of nuclear wastes.

In addition, to ensure safety of the deep geological repository project, ASN acts on several levels. It is involved, at national and international level, in drawing up regulations and reference texts, such as the safety guide on the permanent disposal of radioactive waste in deep geological repositories.

ASN's work on the international stage is important in that it offers an opportunity to share its skills, compare its practices and working methods with its peers (see peer reviews of the preliminary safety assessments) and make a contribution to harmonising nuclear safety and radiation protection principles and standards.

Furthermore, in its capacity as joint co-ordinator of the PNGMDR working group, ASN plays an active role in drawing up the provisions of the PNGMDR aimed at improving and optimising radioactive waste management.

3.3 Sweden (Forsmark and Laxemar-Simpevarp)

3.3.1 Introduction and overview

SKB carried out site characterisation in 2 different areas, Forsmark and Laxemar-Simpevarp, to identify a suitable location for a GDF based on the KBS-3 concept. The Environmental Code required alternative sites to be considered. The site investigations were conducted simultaneously in both areas between 2002 and 2007 (SKB 2008c, SKB 2009). The investigations were conducted in discrete campaigns punctuated by data freezes. After each data freeze, the site data were analysed and modelling carried out to develop a Site Descriptive Model (SDM). This provides an integrated understanding of the geology, thermal properties, rock mechanics, hydrogeology, hydrogeochemistry, radionuclide transport properties and a description of the surface system (see Skaguis et al. 2008, for example). The SDMs have been used to inform the design of the underground facilities and to develop disposal facility layouts adapted to the sites. They were also used as the basis for performance assessment and in the EIAs. The SDMs were underpinned by geoscientific data and understanding gained through experiments at the Äspö HRL, located in the Simpevarp area.

SKB has used Äspö HRL for RD&D of disposal facility technologies in a realistic and undisturbed rock environment (SKB 2010). Research has been concerned with processes of importance for the long-term safety of a disposal facility and the capability to model the processes taking place. The performance of the engineered barriers and practical means of constructing a disposal facility and emplacing the canisters with spent fuel has been demonstrated in the URL.

SKI was responsible for oversight of all aspects of SKB’s programme related to the engineering and implementation of the disposal facility to meet operational and post-closure safety requirements up to 2008. SSI was responsible for ensuring the compliance of the actual radiological impact evaluation that SKB would submit as part of its safety case for spent fuel disposal. In 2008, the 2 regulatory authorities were amalgamated into a single authority, SSM, which will make a regulatory evaluation of all aspects of the operational and post-closure safety of the spent-fuel disposal facility.

During the site investigations, SKI and SSI set up groups to track SKB’s activities. The INSITE (INdependent Site Investigation Tracking and Evaluation) group, set up in 2002, was a team of earth scientists to review SKB investigations and provide SKI with advice. Subsequently, SSI formed a similar advisory group (OVERSITE) to look principally at the near-surface and biosphere aspects of site investigation and understanding, although this group operated at a lower level of activity than INSITE. It was expected that these groups would be required to evaluate the large amounts of information generated by the site investigations in sufficient time to provide close scrutiny to SKB and advice to government. It was thought this approach would identify potential difficulties that emerged in the licence review as early as possible so that measures could be taken to fill information gaps and resolve misunderstandings during, rather than after, the site investigations (Chapman et al. 2010).

In 2009, SKB selected Forsmark as the site for the GDF. The preference for this site over Laxemar was based on considerations relating to long-term safety (SKB 2011a).

In March 2011, SKB submitted applications for a KBS-3 type spent nuclear fuel disposal facility system at Forsmark (Dverstorp 2011). According to the Act on Nuclear Activities, applications are needed for:

- a spent nuclear fuel disposal facility at Forsmark

- an encapsulation plant to be co-located with the existing interim storage facility for spent nuclear fuel (CLAB[6]) in Oskarshamn

The application for the encapsulation plant had been submitted in 2006, but was supplemented in 2011. SKB also submitted a licence application for the disposal facility system according to the Environmental Code. Finally, SKB submitted an Environmental Impact Statement that is in common for all 3 applications. The licence application documentation consists of an application document and a set of supporting documents. Important supporting documents are the EIA and the Safety Report. The Safety Report consists of a top document summarising and integrating various aspects of radiological safety during operation and after closure of the disposal facility.

The current licence application is an important step because it involves stakeholder engagement and because there will be a Decision in Principle on the disposal concept. Plans for a KBS-3 disposal facility are a prerequisite, but alternative concepts must be considered. Under the Environmental Code, the host community has the right to veto the licence application (see Figure 3.6). If it approves at that point, it can no longer veto the construction and operation. Later permits will be required to begin operations, planned around 2020, and closure.

3.3.2 Stages of site identification, characterisation and regulation

Throughout the site investigations, SKB was regulated under the Act on Nuclear Activities through the review of its proposed work programmes, which were published as RD&D reports in 2001, 2004, 2007 and 2010. The regulatory review of these reports includes an evaluation of the progress of the Swedish nuclear waste programme, as well as an assessment of SKB’s plans for future work (e.g. SKI, 2008a). The government (Ministry of the Environment 2000) stipulated conditions for SKB’s planning prior to the site investigations, based on advice from SKI. It stated that a distinct programme for site investigations should be prepared, predicated on insights from the work on a safety assessment for the KBS-3 method.

SKB responded with reports (SKB 2000c, SKB 2001c) outlining its proposed site characterisation strategy for both Forsmark and Laxemar. Important features of this plan were the division of the site investigations into Initial Site Investigations and Complete Site Investigations. The Initial Site Investigations were to be followed with a preliminary safety evaluation, called SR-Can (‘Can’ stands for ‘canister’). The Complete Site Investigations would lead to a safety report, called SR-Site.

The site investigations were better delimited at Forsmark than Laxemar-Simpevarp because the boundaries of the investigation area at Forsmark were well defined from the beginning and focused on a tectonic lens of rock with exceptional high strength. At Laxemar-Simpevarp a stepwise process was necessary to refine the investigation area down to identify sufficient disposal facility panels outside of major deformation zones. This led to a gradual shift of focus westwards.

The main purpose of the Initial Site Investigations (SKB 2000c) was:

- to identify and select the site within a specified candidate area that is deemed to be most suitable for a geological disposal facility and thereby also the part to which further investigations would be concentrated

- to determine whether the feasibility study’s analysis of the suitability of the candidate area holds up in the light of detailed site-specific data

[6] Centralt mellanlager för använt kärnbränsle [Central holding storage for spent nuclear fuel]

If the overall assessment showed that the prospects for siting a GDF on the investigated sites were good, Complete Site Investigations would follow on these sites. The purpose of the Complete Site Investigations was to gather the information that would be required to select a site and apply for a licence to begin construction of the disposal facility. This meant that knowledge of the host rock and its properties needed to be increased so that:

- a geoscientific understanding of the site could be obtained regarding current states and naturally ongoing processes
- a site-adapted disposal facility layout could be derived
- an analysis of the feasibility and consequences of the construction project could be made
- a safety assessment could be carried out to determine whether long-term safety could be ensured on the site

SKB identified 5 technical activities involved in site characterisation:

- site investigations
- site descriptive modelling
- safety assessment
- facility engineering
- environmental impact assessment

The relationships between these activities are illustrated in Figure 3.5.

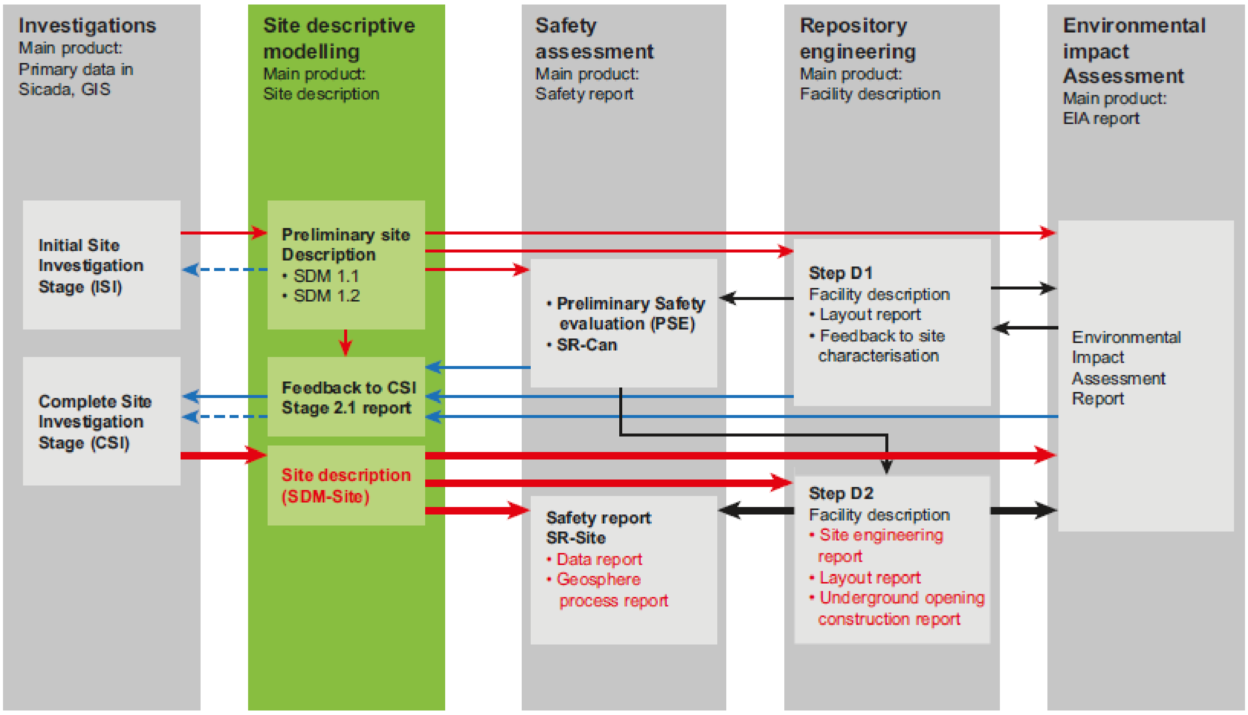


Figure 3.5 Exchanges of data between different technical activities used in the site characterisation programme in Sweden

Notes: Red arrows indicate deliveries and blue arrows indicate feedback.
Source: SKB (2008)

Initial Site Investigations: Phases SDM 1.1 and 1.2

The Initial Site Investigation activities were scheduled to be based on general field studies (mappings and surface geophysics) over the entire candidate area (~20km^2). When a priority site was chosen (~5–10km^2), it was envisaged that a limited number (2–3) deep cored boreholes would be drilled (SKB 2000c).

The Initial Site Investigations were organised into 2 phases, with data freezes called SDM 1.1 and SDM 1.2.

Complete Site Investigations: Phases SDM 2.1, 2.2 and 2.3

The scope of the Complete Site Investigations would be determined at each site, informed by the initial investigations and the requirements of the disposal facility design and safety assessment. SKB estimated that the Complete Site Investigations would consist of 10–20 cored boreholes, which allow extraction and examination of the borehole core for fractures, on each site (SKB 2000c), plus at least as many percussion boreholes (typically shallower). SKB envisaged a series of investigation campaigns, with a limited number of boreholes (3–4) in each campaign. New boreholes would be drilled where the previous investigations indicated more information was needed.

The Complete Site Investigations were organised into several phases, with data-freezes called SDM 2.1, SDM 2.2 and so on until it was considered that sufficient information was available.

Safety Assessments: SR-Can and SR-Site

Reports summarising safety assessments were submitted at 2 points in the site investigation programme, initially as a preliminary evaluation of safety based on data from the Initial Site Investigation (SR-Can, and subsequently as a safety assessment based on data from the complete site investigation (SR-Site). The assessments and analyses made as part of the preliminary safety assessment work were expected to be used in the planning of the subsequent investigations. The SR-Can assessment was based in part on the methodology developed in the earlier SR-97 assessment (SKB 1999).

The preliminary site assessment (SR-Can) was submitted to the regulator as an interim report in 2004 (SKB 2004). This report was reviewed by a group of experts with international experience commissioned by SKI (Sager et al. 2004), and by SKI and SSI (Dverstorp et al. 2005). A final version of the SR-Can safety assessment was produced in 2006, taking into account the review of the regulators (SKB 2006). This was reviewed by SKI and SSI, which commissioned external experts to carry out in depth reviews of different topics (for example, SKI and SSI, 2008).

The stages of the site investigations and safety assessment, with corresponding regulatory reviews, are indicated in Table 3.1.

The licence application for the proposed disposal facility, including the safety assessment SR-Site (SKB 2011b) was submitted to SSM in 2011. The licensing review for the proposed disposal facility will be carried out in 2 parallel processes (see Figure 3.6), one according to the Environmental Code and one according to the Act on Nuclear Activities (Dverstorp 2011). The licence application for the disposal facility system has been submitted to the Environmental Court in Stockholm. SSM and the Environmental Court will both prepare statements to the government. The

Environmental Court will make a permissibility assessment according to the Environmental Code that involves a public hearing and a broad assessment of all types of environmental consequences, including radiation protection aspects, selection of site and method and the application of the general precautionary principles. SSM will be an important review body to the Environmental court regarding SKB's reporting of radiation safety aspects in the Environmental Impact Statement, but might be requested by the court to give statements about other more technical documents.

Based on the statements from SSM and the Environmental Court, the government will make its decision, after consulting the concerned municipality (Östhammar). The municipality has a veto right in the permissibility assessment. If the government grants SKB the licences, SSM will stipulate conditions under the Acts on Nuclear Activities and Radiation Protection, and the Environmental Court will issue a licence and stipulate conditions under the Environmental Code.

At the time of writing these reviews are underway.

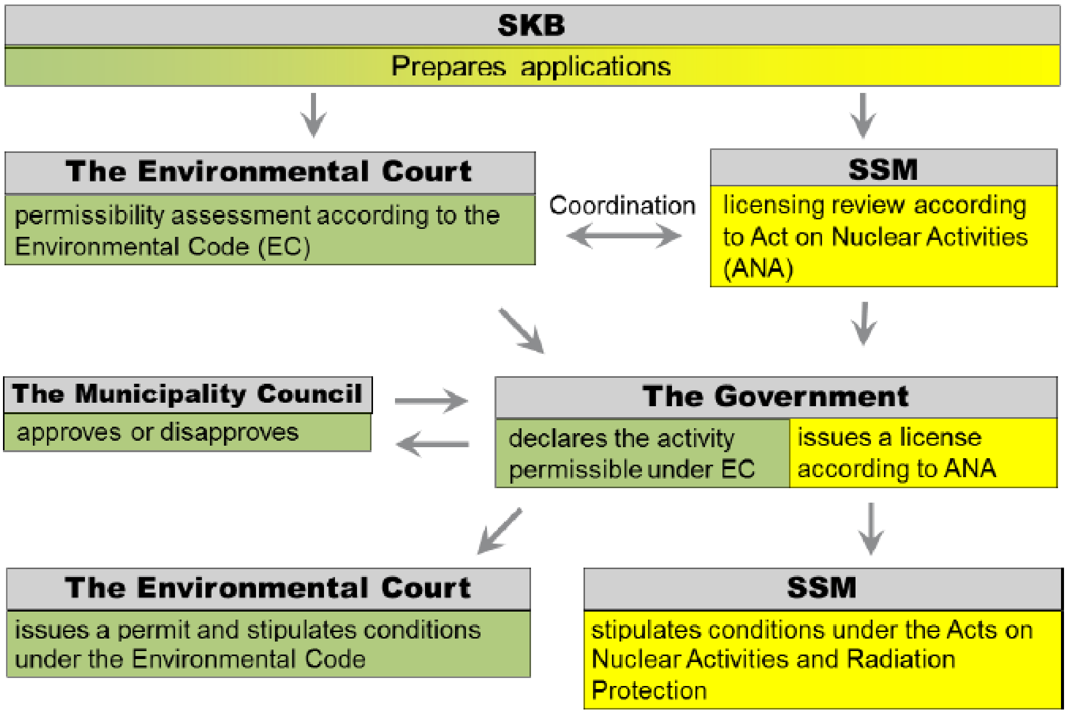


Figure 3.6 Swedish licensing process for the proposed geological disposal facility

Source: Dverstorp (2011)

Table 3.1 Important stages in the Swedish site selection process, including safety assessments and regulatory reviews

Programme phase	Aim	Basis	Corresponding regulatory review
Feasibility studies	Identification of candidate areas	Processing of existing data Field checks.	Review by SKI of RD&D 98 Supplement
Planning for site investigations	Description of the aims and methods of the site investigations	SR-97 Safety assessment, Experience at Äspö HRL, Studies of	Review by SKI of RD&D 2001

Programme phase	Aim	Basis	Corresponding regulatory review
		requirements and criteria for a KBS-3 disposal facility	
Initial Site Investigations (SDM 1.X)			
SDM 1.1	Choice of priority area within candidate area	Geophysical surveys and near-surface boreholes	Review by SKI of RD&D 2004
SDM 1.2	Preliminary model of area	Deep boreholes	
SR-Can	Preliminary safety assessment	SDM 1.2 model	Reviews by SKI, SSI, INSITE and OVERSITE, and international peer reviews
Complete Site Investigations (SDM 2.X)			
SDM 2.1	Model version 2.1	Investigations in many deep boreholes and supplementary ground surveys	Review by SKI of RD&D 2007
SDM 2.2	Model version 2.2	Additional investigations	Review by SKI of RD&D 2007
SDM 2.n	Site Descriptive Model	Additional investigations	Review by SKI of RD&D 2007, 2010
Site selection	Choice of a disposal facility site	Site Descriptive Model	
Licence application	Safety assessment SR-Site, EIA, disposal facility design	Site Descriptive Model	Review by SSM ongoing

Notes: Regulatory reviews of the RD&D reports did not focus on the site investigations programme specifically, but considered SKB's waste management plans more generally.

Work after submission of licence applications

The timetable for development of a disposal facility after licence applications have been submitted has 3 phases:

- an initial design and licensing period
- construction and commissioning
- operation with deposition of spent nuclear fuel

Current planning by SKB is based on the assumption that licensing will take about 5 years. Before construction of the spent fuel disposal facility can begin, a preliminary safety analysis report (PSAR) must also be submitted and approved by SSM. SKB therefore expects to begin construction of the geological disposal facility in 2015.

3.3.3 Geoscientific information acquired for site characterisation

Planning the site investigations

SKB conducted studies (Andersson et al. 1998) and a report on requirements and criteria (Andersson et al. 2000) to determine what site-specific information was needed to carry out safety assessment and design during the site investigation phase. The choice of parameters that need to be determined was based on SKB's experience from rock investigations, including the Äspö HRL, and from performance and safety assessments, particularly SR-97 (SKB 1999).

The data acquisition for the bedrock and the surface system were conducted in campaigns, resulting in 'data freezes' with sets of well-specified data. Altogether, there were 5 campaigns and associated data freezes – 2 for the initial investigation phase and 3 for the complete investigation phase. SDMs were constructed at the end of the first 2 campaigns and following the last campaign. At the start of the second phase, there was feedback to the investigation programme from safety and engineering teams.

To find out whether the investigated site satisfied the fundamental requirements made on the rock and to what extent it satisfied formulated preferences, the following issues were identified as being particularly important to assess during investigations (SKB 2000c):

- the distribution and homogeneity of the rock types, and in particular whether valuable minerals occur within the investigated volume that this could justify mining at a depth of hundreds of metres
- the location of regional plastic shear zones and location of regional and local major fracture zones
- the statistical description of fractures and local minor fracture zones
- the initial rock stresses and distribution of the mechanical properties of the rock and the fractures (strength, deformation properties and coefficient of thermal expansion)
- the rock's thermal conductivity and natural temperature conditions at disposal facility depth
- the statistical distribution of hydraulic conductivity on a deposition hole scale within the planned deposition areas
- the statistical distribution of groundwater flux (Darcy velocity) on a deposition hole scale within the planned deposition areas
- the hydraulic conductivity and possible technical construction difficulties related to the fracture zones that would need to be intersected during the underground construction work
- the natural hydraulic gradient conditions at disposal facility level
- the chemical parameters that indicate the absence of dissolved oxygen in the groundwater, that is, redox potential, occurrence of divalent iron or occurrence of sulphide
- the total salinity of the groundwater
- the pH, concentration of organic substances, colloid concentration and ammonium concentration

- the concentrations of calcium, magnesium, radon and radium
- the statistical description of the transport resistance of flow paths from the deposition area
- the statistical distribution of matrix diffusivity and matrix porosity along conceivable flow paths
- a description of surface ecosystems and other ground conditions

The investigation programme was structured in disciplines, partly to obtain a better overview and partly to rationalise the practical execution of the programme. The programme was based on previous experience at Äspö HRL (Almén et al. 1994). Discipline-specific programmes were developed for the following 7 disciplines (SKB 2001c):

- surface ecosystems
- geology
- hydrogeology
- hydrogeochemistry
- rock mechanics
- thermal properties
- transport properties of the rock

Each discipline was charged to a team of SKB staff and consultants, called SurfaceNet, GeoNet, HydroNet and so on. Their work was overseen within SKB by the Site Investigations Expert Review Group (SIERG). Within each discipline, a list of the types of information it was planned to obtain was given for the Initial Site Investigations and the Complete Site Investigations. The factors influencing borehole positioning, orientation, density, plugging and the sequence of measurements performed within boreholes were described (SKB 2001c).

Site-specific work programmes for the Initial Site Investigations are detailed in SKB (2001a) and SKB (2002) for Forsmark and Laxemar respectively. These reports also present the impact on the natural environment and the local communities, and the protective actions SKB intended to take.

Geoscientific information acquired during the Initial Site Investigations

The SDM developed for the Forsmark site during the Initial Site Investigations is described in SKB (2005a), and for Laxemar-Simpevarp in SKB (2005b).

As an example of the types and quantities of geoscientific information obtained during the Initial Site Investigations at Forsmark, phase 1.1 lasted from February 2002 to April 2003. The following surveys were conducted:

- mapping of bedrock outcrops and quaternary deposits
- airborne and ground geophysical surveys
- hydrochemical analysis of surface waters
- ecological investigations
- core drilling of one borehole to ~1,000 metres deep with:

  - geological analysis of borehole cores, together with BIPS (Borehole Image Processing System) logging, radar logging, hydraulic testing and groundwater sampling
  - mechanical analysis of the borehole cores
- 8 percussion drilled boreholes (up to ~200 metres deep) with BIPS logging, radar logging, hydraulic testing and groundwater sampling
- 53 near-surface boreholes to measure groundwater levels

Phase 1.2 of the Initial Site Investigations lasted from May 2003 to July 2004. It included additional bedrock outcrop mapping, ground-based geophysical surveys and ecological investigations. Additional types of data acquired included:

- sediment analysis in lakes and the sea
- meteorological and hydrological monitoring (precipitation, ground frost, surface water levels, stream flows)
- hydrochemical analysis of precipitation, surface waters and shallow groundwater
- 6 deep cored boreholes (up to ~1,000 metres deep) – as well as to the types of analysis used in SDM 1.1, the thermal properties and transport properties of the borehole cores were assessed, the latter involving resistivity measurements on core samples to assess the formation factor
- 12 percussion boreholes (up to ~200 metres deep)
- 12 near-surface boreholes

Interpreting the Initial Site Investigations and planning the Complete Site Investigations

At the conclusion of the Initial Site Investigation phase, SKB published reports describing the SDM for Forsmark (SKB 2005a) and Laxemar (SKB 2005b). SKB considered that both sites had the potential to site a disposal facility (SKB 2005c, SKB 2006). These judgements were based on comparison with criteria developed in (Andersson et al. 2000), which had to be demonstrated for a site to be considered for the final disposal facility (see Section 3.3.5).

At Laxemar-Simpevarp, the Simpevarp area was considered less suitable due to the limited area available to host the disposal facility on the peninsula (SKB 2006) and it was decided to concentrate on the larger Laxemar area instead. The planned Complete Site Investigations for Forsmark and Laxemar are described in SKB (2005c) and SKB (2006) respectively.

In preparation for the Complete Site Investigations, Andersson et al. (2004) considered how to assess when enough data had been acquired. Specifically, the project objectives were stated as being to:

- develop the logical reasoning to be used for assessing sufficiency of the investigations
- identify different quantitative analyses to be used in support of an assessment whether sufficient investigations have been made

These objectives were refined based on the requirements of the safety assessment and disposal facility design activities. In addressing these objectives the respective reports describe some formal decision analyses tools which might be applied.

Geoscientific information acquired during the Complete Site Investigations

The SDM developed for the Forsmark site during the Complete Site Investigations is described in SKB (2008c) and for Laxemar-Simpevarp in SKB (2009).

As an example of the types of information obtained during the Complete Site Investigations, at Forsmark an additional 18 cored boreholes (100–1,000 metres deep) and 19 percussion boreholes (130–300 metres deep) were constructed (SKB 2008a), as well as additional soil or rock boreholes through the Quaternary deposits. The deep boreholes were subjected to geological, geophysical and hydraulic investigations, as well as borehole imaging of fractures. Boreholes were also subjected to:

- vertical seismic profiling
- in situ thermal experiments
- hydraulic fracturing tests
- hydrochemical logging and microbial investigations
- porewater sampling through out-diffusion methods
- in situ measurements of the formation factor

In addition, single-borehole tracer tests and multiple borehole interference tests were conducted.

An additional 25km of reflection seismic surveys were conducted, along with 23km of refraction seismic surveys. Lineament characterisation was improved using magnetic measurements over 11km^2, trenches through previously identified lineaments and fracture distribution mapping. Trenches were also used to evaluate fractures not associated with lineaments.

Offshore mapping of the Quaternary domain was completed and stratigraphic investigations undertaken. Ecological characterisation of aquatic systems, vegetation and soil was performed, and terrestrial mammals surveyed using snow tracking.

Phase SDM 2.1 lasted until July 2005, SDM 2.2 lasted until September 2006 and SDM 2.3 lasted until March 2007.

Role of Äspö HRL

SKB has operated the Äspö HRL since 1995. The underground part of the laboratory consists of a spiral tunnel from the Simpevarp peninsula to a depth of 460 metres. The total length of the tunnel is 3,600 metres; the main part of the tunnel was excavated using a conventional drill and blast technique and the last 400 metres by a tunnel boring machine with a diameter of 5 metres.

Activities at Äspö can be considered in the following categories (SKB 2010):

- **Verification of pre-investigation methods.** Demonstrate that investigations on the ground surface and in boreholes provide sufficient data on essential safety-related properties of the rock at disposal facility depth.

- **Finalising investigation methodology**. Refine and verify the methods and technology used for characterisation during site investigations.
- **Testing models for description of the barrier functions in natural conditions.** Further develop, and at disposal facility depth, test methods and models for description of groundwater flow, radionuclide migration and chemical conditions during the operation of a disposal facility as well as after closure.
- **Demonstrating technology for, and functions of, important parts of the disposal facility system.** Investigate and demonstrate in full-scale tests the different components of importance for the long-term safety of a final disposal facility, and show that high quality can be achieved in design, construction and operation of disposal facility components.

Examples of experiments carried out at Äspö include the TRUE, DECOVALEX and ZEDEX projects.

The TRUE (Tracer Retention Understanding Experiments) Block Scale project was carried out between 1996 and 2002 (Andersson et al. 2006) by the Äspö Modelling Task Force (an international collaboration). It aimed at understanding sorbing tracer experiments in single structures and networks of structures over distances ranging between 15 and 100 metres. It involved a unified application of various model approaches for modelling the in situ experiments.

The DECOVALEX project (see, for example, Bäckström and Bygg 2008), initiated in 1992, was used to advance the understanding and mathematical modelling of coupled thermo-hydro-mechanical (THM) and thermo-hydro-mechanical-chemical (THMC) processes in fractured rocks and buffer or backfill materials. The project was conducted by research teams supported by a large number of radioactive waste management organisations and regulatory authorities, including those of Canada, China, Finland, France, Japan, Germany, Spain, Sweden, the UK and the USA.

The ZEDEX programme was aimed at understanding the behaviour of the EDZ in terms of its mechanical and hydraulic properties, and its dependence on the type of excavation method used (Emsley et al. 1997).

Äspö was used to investigate borehole sealing methods (Pusch and Ramvquist 2007). The borehole sealing project was a joint project with Posiva. Experiments were also conducted at Olkiluoto.

Greenland Analogue Project

The Greenland Analogue Project is a multilateral research project between SKB, Posiva and the Nuclear Waste Management Organisation (NWMO) of Canada on Greenland’s west coast (east of Kangerlussuaq) (Wallroth et al. 2010). The aim of the project is to improve the understanding of how an ice sheet affects the groundwater flow and water chemistry around a deep geological disposal facility in crystalline bedrock during glacial periods, and with the presence of permafrost. It is hoped that the project will improve safety assessments by reducing the large uncertainties and pessimistic assumptions in the glacial scenarios considered. The Greenland Analogue Project is planned to run for 4 years (2009 to 2012), with initiating studies performed during 2008. A final report will be published in 2013.

Quality assurance (QA) issues

Data collected during the site investigations were held in the SICADA database (Munier and Stigsson 2007) and SKB geographic information system (GIS). All field data were reported in an SKB special P-report series. All of these were reviewed by the same person to ensure consistency of quality checks. Part of the quality management system included a procedure for reporting errors detected in data provided from SICADA. An example of this was errors discovered in the borehole image processing system which records fracture orientations and depths.

Handling integration between investigations and modelling between sites

The field investigations were managed by site offices at the 2 sites, whereas the site descriptive modelling was organised as 2 projects managed by the SKB central office in Stockholm. It was recognised early on that the project organisation implied several integration challenges. SKB took the following actions to mitigate these potential problems:

- publishing joint methodology reports and plans as a basis for the work
- involving some crucial technical staff from the site offices, like the site geologist, to also be part of the site modelling project
- organising discipline-specific expert groups (‘NETgroups’) where all staff (that is, from both sites and both projects) from a specific discipline come together and assess how modelling should be conducted within their discipline
- focusing site-specific modelling project meetings on cross-discipline interaction
- organising special workshops and meetings focusing on different integration aspects such as confidence and uncertainty assessments
- maintaining a small modelling management group, including the project managers, to supervise the work

3.3.4 Refinement of the disposal facility concept and design

The concept and design for the disposal facility is described in SKB (2007). The final KBS-3 disposal facility is planned to be extended stepwise and to begin with an initial 3-year period for 300 canisters. Normal operation would then commence in steps of 150–200 canisters per year until a total of 6,000 canisters had been deposited.

Adaptation of the underground facility to the existing conditions was made during an iterative process between the various investigation and design phases. The disposal facility design was determined based on the Site Engineering Report (SER) (see, for example, SKB 2008a). The SER presents general guidelines and site-specific constraints for the design of underground openings required for the disposal facility. For example, the disposal facility depth was specified based on considerations of temperature, fracture frequency, potential for spalling, geochemistry, and available space and construction costs.

The site-specific constraints provided in the SER are based on the site descriptive model. The constraints include the following.

- No site investigation borehole could be closer than one tunnel diameter from a tunnel in the disposal facility.
- A 'respect distance' of at least the transition zone width and a minimum of 100 metres was required between major deformation zones (longer than 3km) and deposition holes.
- To avoid erosion of the buffer, only deposition holes with limited inflows could be used. The acceptable inflow criteria into a deposition holes were 0.1 litres per minute and 5 litres per minute for 300 metres of deposition tunnel length, and for all other openings 10 litres per minute per 100 metre tunnel length (SKB 2007). Estimates of the numbers of deposition holes which might be affected were based on discrete fracture network (DFN) groundwater flow modelling.

3.3.5 Criteria for site selection and/or evaluation

Criteria were developed to aid decisions regarding the potential suitability of sites at the Initial Site Investigations phase and to choose between Forsmark and Laxemar as the proposed disposal facility location.

Criteria to select sites from candidate areas and proceed to the Complete Site Investigations

These decisions, made during the Initial Site Investigations, were based on comparison with criteria developed in Andersson et al. (2000), which had to be demonstrated for a site to be considered for the final disposal facility. If one or more requirements were not met, the site would be disqualified. The requirements were summarised as follows:

- Regional ductile shear zones shall be avoided
- The bedrock within the disposal facility volume may not have ore potential
- A disposal facility must be able to be emplaced and given a technically reasonable layout within the available rock volume and taking into account fracture zones and so on
- The rock mechanical conditions must be such that serious stability problems do not arise in deposition tunnels and deposition holes
- The groundwater at disposal facility level may not contain dissolved oxygen
- The total salinity (TDS = total dissolved solids) of the groundwater at disposal facility level must be lower than 100 g L^{-1}

Beyond these requirements, it was stipulated that the suitability of a site could be questioned if a large fraction of the rock mass between fracture zones has a hydraulic conductivity greater than 10^{-8} m s^{-1}.

Selection of Forsmark instead of Laxemar

The strategy established by SKB for choosing between the siting alternatives of Forsmark and Laxemar at the end of the Complete Site Investigations (SKB 2011a) was formulated according to the following 2 points:

- The site that offers the best prospects for achieving long-term safety in practice will be selected
- If no decisive difference is found between the sites in terms of their prospects for achieving long-term safety, the site that is judged to have the most favourable other aspects to develop the geological disposal facility will be selected

The evaluation of long-term safety was framed in terms of:

- bedrock composition and structure
- future climate
- rock mechanical conditions
- groundwater composition
- solute transport
- groundwater flow
- biosphere conditions
- site understanding

Site-specific dose calculations were used to compare the long-term safety of the sites. They were based on the understanding developed through the development of the STMs.

3.3.6 Development of safety assessments

There are no prescriptive requirements in Swedish legislation detailing what a licence application should contain at the outset. Therefore, SSM held meetings with SKB pre-licensing to explain what it expected to be submitted in the application.

The following safety assessments were submitted to the regulators based on information obtained during the site investigations:

- interim SR-Can safety assessment (SKB 2004)
- SR-Can safety assessment (SKB 2008b)
- SR-Site safety assessment, which formed the basis for a licence application for the disposal facility (SKB 2011b)

The Can in the acronym SR-Can stands for canister. This title of the project was chosen since it was originally intended to support the application to build an encapsulation plant. However, it was later decided that a report on long-term safety was not required for that application.

Interim SR-Can safety assessment

The Interim SR-Can report (SKB 2004) was used to demonstrate the methodology that would be applied in the subsequent assessments. It was intended that the assessment would also demonstrate that the substance of the review comments (SKI 2001a) concerning methodological issues in SKB’s previous safety assessment, SR-97 (SKB 1999) had been adequately addressed.

Preliminary data from the Forsmark site (SDM 1.1) were used to some extent as examples. However, at this stage the collected data were considered too sparse to allow an evaluation of safety. Data from boreholes were limited to information from one ~1,000 metres deep core-drilled borehole and 8 percussion-drilled boreholes each 150–200 metres deep from Forsmark (SKB 2004). However, it was an important step in demonstrating that tangible progress had been made on developing a safety assessment methodology. The work illustrated SKB plans, and trained its team. It also provided a focus for discussions with the regulator and provided a basis for discussing the planning of investigations with the review groups, as well as for engaging with local communities about local conditions.

A methodology in 11 steps was developed for the interim SR-Can report and further elaborated through the SR-Can and SR-Site safety assessments. The culmination of this methodology in SR-Site is shown in Figure 3.7. A FEP (Features, Events and Processes influencing long-term safety) analysis was used to develop a terminology of safety functions and how these could be evaluated by means of a set of function indicators that were, in principle, measurable or calculable properties of the system. Criteria for the function indicators were provided.

Evaluation of the long-term safety was based on the premise of a reference scenario. Other scenarios are then selected to cover less probable conditions not included in the main scenario or to gain insights into the functioning of the system.

The results of the preliminary evaluation of the function indicators were reported to suggest that several of the criteria would be fulfilled for the range of expected disposal facility conditions. Data that need to be further evaluated were specified and a number of issues requiring further analysis identified.

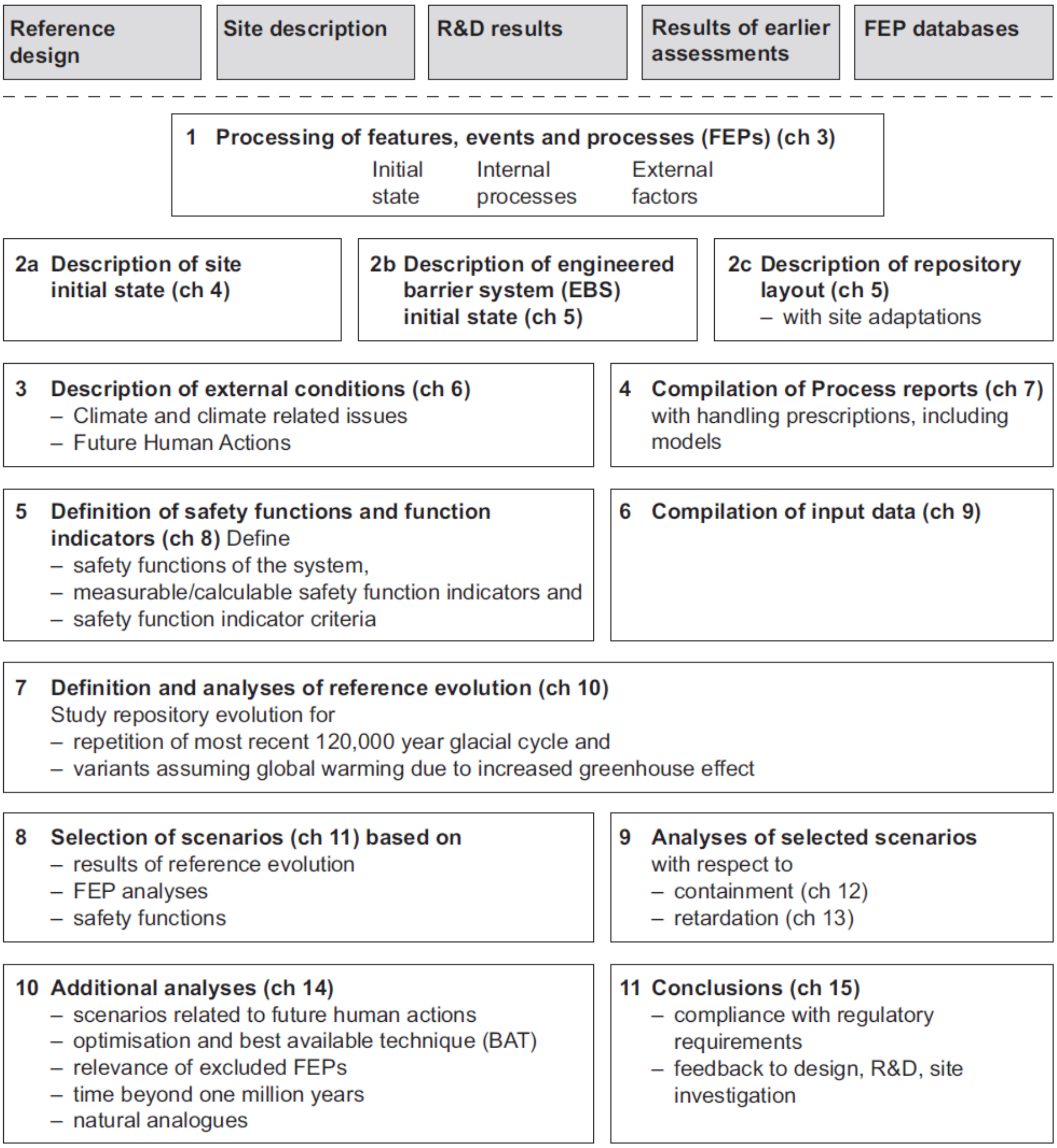


Figure 3.7 Outline of the 11 main steps of the safety assessment SR-Site

Notes: The boxes at the top above the dashed line are inputs to the assessment. The chapters of SKB (2011b) where each step is documented are shown. Source: SKB (2011b)

SR-Can safety assessment

The purposes of the SR-Can safety assessment were to (SKB 2006):

- make a first assessment of the safety of potential KBS-3 repositories at Forsmark and Laxemar
- provide feedback to design development, SKB's R&D programme, further site investigations and future safety assessment projects
- focus the dialogue with the regulators which oversee SKB's activities (that is, SKI and SSI) regarding interpretation of applicable regulations, as a preparation for the SR-Site project

Unlike the interim SR-Can safety assessment, the SR-Can safety assessment therefore aims to qualify the feasibility of disposal facilities at Forsmark and Laxemar. The interim SR-Can safety assessment was reviewed by SKI and SSI, aided by an evaluation by an international review team (see Section 3.3.7). The conclusions from these reviews were considered in the preparation of the SR-Can report.

The SR-Can safety assessment was based on site-specific data acquired during the Initial Site Investigations (version SDM 1.2) as described in the SDMs of the Forsmark (SKB 2005a) and Laxemar (SKB 2006) sites. The relationships between these different work programmes are illustrated in Figure 3.8.

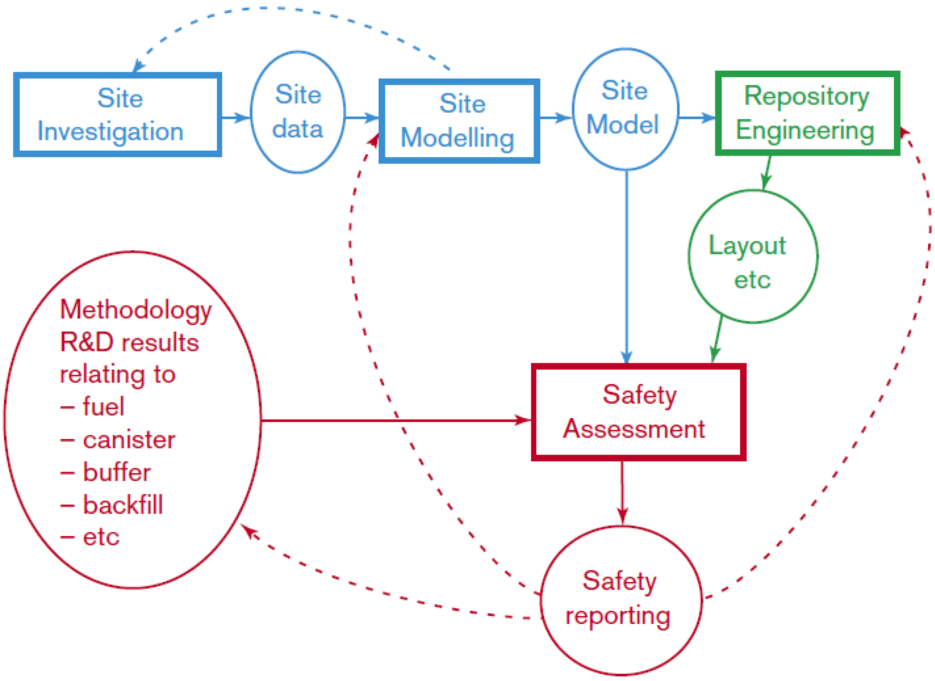


Figure 3.8 Relationship the safety reporting to other projects in SR-Can

Notes: Activities are shown as rectangles and products as ellipses.
As indicated by the dashed lines, the safety report provides feedback to disposal facility engineering (about, for example, layout issues and choice of backfill materials) and to site investigations, via the site model, concerning further site investigation needs. The latter type of feedback is also given by the site modelling group independent of the safety assessment. Feedback is also given from the safety assessment to SKB's RD&D programme.
Source: SKB (2004)

Several of the steps carried out in the SR-Can assessment resulted in specific reports that were of importance for the conclusions and analyses of the main report. There were also a large number of additional references, treating more specific issues. The SR-Can safety assessment was therefore organised as a hierarchy of reports.

Risk as a function of time was presented by weighting together the time-dependent mean annual effective doses from each scenario to obtain a time-dependent risk. The potential for 'risk dilution' was discussed. The term 'risk dilution' is sometimes used to denote a situation where a higher degree of uncertainty in input parameters (that is, a broader input distribution) leads to a lower mean value of an output quantity (for example, mean dose or risk). A lack of knowledge can lead to the assessed dose being spread over more individuals and over longer times than in cases where more precise knowledge is available. Calculations of the radiological risk associated with disposal facility performance were complemented with alternative indicators that did not require detailed assumptions about the biosphere or human habits. This was considered to be consistent with the recommendations accompanying SKI's regulations concerning safety in the final disposal of nuclear waste. These mention that, for distant times, the risk indicator can be complemented with other safety indicators, for example, concentrations in groundwaters or near-surface waters of radionuclides from the disposal facility or the calculated fluxes of radionuclides to the biosphere.

The methodology developed in the SR-Can interim report was only modified slightly, and the same terminology of FEPs and safety functions pursued and elaborated. An illustration of the safety functions, indicators and criteria is given in Figure 3.9.

Figure 3.9 Safety functions, safety function indicators and safety function indicator criteria related to containment

Notes: When quantitative criteria cannot be given, terms like 'high', 'low' and 'limited' are used to indicate favourable values of the safety function indicators.
The colour coding shows how the functions contribute to the canister safety functions Can1 (red), Can2 (green) and Can3 (blue).
Source: SKB (2011b)

The analysis carried out in SR-Can was interpreted to suggest that a KBS-3 disposal facility at Forsmark would comply with the regulatory risk criterion issued by SSI. Uncertainties in the hydrogeological interpretation and understanding of the Forsmark site were thought to be considerable and, when propagated to various parts of the analyses, led to a wide range of conclusions regarding, for example, buffer colloid release and water flow properties. Even the most pessimistic interpretation of the Forsmark site was, however, assessed to comply with the regulatory risk criterion.

The Laxemar SDM version 1.2 was not thought to be sufficiently representative of the potential disposal facility volume to allow definite conclusions regarding compliance. In particular, the hydraulic interpretation of the site was based on data partly obtained outside the candidate volume for the disposal facility. However, it was noted by SKB that, with the data used for Laxemar, the site is assessed to comply with the risk criterion.

The main risk contributors in SR-Can were found to be related to the occurrence of large and/or highly transmissive fractures intersecting deposition holes. This applies to the buffer colloid release process and the impact of earthquakes in the vicinity of the disposal facility. These 2 phenomena might result in canister failures due to canister corrosion and to secondary rock shear movements respectively. The retention in a large, highly transmissive fracture is small, so such failures were thought to be associated with high consequences. The likelihood of occurrence of such fractures and the probability of unsuitable deposition holes remaining unidentified were judged to be uncertain and the results of the analysis were sensitive to these uncertainties. The most severe impact on the disposal facility was anticipated to occur during future glacial conditions.

A number of stylised, bounding cases illustrating complete loss of important safety functions were analysed, including the following cases:

- an initial, large opening in the copper shell for all canisters
- an initial absence of enough buffer which leads to advective conditions in the deposition hole for all deposition holes
- a combination of the above cases, that is, an initial large opening in all canisters and advective conditions due to loss of buffer for all deposition holes

The results were reported to indicate that the calculated doses were below the natural background radiation for these severe losses of safety functions. For example, an initial total loss of the canister and buffer performance in all deposition holes yields, for the Forsmark site, doses that are comparable to those caused by the background radiation.

The SR-Can report concluded with implications of the safety assessment for site investigations and site modelling. Examples of aspects identified by SKB as requiring further study are given below.

- The existence and location of deformation zones larger than 3km should be clarified
- Development of the hydrogeological DFN models: fractures with high flow rates intersecting deposition holes might cause substantial buffer erosion. More data were thought to be needed from the potential disposal facility volumes as well as efforts in exploring the consistency between outcrop and drill core mapping. Furthermore, the DFN modelling (of all fractures)

was thought to need better co-ordination with the related hydrogeological DFN modelling of hydraulically significant fractures

- Rock mechanics: high in situ stress of the intact rock may result in spalling of deposition holes, both during construction and later, after deposition, due to the added thermal load. Considering the high and uncertain stress levels observed at Forsmark, further reduction of the uncertainties in stress and rock mechanics properties was thought to be needed.
- Additional hydrogeochemical data and data relating to surface ecosystems were thought to be required at both sites.

Implications for R&D and safety assessment methodology were also elaborated.

SR-Site safety assessment

The purpose of the safety assessment SR-Site was to demonstrate to the regulators that a spent nuclear fuel disposal facility of the KBS-3 type could be built at Forsmark and meet requirements relating to long-term safety. It formed part of the licence application to begin construction of the disposal facility.

The Forsmark site was selected instead of Laxemar based on the results of the site investigations, as described in Section 3.3.5. The site selection was not justified in the SR-Site assessment, but in other documents supporting SKB's licence application (SKB 2011a).

The detailed analyses were performed based on the methodology developed in the SR-Can project. SKB concluded that the disposal facility met the regulatory requirements, based on the following important assessments.

- The likelihood of canister failures during the initial 1,000 years was assessed as negligible.
- Advective conditions in a deposition hole will enhance the canister corrosion rate. In a one million year time perspective, this may lead to failures of canisters when applying the more pessimistic of the hydraulic interpretations made of the Forsmark site, with cautious assumptions regarding concentrations of corrosive agents and deposition hole acceptance rules.
- Freezing of the buffer was ruled out – even for pessimistically chosen climate conditions.
- Canister failure due to isostatic load was ruled out – even for pessimistically chosen climate conditions.
- Oxygen penetration was considered very unlikely – even for very pessimistically chosen climate conditions – and the consequences thought to be small.
- Disposal facility safety for a prolonged period of warm climate before the next glacial period was assessed as comparable with safety for a climate unperturbed by enhanced global warming.
- The heat from the canister was thought likely to fracture the rock in the deposition hole wall, which would enhance the inward and outward transport of dissolved substances. However, this was assessed as having little impact on risk.

- The importance of the engineering disturbed zone in the rock around the deposition tunnels as a transport path for radionuclides was assessed to be limited.

It was also thought to be crucial to avoid deposition positions intersected by large or highly water conductive fractures and the low frequency of water conducting fractures allows efficient application of such rejection criteria.

The scenario of buffer colloid release became an important consideration for the long term of a KBS-3 disposal facility during the SR-Can assessment. This was a significant change in the role of the geological environment from one of providing isolation and radionuclide transport retention to one of providing conditions under which the integrity of engineered barrier system (EBS) is maintained for a long period of time. Previously, radionuclide transport calculations were made for hypothetical canister failure scenarios, whereas in SR-Site, the evolution of EBS performance is calculated. The new emphasis on EBS integrity in the safety case is because it is harder to evaluate this aspect of disposal facility performance given the new knowledge of, for example, buffer colloid release. In addition, mechanical EBS failures are much more carefully analysed in SR-Site; this was not done in the early assessments of KBS-3 simply because the advanced procedure to do this was not available. This changed the emphasis of the safety case. It made it less straightforward to be able to make a safety case using the KBS-3 concept at virtually any site in the Fennoscandian shield and hence site selection became more important.

3.3.7 Critical review and its influence

According to the government decisions of 1996 and 2001, SKB was to consult with the regulators on the site investigation programme before and during the site investigations (SKI 2002). SKI and SSI (later SSM) had a regulatory role throughout the investigations due to their obligation to review SKB’s RD&D programme every 3 years. In addition, they also reviewed the Interim SR-Can and SR-Can safety assessments. The regulator also commissioned independent peer reviews of the interim SR-Can assessment. The regulatory review of the licence application, including the SR-Site assessment of long-term safety is currently being undertaken.

The regulator was not required in law to issue permits to begin site investigations. It is the responsibility of SKB to make suitable plans for site investigations. Therefore, the regulator did not consider it appropriate to set detailed requirements for the site investigation strategy. It is through the regulator’s obligation to review the RD&D programme that it has a supervisory role on the site investigations. During the site investigations, SKI and SSI used expert groups (INSITE and OVERSITE) to track SKB’s activities. INSITE was the main review group involved with the investigations, although they had no formal role. However, the groups expressed opinions and maintained an issue tracking system of technical questions on which SKB was required to provide answers. SSM’s main objectives in following the site investigations was to ensure it had the information and knowledge necessary for the licence application, as well as avoiding the need to review the safety case and site investigations in a single step.

The regulators’ reviews of the RD&D plans considered all aspects of work relating to disposal of spent fuel. That is, they were not focused on the site investigations specifically. As noted previously, the RD&D programme provides a forum for engagement with the scientific community as it is sent to a number of organisations, including universities, which can also comment if they wish.

The emphasis in the following sections is on the regulatory response to plans relating to geoscientific characterisation, modelling and safety assessment methodology.

Review of SKB’s planning for Initial Site Investigations

In preparation for the Initial Site Investigations, SKI commissioned reports considering various aspects of SKB’s plans. These included reviews of their geochemical (Bath 2002) and biosphere characterisation plans (Klos 2002).

An initial assessment of SKB’s geochemistry programme was thought important as it was considered that site investigation activities might disturb the conditions. The best opportunity of receiving an accurate picture, of for example the distribution of various groundwater types, would therefore be at the start of the site investigations. It was thought that the value as evidence of geochemical information during the subsequent stages of interpreting data and assessing the long-term safety would be enhanced if potentially controversial issues had been resolved at an early stage (Bath 2002).

In terms of planning and EIA, SKI reviewed experiences from other countries and from other large development projects, with a focus on public involvement. Issues for consideration in the design of the EIA and decision-making processes for siting the disposal facility were highlighted (Bjarnadottir and Hilding-Rydevik 2001).

With regard to planning the site investigations (SKI 2002), SKI noted that the reporting in SKB’s RD&D Programme 2001 was out-of-date when submitted to review and had been replaced by more detailed activity plans which were being discussed in the ongoing consultation between SKI, SSI and SKB.

- SKI considered that characterisation of geochemical conditions should be allocated a very high priority in the initial phase of undisturbed conditions.
- SKI expressed the importance of traceability and QA concerning data management in the field and in SKB’s databases.
- SKI considered that SKB should describe clearly how it intended to measure properties relevant to radionuclide transport. SKI also considered that SKB should study the matrix diffusion process further and conduct sorption studies on site-specific material so as to be able to better determine the site-specific importance of the sorption process.
- SKI identified issues of erosion, the potential for new fracturing in response to a glacial cycle and the influence of recharge and discharge areas on siting as areas for further study.

With regards to safety assessment methodology, SKI noted deficiencies in how results from geochemical models, experiments and field measurements are integrated into the safety assessment work. In SKI’s view, the most important geochemical issue with respect to the long-term safety was the stability of the groundwater chemistry over a glacial cycle, particularly the salinity of the groundwater. SKI therefore asked SKB to report calculations of how the salinity may change for scenarios that involve extensive climate changes over long time periods. This issue was addressed by SKB in the SR-Site assessment (SKB 2011b).

Review of interim SR-Can

The purpose of the interim SR-Can report (SKB 2004) was to set out and demonstrate the methodology for safety assessment. This, in turn, was intended to enable review by the regulators before the methodology was used in support of future licence applications.

The NEA IRT's review (Sagar et al. 2005) focused on methodological aspects and sought to determine whether the following questions about SKB's proposed safety assessment methodology.

- Was it fit for the purpose of supporting a licence application?
- Did it have a reasonable prospect of leading to a safety assessment, that is, was it sufficiently comprehensive, reproducible, traceable and transparent?
- Was it compatible with the regulators' regulations and guidance?

No evaluation of long-term safety or site acceptability was attempted by the NEA IRT.

The NEA IRT reported the main deficiencies as being the development of scenarios and the management and treatment of uncertainty, where current evidence was reported to suggest a need for greater clarity and traceability. It was recommended that SKB should ensure that all aspects of the safety assessment are conducted in accordance with auditable project-specific guidance and QA procedures.

The NEA IRT made a number of specific recommendations, including that SKB performs additional sensitivity analyses that examine sub-system performance measures, for example, by reference to function indicators, in addition to dose and risk. It also considered that SKB needed to set out more clearly its strategy for conducting and using the results of sensitivity analysis. It advised SKB to consider using a range of sensitivity analysis methods to complement its current use of regression analysis.

The NEA IRT review provided input to the regulators' review (Dverstorp et al. 2005). The regulators agreed that there were discrepancies in the QA of the interim report and that this has in some respects made it more difficult to assess SKB's methods of safety assessment. The regulators recommended that SKB produced a quality plan prior to the completion of SR-Can.

SKI and SSI considered that SKB had made substantial progress in several areas since the last safety assessment, SR-97 (Dverstorp et al. 2005). Improvements included SKB's method of systematically identifying and describing all the processes and features that need to be taken into account in the safety assessment.

However, the regulators considered that there were deficiencies in SKB's method for the identification and choice of scenarios. In particular, a description of how variants and calculation cases should be identified and integrated in the risk analysis was criticised. The regulators did not think that SKB's preliminary choice of scenarios generated a comprehensive set of variants and calculation cases for the complete risk analysis and requested a more systematic and traceable way of assessing the significance of all the adverse processes and features that were identified.

The regulators considered that it was not clear how SKB would apply the regulatory requirements on optimisation and use of the best available technology, and what role the safety assessment has in demonstrating this. It was thought important with regard the final licence applications that SKB could show that these principles had been taken into consideration during the development work with the disposal facility (Dverstorp et al. 2005).

Review of SR-Can by external experts

The Swedish regulators engaged external experts with the aim of providing a range of opinions related to the sufficiency and appropriateness of various aspects of SR-Can. Three parallel reviews by international teams were conducted to support the regulatory review by SKI and SSI, covering safety assessment methodology, the representation of the EBS in the safety assessment and the handling of information from the site investigations (SKI and SSI 2008).

The review of aspects of the site investigations was asked to consider:

- whether site-specific information was accurately represented and fully utilised
- whether there was sufficient understanding of site features and processes for purposes such as risk calculation and assessment of long-term site evolution
- whether the site-specific information used in SR-Can was likely to be sufficient for SR-Site

The reviewers were asked to pay particular attention to:

- quality and quantity of site data with respect to their use in safety assessment
- data gaps with respect to the data requirements of models
- how data were abstracted for use in safety assessment modelling
- the handling of uncertainty
- consistency in parameter choice and use across the various parts of the safety assessment
- understanding of site evolution and how it is described, as a basis for the safety assessment
- scenarios for future site evolution
- feedback from the safety assessment to continued site investigations

The review team organised its findings thematically as outlined below.

Appropriate depth for the disposal facility

SKB describes the effects of disposal facility depth on long-term safety with respect to:

- salinity and upconing
- length of transport resistance
- fracture frequency and fracture transmissivity
- groundwater pressure
- rock stress and related risk of spalling
- initial temperature
- freezing
- human intrusion

The review team thought that SKB would need to provide a clear explanation of the depth choice it eventually made that balanced all the safety-related and design factors carefully.

Spalling and the EDZ

The review team considered there were several issues that SKB should address before SR-Site. The first issue was the choice of modelling strategy to determine the shape and depth of drilling- and thermally-induced spalling in the deposition holes. Other issues related to the methods SKB considered for the mitigation of spalling from drilling and thermal loading, and what the effects of spalling on safety would be.

Transforming site data into performance assessment input data

Two important aspects of site data transfer to the safety assessment arose from the review. These concern the groundwater flow models and the biosphere models.

The concerns about the groundwater flow modelling related to issues that had a significant influence on performance measures such as travel time from each canister position, initial Darcy velocity, path length and flow related transport resistance, which represents transport retardation. These performance measures had direct implications on safety assessment and geosphere safety functions.

It was considered that alternative calculation models such as Continuous Porous Medium (CPM), Equivalent Continuous Porous Medium (ECPM) and DFN models would need to be justified for their applicability to the site under study. Various ‘smoothing effects’ were identified in the CPM and ECPM representations, which it was thought could artificially reduce the channelling phenomenon at the regional as well as the disposal facility scale. It was judged that they should be evaluated in future work.

Regarding the biosphere modelling, the review group found it difficult to understand the relationships between site data and assessment data, and queried some assumptions made in deriving assessment data.

In terms of the site-specific sampling and measurement programmes to support the SDMs, it was thought that there was a relatively sparse distribution of stream measuring points and it was unclear to the review team if this was enough to provide a good understanding of the stream flow velocities. Similarly, the spatial distribution of observation points used for estimating the thickness of Quaternary deposits and water chemical parameters was judged to be limited and the hydrological time series short.

The review team found it surprising that neither SR-Can nor the supporting reports describing the site investigations include any statistical evaluation of data adequacy.

Uncertainties in site features and groundwater flow

Examples where uncertainties might not have been evaluated to the reviewers’ satisfaction included:

- uncertainties related to transmissivity–size correlation in the DFN model
- potential effects of spatial heterogeneity fracture intensity
- potential impact of undetected deformation zones on flow and transport
- characteristics of observed deformation zones, as well as connectivity between deformation zones
- fracture size distribution and correlations among fracture properties

Criteria for selecting canister deposition locations

It was noted that SKB was uncertain about how its development of acceptance criteria for hydraulic properties around deposition holes would be implemented. Therefore, it was considered that there was a potentially large uncertainty about the hydraulic properties of deformation zones and connected micro-fractures that may intersect the deposition holes.

Effects of glaciation

It was noted that there is limited evidence from analogue processes to provide a strong scientific basis for an assessment of possible glacial impacts. Therefore it was thought that a robust justification for the assumptions and models for dealing with this issue would be required in SR-Site. It was suggested that the potential for taliks to concentrate discharge from the deep system during permafrost conditions should be considered.

Development of biosphere assessment models

It was thought that there was neither detailed discussion nor justification of the assessment models used. The review group had the impression that important parts of the assessment database included generic parameters of the transport and accumulation models, rather than measurable properties reflecting processes being accounted for in the FEP analysis combined with derivation of parameter values from site data.

The review group raised concerns about the landscape dose factor approach used in risk assessment. In particular it was concerned that the method assumes a release from all canister positions simultaneously, distributed over several landscape objects, which could lead to dilution of risk for the most exposed group.

Review of SR-Can by Swedish regulators

The regulators conducted their own joint review of SR-Can (Dverstorp et al. 2008), which included the input from expert review groups. The regulators also carried out independent calculations to check important results in SR-Can with the assistance of external consultants.

An important objective of the review was to provide guidance to SKB about the regulators' expectations of the safety report that SKB was to produce for the licence application. Important review areas included:

- SKB's compliance with the regulators' regulations
- SKB's methods for safety assessment
- SKB's follow-up of review comments from previous reviews of its preliminary safety analyses
- further investigation needed into critical research and technology-related issues before the licence application

Main findings

The main findings of the review were that:

- SKB's overall safety assessment methodology was in accordance with applicable regulations, but that parts of the methodology needed to be further developed for the licence application
- SKB's quality assurance of SR-Can was not sufficient for a licence application

- the knowledge base needed to be strengthened for a few critical processes, such as buffer erosion, which have a potentially large impact on the calculated risks
- the link between the assumed initial properties of disposal facility components and the quality routines of manufacturing, testing and operation needed to be strengthened before the licence application
- a more detailed description of the potential for early releases from the disposal facility was required

More specific issues relating to the characterisation of the geosphere and biosphere included the following.

- It was thought that SKB should show that there is a high level of confidence in the existence and extent of the deformation zones. According to SKB, undetected deformation zones may exist. The regulators considered that SKB needed to deal with and discuss the significance of this conclusion prior to SR-Site.
- The regulators considered that the reliability of the stress levels at Forsmark was limited due to few initially successful measurements.
- The regulators took a positive view of the considerable efforts made in SR-Can to integrate hydrogeology with structural geology and geochemistry.
- Concerns were raised over the modelling of the salt content of the groundwater. In the case of Forsmark, it was stated that the modelled salt contents at a depth of less than 200 metres were lower than those measured.
- Regarding the DFN models, the regulators considered that SKB should discuss in more detail uncertainties linked to the choice of relation between the size of the fractures and their transmissivity. The regulators commissioned a consultant to carry out independent fracture network modelling of flow and flow paths on a regional scale based on site-specific data.
- The regulators noted that generic sorption data had been used in SR-Can to a great extent. The regulators considered that SKB should have a clearer method for the parallel use of site-specific and generic sorption parameter data. It was thought that the choice of sorption parameters should be linked to results from studies of the rock matrix and the mineralogy of the fracture fillings.
- The regulators asked SKB to report on the importance of geochemical boundary layers in soil and Quaternary deposits for accumulation of radionuclides.

Review of planning and execution of the Complete Site Investigations

The Initial Site Investigations were completed in 2004, with RD&D 2004 submitted at the start of the Complete Site Investigations phase. However, SKI considered that RD&D 2004 lacked clear links to specific issues that were of particular importance for the evaluation of the different sites, such as the occurrence of high rock stresses and saline groundwater (SKI 2005).

SKI considered that RD&D Programme 2004 did not provide an adequate description of the research being conducted on the biosphere. Clear links between site investigations and model development and a complete description of the models that were to be used in the safety assessment were absent (SKI 2005). SKI and SSM thought that SKB should also take into account the possibility of using radionuclide concentrations and flows as complementary safety indicators.

In SKI's opinion, the set of experiments that SKB planned to conduct at the Äspö HRL would provide valuable information on individual processes under in situ conditions. Furthermore, it was thought that these experiments would provide a good opportunity for evaluating the integrated function of the disposal facility in the initial phase and for testing the coupled models that SKB had developed (SKI 2005).

The completion of site investigations and site selection was not a formal decision point for the regulator. Instead as part of the licence application, SSM has to review whether SKB has made due consideration of possibilities to increase the long-term integrity of the disposal system.

The Complete Site Investigations were largely concluded by 2007, so the regulators review of RD&D 2007 focused on data interpretation and identification of outstanding issues (SKI 2008b).

- At Forsmark, SKI noted that the possibility of high rock stresses could not be eliminated. It therefore considered that SKB should plan measures for implementation of the programme as if the rock stresses are higher than currently assumed.
- At Laxemar, SKI considered that a potential problem in understanding the characteristics of the rock was its heterogeneous geology and limited information about the high-priority area to the south and the south-west.
- To permit the evaluation of the various stages in the siting process that had led to SKB's final choice of site, it was thought that SKB must be able to:
  - show that it had investigated and taken into account all the relevant factors for the long-term operation of the disposal facility
  - report the balances struck when comparing different siting factors and other measures to improve the disposal facility's protective capability.
- SKI considered that there had been some deficiencies in the data supplied by SKB to its contractors, for example data had been adjusted by SKB as a result of certain defects in oriented data (fracture data from boreholes), resulting in delays. Examples of other QA deficiencies in SKB's data processing were identified.
- SKI noted that SKB had made considerable progress in the development of modelling strategies for rock thermal characteristics. This methodology might also be used in other disciplines such as rock stresses and matrix diffusion. SKI also noted that SKB has made considerable progress in the integration of various geological and geoscientific disciplines.
- SKI noted that SKB did not discuss plans for detailed investigations during the construction of the disposal facility in RD&D Programme 2007 and this was regarded as a deficiency. SKI had also previously highlighted the need to prepare a programme for detailed investigations well before the application. This was because SKI wanted an adequate basis for assessment of what data collection was feasible during the design stage from the long-term safety perspective.

INSITE review at the conclusion of Complete Site Investigations

With the conclusion of the surface-based investigations, the INSITE group summarised its work over the period of the site investigations (Chapman et al. 2010). This report constitutes part of the record that will support the regulatory review of SKB's licence application. The report describes INSITE's methods and summarises its views on site understanding at both Forsmark and Laxemar. It also outlines the recommendations regarding future site characterisation work that will be needed if SKB begins to move underground at the Forsmark site. INSITE comments on SKB's rationale for the selection of the site and assessment of how site information and understanding were used to justify the initial design decisions for the Forsmark disposal facility.

INSITE identified 7 major topics, described below, that arose during the investigations, as well as site-specific issues. The major topics concerned the interpretation of groundwater flow and solute transport in fractured rocks. Some of these issues were resolved to INSITE's satisfaction during the site investigations.

- **Alternative Conceptual Models (ACMs) in the management of uncertainties.** ACMs were defined by INSITE as alternative SDMs that are consistent with all or most of the available data, and where there is no basis to prefer one to another. INSITE made a distinction between ACMs and model refinements or model variants. Model refinements were considered improvements on a model when new information or new insights are obtained. Model variants were obtained by varying the properties of some of the parameters or making minor adjustment on portions of the geometry. INSITE thought that ACMs should be considered during site investigations, and should not be left to be represented later as a variant or as part of the overall uncertainty in performance assessment, because an ACM demands particular data gathering and interpretation, as well as providing feedback to the site investigations.
- **Fracture network modelling.** INSITE considered the most important single aspect of the site investigations was to build an understanding of the nature of the network of fractures that characterise the rock. The fractures were identified as the dominant control on groundwater movement, the mechanical response of the rock to stress and the engineering behaviour of eventual disposal facility openings. SKB applied an approach to classifying and dividing up fractured rock domains that consisted of deterministic mapping of major fractures and stochastic representation of the small fractures that dominate the bulk of the rock mass. The statistical approaches that had been applied to model the stochastic fractures were discussed in depth at a number of expert meetings. However INSITE was left with the view that SR-Site would need to address the non-uniqueness of the DFN models by incorporating ACMs. INSITE observed that such a central matter, recognised as highly important by all parties from the outset, could not be fully resolved in the surface-based investigations. This was considered to be a feature of the limitations of investigation techniques in this type of geological environment, which would only be ameliorated by the opportunities provided for much more extensive observations as excavations proceed.
- **Use of large-scale flow and transport tests.** The issue of upscaling measurements concerning flow and transport properties was raised by INSITE in 2004, with the aim that information more representative of a large volume of rock could be obtained from the investigations. SKB developed DFN and larger-scale hydrogeological network models based on extrapolations from statistical analyses of borehole and outcrop data.

INSITE felt that large-scale tests would be the only way to obtain information on the flow properties and the influence on the larger-scale flow field of major deformation/fracture zones. The ‘large-scale confirmatory test’ programme that SKB embarked upon eventually prolonged field activities at both sites and merged into the long-term monitoring programme.

- **Palaeohydrogeology.** INSITE and SKB agreed that an understanding of the past evolution of the groundwater system would be an important means of underpinning the forecasts of future groundwater flow behaviour. Subsets of geochemical and isotopic data for groundwaters and minerals were integrated to develop interpretations of how the groundwater systems have evolved over time, that is, palaeohydrogeology. These interpretations include descriptive or semi-quantitative estimations of groundwater ages and solute residence times, and the use of parameters as natural tracers to calibrate or test quantitative palaeohydrogeological models for the regions and the sites. At the end of the site investigations, INSITE observed that, for both sites, variations of hydrochemistry were evident in the target volumes (for example, increasing salinity at Forsmark and more general variations with apparent uncertainty about water sources and ages at Laxemar) and that, in reviewing SR-Site, SSM would need to assess SKB’s arguments that any possible present and future variability of geochemical parameters affecting near- and far-field conditions had been reasonably constrained in terms of their potential impacts.

- **Regional groundwater flow.** The issue of regional groundwater flow, and in particular, whether areas of recharge offered advantages in siting was considered in a series of reports produced during the site investigations. As a result of these studies, INSITE concluded that super-regional flow, in this geological environment, is a modelling concept that could not be confirmed by observational evidence and was thus untestable. Consequently, endeavouring to make it a high-level consideration in the complex process of identifying a suitable disposal facility site was considered inappropriate.

- **Ore potential at Forsmark.** The Forsmark area is located within an ore province, Bergslagen. INSITE addressed this issue and agreed with SKB that the granitoids in the central part of the Forsmark lens have no minerals of economic interest. Nevertheless, the site is located in an ore province and ore-bearing lithologies occur just outside the granitoids, where mineralisation has been mined on a small scale. In this environment INSITE thought that a disposal facility for spent nuclear fuel will form a geophysical anomaly (in terms of its magnetic and gravimetric properties) that may draw the attention of future prospectors. As a part of SR-Site, they recommended that SKB should consider modelling the geophysical character of a disposal facility to evaluate whether such an occurrence is feasible, or whether a disposal facility would have geophysical characteristics that will indicate to future prospectors that the disposal facility anomaly is not an ordinary mineralisation.

- **Measurement of high rock stresses.** The possibility that anomalously high horizontal stresses might be encountered at depth at the Forsmark site had been known at the time the site was selected for investigation. High and anisotropic horizontal stresses were thought to be important as they could cause spalling of deposition holes and tunnels (affecting both operational approaches and, potentially, the safety case) and force specific disposal facility layout orientations on the designer. INSITE considered the situation unresolved at the end of the site investigations.

INSITE also evaluated its experience in planning review activities in relation to other major stages of the radioactive waste management programme in Sweden. The group hoped that this experience might be useful to other national programmes.

INSITE considered it invaluable to ‘grow into’ the data and go along the same learning curve as SKB. It meant they had a better position to recognise the strengths and weaknesses of the SDMs. INSITE stressed that this did not mean it always shared SKB’s conclusions.

INSITE developed written documentation to resolve issues when interacting with SKB. This led to the development of the Tracking Issues List (TIL). This became the single means of eliciting written responses from SKB to allow INSITE to establish its position or view properly. INSITE state that, for some issues, this process worked well and there was a constructive interchange that allowed issues to be concluded. Elsewhere, INSITE stated that SKB was less forthcoming and it had withheld comment, in some cases, for many iterations of the TIL. In the middle period of the investigations, ‘no comment’ returns apparently became so prevalent that SKI asked SKB to address the TIL more rigorously. INSITE noted that in retrospect, it would have been useful for SKI to formally request full responses from SKB to the TIL as a matter of course.

INSITE used Field Technical Reviews (FTR) to provide SKI with a view on the scientific and technical quality of the site investigations and whether it was achieving necessary goals. In the course of the work, the expert reviews turned up practical issues, problems and questions that needed to be considered by SKB. In this sense they proved to be as useful to SKB as to SKI. A requirement was initiated by SKI for a formal response to FTRs from SKB. INSITE members who participated in FTRs stated they were one of the most successful means of gaining an understand of field investigation issues.

INSITE also interacted with the OVERSITE and BRITE groups; BRITE was established to look at engineered barrier behaviour. INSITE observed that it would have been more technically effective and more efficient to have had a single group looking at all the site investigation work.

Interaction with SKB was based around regular one-day meetings. Normally these would focus on one of the sites, with shorter updates on the other(s). INSITE found the expert group meetings involving SKB, SKI, INSITE and SKB’s contractors to be valuable in building its understanding and to defuse some difficult issues and misunderstandings.

At the end of 2008, apart from attending some outstanding expert group meetings, it was considered no longer appropriate to hold information exchange meetings with SKB about topics for which SKB was finalising its licensing position.

Review of SR-Site

SSM’s plans for the review of the licence application for a spent nuclear fuel disposal facility system at Forsmark are outlined in Dverstorp (2009). This envisages 30 SSM staff carrying out the review, using an expert review team, and with an annual budget of €1.5–2.0 million. The review is expected to take more than 2 years. In preparation for the review of the licence application, SSM has collated issues from the INSITE group, reviews of SR-Can and reviews of RD&D plans.

As part of the review of the licence application, SSM may stipulate requirements for the underground investigations, or may do so as part of its oversight of the RD&D programme.

SSM is expecting to analyse specific issues on request from the review team, including reproducing SKB's calculations and modelling with alternative models. Some of this work, such as dose calculations, is expected to be done by SSM staff. SSM has put in place a public procurement process to appoint external consultants. There are strict rules on impartiality and conflicts of interest. The procurement process has delayed the review of the licence application, but it is a legal requirement.

The NEA has been asked by the Swedish government to organise an international review team to undertake a peer review of SKB's reporting of post-closure safety in the licence application for the spent nuclear fuel disposal facility. The NEA's peer review is expected to support the independent review by the SSM and other Swedish decision makers (the concerned municipalities and eventually the government) by providing an international reference regarding the maturity of SKB's spent fuel disposal programme compared with the best practice in the area of long-term nuclear safety and radiation protection. However, the NEA's peer review is not a formal part of the Swedish licensing or decision-making process.

The terms of reference for the NEA's peer review were set by SSM (Dverstorp 2011). They relate to the presentation of safety arguments, safety assessment methods, completeness, handling of remaining issues, site selection, and disposal method and feasibility.

SSM acknowledges that all issues in SKB's safety case might not be resolved at this licensing step (Dverstorp 2011). Therefore it was foreseen that licensing conditions will play an important role in formalising requests for resolution of remaining issues, should SKB receive a licence to proceed.

SSM has organised workshops as part of its review process (SSM 2011). The objective is to:

- learn from other programmes' experiences of the planning and review of a licence application for a nuclear waste disposal facility
- document recommendations and ideas for SSM's further planning of the licensing review

The municipalities organised study groups and invited SSM to be involved. They were keen to have SSM involved as a counterpart to SKB. The municipalities receive central funding to organise such initiatives, as do non-government organisations (NGOs).

In addition to external reviews, SKB selected an external review group (SIERG) to perform a review of the main technical reports. This provided a group with which to scrutinise the standard of work prior to publication.

3.3.8 Summary

What was the regulator's role during surface-based characterisation?

Throughout the surface-based site characterisation work, SKB was regulated under the Act on Nuclear Activities through the review of its proposed work programmes. The work programmes were published by SKB as RD&D reports every 3 years. The regulators would recommend to government whether or not they considered SKB had fulfilled its obligations under the Act on Nuclear Activities.

The regulators collated the views of other stakeholders, such as representatives of the municipalities, NGOs and universities. Their views, along with those of the regulator, were published in the regulators response to SKB's RD&D reports.

In addition to reviewing the RD&D reports, the regulators reviewed preliminary safety assessments (interim SR-Can and SR-Can) with the intention of providing guidance to SKB about the their expectations for the final safety report which SKB was to produce for the licence application.

The regulator is currently reviewing the licence application (submitted in 2011) to construct a disposal facility at Forsmark.

What criteria did the regulator use to allow development of a radioactive waste disposal facility to proceed to subsequent stages?

The regulators' reviews were informed in their decisions by:

- calculations performed in-house to reproduce those of SKB, for example dose calculations
- commissioning work on specific issues
- reviews of the interim safety assessments by independent expert groups commissioned by the regulator
- input from groups of experts who were asked to follow different aspects of SKB's work during site characterisation – these included the INSITE, OVERSITE and BRITE groups, with remits relating to site investigations, near-surface and biosphere characterisation and the EBSs respectively.

What decisions were made by the developer, the regulator and any other body (for example, government) based wholly or partly on information from surface-based site investigation?

Two sites, at Laxemar and Forsmark, were investigated with surface-based intrusive methods. The investigations were divided into 2 phases: an Initial Site Investigation phase and a Complete Site Investigation phase. The decision to proceed to the Complete Site Investigation phase was supported by the regulator based on comparisons between the data obtained during the Initial Site Investigation phase with criteria, developed by SKB, which where thought necessary to demonstrate the long-term safety of a disposal facility.

The conclusion of the surface-based intrusive investigations has led to licence applications being submitted to construct and operate a disposal facility at Forsmark. These applications supported by information obtained from the Äspö URL. Forsmark was selected, by the developer, in preference to Laxemar based on considerations of long-term safety.

The licence applications will be assessed by the regulator and a recommendation made to government. The licence applications will also be considered by the Environmental Court. The municipality has a veto right. If the government grants SKB the licences, SSM will stipulate conditions under the Acts on Nuclear Activities and Radiation Protection.

How were data from desk-based studies and non-intrusive studies used to determine the purpose and location of the initial boreholes? How were the data from the evolving characterisation programme then used to determine the purpose and location of further sets of boreholes?

During the site investigations, SKB placed considerable emphasis on identifying and characterising large (>1km length) fault zones, as these were thought to be detrimental to long-term safety. These fault zones were thought to potentially provide fast pathways for radionuclide release, were associated with potential shear movements during any future earthquakes, and were associated with volumes where the chemical composition of the groundwater might change most significantly during glacial cycles. The presence of fault zones was inferred by geophysical surveys. These surveys were used to guide the siting of boreholes to confirm the existence of the fault zones and assess their hydrogeological significance.

The Complete Site Investigations were planned iteratively, with distinct campaigns of investigation aimed at resolving issues identified from interpretation of data from earlier campaigns. An example of the investigation programme evolving is the decision to move the area under investigation away from Simpevarp peninsula to Laxemar, when it became clear that the network of fractures and fault zones was such that there might not be sufficient space to host the disposal facility on the Simpevarp peninsula. An example of the influence of the regulator was the instigation of a programme of large-scale hydraulic interference tests.

3.4 USA (Waste Isolation Pilot Plant)

3.4.1 Introduction and overview

The Waste Isolation Pilot Plant (WIPP) is a GDF licensed for transuranic waste. Transuranic waste contains alpha emitting transuranic elements, often with long half-lives. This waste type corresponds approximately to long-lived ILW defined in other countries. WIPP's capacity is around 176,000m^3 of transuranic waste derived from the USA's defence programmes. The WIPP facility is sited at approximately 655 metres depth in an evaporite host formation, located near Carlsbad, New Mexico. The WIPP facility became operational in 1999.[7]

Two main types of waste are distinguished for disposal at the WIPP facility – contact handleable and remote handleable – classified according to dose rate at the package surface. The waste may be packaged in a variety of containers including steel drums of several sizes and steel box-sized containers. Smaller waste containers may be over-packed in a larger waste container.

Contact handleable waste packages are stacked in rooms excavated within the bedded salt. Remote handleable waste is emplaced in horizontal holes drilled into the walls of the rooms. Magnesium oxide backfill is placed on top of the stacked contact handleable waste packages. This is intended to buffer the chemical composition of any water (in

[7] On 14 February 2014, an incident in a disposal panel of the WIPP resulted in the release of radioactive material into the environment and contaminated 21 people with low-level radioactivity. The US Department of Energy (DOE) ceased operations at the facility following this event. A review team established by DOE concluded in March 2015 that one drum was the source of radioactive contamination released during the 14 February 2014 event. The review team further concluded that the contents of drum were chemically incompatible and that the drum breached as a result of internal chemical reactions.

the form of brine) entering the facility following closure, leading to reduced actinide solubility.

The host rock for the WIPP facility is the Salado salt formation which is located in the Delaware Basin, New Mexico (see Figure 3.10). The salt beds were deposited during evaporation of an ancient ocean, approximately 250 million years ago. The Salado Formation consists mainly of halite with inter-bedded lenses of anhydrite and clays. These lenses, since they are nearly horizontal at repository depth, are used as 'marker beds'. The Saledo Formation is about 700 metres thick, beginning ~250 metres below the surface.

The Salado Formation is overlain by the Rustler Formation (see Figure 3.11). The Rustler Formation is of particular importance for the WIPP facility because it contains the most transmissive units above the disposal facility. In general, fluid flow in the Rustler is characterised as exhibiting very slow vertical leakage through confining layers and faster lateral flow in conductive units. Of the 5 members of the Rustler Formation at the WIPP facility, the Culebra and the Magenta are considered conductive units and the Los Medaños, the Tamarisk and the Forty-niner are considered confining units.

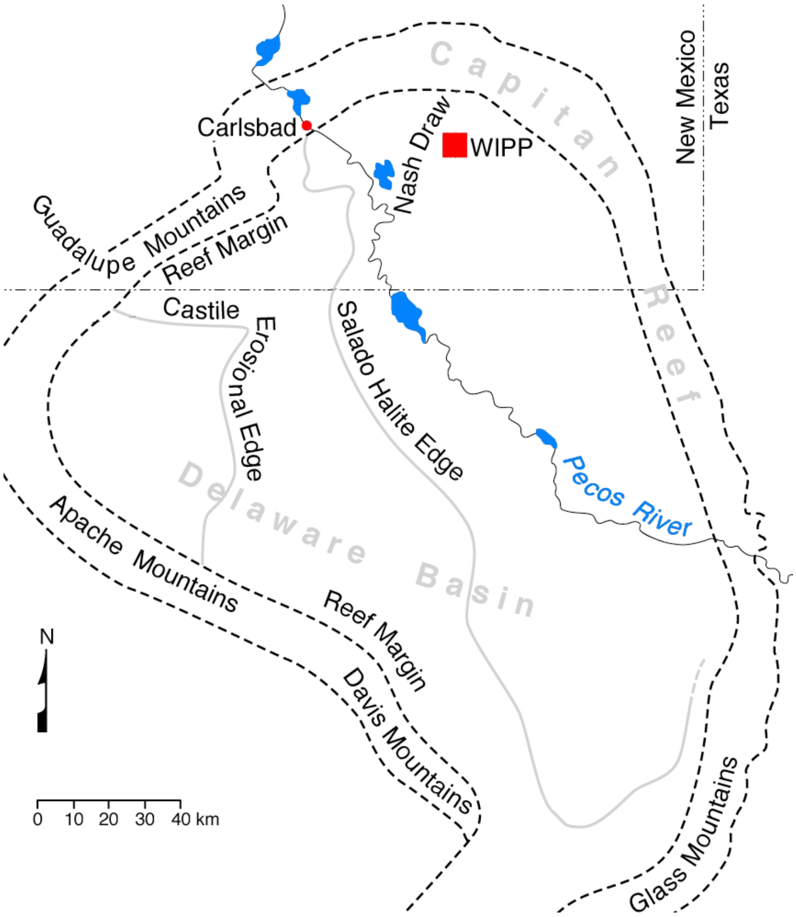


Figure 3.10 Location of the WIPP facility in the Delaware Basin

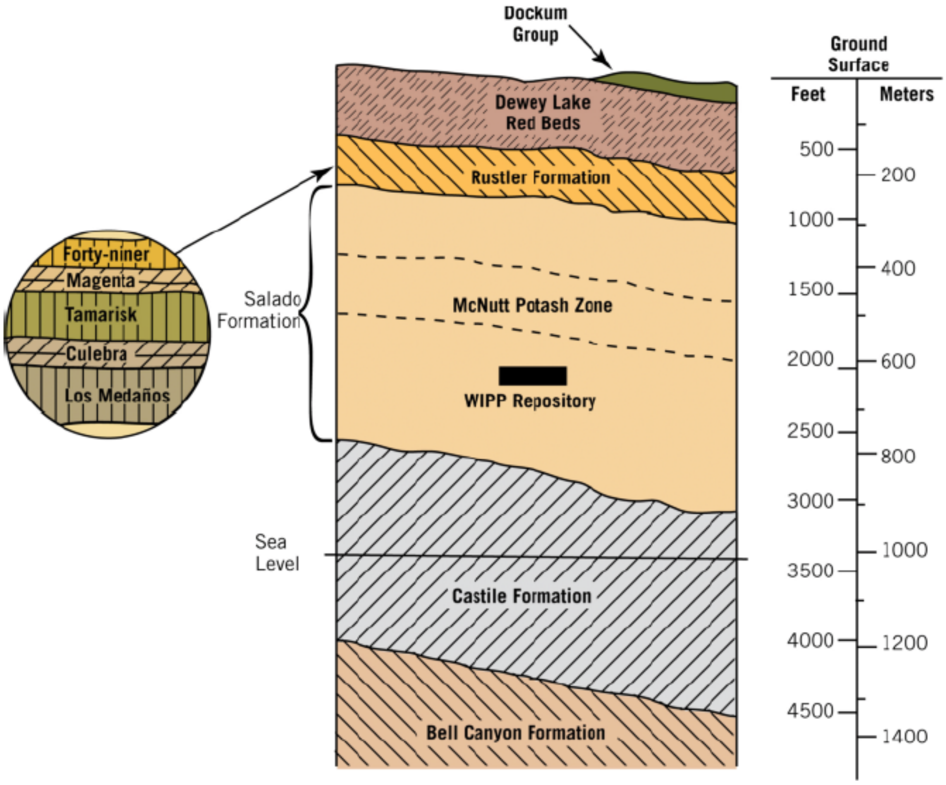


Figure 3.11 Main geological formations present at the WIPP site

The WIPP facility is located in an area with economic natural resources. For example, potash is mined around the site in a horizon in the upper part of the Salado Formation, the McNutt potash zone, which is located approximately 200 metres above the horizon in which WIPP is located. However, no mining occurs in the vicinity of the facility. Oil and gas are produced around the WIPP site from strata situated below the Salado Formation, at depths of 2–3km below the surface; these activities preclude potash mining by state law. The presence of natural resources around and below the WIPP site increases the potential frequency of post-closure inadvertent human intrusion.

The WIPP facility was developed by the US Department of Energy (DOE) and its predecessor organisations, the US Atomic Energy Commission (AEC) up to 1974 and the Energy Research and Development Administration (ERDA) up to 1977. AEC commissioned the Oak Ridge National Laboratory (ORNL) and the United States Geological Survey (USGS) to conduct site investigations. Sandia National Laboratories (SNL) was tasked with the conceptual design and site investigations (post-1974) by ERDA.

The main regulators of the WIPP facility are the US Environmental Protection Agency (USEPA) and the New Mexico Environment Department (NMED). DOE was self-regulating until the Land Withdrawal Act 1992.

The WIPP facility is required to meet the environmental standards for disposal and groundwater protection found in USEPA regulations 40 CFR Part 191 and 40 CFR Part 194.

- 40 CFR Part 191 (USEPA 1994) applies to any nuclear waste disposal facility apart from Yucca mountain, for which Congress required a special standard. The individual protection requirements of this regulation require that a disposal facility be designed to provide a reasonable expectation that, for 10,000 years after disposal, undisturbed performance of facility should not cause the annual committed effective dose to exceed 150μSv. This regulation also incorporates a requirement to limit the cumulative releases to the accessible environment, based on considerations of collective dose.

- 40 CFR Part 194 (USEPA 1998a) applies specifically to the WIPP facility. The purpose of the rule is to establish criteria that implement the 40 CFR Part 191 disposal regulations at the WIPP facility. The requirements of 40 CFR Part 194 are quite prescriptive, specifying details of the scenarios to be considered and the way results of dose calculations are to be presented. They also include requirements for engineered barriers and post-closure monitoring.

The WIPP facility requires recertification by USEPA every 5 years. Recertification is not a reconsideration of the decision to open the facility, but a process to verify that changes at the facility in the preceding 5 year period continue to comply with USEPA's disposal standards for radioactive waste.

NMED regulates the Resource Conservation and Recovery Act, as it is applicable to the WIPP facility. This relates to hazardous waste (exhibiting a hazardous trait such as flammability, reactivity, corrosivity, toxicity). Mixed waste (radioactive waste that is also mixed with hazardous chemicals, solvents and heavy metals such as mercury and lead) is therefore regulated by NMED. Purely radioactive waste is regulated by USEPA. NMED regulates the hazardous component of the waste under WIPP's Hazardous Waste Facility Permit. This permit prohibits certain types of wastes from coming to WIPP including liquid wastes, corrosive, ignitable and reactive wastes, wastes with high concentrations of polychlorinated biphenyls (PCBs), and wastes that have not been adequately characterised.

The New Mexico Environmental Evaluation Group (EEG) was an interdisciplinary group of scientists and engineers employed by the State of New Mexico and funded by DOE. EEG provided independent technical evaluation of WIPP bur ceased to exist in 2004.

3.4.2 Stages of site characterisation and regulation

In 1957, the US National Academy of Sciences recommended salt deposits as the most immediately promising medium for the disposal of liquid HLW. It was noted that the technical difficulties would be reduced if the wastes could be rendered solid and relatively insoluble. The potential advantages of salt are that it is essentially impermeable and any fractures are self-sealing. It is known to plastically deform slowly under the pressure of overlying beds and would therefore consolidate around waste and isolate it in place.

Project 'Salt Vault' was conducted in the Permian evaporite formations near Lyons, Kansas, beginning in 1964. It was intended to research the possibility of HLW disposal in salt. The area was rejected as a potential disposal facility site in 1972 due to technical problems and local opposition. In particular, concerns over the exact location and lateral extent of a nearby solution-mined cavity, the possibility of a volume of water in a related hydraulic-fracturing test project and related water-infiltration problems caused by old boreholes within the mine proper collectively contributed to a loss of confidence in the Lyons site and its eventual abandonment (Lomenick 1996). In 1971, New Mexico political leaders proposed the south-east New Mexico area to AEC as a suitable location for further studies.

Progress in developing the WIPP facility has been complicated by political and legal interventions and a regulatory framework which developed while the programme was underway. The most important milestones in the WIPP programme are as follows:

1973	AEC carries out a literature review of the south-east New Mexico area and determines that the salt deposits are potentially suitable for a disposal facility.
1974	Site characterisation work commences on a site chosen by AEC some 26 miles east of Carlsbad. The initial phase was completed between 1974 and 1978. The main phase occurred between 1978 and 1988. Studies continued after 1988.
1977	A location for the WIPP facility is proposed, but subsequently adjusted to avoid possible pockets of pressurised brine.
1979	Congress authorises the WIPP facility for the R&D of methods of disposal of radioactive wastes generated by defence facilities that are exempt from regulation by the Nuclear Regulatory Commission (NRC) under Public Law 96-164.
1981	The state of New Mexico sues DOE and the US Department of Interior. The suit was settled by an agreement for more study and more communication with the state.
	First exploratory shaft drilled – the salt handling shaft.
1981 to 1988	Construction of the underground research laboratory, called the North Experimental Area, and the disposal areas
1984	DOE and the state of New Mexico agree that the WIPP facility must comply with all state, federal, and local laws and regulations, including those by imposed by USEPA.
1985	USEPA establishes radioactive waste disposal regulations.
1987	The Federal Court invalidates part of USEPA's radioactive waste disposal rules, leaving no regulations applicable to the WIPP facility. A modified agreement between DOE and the state of New Mexico commits the WIPP facility to original rules until revised rules are in place.
1992	Congress enacts the WIPP Land Withdrawal Act. This requires the USEPA to issue criteria that implement the final radioactive waste disposal standards specifically for the WIPP facility. In addition, USEPA must determine whether the WIPP facility can be recertified every 5 years until the facility is decommissioned. This act also withdrew land around the WIPP facility (~40km^2) from public use.
1996	USEPA releases final licence regulations in January. In October DOE submits the WIPP Compliance Certificate Application to USEPA for review and approval.
1998	USEPA certifies the WIPP facility for the disposal of transuranic waste.
1999	WIPP facility becomes operational on 26 March 1999. In November, NMED issues a Resource Conservation and Recovery Act permit allowing the disposal of transuranic waste mixed with hazardous constituents.
2004	DOE submits a Compliance Recertification Application.
2006	USEPA recertifies the WIPP facility.
2009	DOE submits a Compliance Recertification Application.

2010 USEPA recertifies the WIPP facility.

The focus of this case study is on the site investigations and other research conducted by DOE and its predecessor organisations after 1974 and USEPA's regulatory role.

3.4.3 Geoscientific information acquired for site characterisation

The geoscientific programme at the WIPP facility is considered under the following headings:

- **Desk-based studies of feasibility for siting.** Undertaken by AEC in 1973, these studies relied on the data available due to potash and oil exploration in the region. These studies are not considered further in this report. They are not considered as analogous to the MRWS site selection process as the more recent case studies presented in Section 2.
- **Preliminary siting investigations.** Geophysical and borehole surveys between 1974 and 1978 allowed the selection of a site for the WIPP facility.
- **Experiments in URLs.** A URL was developed in the WIPP facility after 1981. Prior to that experiments had been conducted in nearby salt mines.
- **Main phase of investigations.** Geophysical and borehole surveys were conducted between 1978 and 1988.
- **Post 1999 investigations.** Geoscientific investigations were used to support re-licensing applications in 2004 and 2009.
- **Monitoring after construction.** USEPA requires monitoring to provide additional assurance that the disposal facility is performing as expected. The area around the WIPP facility has been subject to additional investigations after the initial certification was granted.
- **Development of QA procedures.** QA procedures evolved over the course of the programme.

Preliminary siting investigations

A summary of the preliminary siting investigations is given in Weart (1979) and DOE (1998a). One important issue was determining the potential for dissolution of the salt rocks by groundwater. This was done through regional geological studies in the Delaware Basin to reveal areas of past and present dissolution activity. Local dissolution features were also recognised in the Delaware Basin. These may be of either shallow or deep origin, but it was the latter that were considered to pose the greater potential hazard to the disposal facility. These features, sometimes called collapse chimneys or breccia pipes, form when localised dissolution occurs deep in the analysed section, resulting in a void into which overlying beds collapse. These collapse chimneys are known to exist in portions of the basin which have seen extensive dissolution activity. Seismic and resistivity surveys were used to search for such features within the site area.

Field geology, geophysical surveys and boreholes were used to map the stratigraphy and structure of the area around the WIPP facility. Stratigraphic information already existed for the general region in the form of research publications and data from petroleum and potash companies.

The 56 boreholes drilled in this phase served a variety of purposes and many of the boreholes were multipurpose. About 20 of the boreholes were used to acquire hydrological data and 3 boreholes were principally for dissolution and/or palaeoclimatic studies. A total of 12 boreholes were used to acquire stratigraphic and lithologic data related to the site and to evaluate geophysical indications of possible subsurface structures. Finally, 21 boreholes to obtain samples for potash assay were drilled to supplement about 30 potash industry boreholes. Locations of boreholes are indicated in Figure 3.12.

With the exception of borehole ERDA 9, which was drilled to the proposed facility depth at the centre of the site, none of the other boreholes within the 3 square mile disposal facility zone penetrated to facility depth. WIPP 12, a borehole completed one mile north of the site centre, provided a sample of the geology in the vicinity of the eventual disposal facility.

Geophysical techniques were used at the WIPP site (Weart 1979), including seismic reflection surveys, electrical resistivity, magnetic and gravimetric methods. Seismic reflection techniques were used to provide information on the structure and depth of subsurface formations. Early in the preliminary site evaluation, a 2,400km line of existing petroleum company seismic reflection data and a 42km line of a newly acquired seismic reflection survey were examined for evidence of major faults and other structures. The nature of the data limited their usefulness for examination of shallow (less than 1,200 metre) horizons. Information on shallow horizons was subsequently acquired by instituting a 209km line of seismic reflection surveys. Early seismic surveys are described in Hern and Powers (1978).

Surface electrical resistivity was assessed as being a valuable tool to search for dissolution related features in the Delaware Basin (Weart 1979). Resistivity surveys over known deep solution features, such as roughly cylindrical collapse chimneys or breccia pipes, were thought to give characteristic signatures. Consequently, closely spaced resistivity surveys were made over the site to examine it for anomalies. Indicated anomalies were then assessed by test drilling. The surveys, using a modified Werner electrode array, were run along lines approximately 150 metres apart over the entire 80km^2 of the site area and resulted in about 9,000 data points. An ‘expander’ or Schlumberger array was used to investigate changes in resistivity with depth at a given location.

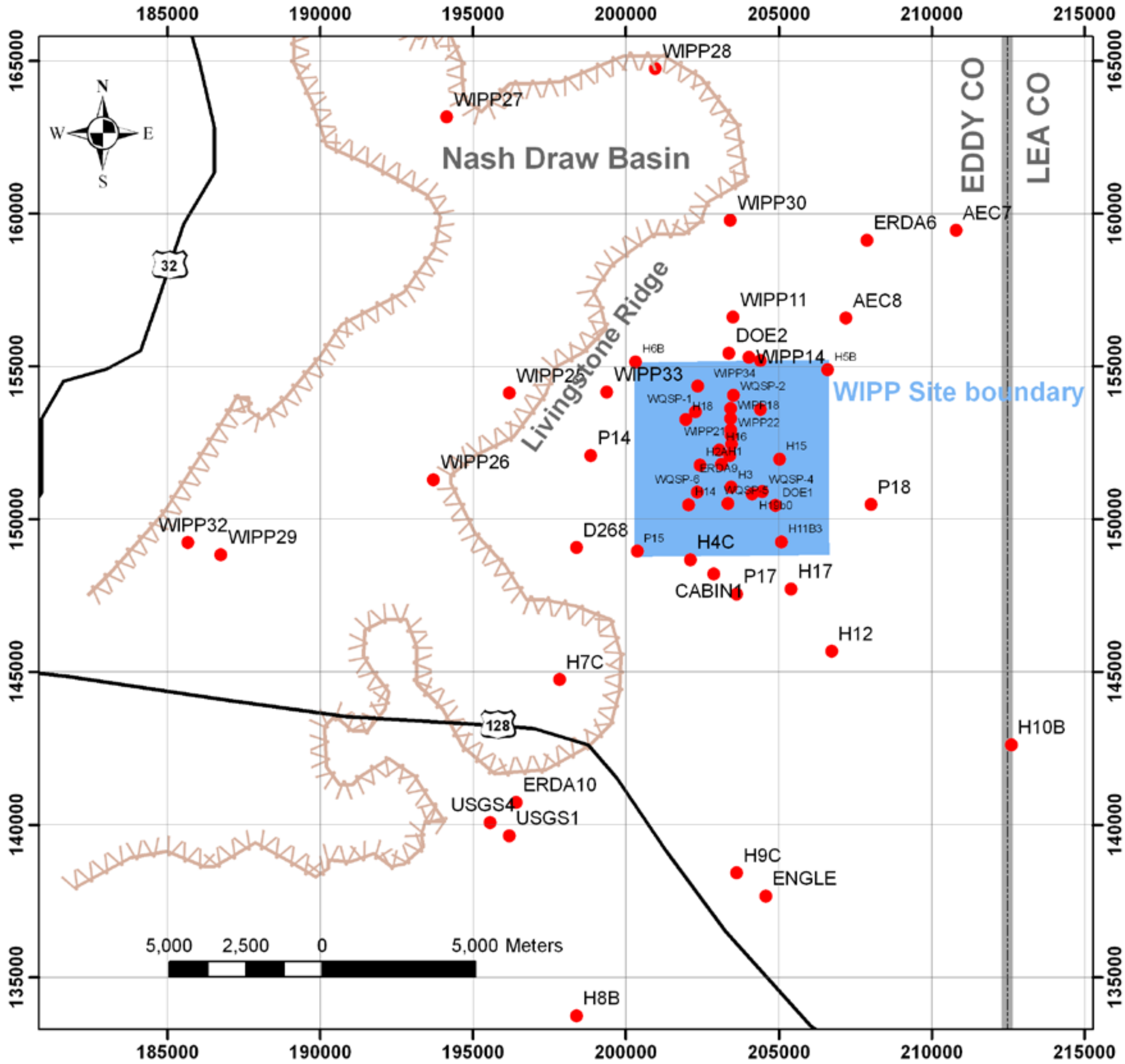


Figure 3.12 Map of borehole locations (red points) in the WIPP site (blue square) and vicinity, using the state plane co-ordinate system

Notes: Roads are shown as black lines.

Magnetic methods were employed to search for both regional and local features expected to show magnetic contrast. Existing aeromagnetic surveys of the Delaware Basin were examined for indications of major faulting or igneous intrusions. A known igneous dike 9 miles north-west of the site was the only intrusive feature observed in these data.

Gravity data for the Delaware Basin were examined for indications of major geological structures and assessed for their utility in detecting collapse features. The absence of the former in the WIPP site and the failure of collapse features to exhibit significant density differentials were reported to limit the usefulness of the gravimetric surveys.

Physical and geochemical properties required for site evaluation were obtained from laboratory tests on core samples. Rock mechanical and thermal properties were characterised for the disposal facility horizons. Brine content and the degree of halite impurities were also established.

The parameters important to the hydrogeological understanding of the area were listed as:

- head or reservoir pressure

- the hydraulic conductivity of the rock strata
- the chemistry of formation waters

Complementary laboratory measurements were used to develop ion exchange (retardation) coefficients for the transport model.

Biological studies of the site began in 1975 to gather information for the Environmental Impact Statement. Meteorological studies began in 1976. Baseline environmental data were initially reported in 1977 and are updated annually by DOE (DOE 2004a). Environmental monitoring is also performed independently. Samples from WIPP and the environment are taken, analysed and reported independently by the Carlsbad Environmental Monitoring and Research Center.

Experiments in URLs

Before the experimental facilities at WIPP became available, in situ experiments were conducted at comparable salt mines. Sattler and Hunter (1979) describe activities undertaken at the Avery Island mine that included instrumentation development and in situ performance verification.

Planning for the in situ experiments at the WIPP site is described by Sattler and Hunter (1979). The initial activities were associated with the early shaft complex to be developed in 1980 to 1981. There were expected to be experiments to address the following issues:

- large-scale rock mechanics design verification
- drifts with the heat load of anticipated waste
- transuranic waste emplacement and retrieval (without radioactivity)
- non-radioactive high-level waste interactions
- thermal structural experiments
- stable nuclide migration
- brine migration
- permeability
- borehole plugging
- operation and design
- instrumentation development and monitoring

IAEA (2001) identifies the main experiments to be in the areas of:

- rock mechanics of a heated salt pillar
- seal system performance tests for various seal materials
- disposal room interactions to determine degradation mechanisms of glass and waste package materials
- fluid flow and transport permeability measurements throughout the underground area

The experiments conducted in the URL prior to the licence application are summarised in Weart (1999).

A series of tests to assess the effects of gas generation are reported by Wawersik et al. (1997). All the tests were performed in the north-east portion of the WIPP experimental area, 642 metres below ground surface. Hydraulic fracturing tests were integrated with hydrological tests to estimate the conditions under which gas pressure in the disposal rooms would initiate and advance fracturing in nearby anhydrite interbeds. The measurements were made in 2 marker beds in the Salado Formation to explore the consequences of existing excavations for the extrapolation of results to undisturbed ground. The interpretation of these measurements was based on the pressure–time records in 2 injection boreholes and several nearby hydrological observation holes. Data interpretations were aided by post-test borehole video surveys of fracture traces that were made visible by ultraviolet illumination of fluorescent dye in the hydraulic fracturing fluid.

Main phase of investigations

Since 1978, DOE has drilled additional holes to support hydrological studies, geological studies and facility design. Geophysical logs, cores, basic data reports, geochemical sampling and hydrological testing and analyses are reported (Weart 1999, DOE 2004a).

The potential presence of pressurised brine pockets was identified as an important issue for the safety case. To assess the potential presence of brine under the disposal facility, DOE conducted a series of 38 time-domain electromagnetic soundings at the WIPP site in 1987 (USEPA 1998d). A total of 36 soundings were executed over a 1km × 2km area, with the central soundings located directly over the waste panels.

The electromagnetic data collected were reported to indicate differences in electrical resistivity, which were interpreted as occurring in the Castile Formation. Regions of relatively low resistivity in the Castile Formation were presumed to be due to a greater abundance of interconnected brine compared with higher resistivity regions. A sounding executed near the brine reservoir penetrated at borehole WIPP-12 was used to provide an independent calibration on the interpretation of the data. The study indicated the presence of electrically conductive regions below the waste panels at the WIPP site. However, because of the inherent coarse resolution of the method, the data do not support the development of a unique map of the extent of conductors in the Castile Formation.

An interpretation of the data appended to the licence application (USEPA 1998d) suggests that 10–55% of the waste panel area may be underlain by relatively conductive units, interpreted to be one or several brine reservoirs. Because of the spatial resolution provided by time-domain electromagnetic data, however, the data do not support distinguishing boundaries between reservoir and non-reservoir areas.

Post 1999 investigations

The conceptual model for the hydrology at the WIPP site developed for the 1996 compliance certification application assumed that all units below the water table aquifer were effectively isolated from rainfall and other surface hydrologic processes, and that all heads were slowly declining since the end of the last glacial pluvial period approximately 14,000 years ago (Beauheim 2010). In particular, the original conceptual model for the Culebra Dolomite member assumed that it could be conservatively treated as a fully confined unit with heads that would appear to be at steady state over the operational period of the WIPP. The primary groundwater release pathway for radionuclides released from the WIPP facility was thought to be by inadvertent human intrusion leading to migration through the Culebra Dolomite member, along a high transmissivity region in the south-eastern portion of the WIPP site.

Some aspects of the original conceptual model have been cast into doubt by subsequent observations. Ongoing monitoring has shown that groundwater heads in the Culebra Dolomite member are rising (Beauheim 2010). Furthermore, calibration of the transmissivity fields for the Culebra Dolomite member in the 2004 recertification application did not produce the high transmissivity offsite transport pathway through the south-eastern part of the WIPP site previously thought to be present. The original peer review of the Culebra Dolomite member conceptual model criticised it for a lack of geological understanding of spatial variations in transmissivity.

USEPA requested that DOE carry out additional studies of the Culebra Dolomite member and develop a revised conceptual model consistent with subsequent observations. In response to USEPA requests, DOE initiated a variety of geoscience investigations including:

- drilling (with selected intervals cored) and hydraulic testing of 19 new boreholes
- large-scale hydraulic testing designed to produce transient responses over tens of km^2
- high resolution monitoring of heads in the Culebra Dolomite member and precipitation
- mapping of catchment basins in a nearby dissolution trough (Nash Draw)
- sampling, age dating and geochemical evaluation of Culebra Dolomite member groundwaters
- correlation of geophysical logs from hundreds of exploratory potash and oil and gas holes around the WIPP site
- refinement of the sedimentological model of the basin
- detailed evaluation of post-depositional processes (for example, dissolution)
- collection of information on potash industry water usage and disposal
- evaluation of borehole plugging and abandonment records
- collection of information on recent and ongoing oil and gas drilling
- modelling of various scenarios that could introduce water into the Culebra Dolomite member
- refinement and recalibration of transmissivity fields for the Culebra flow model

Compliance monitoring after operations

USEPA defined assurance requirements in 40 CFR Part 191 which included the obligation to:

> 'monitor to detect substantial and detrimental deviations from expected performance until there are no significant concerns to be addressed by further monitoring' (Wagner et al. 2002).

USEPA has stated that monitoring for releases would not likely be productive, since even poorly performing GDFs are unlikely to allow for releases to the accessible environment for hundreds of years.

As USEPA developed its regulations, it expanded its monitoring requirement to include pre- and post-closure monitoring. This was because it concluded that pre-closure monitoring would provide a baseline for comparison with future measurements of parameters that are important to the long-term performance of the disposal facility. Additionally, USEPA determined that a monitoring parameter analysis is necessary to determine the important monitoring parameters. It also included a list of parameters that needed to be considered in this analysis.

DOE performed the required monitoring parameter analysis and documented it in an appendix to the Compliance Certification Application (DOE 1998b). In addition to parameters related to the behaviour of the physical elements of the disposal system (for example, subsidence and water levels), the WIPP monitoring programme also included parameters related to human activities. For example, the intensity of exploratory drilling for oil and gas around the site has increased significantly since disposal facility construction began.

DOE developed a ‘trigger value’ concept, where values or ranges were assigned to ‘compliance monitoring parameters’ that would indicate a condition that is outside performance assessment expectations or represents a point at which further analysis is necessary to determine the potential impact the data may have on WIPP containment performance. No specific actions necessarily occur if a trigger value is exceeded. Instead, an investigation would be initiated to determine the cause of the unexpected value and an assessment would be made of the possible impact on compliance.

Development of QA procedures

QA procedures evolved significantly (Larson et al. 1998) during the WIPP investigations programme, culminating in the 1996 USEPA 40 CFR Part 194 requirement where only ‘qualified’ data could be used for regulatory purposes. Qualified data are defined as those data collected under a QA programme conforming to the specifications of 40 CFR Part 194, or those data accepted as fact by the scientific community (literature values).

A data qualification programme was implemented to qualify data collected under earlier QA arrangements. These data were collected prior to DOE’s certification of SNL’s QA programme or developed outside DOE’s WIPP programme in other institutions. SNL’s approach to qualifying existing data was to:

1. Identify the subset of all data comprising ‘existing’ data.
2. Determine the potential use of existing data.
3. Create record packages by topically grouping existing data.
4. Qualify existing data first by demonstrating that the data was collected under an equivalent QA programme.
5. Qualify any remaining data record packages by peer review to establish technical credibility of the data itself.

Independent review teams were used initially to qualify existing data records packages under the equivalent QA programme provision. Two independent QA representatives and 1–3 technical representatives served on each review team.

3.4.4 Refinement of the disposal facility concept and design

The development of the disposal facility design is described in the Design Validation Report (DOE 1998g). This appendix to the compliance certification application describes how geoscientific information from observations of the behaviour of underground openings, descriptions of the geological conditions encountered construction, data from core samples and data from in situ geomechanical instruments affected the design of the disposal facility.

In the Compliance Certification Application, DOE presented 4 options for the design of the panel closure system, but did not specify which one would be constructed at the WIPP facility. USEPA based its certification decision on DOE's use of the most robust design – referred to in the licence application as 'Option D'. USEPA's certification required DOE to implement the Option D panel closure system at the WIPP facility, with Salado mass concrete replacing fresh water concrete (USEPA 1998b).

USEPA established the requirements for passive institutional controls in 40 CFR Part 191. Specifically, 40 CFR §191.14(c) requires that:

> 'disposal sites shall be designated by the most permanent markers, records, and other passive institutional controls practicable to indicate the dangers of the wastes and their location'.

In 1994, DOE created a task force to comply with this requirement (Wagner et al. 2002). The Passive Institutional Controls Task Force assessed the effectiveness of passive institutional controls in deterring inadvertent human intrusion. It developed a conceptual design for permanently marking WIPP, establishing records, and identifying other practicable controls to indicate the dangers of the wastes and their location.

3.4.5 Criteria for site selection/evaluation

The original site selection criteria were developed by ORNL and USGS. These criteria included (Griswold 1977):

- a 2 mile radius from any boring through the evaporites down into the Delaware Formation (below the Castile Formation) or deeper formations
- salt of high purity at less than 3,000 feet
- a minimum depth to suitable salt of 1,000 feet
- avoidance of obvious mineral resources

The cores from boreholes AEC Nos. 7 and 8 intercepted commercial grades of potash. At borehole ERDA No. 6, the complex structure and brine flow were sufficient evidence that more selective criteria were needed in selecting future sites.

The 2 mile radius from deep borings was reduced to 1 mile. This change, which resulted from studies performed for ORNL on the dissolution effects in boreholes, was reported as being desirable due to the extensive deep gas exploration drilling in the Delaware Basin. Results of borehole plugging and dissolution studies were reported to indicate that a 1 mile buffer was conservative. Selection criteria were expanded to include (Griswold 1977):

- avoidance of known oil and gas
- avoidance of the known potash enclave for the site

- allowance for a probable salt deformation belt 6 mile wide out into the basin and away from the Capitan Reef
- establishing a distance of 1 mile or more from erosion of the top of the Salado Formation
- avoidance of existing potash lease rights
- avoidance of known anticlinal structures

In 1978, borehole ERDA-6 encountered brine and the original proposed disposal facility location was changed. In 1981, borehole WIPP-12, one mile north of the present disposal facility also hit pressurised brine, resulting in the relocation of proposed disposal facility panels (DOE 2004a).

3.4.6 Development of safety assessments and environmental impact assessments

The performance assessment methodology and the associated regulatory requirements were developed over several years. Regulation 40 CFR 191 was first issued in 1985, remanded in 1987, and re-issued in 1993. 40 CFR 194 was issued in 1996. The regulations' requirements relating to performance assessment are outlined below.

USEPA considers requirements for the 'undisturbed' disposal facility, and 'performance taking account of all significant processes'. Undisturbed performance is defined in 40 CFR Part 191 to mean that the predicted behaviour of a disposal system, including consideration of the uncertainties in predicted behaviour, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events. The conceptual models associated with undisturbed performance were developed by DOE using screening of FEPs.

The undisturbed performance scenario consists of radionuclide migration through anhydrite interbeds in the Salado Formation to a degraded borehole, up the borehole to the Culebra Dolomite member, and through this unit to the accessible environment. The flow in the Salado Formation was thought to be driven by enhanced pressure resulting from gas generation within the facility as a result of metal corrosion.

There are 3 long-term numerical performance requirements contained in 40 CFR Part 191 relating to disposal facility performance in an 'undisturbed' state over a period of 10,000 years. They relate to individual protection, groundwater protection and cumulative release respectively:

- Dose rates to any member of the public in the accessible environment should not exceed 150µSv
- Activity concentrations in groundwater should not exceed specified limits
- The probability of cumulative releases of radionuclides to the accessible environment should not exceed certain limits

The regulatory cumulative release rates were set based on arguments relating to collective doses. The regulations require that probabilistic dose and cumulative release calculations are performed. In addition to the undisturbed performance requirements, the cumulative releases of radionuclides are assessed under specific assumptions that involve:

- mining within the controlled area

- deep drilling that intersects the waste disposal region and a brine reservoir in the Castile Formation
- deep drilling that intersects a waste disposal panel

The WIPP facility is located in an area with economic natural resources (DOE 1998c). The presence of natural resources around and below the WIPP facility has been treated in performance assessment using scenarios that account for the possibility of resources being extracted over the next 10,000 years. These are derived from a drilling rate based on actual drilling in the area over the last 100 years (for borehole intrusion scenarios) and the probability for mining based on the potential location of potash over the disposal facility (for mining scenarios).

Figure 3.13 illustrates representative intrusion scenarios in which a borehole penetrates both the disposal facility and a hypothetical pressurised brine reservoir in the Castile Formation underlying the Salado Formation that hosts the disposal facility. Radionuclides could be released during drilling when cuttings and material eroded from the borehole wall are carried to the ground surface by circulating drilling fluid. Radionuclides could also reach the accessible environment in the subsurface, following lateral transport in groundwater in the Culebra Dolomite member of the Rustler Formation overlying the disposal facility. Intrusion scenarios are considered in which a brine reservoir is not present or not penetrated.

USEPA regulations specify certain assumptions for DOE to use when assessing these scenarios, including that future drilling practices and technology will remain consistent with practices in the Delaware Basin at the time a compliance application is prepared. Such future drilling practices include:

- the types and amounts of drilling fluids
- borehole depths, diameters, and seals
- the fraction of such boreholes that are sealed by humans

Historic abandoned wells, and the potential for their sealing to degrade over the regulatory timeframe, were to be considered. With respect to mining, only effects of changes in the hydraulic conductivity of hydrogeological units were required to be considered in the assessment.

The first performance assessment which calculated doses from transuranic wastes at WIPP is reported by Brannen (1979). This preliminary safety assessment was limited to a consequence assessment in terms of the dose to a maximally exposed individual as a result of introducing the radionuclides into the biosphere.

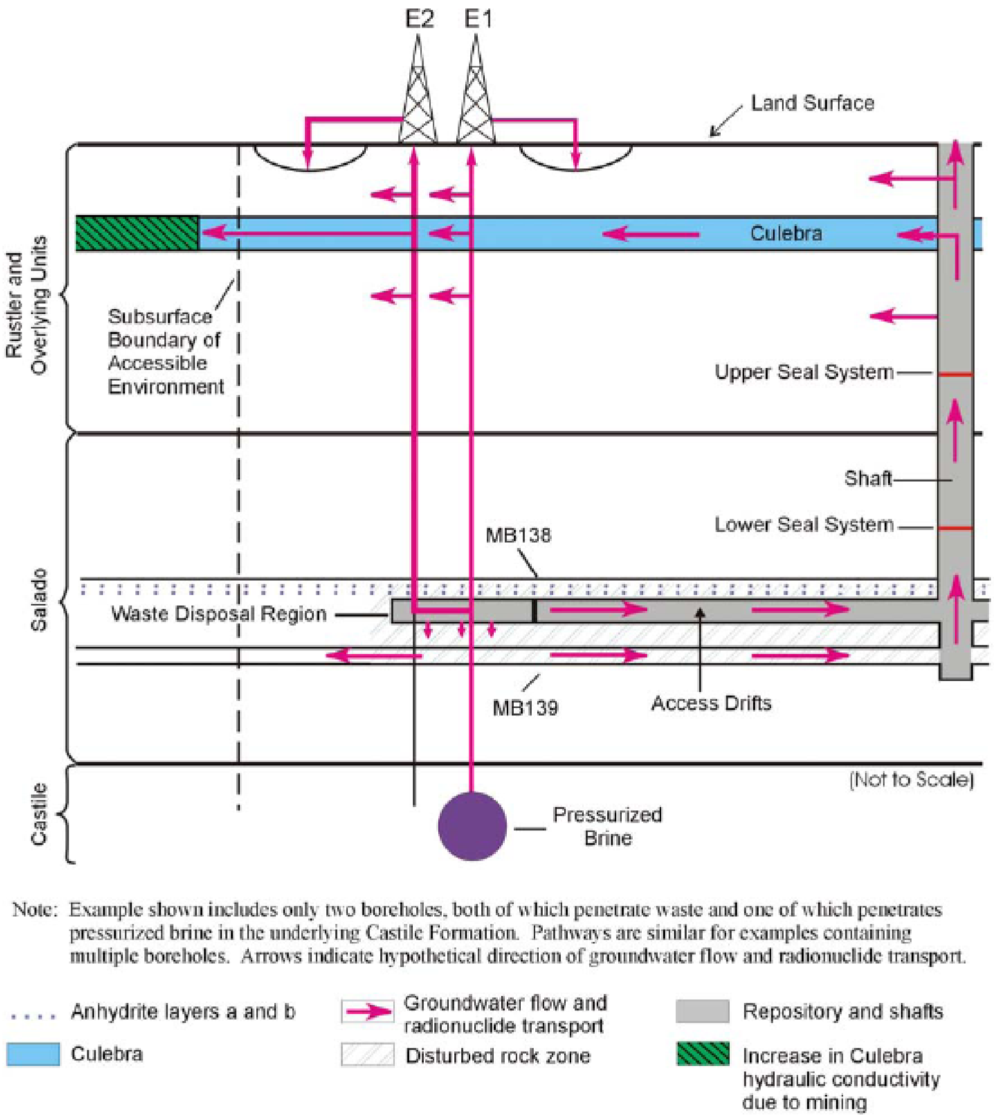


Figure 3.13 Conceptual release pathways for disturbed performance

Source: DOE (2004b)

Iterations of preliminary performance assessments are reported in 1989, 1990, 1991, 1992 and 1994 (Anderson 1994). Preliminary performance assessments are described as providing interim guidance to the project and allowing early peer review. Calculations used a Monte Carlo technique with multiple simulations using sampled parameter values.

Anderson (1994) suggested iterative performance analyses can be used to guide research and development needs. Figure 3.14 illustrates important developments in performance assessment methodology, along with the main influences on the licensing and experimental programmes. Human intrusion was identified as the most important potential release pathway.

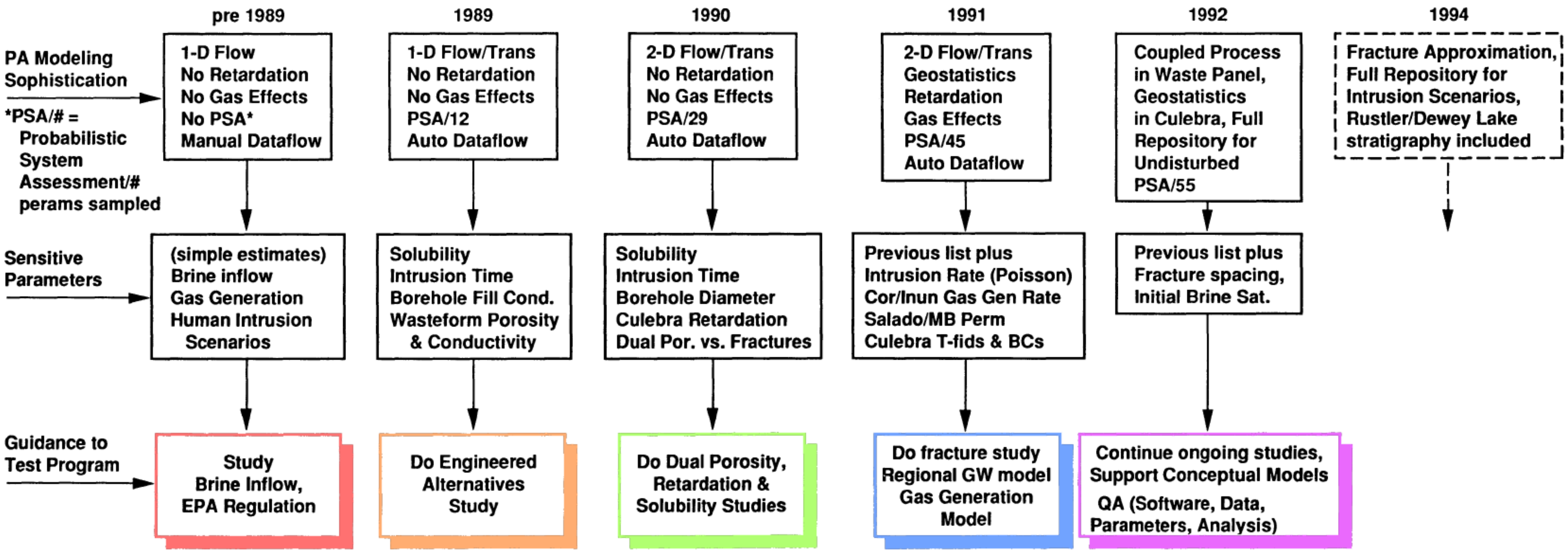


Figure 3.14 Developments in performance assessment between 1989 and 1994, including the understanding of the most sensitive parameters and influences on the test programme.

Notes: Modified after Anderson (1994).

The structure and content of the Compliance Certification Application was determined by the requirements of 40 CFR Part 191 and 40 CFR Part 194, and associated guidance documents published by USEPA (USEPA 1996).

In the Compliance Certification Application, DOE applied a bounding analysis approach to the individual and groundwater protection requirements by using conservative assumptions that resulted in the overestimation of potential doses and contaminant concentrations (DOE 1998d). Using this conservative approach, DOE calculated the maximum potential dose to an individual would be about one-thirtieth of the individual protection standard. Concentrations of contamination in the hypothetical groundwater drinking source were calculated to be below USEPA groundwater protection limits (DOE 1998d).

Regarding cumulative release rates, the results of the performance assessment in the Compliance Certification Application (DOE 1998e) are displayed as complementary cumulative distribution functions that display the probability that cumulative radionuclide releases from the disposal system will exceed the values calculated for each scenario considered in the analysis. Based on the calculated complementary cumulative distribution functions, the WIPP facility was thought to satisfy the containment requirements of 40 CFR Part 191. Sensitivity analysis of results shows the cumulative release rates were dominated by releases of radionuclides that could occur directly at the ground surface during the inadvertent penetration of the disposal facility by a future drilling operation. Releases of radionuclides to the accessible environment resulting from transport in groundwater through the shaft seal systems and the subsurface geology were calculated to be negligible, with or without human intrusion, and to make no contribution to the cumulative release rates. No releases were predicted to occur at the ground surface in the absence of human intrusion.

DOE submitted Compliance Recertification Applications in 2004 and 2009 to demonstrate WIPP’s continuing compliance with regulations. The 2004 recertification application included:

- changes from the licence application with respect to inventory and disposal facility configuration
- consequences of extensive creep closure of excavations in Panel 1
- changes to the use of magnesium oxide buffer material
- changes to the performance assessment
    - making the representation of the shafts and of the disposal facility geometry more appropriate for modelling the disposal facility’s performance
    - responding to USEPA’s recommendation that the conceptual model of groundwater flow in the Rustler Formation needed modification; DOE also developed a new model to predict possible spall releases
    - implementing some changes to the parameter set used in the performance assessment

The 2009 recertification application included additional changes compared with that submitted in 2004, including:

- changes in gas generation modelling
- performance assessment parameter changes
- new transmissivity fields for the Culebra Dolomite member

- revisions to the calculations of spalling releases during drilling

These were made at USEPA's request following its review of the 2004 recertification application.

3.4.7 Critical review and its influence

Peer reviews organised by DOE

The certification criteria in 40 CFR Part 194 prescribe the use of peer reviews, organised by DOE, to support areas of the compliance evaluation. Guidance is provided concerning the definition of peer reviews, the areas for which a peer review is appropriate, the acceptability of peers, and the conduct and documentation of peer reviews. Peer reviews were conducted in the following topics (DOE 1998f):

- conceptual models
- waste characterisation analysis
- engineered alternatives cost/benefit study
- engineered systems data qualification
- natural barriers data qualification
- waste form and disposal room data qualification
- passive institutional controls

DOE was obliged to respond to criticisms made by reviewers and reviewers were asked if DOE responses were adequate. This process resolved most of the issues raised. An example of an issue outstanding was the reviewers' comment that radionuclide transport through entrainment of brine and waste solids in rapid, 2-phase liquid–gas releases during inadvertent borehole intrusions did not appear to have been evaluated. This transport mechanism was considered by the reviewers to be potentially an important component of the conceptual model. The review panel accepted that DOE understood the issue; however, the panel concluded that its response did not reasonably address its concern (DOE 1998f).

Earlier reviews, which might not necessarily conform to the peer review guidelines, were also described in the Compliance Certification Application.

Joint NEA/IAEA review of the 1996 performance assessment

In 1996, DOE asked NEA and IAEA to conduct a joint review of the post-closure performance assessment to be submitted with the compliance certification application. The NEA/IAEA review was not completed in time to be incorporated into the application, but was reported in the 2004 recertification application. DOE did not respond to the NEA/IAEA comments, as this review was in addition to those required by 40 CFR Part 194.

The review group made the following observations on the specificity of the WIPP project.

- The WIPP project and the compliance certification application are different in several respects from geological disposal projects and assessment documentation in other countries.
- The WIPP facility is sited in an area in which mineral resources are being actively and extensively exploited.
- The regulator has provided detailed guidance on the assessment approach, documentation and, for the assessment of future human actions, model assumptions.
- The compliance certification application is tightly focused on compliance with USEPA regulations and does not represent a full safety case as understood in most other countries.

These observations were made as 'statements of fact, not criticisms'. Such differences were thought to have had a strong influence on the performance assessment carried out by DOE and were taken into account by the reviewers in formulating their conclusions.

The methods used to assess the performance of the WIPP facility were found to be generally in conformity with practices used in other countries. These include:

- the selection of FEPs
- development of scenarios and models representing the evolution of conditions in the disposal facility and the release of radionuclides
- quantitative analysis of selected scenarios by means of a linked set of models and comparison of the results to regulatory limits

Specific aspects of the assessment carried out by DOE were not thought to be in accordance with assessment practices in other countries. This was traced in part to the influence of USEPA regulations and the strong focus of the compliance certification application on regulatory compliance. Some examples are given below.

- The probabilistic approach applied by DOE deals only with parameter-based uncertainty. Conceptual model and scenario uncertainty are not discussed in the compliance certification application. These were considered to be important internationally.
- Results in the compliance certification application focus on the complementary cumulative distribution functions of cumulative radionuclide release. Information on the behaviour of intermediate parameters and results of representative deterministic calculations, especially as a function of time, was found to be lacking. Without this, it was thought that it might not be possible to develop a good understanding of the disposal system's behaviour.
- Intermediate results were documented in the supporting analysis requested by USEPA during the compliance certification application completeness determination and were used in its compliance determination.
- USEPA ruled that DOE only needs to consider a limited set of future human actions and specified the assumptions to make in assessing these actions. Thus, some scenarios that might affect safety have not been evaluated. The lack of a logically argued explanation for the choice of scenarios analysed, or evaluation of these other scenarios, leads to the impression that the assessment is arbitrary.

- The review group was surprised that there were no arguments indicating the expected performance of the WIPP facility beyond the 10,000 year regulatory period. Such descriptions were thought to be important in performance assessment in other countries.

The compliance certification application documentation was considered not to be transparent and was found to be difficult to follow even from the point of view of experienced performance assessment practitioners. Technical issues were thought to be difficult to trace and some of the choices made and modelling assumptions were not well supported. This, combined with the specificity of USEPA regulations, made it challenging to distinguish between decisions determined by the regulator and those made by DOE.

On specific points, the review team considered that DOE should give further attention to:

- the implications – favourable and unfavourable – the behaviour of the magnesium oxide backfill might have on the performance of the facility
- the basis for assuming that homogeneous conditions will be rapidly reached in the disposal rooms and the potential consequences of heterogeneities in the source term

Review by the New Mexico Environmental Evaluation Group

The EEG conducted independent technical evaluations of the WIPP facility for the state of New Mexico up to 2004, when it ceased to exist. Between 1978 and 2004, EEG published around 90 reports relating to numerous aspects of the WIPP project, of which 15 qualified as peer reviews according to the guidelines and were considered by DOE in the compliance certification application. An additional 11 reports were considered in the 2004 recertification application.

DOE has stated that the issues and concerns raised by EEG have been continually evaluated by the WIPP project. A considerable amount of additional testing and analysis have been performed because of EEG’s involvement and substantial changes have occurred in the WIPP project as a result (DOE 1998f).

In its review of the draft compliance certification application, EEG claimed that a basic understanding of the hydrology of the site had not yet been attained (Neill et al. 1996). The location of the water table at the site had not yet been identified, which would require an investigation of the hydrology of the shallow zone overlying the Rustler Formation, including the Dewey Lake Redbeds.

The Culebra Dolomite member was thought by DOE to play an important part in the postulated breach scenarios, yet knowledge of its recharge and discharge locations and the mechanics of flow and transport were assessed to be inadequate by EEG. The postulated direction of flow, as indicated by the potentiometric heads, was thought to differ from that interpreted by analysis of water chemistry. EEG noted that several wells located in the unit had shown an unexplained rise in water levels in recent years; EEG thought that this should be explained in a compliance certification application.

Regulatory review of the Compliance Certification Application 1996

The USEPA provision certification was made in 1997, with a period of public comment before the final certification decision was made in 1998. USEPA made its certification decision by comparing relevant information with the WIPP compliance criteria (40 CFR Part 194).

The primary source of information examined by USEPA was the Compliance Certification Application submitted by DOE in 1996. USEPA also relied on:

- materials prepared by it or submitted by DOE in response to its requests for specific additional information necessary to address technical sufficiency concerns
- technical reports generated by USEPA and its contractors
- USEPA audit and inspection reports
- public comments submitted on USEPA's proposed certification decision during the public comment period

USEPA organised and chaired public hearings about the WIPP facility. In 1998, 6 hearings in local towns were held to receive comments about the proposed decision to certify WIPP. USEPA responded to these comments in its final decision to certify WIPP (USEPA 1998c).

The original peer review of the Culebra Dolomite member conceptual model criticised it for a lack of geological understanding of variations in transmissivity. Consequently, USEPA made a series of requests from 2002 through 2005 that DOE undertake additional studies of the unit and develop a revised conceptual model consistent with recent observations. Specific requests included (Beauheim 2010):

- justify continued use of the old conceptual model, or revise the conceptual model and subject it to peer review
- develop new transmissivity fields calibrated to the current (higher) heads
- install new wells to understand the reasons for rising water levels
- enhance the monitoring system
- install a new well to show if the high transmissivity offsite pathway exists or not
- update groundwater geochemistry interpretations and collect new samples for age dating
- update the 3D groundwater basin model

The WIPP compliance criteria provide USEPA with the authority to conduct inspections of activities at the WIPP facility and at all off-site facilities which provide information included in certification applications. Since 1998, USEPA has conducted periodic inspections to verify the adequacy of information relevant to certification applications. USEPA has conducted annual inspections at the WIPP site to review the monitoring programme. It has also inspected the emplacement and tracking of waste in the disposal facility.

Regulatory review of Compliance Recertification Application 2004

The 2004 recertification application included several changes to technical information initiated by DOE or directed by USEPA including:

- an increased assumed drilling rate for resources in the performance assessment

- updated understanding of the transmissivity of the Culebra Dolomite member and new transmissivity field calculations
- new monitoring data including water levels in this unit
- a modified gas generation rate
- updated actinide solubility and actinide solubility uncertainty values
- an increase in the uranium (+VI) solubility

Items related to the waste inventory were also updated with inclusion of super-compacted waste from Idaho National Laboratory, a new estimate of radionuclides and DOE's use of overpacks.

The Culebra Dolomite member was considered by DOE to be the prime pathway for long-term radionuclide transport in groundwater. As part of the required monitoring programme, DOE identified that the water levels in the Culebra Dolomite member had continued to fluctuate and generally increase, for unknown reasons. DOE hypothesised that human influences such as potash mining and petroleum production were responsible. DOE concluded that these human influences would therefore be short-lived compared with the 10,000 year regulatory time period and that the effects of water levels are captured in the performance assessment. The 2004 recertification application used water levels that were measured in 2000. These showed a change in water levels across the site since the licence application. The hydraulic gradient was less than in the licence application, increasing estimated radionuclide travel times.

USEPA agreed with DOE that the change in the water levels in the Culebra Dolomite member and other units are most likely due to anthropogenic sources. Natural recharge was eliminated because there was no response in well data to precipitation events. Because of the confining nature of the Rustler Formation units and the fact that the pumping tests in the Culebra Dolomite member indicated that pressure changes were propagated throughout the vicinity of the WIPP site, the change in water levels was thought most likely due to natural resource extraction or fluid injection somewhere in the vicinity of the WIPP site. USEPA reasoned that, if this were the reason for the changes in water levels, then it would stop once the resource-related activity ceased and its impact would be short term. Thus, USEPA agreed that the water level changes would be a transient phenomenon. DOE was required to monitor the water levels in the Rustler Formation units, so any changes in water levels could be incorporated into future performance assessments. USEPA therefore found DOE's approach to the water level changes to be adequate.

Regulatory review of Compliance Recertification Application 2009

USEPA issued a recertification decision in 2010. Changes in the Compliance Recertification Application 2009 included changes to the inventory in response to USEPA comments. Changes to the performance assessment included:

- changes in gas generation modelling
- parameter changes
- new transmissivity fields for the Culebra Dolomite formation
- revisions to the calculations of spalling releases during drilling

USEPA examined the peer reviews commissioned by DOE of the new conceptual model of the Culebra unit and associated changes to the models (USEPA 2009a).

Due to continuing public concern, USEPA commissioned a review of issues relating to karst (USEPA 2009b). During the recertification process, reviewers again raised questions about the potential formation of karst in the Culebra or Magenta Formations and whether preferential groundwater pathways could exist or develop that could affect groundwater transport of radionuclides from the disposal facility. Some comments proposed using a proprietary magnetotellurics technology, called Z-SCAN, to search for karst at the WIPP site.

USEPA (2009b) provided additional discussion on a number of topics it had considered previously and responded to some new interpretations of the old information. USEPA re-evaluated the available evidence relating to whether karst exists or could form at the WIPP site and provide preferential groundwater transport pathways for the release of radionuclides. This evaluation consisted of:

- a renewed review of the data available at the time of the compliance certification and recertification applications
- an examination of magnetotellurics and other geophysical methods to detect karst in the Magenta or Culebra units at the WIPP site
- development of a conceptual model of groundwater flow in the Magenta and Culebra units at the WIPP site
- comparison of the conceptual model to alternative proposed conceptual models

USEPA concluded that dissolution may have occurred in the immediate vicinity of borehole WIPP-33. However, it found no evidence that dissolution was pervasive, widespread, or had led to connected groundwater pathways.

Summary of lessons learnt

Following the certification of the WIPP facility, several authors have reviewed the programme with the intention of propagating some of the lessons learnt. These reviews are from the point of view of the developer.

Beauheim and Larson (1998) suggest that:

- site characterisation and performance assessment should evolve together through an iterative process, with neither activity completely dominating the other
- defensibility and credibility require a much greater depth of understanding than can be represented in performance assessment models
- experimentalists should be directly involved in model and parameter abstraction and simplification for performance assessment
- external expert review should be incorporated at all stages of a project, not just after an experiment or modelling activity is completed
- important individuals should be retained for the life of a project, or a process must be established to transfer their working knowledge to new individuals
- an effective QA programme needs to be stable and consistent for the duration of a project and focus on best scientific practices

Richards (1998) provided a summary of lessons learned in implementation of quality assurance controls surrounding inputs for performance assessment analysis.

Larson et al. (1998) suggested that many of the lessons learned during the WIPP project's transition from site characterisation and experimental research to the preparation of a successful application may be of general interest to other disposal facility development programmes. They identified the following issues as important.

- **Engaging the regulator.** Once USEPA was designated as regulator of the long-term performance of WIPP, DOE was involved in a programme of educational technical exchange and training with USEPA staff. Beginning in 1994, a series of USEPA stakeholder technical exchange meetings oriented USEPA technical staff on the status and history of data collection and model development. Performance assessment model training sessions were used to familiarise USEPA staff with methods and models. These exchanges were reported to provide opportunities for raising technical questions and concerns early, resulting in improvements in the technical quality of the compliance application. Familiarisation with the use of FEP screening as a method of resolving issues was identified as important. USEPA QA staff were invited to observe audits to relevant procedures and corrective action requests from the audits were reported to result in significant improvement in the implementation of the WIPP QA programme.

- **Deciding what data to collect.** The focus of data collection was thought to steadily narrow during the evolution of a siting project. The stages leading to waste disposal operations were identified as feasibility, viability and compliance certification.

  The feasibility phase of site selection was thought to confirm the absence of unacceptable features. In feasibility studies, the scope of data collection was broad. Few specific details were known about the disposal system, and wide ranges of data were needed to support the feasibility analysis.

  The viability phase provided evidence that total system performance satisfied applicable safety standards. As system understanding matures, site-specific data were sufficient to support preliminary quantitative estimates of uncertainty in overall performance. Conceptual models allowed assessing the relative importance of specific FEPs.

  The compliance certification phase confirmed the acceptable performance of the disposal system in documented evidence that was independently confirmed by the regulator through auditing and testing. In the final period before a compliance certification application was submitted, data collection focused on areas needed either to support the performance assessment or required explicitly by other regulatory conditions.

- **Developing model input parameters.** In large, mature projects it was thought that the scientists and engineers who collect data were seldom also responsible for the development and application of system-level performance assessment calculations. It was thought that in projects anticipating thorough external review, agreement between model developers and experimental scientists is critical. Therefore, a managed process was recommended as crucial to developing defensible model input parameters.

3.4.8 Summary

What was the regulator's role in judging the suitability of proposals for surface-based characterisation?

The decision by the regulator to allow disposal of transuranic waste at the WIPP facility was made through compliance certification in 1998. The main site investigations and construction of the disposal facility took place before USEPA was assigned a formal regulatory role in 1992. The developer was self-regulated before this.

USEPA issued guidelines for the methods to be used in the compliance certification determination. USEPA ruled that DOE only needed to consider a limited set of future human actions and specified the assumptions to make in assessing these actions.

USEPA has had a continuing role at the WIPP facility since the 1998 decision to issue a certification licence. It assesses the compliance recertification applications which the developer is required to submit every 5 years. This process is intended to verify that changes at the facility in the preceding 5 year period continue to comply with USEPA's disposal standards for radioactive waste.

NMED regulates the hazardous component of the waste under WIPP's hazardous waste facility permit. This permit prohibits certain types of wastes from entering the WIPP including liquid wastes, corrosive, ignitable and reactive wastes, and waste that has not been adequately characterised.

What decisions were made by the developer, the regulator and any other body (for example, government) based wholly or partly on information from surface-based site investigation?

The development of the WIPP facility occurred largely when the developer was self-regulated. The developer based the location of the repository on the results of surface-based drilling investigations. USEPA made the subsequent decision to allow waste emplacement at the site. NMED made the decision to allow the waste regulated under the Resource Conservation and Recovery Act (relating to waste exhibiting a hazardous trait such as flammability, reactivity, corrosivity, toxicity) to be disposed in WIPP.

URLs were used from the early stages of development at WIPP, either in nearby salt mines or in facilities later incorporated into the disposal facility. During the licence application, data from URLs were used to support information from boreholes and non-intrusive surveys.

How were data from desk-based studies and non-intrusive studies used to determine the purpose and location of the initial boreholes? How were the data from the evolving characterisation programme then used to determine the purpose and location of further sets of boreholes?

The Delaware Basin has a significant potash, oil and gas reserves. Early siting studies used the extensive amounts of data available from the associated prospecting activities – particularly borehole logs and the results of seismic surveys.

Subsequent borehole surveys by the developer were conducted to evaluate the effectiveness of various geophysical survey techniques in detecting karst features; deep karstic features were thought to potentially undermine the safety of any disposal facility. Boreholes were also used to acquire hydrological data and perform dissolution studies. Boreholes to obtain samples for potash assay were drilled to supplement the potash industry boreholes.

More recent geophysical investigations have included time-domain electromagnetic surveys to try and identify pressurised brine pockets beneath the disposal facility horizon. The results of these geophysical surveys were compared with brine pockets identified when they were penetrated by boreholes.

What criteria did the regulator use to allow development of a radioactive waste disposal facility to proceed to the subsequent stage?

USEPA's decision to certify compliance with the radioactive waste disposal standards in 1998 was based partly on assessment of the compliance certification application against its guidelines. These included details of the scenarios that the developer should consider and how specific parameters should be estimated, as well as instructions for the presentation of the application.

USEPA required the developer to:

- organise peer reviews of specified aspects of its work supporting the certification application
- address any comments made by reviewers

Before reviewing the certification application, USEPA arranged meetings with DOE staff for technical exchange and training. These meetings gave an understanding of data collection, model development and performance assessment methods.

Before publishing its decision to licence the WIPP facility, USEPA organised a series of public hearings at venues local to the WIPP site. Public comments submitted concerning USEPA's proposed certification decision were addressed in the certification decision.

3.5 Summary

3.5.1 Overview of surface-based investigations and the site selection/evaluation process

The review of surface-based investigations considered 3 case studies, which included the site investigations:

- in lower-strength sedimentary rock in the Meuse/Haute-Marne area of France
- in the crystalline rock at Forsmark and Laxemar-Simpevarp, Sweden
- to develop the WIPP facility, hosted in an evaporite formation in the USA

In each case, the focus is on GDF development to dispose of higher activity waste:

- spent fuel, vitrified HLW and long-lived ILW in France
- spent fuel, in a KBS-3 type disposal facility, in Sweden

- transuranic waste in the WIPP facility (corresponding approximately to long-lived ILW)

Stages of site investigations

The 3 GDF development programmes all involved site investigations conducted in phases. For each programme the most important phases are summarised below.

France

The development of a URL was a requirement of the 1991 Waste Act. The URL was to be used to investigate the potential to subsequently develop a GDF for higher activity waste. However, it was stipulated that the URL itself could not be used to dispose of waste. After preliminary intrusive surveys in 3 areas (Gard, Vienne and Meuse/Haute-Marne), the Meuse/Haute-Marne area was selected by the French government in 1998 to host the URL.

Andra’s investigations in the Meuse/Haute-Marne area developed in 2 strands: one relating to investigations in the URL to determine the feasibility of disposal, and the other on investigating the wider area around the URL. This second surveying programme involved defining a geographic domain (~250km^2) considered to be consistent with that the URL site with respect to the confining properties of the potential host formation. This area is called the ‘transposition zone’.

The results of Andra’s preliminary investigations were summarised in the Dossier 2005 Argile (Andra 2005a). After regulatory and other review of Dossier 2005 Argile, the 2006 Radioactive Materials and Waste Planning Act was passed (Andra 2006), specifying the framework for deep geological disposal. Based on geological criteria, Andra identified an area known as the ZIRA (zone of interest for further investigation) of ~37km^2 within the 250km^2 of the transposition zone. It is intended that the GDF will be sited within the ZIRA. It is expected that the results of ongoing investigations will be incorporated into a licence application for a GDF in the Meuse/Haute-Marne area to be submitted in 2015.

Sweden

The site investigations at Forsmark and Laxemar-Simpevarp were structured into 2 distinct phases called Initial Site Investigations and Complete Site Investigations. Only a limited amount of data were available on completion of the Initial Site Investigations. For example, at Forsmark this included data from 6 deep core-drilled boreholes. Both the Initial and Complete Site Investigations were organised into a series of 5 data acquisition campaigns followed by data freezes. There were 2 data freezes during the Initial Site Investigations and 3 during the Complete Site Investigations. At the start of the second phase there was a feedback to the investigation programme from teams involved in safety and engineering. At the conclusion of the Complete Site Investigations, there were 25 core-drilled deep boreholes at Forsmark and 46 at Laxemar-Simpevarp.

SKB's plans for site investigations at Laxemar-Simpevarp and Forsmark were based on criteria developed in 2 reports (Andersson et al. 1998, Andersson et al. 2000).

USA

Preliminary site investigations for the WIPP facility were conducted between 1974 and 1978, with the main phase of investigations taking place between 1978 and 1988. There have been investigations to support the compliance recertification applications submitted in 2004 and 2009, and geoscientific monitoring is continuing. A URL was developed in the WIPP facility in 1981. Both the preliminary and main phase of investigations included geological surveys, geophysical surveys and borehole investigations.

Geoscientific data acquired during site investigations

The 3 site investigations programmes share certain similarities. Each site investigation programme included an initial, limited campaign to establish or confirm the basic properties of the site of relevance to long-term safety and feasibility of construction. In particular geophysical methods and boreholes were used at an early stage of each site investigation programme to make an assessment of the geological, geochemical, geomechanical and hydrogeological properties of the sites.

Following these initial investigations, the case studies reveal a tendency to focus on a number of important issues specific to each site. Some examples of site-specific issues are given below.

- Andra devoted resources to establish the geometry and homogeneity in hydraulic properties of the Callovo-Oxfordian formation in a large area (~250 km^2) around the Meuse/Haute-Marne URL.
- SKB focused on understanding the complex flow paths and hydrochemical conditions present in the crystalline rocks present at Forsmark and Laxemar. The flow aspects involved hydraulic tests on single boreholes which measure the hydraulic properties of individual fractures (so-called Posiva Flow Log tests) and hydraulic tests in several boreholes separated by large distances in response to pumping.
- DOE conducted geophysical surveys to try to identify the location of pockets of pressurised brine beneath the disposal facility horizon after boreholes penetrated such pockets during site investigations. It also used geophysical surveys to search for karstic features.

These examples are strongly influenced by the type of geological environment being considered to host the GDF. Some aspects of the site investigations are also influenced by the type of waste and disposal facility concept being considered.

For example, the Swedish KBS-3 concept requires suitable hydrochemical conditions if the integrity of the copper waste canisters and bentonite buffer is to be maintained as designed. SKB devoted resources to establishing the present day hydrochemical conditions at Forsmark and Laxemar, and developed arguments that perturbations in groundwater chemistry during glacial episodes will not undermine long-term safety. SKB is also participating in the Greenland Analogue Project to improve the understanding of how an ice sheet could affect the groundwater flow and water chemistry around a deep GDF in crystalline bedrock during glacial periods and with the presence of permafrost.

The presence of materials in the waste packages (principally steel) which are expected to generate gas once a disposal facility is saturated has lead Andra in France to perform experiments in the URL to establish the effect of the expected gas pressures on the integrity of the host rock.

Even for identical disposal facility concepts and similar geological environments, the specific characteristics of a site might lead to differences in the course of the site investigations. For example, the relative lack of heterogeneity in the hydraulic properties of the rock at disposal facility depth and low numbers of flow-conducting fractures at the Forsmark site, compared with the conditions encountered at Laxemar-Simpevarp, lead to a smaller number of boreholes being drilled at Forsmark. There were 25 deep core-drilled boreholes at Forsmark compared with 46 at Laxemar-Simpevarp.

While many of the important issues requiring attention during site investigations might be apparent during planning activities, there remains the potential for unexpected results to influence the subsequent course of investigations. An example of this was the investigations by DOE in response to the observation that groundwater heads were increasing unexpectedly in a particular overlying geological unit. Investigations to account for these observations were made at the request of the regulator after the facility had been certified to dispose of waste.

Site evaluation and selection

In the programmes reviewed, the following types of decision have been made by developers, regulators, governments or other stakeholders:

- a decision, based on the evidence of preliminary site investigations, to continue site investigations in the expectation that there is a reasonable chance that it will be possible to develop a convincing safety case for that site
- consideration of the issue of how to select a volume of rock to host a disposal facility, with area ~5km^2, from a larger candidate area

SKB has, in addition, considered the problem of how to choose between 2 potential disposal facility locations, both of which had been characterised by extensive site investigation programmes.

In the French programme, the decision to proceed from feasibility studies to investigations to support the licensing of a GDF was marked by a new law, the 2006 Radioactive Materials and Waste Planning Act, which specifies the framework for deep geological disposal. The government decision to proceed with siting studies was based on regulatory and other reviews of the preliminary safety assessment known as Dossier 2005 Argile (Andra 2005a).

In France, Andra's approach to site selection was to identify an area of ~37km^2 within the 250km^2 of the transposition zone, known as the ZIRA (zone of interest for further investigation). The perimeter of the ZIRA was determined based on geological criteria – principally the depth and thickness of the clay formation and the hydraulic pressure gradients. It is intended that the GDF will be sited within the ZIRA and the locations of surface facilities will be informed by the wishes of local stakeholders.

In the Swedish programme, the decision to proceed from the Initial Site Investigations to the Complete Site Investigations was made by SKB on the basis of a comparison on the measured properties of the sites against criteria in Andersson et al. (2000) with additional confirmation from the SR-Can preliminary safety evaluation.

SKB's approach to site selection has focused on identifying areas which are sufficiently large to host a disposal facility while avoiding deformation zones. The decision to submit licence applications to construct a disposal facility at Forsmark instead of Laxemar was based on considerations related to long-term safety. The decision was justified by an evaluation of both sites in terms of the bedrock composition and structure, future climate, rock mechanical conditions, groundwater composition, solute transport, groundwater flow, biosphere conditions and site understanding (SKB 2011a).

A site for the WIPP facility in the USA was chosen based on a set of criteria which included the requirement to avoid known resources, dissolution features and boreholes along with a minimum required depth to the host formation. The proposed location of the WIPP facility was adjusted in response to the discovery of pockets of pressurised brine beneath the disposal facility horizon.

3.5.2 Use of geoscientific information in site investigations

Non-intrusive investigations

Following desk-based studies involving literature reviews and reviews of pre-existing geoscientific data, each of the programmes considered conducted geophysical surveys at an early stage of site investigations.

In the Meuse/Haute-Marne area:

- Two-dimensional seismic surveys along a 15km length were conducted in 1997 to make an initial assessment of the geological stratigraphy of the area (Lebon and Mouroux 1999).
- A 3D seismic survey covering 4km^2 around the URL site was conducted between 1999 and 2000 to provide a greater level of detail in this area (Andra 2005a).
- A total of 11 seismic lines, totalling 185km, were investigated between 2007 and 2008 to provide information about the geometric properties of the Callovo-Oxfordian host formation within the transposition zone (Delay et al. 2010).

SKB conducted airborne and ground geophysical surveys during the Initial Site Investigations. During this preliminary stage of investigations, SKB also performed other types of non-intrusive investigations such as outcrop mapping, hydrochemical analysis of surface waters, hydrological monitoring and ecological investigations. An important output from the geophysical surveys was lineament maps. Lineaments were assumed to be deformation zones and were subsequently investigated using boreholes. They were crucial features in determining the design and location of the proposed disposal facility.

Non-intrusive investigations at the WIPP site included geological surveys, seismic reflection surveys, electrical resistivity surveys, magnetic surveys and gravimetric surveys.

- Regional geological studies in the Delaware Basin were used to reveal areas of past and present dissolution activity.
- Seismic reflection techniques were used to provide information on the structure and depth of subsurface formations. Existing petroleum company seismic reflection data were supplemented with 42km of seismic reflection survey data, which were examined for evidence of major faults and other structures. More information on shallow horizons was subsequently acquired by instituting 209km of seismic reflection surveys.
- Surface electrical resistivity was assessed as being a valuable tool to search for dissolution related features in the Delaware Basin (Weart 1979). Resistivity surveys over known deep dissolution features, such as roughly cylindrical collapse chimneys or breccia pipes, were thought to give characteristic signatures.
- Magnetic methods were employed to search for both regional and local features expected to show magnetic contrast. Existing aeromagnetic surveys of the Delaware Basin were examined for indications of major faulting or igneous intrusions.
- Gravity data for the Delaware Basin were examined for indications of major geological structures and assessed for their utility in detecting collapse features. The absence of the former in the WIPP site and the failure of karstic collapse features to exhibit significant density differentials were reported to limit the usefulness of the gravimetric surveys.

In each of the programmes reviewed, non-intrusive surveys were supplemented with borehole investigations at the early stages of site investigations.

Intrusive investigations

Intrusive site investigations have included 2 components:

- borehole investigations
- experiments in URLs

The role of URLs has included research to determine feasibility in terms of long-term safety and demonstrations of the technology which would be used in the GDFs.

- Andra has developed a URL in the Meuse/Haute-Marne area. This URL cannot be used to dispose of waste as a condition of its construction. However, it is expected that the GDF will be located in an area nearby, with equivalent properties to the URL in terms of long-term safety and constructability.
- SKB has developed a URL at Äspö, near Simpevarp. It is not claimed that the rock here necessarily has the same properties as that at Forsmark or Laxemar. This facility has been used to build confidence in the

understanding of groundwater flow and transport in fractured crystalline rocks, for example, through the TRUE, ZEDEX, DECOVALEX and borehole sealing programmes. It has also been used to test operational procedures and engineered components of the proposed disposal facility.

- The URL developed at the WIPP site has subsequently been incorporated into the final disposal facility.

Geophysical surveys have been used to guide the location of subsequent intrusive investigations. This is most obvious in the case of the investigations at Forsmark and Laxemar-Simpevarp, where borehole investigations focused on confirming the existence of deformation zones previously identified by geophysical surveys. In the site investigations at the Meuse/Haute-Marne, boreholes were also used to investigate anomalies discovered during geophysical surveys.

Deep boreholes (~1,000 metres) have played an important role in understanding conditions at disposal facility depth in each of the case studies. Boreholes drilled for site investigations must be sealed no later than at the closure of the disposal facility so that they do not constitute flow paths from disposal facility depth to the biosphere. This might be done by filling the holes with bentonite or cement. Disposal facilities have been designed to avoid placing waste within specified distances of boreholes used during site investigations. SKB, in partnership with Posiva, has developed and tested materials and methods for sealing boreholes at Äspö HRL (Pusch and Ramqvist 2007).

Quality assurance and expert review

QA and knowledge management has been achieved through a combination of internal QA procedures, internal reviews and formal external peer review.

SKB developed the SICADA database to store the geoscientific information collected during site investigations. There was a system for reporting errors detected in data provided from SICADA.

QA procedures evolved during the course of site investigations at WIPP. In 1996, USEPA issued a requirement that only ‘qualified’ data could be used in DOE’s submissions to the regulator. DOE developed a procedure to qualify its existing data to the required QA standard. USEPA staff were invited to audit DOE QA procedures and corrective action requests from the audit were reported to result in significant improvement in the implementation of the WIPP QA programme.

SKB used the Site Evaluation and Design Review Group (SIERG), a review group of experts selected by SKB, to assess the main technical reports. SKB also organised uncertainty workshops involving people with responsibilities for engineering, site investigations and safety. These workshops reviewed what had been achieved in the site investigations and screened data for quality.

All the programmes considered in the case studies used external reviews to inform regulatory and government decisions.

The French government asked NEA to review Dossier 2001 Argile and Dossier 2005 Argile. These reports were also reviewed by CNE and the regulators. Positive reviews of Dossier 2005 Argile lead to the government decision to proceed to the next stage of GDF development, as specified in the 2006 Radioactive Materials and Waste Planning Act. The regulator reviewed the Andra’s proposed delineation of the ZIRA.

SKB’s SR-97 safety assessment was submitted to NEA to review. The regulator proposed to government that SKB be required to publish the SR-97 report before site investigations. The interim SR-Can and SR-Can safety assessment were also subjected to independent peer reviews. The SR-Site safety assessment is currently being reviewed by NEA. SKB's RD&D reports, which it is required to submit to the authority every 3 years, provide a forum for stakeholder involvement including the scientific community.

USEPA required DOE to commission independent peer reviews of specified aspects of its work regarding the WIPP facility. USEPA gave detailed instructions for how these reviews should be conducted and reported.

Safety assessment, engineering and design, and environmental impact assessments

The 3 principal 'end users' of geoscientific data acquired during site investigations are the groups responsible for safety assessment, disposal facility engineering and design, and environmental impact assessments.

The safety assessments and disposal facility designs have evolved during the course of site investigations, becoming more detailed or specific as more information becomes available. Safety assessments have been used to:

- mark the end of particular stages of investigations
- demonstrate and build confidence in methodologies
- inform government decisions to proceed to subsequent stages of GDF development

In France, the most important safety assessments have been Dossier 2001 Argile and Dossier 2005 Argile. Dossier 2001 Argile was based on limited site-specific data, as investigations in the Meuse/Haute-Marne had not produced many results at that time. Some of the data used were derived from the Mont Terri laboratory. The report was used to demonstrate methodology, and the calculations were used to inform disposal facility design and guide future plans for investigations, for example by revealing the importance of the disposal facility sealing. Dossier 2005 Argile was based on a substantial amount of geoscientific information from the Meuse/Haute-Marne area, although many experiments in the URL had not been completed at this time. Positive reviews of this feasibility assessment lead to the government decision to proceed with GDF development, by passing the 2006 Radioactive Materials and Waste Planning Act.

In Sweden, the SR-97 safety assessment was based on data from 3 analogue sites, as there was very limited data available from Forsmark or Laxemar-Simpevarp prior to the site investigations. The assessment was intended to demonstrate methodology.

SKB's interim SR-Can safety assessment was also intended to demonstrate improved methodology and to guide the developer in planning the subsequent stages of site investigations. It was based on limited data from Forsmark (data sets from boreholes were limited to information from one ~1,000 metre deep core-drilled borehole and 8 percussion-drilled boreholes each 150–200 metre deep). The SR-Can safety assessment was based on site-specific data acquired during the Initial Site Investigations (6 deep core-drilled boreholes each ~1,000 metres deep at Forsmark, for example). It was used to make a first assessment of the safety of potential KBS-3 repositories at Forsmark and Laxemar. The scenario of buffer colloid release became an important consideration in the assessment of long-term safety in SR-Can and placed extra requirements on the geosphere.

The SR-Site safety assessment produced recently by SKB uses a similar methodology to that developed in SR-Can. However, it is based on the SDMs developed at the conclusion of the Complete Site Investigations and so draws on a significantly larger pool of geoscientific data. The SR-Site safety assessment is a crucial component of SKB's licence applications to construct a GDF.

Regulatory involvement at the WIPP facility began after site investigations and construction were substantially complete, although an iterative development of the performance assessment calculations is reported prior to this.

To develop an EIA for the proposed disposal facility, Andra set up a permanent Observatory of the Environment at Meuse/Haute-Marne. It is intended that the observatory will track the evolution of the local environment for over a century (the period of operation of the disposal facility). Once the site is selected in late 2013, Andra will summarise the data available to establish the initial state of the disposal facility environment. The initial state will describe natural resources and natural areas of agriculture, forestry, forestry or recreation, as well as material assets and cultural heritage likely to be impacted by the project.

SKB considered that the EIA would be informed by the SDMs developed during site investigations, particularly those relating to the surface ecosystems discipline. As part of its preparations for the site investigations, the regulator in Sweden reviewed experiences from other countries and from other large development projects. Issues for consideration in the design of the EIA were discussed as part of this review activity (Bjarnadottir and Hilding-Rydevik 2001).

Biological studies of the WIPP site began in 1975 to gather information for the Environmental Impact Statement. Meteorological and environmental studies were developed over the subsequent 2 years.

3.5.3 Roles of the regulator during site investigations

Regulatory permitting to start intrusive investigations

A regulatory distinction between non-intrusive and surface-based intrusive investigations is not marked in the French and Swedish programmes. Site investigations at WIPP were self-regulated by the developer (DOE and predecessor organisations).

The French government made the decision to proceed with development of a URL in the Meuse/Haute-Marne area, intended to establish the feasibility of development of a GDF, on the basis of limited (intrusive) investigations at 3 sites (Vienne, Gard and Meuse/Haute-Marne). The geoscientific information available about the Meuse/Haute-Marne area in 1999 amounted to 15km of 2D seismic surveys and 3 boreholes 530–1,100 metres deep, with measurements of the bedrock geology, hydraulic conductivity, mechanical and thermal properties and mineralogy (Lebon and Mouroux 1999), in addition to that obtainable from desk-based studies.

In Sweden, the regulator has had a role prior to, and during, site investigations due to the requirement that it reviews SKB's work programme every 3 years. The regulator therefore reviewed decisions to choose Forsmark and Laxemar-Simpevarp as candidate areas. SKI proposed that the government should impose the condition that before site investigations were initiated, SKB should present a safety assessment of the proposed main system alternative as well as commissioning and presenting an independent peer review of the safety assessment by national and international experts. This proposal was accepted by the Swedish government and implemented by SKB as the SR-97 Safety Assessment (SKB 1999). The SR-97 assessment was based on data from analogue sites. Planning for the site investigations was reported in 2000 (SKB 2000c).

The regulators commissioned reviews of specific aspects of SKB's proposed approach to the site investigations such as their geochemical and biosphere characterisation plans (Bath 2002).

The geoscientific information available at Forsmark from the desk-based studies stage (called feasibility studies in the Swedish programme) included bedrock geology maps, magnetic and electrical survey results from airborne measurements, near-surface borehole data, outcrop mapping and hydrochemical data from a deep borehole (700 metres) at Finnsjöområdet.

Regulatory involvement during site investigations

Regulatory involvement during site investigations can be considered under the following headings:

- regulatory advice to government based on reviews of reports as part of a staged process of authorisation
- regulatory advice to government based on periodic review of the developer's plans
- meetings between the regulator and developer to track the developer's progress or discuss issues of concern

According to government decisions, SKB was to consult with the regulators on the site investigation programme before and during the site investigations. The regulators reviewed the interim SR-Can and SR-Can safety assessments. The regulatory review of the licence application, including the SR-Site assessment of long-term safety, was taking place at the time of writing. The regulator has had a role throughout the site investigations due to their obligation to review SKB's RD&D programme every 3 years.

During the site investigations, the regulator used expert groups (mainly the INSITE group) to track SKB's activities. INSITE developed written documentation to resolve issues when interacting with SKB. This led to the development of the Tracking Issues List, which became the single means of eliciting written responses from SKB to allow INSITE to establish its position or view properly. INSITE noted that, in retrospect, it would have been useful for SKI to formally request full responses from SKB to the Tracking Issues List as a matter of course. INSITE used Field Technical Reviews to provide the regulator with a view on the scientific and technical quality of the site investigations.

The main phase of investigations at the WIPP site was self-regulated by the developer. However, after USEPA was appointed as regulator, there was a programme of educational technical exchange and training between DOE and USEPA. Beginning in 1994, a series of USEPA stakeholder technical exchange meetings discussed the status and history of data collection and model development. Performance assessment model training sessions were used to familiarise USEPA staff with the methods and models used by DOE.

The WIPP compliance criteria provide USEPA with the authority to inspect activities at the WIPP facility and at all off-site facilities that provide information in certification applications. Since 1998, USEPA has conducted periodic inspections to verify the adequacy of information relevant to certification applications. It has also conducted annual inspections at the WIPP site to review the monitoring programme. USEPA has also inspected the emplacement and tracking of waste in the disposal facility.

Permitting to begin construction and operations

Andra is working to prepare a licence application for a GDF in the Meuse/Haute-Marne. It is expected that this will be submitted in 2015.

In 2011, SKB submitted the licence applications to construct a disposal facility, including the SR-Site safety assessment. The regulator currently envisages approximately 30 staff carrying out the review, using external expert support, and with an annual budget of €1.5–2.0 million. The review is expected to take over 2 years. The regulator is expecting to independently check SKB's calculations. Some of this work, such as dose calculations, is expected to be done by SSM staff. Other work will be done by external contractors. NEA has been asked by the Swedish government to organise a peer review of SKB's post-closure safety assessment. However, this is not a formal part of the Swedish licensing or decision-making process. It is expected that the regulator will impose conditions on underground investigations.

USEPA gave provisional certification for the WIPP facility in 1997, with a period of public comment before the final certification decision in 1998. USEPA made its certification decision by comparing relevant information to the WIPP compliance criteria. These compliance criteria, which were developed by USEPA, are quite prescriptive, specifying details of the scenarios to be considered and the way results of dose calculations are to be presented. They also include requirements for engineered barriers and post-closure monitoring. In making decisions, USEPA relied on:

- materials prepared by it or submitted by DOE in response to USEPA requests for specific additional information necessary to address technical sufficiency concerns
- technical reports generated by USEPA and its contractors
- USEPA audit and inspection reports
- public comments on USEPA's proposed certification decision during the public comment period

Regulatory involvement with stakeholders

In France, the CLIS (committee for local information and monitoring) at Bure was established in 1999 with the mission to inform its members and local people about the activities in the URL, and monitoring and research results. It has 91 members, including democratic representatives of the 2 regions of Lorraine and Champagne-Ardenne and the 2 departments of the Meuse and Haute-Marne. It also includes independent technically qualified individuals to interpret Andra's work. The CLIS is involved in specifying the location of surface facilities for the proposed disposal facility. ASN provides CLIS with financial support; CLIS throughout France received around €600,000 from ASN. ASN also supports the various CLIS throughout France by regularly informing them about what it is doing. Andra is required to respond to CLIS enquiries.

In Sweden, the regulator collates stakeholder views (for example, from the municipalities hosting site investigations, universities and NGOs) – and publishes them as part of its review of SKB's RD&D report every 3 years. The municipalities organised study groups during the site investigations and invited SSM to be involved.

USEPA organised and chaired public hearings about the WIPP facility. In 1998, 6 hearings at local towns were held to receive comments about the proposed decision to certify WIPP. USEPA responded to these comments in its final decision to certify WIPP.

4. Observations

This chapter contains observations based on discussions with developers and regulators in other countries. These observations do not form part of the case studies as they are based on the experience of the individuals. Furthermore, some of the issues discussed, such as stakeholder compensation, are peripheral to the scope of the project. Nevertheless, it was considered that these observations might provide insights which could be useful in the context of the UK's MRWS programme. It is particularly relevant to highlight issues where there might be consensus and where there are issues which are approached differently by the representatives of different organisations.

The observations in this chapter should be considered in conjunction with the summaries of the case studies relating to desk-based investigations and surface-based investigations in Sections 2.6 and 3.5 respectively. In general, the comments are not attributed to specific programmes unless they confirm views expressed in publicly available documents.

The approach taken is to organise the various issues and points discussed with separate organisations into a series of generic themes so as to enable overall observations to be made as well as highlight issues more specific to individual programmes. Effort is made to distinguish between cases where similar issues and opinions were voiced by several organisations interviewed from ones raised by individual organisations.

4.1 Site selection process

A range of objectives for the site selection process are apparent in the programmes considered. All the developers had the goal to demonstrate that the site selected is adequate to meet requirements on long-term safety, as determined by the regulator, government and possibly other stakeholders. However, other siting objectives have also been evident, such as the intention to:

- identify a site which is at least comparable with normal conditions for the available geological environments
- identify a site such that there is no obviously better site available
- identify a site on the basis of long-term safety, free from short-term economic or societal factors, in a national scale search

Generally the developer is required to give due consideration to possibilities to increase the long-term integrity of the disposal system within the bounds of the site selection strategy. The overall selection process is usually defined by government to provide due consideration of relevant societal impacts, as well as to define measures to ensure quality and transparency. The goals of the siting process may evolve with the programme as understanding of the requirements placed on the site by the disposal facility concept as it develops.

A related issue is that, during desk-based studies, pre-existing geoscientific information is likely to be mainly non-intrusively acquired data with only limited intrusive site-specific data available. For relatively homogeneous and well understood sedimentary host formations, such information may be sufficient to make comparisons between sites based on criteria such as depth and thickness of formation, and those relating to long-term stability. In more heterogeneous high strength rocks, the uncertainties associated with comparing sites at this stage are considered to be greater and hence making desk-based siting decisions is likely to be more difficult.

4.2 Site investigations

The phasing of data acquisition cycles was identified in some programmes as being important (see, for example, Skagius et al. 2008) to perform the site investigations successfully because site-specific information is required to inform safety assessments, facility design and environmental impact assessments. However, some interviewees also noted that sufficient time to update site descriptions is required before the data can be used for these purposes. Such experience suggests that, when planning the phasing of investigations, allowance needs to be made for feedback from end users in safety assessment and facility design, as well as from reviewers and the local communities. In the case of Switzerland, the feedback from the local communities included the request that extra seismic surveys of the siting regions be performed during Stage 2 of the Sectoral Plan. Hence, steps involving review and engagement can have consequences for time schedules and the scope of subsequent stages of investigation.

An observation from several interviewees is that the number of boreholes drilled within the target area, required to support facility layout and safety assessment, has to be weighed against the potential detriment of introducing pathways through the host rock that require sealing. Typically more boreholes are required in heterogeneous host rocks to address uncertainties in structural geology and rock properties, as evidenced in the case studies. Examples of the process of determining when sufficient data from boreholes have been acquired are the confidence assessments carried out by SKB. One interviewee involved in a national programme developing a disposal facility in a high-strength heterogeneous host rock noted that an alternative strategy to determining facility layout using boreholes constructed from the surface could be to place more emphasis on developing an adaptive design during the construction based on conditions encountered underground. In the programmes investigating homogeneous sedimentary formations, drilling within the target area is typically avoided and considered unnecessary, as in the case of the Callovo-Oxfordian formation in France (see Section 3.2.3).

Developers have invested in the development of new characterisation techniques and equipment to provide specific information required in safety assessment. An example is Posiva’s development of a flow logging tool to measure flow in individual fractures. One regulator interviewed advised that technology advances in remote sensing techniques to detect subsurface structures and interpret groundwater chemistry should be followed. Examples given included electromagnetic studies, gravimetric surveys and micro-seismic surveys.

Integration of existing data from various sources had been an important process during the desk studies phase for several developers. An example given by one developer was the integration of borehole and 2D seismic into a consistent 3D geological model, although it was noted that this can be time consuming.

Several developers noted the importance of defining processes for data management, data clearance for end users in safety assessment and design, and handling of errors.

Some interviewees considered that a developed and well explored disposal facility concept and a good general knowledge, though not necessarily site-specific, of the particular host rock environment are essential elements for developing siting criteria. A part of developing a disposal facility concept is that alternative configurations and material selections have been analysed during the process. However, one interviewee pointed out that it would be difficult to define siting criteria if several different or alternative disposal facility concepts are considered at the same time. During the site selection and evaluation processes, definitions of criteria develop alongside knowledge of underground conditions and the performance of the engineered barriers. Several factors have to be weighed in the optimisation of the selection including constructability.

4.3 Use of safety assessments

Safety assessments have been used in the other national programmes reviewed for various purposes, including to:

- provide a means to integrate understanding of disposal facility concepts, engineered barriers and requirements needed from the geological environment
- inform regulatory and other decisions regarding whether to proceed at a site
- guide the site investigations and the development of disposal facility technology and design
- provide a point of engagement with stakeholders

The developer, regulators and governments in the other national programmes reviewed have had to make decisions about how detailed and quantitative a safety assessment should be at different stages of their programmes. The issue of how to present safety assessments is particularly pertinent when the available data are limited, as is likely to be the case during the initial stages of site selection.

Although data might be limited at the early stages of site investigation, experience from the several national programmes reviewed is that site-specific safety assessments may provide the following benefits:

- demonstrating to stakeholders that tangible progress has been made
- providing a focus for discussions with the regulator or other stakeholders
- providing engagement with the local communities
- developing the expected site evolution and identifying potentially problematic scenarios
- developing the teams and capability as well as integrating different disciplines
- demonstrating that the proposed assessment methodology works
- providing a basis for discussing the planning of investigations with stakeholders

However, the same experience demonstrated that safety assessments based on limited site data may also have significant limitations. Hence, when presenting a preliminary safety case it was considered important to explore and illustrate uncertainties. Furthermore, the level of ambition for overall safety assessment and associated siting decisions might be limited in such preliminary assessments. Some site-specific features might readily be included such as geometry of the rocks, depth trends in overburden/stress and some properties.

One observation made by an interviewee was that the role of the geosphere in contributing to the overall demonstration of safety in the KBS-3 concept has varied in importance as understanding of the performance of the engineered barriers and their evolution has developed through successive safety analyses.

One regulator interviewed noted that the developer needs to continue to consider and explore alternative concepts during the site investigations and evaluations at least until licence application. This corresponds to activities that would be carried out during Stage 6 of the MRWS site selection process, although not at the beginning.

4.4 Critical review and experiences of regulators

One developer advised that external review groups can be used by the developer to review technical reports and in advisory/strategic planning.

Some developers, while acknowledging the importance of peer reviews, noted that the peer review process can become dominated by particular issues and the views of the individuals involved. Careful consideration is therefore advised in selecting peer review groups to ensure a good balance.

In most of the national programmes considered in this report, the developer produces research, development and demonstration plans every 3–5 years either through obligation or for engagement purposes. These are reviewed by the regulator. Both developers and regulators saw benefits in doing this in terms of:

- providing an instrument for the regulator to review the developer's progress
- developing and preserving competency internally and externally
- maintaining international contacts
- providing information to the public
- providing a forum for engaging the scientific community in reviews and research projects
- providing an opportunity for critique at an early stage so that issues can be addressed ahead of the licence application

Of the regulators interviewed, most started out with a handful of staff working on the geological disposal project that increased to about 10–15 during the most important review and licensing steps. When bringing in new staff it should be recognised that it takes time for scientists to develop an understanding of the regulatory framework and environment. Some regulators have sponsored PhD studentships to perform research on issues of special interest. It was considered good practice by those interviewed for the regulator to develop a strategy to ensure they have sufficient in-house knowledge to review the main parts of the licence application, such as the assessment of long-term safety, although in some cases it was found difficult to retain specialists over the long course of disposal projects, typically greater than 15 years. Because the regulatory team is typically small in comparison with the developer's, it is susceptible to staff loss. The regulators typically develop detailed understanding in selected areas, and maintain the capability to advise on technical areas and to perform independent safety analyses.

One regulator interviewed advised that engagement between the regulator and developer early in the process is important as often the relevant legislation does not prescribe detailed requirements on what a licence application should include.

4.5 Interaction with stakeholders

Positive engagement with stakeholders, particularly the local community, was stressed by several interviewees as a prerequisite for successful development of a GDF. Related comments and issues raised by several interviewees are collated below.

- When people's concerns about geological disposal were surveyed it was found that they tended to be of a practical nature, similar to concerns about any large construction project, and tended to be limited to timescales of the next few generations. The impact on the reputation of the local community was also a major concern.
- It was thought important for the implementer to have an office in the host community.
- It can be difficult to manage public expectations about the timescales required to make proper decisions on details of siting and facility design. The public might expect important decisions, whether safety-related or not, to be made transparently available at an early stage, while the developer is likely to have a limited basis (in terms of assessing long-term safety) for making such decisions until further data are collected.
- It is important for the regulator to maintain open channels with the developer through meetings and to make records of them publicly available.
- In some countries, the regulator may act as an expert for the public, while also having a role to inform the public about issues and news relating to the disposal facility project and other wider nuclear issues.
- All parties involved in the project should encourage local communities to engage in the process.
- Local communities are often supported by having access to a group of technical experts, but such experts should be restricted to advising on technical matters and have no political or commercial interests in the project.
- Public involvement can become dominated by pressure groups or NGOs.

5. Conclusions

The geological environment at a site (the geosphere) is required as part of a system of multiple barriers to:

- provide a barrier against escape of radioactivity
- isolate the waste from disturbances at the surface
- reduce the likelihood of human interference

The ability of the geosphere to fulfil its roles in ensuring safety potentially changes in time. Some aspects of a site's evolution affect a disposal facility's ability to isolate the waste, for example, through erosion of overlying rocks. Others affect the ability of the geosphere to retard radionuclide transport, for example, future climate change may alter the patterns of groundwater flow.

The types and quantities of radioactive waste, the packaging and conditioning of the waste, and the disposal facility design and construction materials – collectively called the disposal facility concept – determine the requirements on the geological environment that are necessary to ensure safety. Therefore, different disposal facility concepts place different requirements on their geological environment. Quantitative requirements on the geosphere derived for one national programme may not therefore be directly applicable to any other. Hence, the suitability of a site in terms of safety has to be judged in the context of the specific disposal facility concept proposed for the site.

This chapter summarises the findings of the case study reviews of other national programmers relative to the overall MRWS site selection process (Defra et al. 2008), and the framework for desk-based evaluations in MRWS Stage 4 (DECC 2012). The conclusions take account of best practice used elsewhere and the Environment Agency's regulatory guidance for geological disposal (Environment Agency and NIEA 2009). The conclusions are structured according to the process of site selection and evaluation, the use of geoscientific information and the role of the regulator.

5.1 Process of site selection and evaluation

Voluntarism can be seen in all the national approaches to site selection examined in the case studies. All the case studies include requirements for local support or democratic consent, but they come either at later stages of the siting process, or are typically targeted at selected communities. The siting programmes reviewed here have generally involved national scale searches for sites before seeking volunteer communities in potential siting areas. This is different from the former MRWS site selection process, which uses voluntarism from the initial stage of site selection onwards. This approach is similar to those being used in Japan (NUMO 2004) and Canada (NWMO 2010), which also initially rely on potential host communities volunteering to host a facility. However, at the time of this review, site selection within these programmes was not sufficiently advanced to be reviewed to support the objectives of this project.

In other countries, the regulator has either been involved directly in reviewing the site selection process, as in Switzerland, or has other statutory duties relating to reviewing research and development plans, as in Finland and Sweden, which provide an instrument for the regulator to track and comment the selection strategy and its progress. In contrast, the Environment Agency will provide advice and comment on regulatory matters during the site selection process and will only have a statutory regulatory role should surface-based intrusive site investigations start at one or more candidate sites. This difference in role is intended to maintain the Environment Agency's independence from decisions on site selection.

Each of the national programmes reviewed has had to balance safety, technical, environmental and societal factors. Each have also based the selection of suitable areas on safety related factors as far as possible, sometimes including environmental factors within the early screening. For example, the Swiss Sectoral Plan states,

> 'Safety has highest priority: the long-term protection of man and the environment has to be assured. This means that radioactive substances have to be safely isolated from the biosphere until such time as their radiotoxicity has decayed to acceptable levels. After safety come aspects of spatial planning, ecology and economic and societal considerations'.

Similarly, SKB claims that:

> '… there is no other site that is obviously better than the selected one, and that can be made available with reasonable labour inputs' (SKB 2011a).

In the cases of Sweden and Finland where selections have been made between host formations or sites, long-term safety has been the over-riding concern.

All the national programmes reviewed here have evaluated alternative sites and in some way demonstrated that alternative geological formations or sites do not offer clear advantages over the sites selected based on available geoscientific information. Implementing organisations do not claim to have found the 'best' site nationally, but they might be able to argue there is no indication that a clearly better geological solution exists. The investigations or studies necessary to support such arguments have been developed either as a consequence of the form of the site selection process (as determined by government), as a choice by the implementer, or at the instigation of the regulator. It should be allowed that goals of the siting process may have to evolve with the programme as understanding of the requirements put on the site by the disposal facility concept develops.

In choosing a site, the IAEA guidelines (IAEA 1994; IAEA 2011) state that the objective of site selection is not to locate the best site, but to provide a disposal system which can be convincingly shown to comply with established safety and environmental requirements. In light of the IAEA guidance, the focus of desk-studies could be more on selecting a suitable candidate site (or sites) within available areas and constructing convincing demonstrations that the available areas are adequate from a long-term safety perspective. At the desk study stage, this could involve relatively simple comparative studies based on assessment of suitable geological formations, geophysical, geotechnical and geographical information, along with elicitation of properties from analogue studies or engagement of experts. In the countries examined in the case studies, an initial screening process has often been applied to reduce the number of potential sites and sites for investigation have been selected in a stepwise process weighing only 1 or 2 groups of factors to weigh the relative merits and detriments of sites within an individual step.

Swedish experience warns against the exclusion of areas based on low resolution screening (for example, of ore potential) since it can rule out potentially suitable areas on the scale of a site (~5km^2) when considering averaged geoscientific information on the scale of 10–100km^2. This lesson may be relevant to screening processes applied where the availability of suitable areas may be limited.

During desk-based studies, pre-existing geoscientific information is likely to be mainly non-intrusively acquired data with only limited intrusive site-specific data available. For relatively homogeneous and well understood sedimentary host formations, such information may be sufficient to make comparisons between sites based on criteria such as depth and thickness of formation, and those relating to long-term stability. In more heterogeneous high strength rocks, making desk-based comparisons of sites is likely to be more difficult because less information about such criteria may be available.

5.2 Use of geoscientific information

The national programmes considered in the case studies indicate that it is difficult to evaluate the potential suitability of a site based on non-intrusive investigations alone. Sweden and Finland have preferred to develop areas where the host formation is exposed nearby, so that some level of confidence and quantitative surface characterisation (outcrop mapping, trenches or pre-existing tunnels) can be gained for a site prior to intrusive investigations.

In fact, extensive intrusive site investigation programmes were not performed in any of the national programmes considered here without either a preliminary survey with a small number of boreholes (as in Finland and France) or availability of local data from earlier investigations, third party drilling or research programmes (as in Sweden, Switzerland and the USA).

Each country has investigated bedrock conditions (geology, hydrogeology, hydrochemistry) by at least one borehole prior to selecting one or more sites for detailed investigations to address uncertainties and enable quantitative site comparisons.

An objective of surface-based investigations, such as geophysical studies and drilling of boreholes, at potential sites would be to provide geoscientific evidence that a preferred site can be identified at which a GDF could be developed with the required long-term environmental and safety performance. If there is insufficient pre-existing geoscientific data at depth, preliminary investigations may be necessary to:

- provide information to support important site selection arguments, such as the potential volume of host rock within a particular geological formation
- validate decisions made on interpretation of geophysical information, prior to a full investigation programme

It is noted that non-intrusive investigations in Finland and Sweden have been aided by additional outcrop mapping and interpretation of lineaments. Desk studies in Switzerland were supported by widespread existing seismic surveys; at WIPP they were based on information from potash and oil exploration in the region. Experience from other national programmes suggests that, if it is not possible to conduct quite dense geophysical surveys or surface mapping to support identification of potential sites, there may be significant uncertainty in bedrock properties at the time decisions are taken to select a potential site or sites for further characterisation.

The phasing of data acquisition for the site investigations into several campaigns spaced by data freezes is generally seen as good practice. Site-specific information is required to inform safety assessments, disposal facility design and environmental impact assessments, and hence phasing allows end users to provide feedback on data requirement and assess the level of confidence achieved at each phase. However, experience from the Swedish programme is that sufficient time has to be allowed to update site descriptive models before the data can be properly utilised by the end users. In the case of Switzerland, the feedback from the local communities included the request that extra seismic surveys of the siting regions be performed during Stage 2 of the Sectoral Plan. Hence, steps involving review and engagement can have consequences for time schedules and the scope of subsequent stages of investigation.

All the national programmes reviewed have used progressive safety assessments to help inform safety criteria applied within the site evaluation process. Initially this may be in the form of generic assessments to inform the requirements of the disposal facility concept. The concept itself needs to be optimised in terms of considering alternative configurations and material selections during the process. However, one interviewee noted that it would be difficult to define siting criteria if several different or alternative disposal facility concepts are considered at the same time. Generally, site-specific assessments have been deployed at early stages in the site selection. Some examples are given below.

- Stage 2 of the Swiss Sectoral Plan will include radionuclide transport calculations at several sites.
- In Sweden, the SR-97 safety assessment was used to illustrate the performance of a KBS-3 in 3 alternative hydrogeological settings.
- In Finland, successive safety assessments were produced throughout the site selection and investigation.
- In France, safety assessments were produced for the granitic and argillaceous host formations.

Safety assessments will be developed progressively through the process for siting and developing a GDF. Before any potential sites for developing a GDF are identified, a largely generic safety assessment might be sufficient to guide the definition of site requirements, possibly with variants to address broad differences between available geological environments, for example, higher strength rocks versus lower strength sedimentary rocks. Generic assessments might be used to inform the development of safety functions related to the engineered barrier system, or in the identification of relevant scenarios to be assessed or identifying problematic issues, or for screening the importance of features, events and processes (FEPs). After potential sites become available, site-specific safety assessments will be developed taking account of available knowledge and understanding of the potential host geology for a GDF including geoscientific information obtained from site investigation studies.

Depending on the availability of geoscience information and data, limited site-specific quantitative safety assessments might be appropriate in desk-based studies to evaluate the suitability of potential sites. Such site-specific assessments may be focused on answering specific issues raised where a particular site differs from the reference conditions assumed in the generic assessment, such as details of structural features, topography, or groundwater chemistry. Such site-specific assessments were used to compare sites in Stage 2 of the Swiss Sectoral Plan. If appropriate information is available, assessments might involve developing a basic conceptual model for the structural geology and hydrogeology of a potential site. The safety assessments might be supported by limited scoping calculations of, for example, groundwater flow taking into account broad uncertainties in the basic conceptual model. This might provide information to aid decisions on eliminating any sites clearly less suitable than the others.

In the national programmes reviewed, several developers and regulators reported benefits in commencing the development of site descriptions and site-specific safety assessments at an early stage. The main benefits are that such work provides a focus for discussions between the parties involved and for engagement with stakeholders to present the planned site investigations and to demonstrate the credibility of the approach and the team.

5.3 Role of the regulator

The experience from other national programmes is that government and the regulator have often been driving forces in ensuring that the site selection process is objective and transparent. In general, measures have been taken to ensure that sufficient siting alternatives have been considered and that site selection criteria have been developed and applied with appropriate balance and transparency. In the examples considered, initial screening of potential areas was largely based on geoscientific factors, followed by environmental and societal factors after specific sites were located later in the process.

In most of the national programmes reviewed in this report, the developer produces research, development and demonstration plans every 3–5 years which the regulator reviews. Regulators have found this beneficial as an instrument for them to review the developer's progress and in providing a forum for maintaining international contacts and the dissemination of information to domestic stakeholders.

Prior to regulatory decision points, regulators have put in place processes to enable them to develop appropriate plans, resources and capabilities to perform regulatory reviews of submissions supporting applications to develop GDFs. Most regulators have had to expand significantly to meet the responsibilities during the important review and licensing steps. They recognise the challenges in the time taken for new staff to become familiar with the regulatory framework and environment, and in the retention of specialists over the long course of disposal projects. The regulators typically develop detailed understanding in selected areas, and maintain the capability to advise on technical areas and to perform independent safety analyses.

Those interviewed advised that the regulator discusses requirements and what it expects in the licence application with the developer during the pre-licensing phase and maintains open channels of communication throughout the process.

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List of abbreviations

2D	two-dimensional
3D	three-dimensional
ACM	Alternative Conceptual Model
Andra	Agence nationale pour la gestion des déchets radioactifs [National Radioactive Waste Management Agency] [France]
ASN	Autorité de Sûreté Nucléaire [Nuclear Safety Authority] [France]
BGS	British Geological Survey
CLIS	Comité Local d'Information et de Suivi [Committee for Local Information and Monitoring] [France]
CNDP	Commission Nationale du débat public [National Commission on Public Debate] [France]
CNE	Commission Nationale d'Evaluation [National Evaluation Commission] [France]
CRW	Commission for Radioactive Waste Disposal [Switzerland]
DETEC	Federal Department of the Environment, Transport, Energy and Communication [Switzerland]
DFN	discrete fracture network
DGEC	Directorate General for Energy and Climate [France]
DGSNR	Direction Générale de la Sûreté Nationale et de la Radioprotection [France]
DOE	Department of Energy [USA]
EBS	engineered barrier system
EDZ	engineering disturbed zone
EEG	New Mexico Environmental Evaluation Group
EIA	Environmental Impact Assessment
ENSI	Eidgenössisches Nuklearsicherheitsinspektorat [Federal Nuclear Safety Inspectorate] [Switzerland]
ESchT	German expert group that follows geological disposal in Switzerland

FEP	Features, Events and Processes influencing long-term safety
FHP	Fortum Power and Heat [Finland]
FTR	Field Technical Review
GDF	geological disposal facility
GTK	Geologian tutkimuskeskus [Geological Survey of Finland]
HLW	high level waste [radioactive waste]
HRL	Hard Rock Laboratory
HSK	Swiss Federal Nuclear Safety Inspectorate
IAEA	International Atomic Energy Authority
IEER	Institute for Energy and Environmental Research
ILW	intermediate level waste [radioactive waste]
IPSN	Institute for Nuclear Safety and Protection [France]
IRSN	Institut de radioprotection et de sûreté nucléaire [Institute for Radiological Protection and Nuclear Safety] [France]
IRT	International Review Team [of the NEA]
KASAM	Kärnavfallsrådet [Swedish National Council for Nuclear Waste]
KBS	Kärnbränslesäkerhet [nuclear fuel safety] [Swedish spent fuel disposal concept]
KNE	Commission on Nuclear Disposal [Swiss]
KSA	Eidgenössische Kommission für die Sicherheit von Kernanlagen [Swiss Federal Nuclear Safety Commission]
LiDAR	light detection and ranging
LLW	low level waste [radioactive waste]
MEE	Ministry of Employment and Economy [Finland]
MRWS	Managing Radioactive Waste Safely
NEA	Nuclear Energy Agency [of the OECD]
NGO	non-governmental organisation
NIEA	Northern Ireland Environment Agency

NMED	New Mexico Environment Department
NSC	Nuclear Safety Commission [Switzerland]
OECD	Organisation for Economic Co-operation and Development
OPRI	Office for Protection against Ionising Radiation [France]
ORNL	Oak Ridge National Laboratory [USA]
PNGMDR	National Radioactive Materials and Waste Management Plan [France]
QA	quality assurance
R&D	research and development
RD&D	research, development and demonstration
RWMD	Radioactive Waste Management Directorate [UK]
SDM	Site Descriptive Model
SER	Site Engineering Report
SFOE	Swiss Federal Office of Energy
SGU	Sveriges geologiska undersökning [Swedish Geological Survey]
SKB	Svensk Kärnbränslehantering AB [Swedish Nuclear Fuel and Waste Management Company]
SKN	National Board for Spent Nuclear Fuel [Sweden]
SKI	Statens karnkraftinspektion [Swedish Nuclear Power Inspectorate]
SNL	Sandia National Laboratories [USA]
SSI	Statens strålskyddinstitut [Swedish Radiation Protection Authority]
SSM	Strål säkerhets myndigheten [Swedish Radiation Safety Authority]
STUK	Radiation and Nuclear Safety Authority [Finland]
TIL	Tracking Issues List
TDS	total dissolved solids
TVO	Teollisuuden Voima Oy [Finland]
URL	Underground Rock Laboratory [used here for all such facilities although they are referred to by different acronyms in some programmes such as the Äspö HRL for Hard Rock Laboratory in Sweden]

USEPA	US Environmental Protection Agency
USGS	United States Geological Survey
WIPP	Waste Isolation Pilot Plant [USA]
ZIRA	Zone d'Intérêt pour la Reconnaissance Approfondie [zone of interest for further investigation]

Glossary

Acid rock	Volcanic rock with a high silica content (greater than 63% SiO_2 by weight). Sometime used as a synonym for felsic rock.
Anticlinal structure	Anticlinal structures have folds that are convex up and have their oldest beds at their cores. They are associated with oil and gas reserves.
Brittle	A rock is brittle if, when subjected to stress, it breaks without significant deformation. A brittle deformation zone is a fracture zone or fault zone.
Deformation zone	A rock volume which deforms in response to a stress field. A deformation might be either brittle or ductile.
Ductile	A rock is ductile if, when subjected to stress, it deforms without fracturing.
Engineering disturbed zone	The volume around a tunnel or other construction where the surrounding rock is damaged by the process of construction
Fault zone	A fault is a discontinuity in a rock volume with a significant displacement.
Felsic	Rocks which are enriched in elements such as silicon, oxygen, aluminium, sodium and potassium. For example, granite and rhyolite are felsic rocks.
Fracture zone	A rock volume with increased fracturing intensity.
Hydraulic conductivity	A measure of the ease with which groundwater can move through rock.
Karstification	Dissolution of soluble bedrock, usually carbonate rock such as limestone or dolomite.
Mafic	Rock that is rich in magnesium and iron. The term is sometimes synonymous with the basic rock class.
Lineament	A lineament is a linear feature apparent at the ground surface, which is might be the consequence of an underlying geological structure. Fracture zones and shear zones can give rise to lineaments.
Shear zone	A zone of discontinuity or deformation in which parallel internal surfaces slide past one another. A brittle shear zone is a fault zone.
Sorption coefficient	Sorption causes contaminants to move more slowly than the groundwater. This behaviour is quantified by the sorption coefficient.
Specific capacity (of a well)	The volume of water that a well can produce in a given time, per unit of drawdown. It is related to the hydraulic conductivity of the surrounding rock.

Transmissivity	A measure of the ease with which groundwater can move through a fracture. Also, the transmissivity of a layer of rock is equal to the product of its hydraulic conductivity and thickness

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