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Site selection – siting of the final repository for spent nuclear fuel

Svensk Kärnbränslehantering AB

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Summary

SKB has selected Forsmark as the site for the final repository for spent nuclear fuel. The site selection is the end result of an extensive siting process that began in the early 1990s. The strategy and plan for the work was based on experience from investigations and development work over a period of more than ten years prior to then.

This document describes the siting work and SKB's choice of site for the final repository. It also presents the information on which the choice was based and the reasons for the decisions made along the way. The document comprises Appendix PV to applications under the Nuclear Activities Act and the Environmental Code for licences to build and operate an encapsulation plant adjacent to the central interim storage facility for spent nuclear fuel in Oskarshamn, and to build and operate a final repository for spent nuclear fuel in Forsmark in Östhammar Municipality.

The siting of the final repository for spent nuclear fuel is ultimately based on applicable requirements in the Environmental Code and regulations under the Nuclear Activities Act and the Radiation Protection Act. According to the siting principle in the Environmental Code's general rules of consideration, the site selected for an activity shall enable the purpose to be achieved with a minimum of damage or detriment to human health and the environment. The requirement of minimum damage or detriment shall be weighed against the requirement that the labour input required to prepare the site shall be reasonable in relation to the benefit obtained. The site must also be available.

The purpose of the final repository is to dispose of the spent nuclear fuel in order to protect human health and the environment from the harmful effects of ionizing radiation from the spent nuclear fuel, now and in the future. The prospects for achieving this are dependent on the properties of the bedrock, so the fundamental requirement on the selected site is that there must be bedrock there that enables the safety requirements to be met. In order for the site to be available and the project to be feasible, there must also be political and public acceptance in the concerned municipality and among nearby residents. These basic requirements have guided SKB's siting work.

The feasibility study phase

During the 1990s, SKB conducted feasibility studies in eight municipalities. The purpose of the feasibility studies was to determine whether premises existed for further siting studies for a final repository in the municipality in question, at the same time as the municipality and its inhabitants were given an opportunity to form an opinion, without commitments, on the final repository project and their possible further participation. A principal task was to identify areas with bedrock that could be suitable for a final repository. Geological studies based on existing knowledge were therefore a principal component, but no boreholes were drilled at this stage. Technical, environmental and societal conditions were also studied.

The final result of the feasibility studies was that eight different siting alternatives were identified, in the five municipalities of Tierp, Östhammar, Nyköping, Oskarshamn and Hultsfred. These alternatives were all judged to be sufficiently promising to warrant further studies, involving borehole investigations of the bedrock on the site. On the basis of the results of the feasibility studies and previously completed investigations and other studies, SKB concluded that there was sufficient material to move on to the next phase of the siting work, with site investigations for selected siting alternatives.

Comparative evaluations were done to enable the identified siting alternatives to be ranked in order of preference. SKB then concluded that two alternatives stood out as obvious candidates for further studies: Forsmark in Östhammar Municipality and Simpevarp in Oskarshamn Municipality (the Simpevarp alternative also included the Laxemar area). The reasons were that these sites exhibited promising bedrock conditions at the same time as they had a number of other advantages. These included technical, environmental and societal characteristics that offer advantages from the viewpoints of availability and establishment. In addition to site investigations on these two sites, SKB also proposed investigations within an area in Tierp Municipality as well as further studies of the prospects in the Fjällveden area in Nyköping Municipality. The main reason for including these alternatives in the programme was to obtain a good geological breadth in the selection pool, which was judged to be a good idea since the assessments of site-specific rock conditions were preliminary at this stage.

The site investigation phase

SKB's ranking of sites in order of priority for further investigations was presented in a supplement to RD&D-programme 1998 (known as RD&D-K) and was thereby subjected to regulatory review and decision by the Government and later the concerned municipalities. The Government had no objections, and the municipalities of Östhammar and Oskarshamn took a positive stand on site investigations in the Forsmark and Simpevarp areas. The municipalities of Tierp and Nyköping declined further siting studies, however. The political prerequisites for a continuation of the siting work were thereby in place, and site investigations were commenced in Forsmark and Simpevarp in 2002.

The site investigations were carried out during the period 2002–2008, entailing a step-by-step characterization of the two sites. Investigations of the bedrock with a large number of boreholes to different depths comprised a principal component. From initially encompassing large areas, the investigations were gradually focused on locations and rock volumes judged to be the most interesting (in the case of Simpevarp with the result that the Laxemar area was prioritized, after which this alternative was called Laxemar). The results of the investigations have served as a basis for site descriptions, design of site-adapted repository layouts and execution plans, studies of environmental consequences, safety evaluations and safety assessments. All in all, the site investigation phase has generated a body of data that permits a reliable evaluation of the prospects of achieving safe final disposal in Forsmark and Laxemar.

The choice between Forsmark and Laxemar

In the concluding step of the siting process, SKB's task was to choose either Forsmark or Laxemar as the site for the final repository, based on the data from the site investigations. The strategy established for the selection process was based on the purpose of the final repository project and formulated in two points:

1. The site that offers the best prospects for achieving long-term safety in practice will be selected.
2. 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 be the most favourable from other aspects for accomplishing the final repository project will be selected.

In SKB's opinion, the comparative analyses made of Forsmark and Laxemar have provided a basis for a well-founded choice between these alternatives. In an overall evaluation, SKB concludes that a final repository at Forsmark offers significantly better prospects for achieving long-term safety than a final repository Laxemar. In accordance with the strategy for site selection, SKB has therefore decided to locate the final repository at Forsmark.

The basis of the choice between Forsmark and Laxemar

In order to gather the information that was needed as a basis for the choice between Forsmark and Laxemar, the sites were compared with respect to a set of siting factors divided into four main groups, see Figure S-1. The factors are a further development of the structure employed for evaluations at earlier stages, but adapted to the task of comparing two well-investigated alternatives. The siting factors provided a framework for structured comparisons between the sites, where different aspects could be evaluated one by one in a systematic fashion.

The parameters under the heading *Safety-related site characteristics* in Figure S-1 have a direct impact on post-closure safety. Site comparisons have been performed for these parameters, and they have also served as criteria for overall risk analyses. The analyses have generally shown that the processes that could damage canisters in the very long term are corrosion if the buffer is lost and possibly major earthquakes in the vicinity of the repository. If all canisters remain intact, no releases of radioactive substances will occur.

For many of the factors that could affect safety, the outcome for the sites is relatively similar. There are, however, differences in groundwater conditions that have great consequences for the assessment of long-term safety in scenarios where canister damage could occur in the long term. The frequency of water-conducting fractures at repository depth is significantly lower in Forsmark than in Laxemar. This affects the environment for the buffer, which can in turn affect how long it takes for canister

SKB's siting factors

Safety-related site characteristics

- Bedrock composition and structure
- Future climate
- Rock mechanical conditions
- Groundwater flow
- Groundwater composition
- Solute transport
- Biosphere conditions
- Site understanding

Technology for execution

- Flexibility
- Technical risks
- Technical development needs
- Functionality, operational aspects
- Synergies
- Costs

Societal resources

- Suppliers, human resources
- Public and private services
- Transport and communications

Health and environment

- Occupational safety and radiation protection
- Natural environment
- Cultural environment
- Residential environment
- Resource management

Figure S-1. *Factors that have served as a basis for a comparison of the siting alternatives Forsmark and Laxemar for the purpose of site selection.*

damage to occur and the number of canisters that may be damaged. In the case of Forsmark, the analyses show that only a few canisters could be damaged, and the first one only after hundreds of thousands of years. The much higher groundwater flow rates in Laxemar mean that significantly more canisters could be damaged, and that this could occur earlier.

These differences in potential for canister damage have a great impact on the overall risk calculations for the final repository. In the case of Forsmark, the calculations show that the quantitative limit value for annual effective dose specified by the Swedish Radiation Safety Authority (the risk criterion) is met with ample margin. The outcome for Laxemar is much worse. It does not rule out the possibility of building a safe final repository in Laxemar, but this would require a layout and a construction of the repository that would be difficult to achieve in practice for the number of canisters needed.

Comparative assessments of technology for execution have been made for site-adapted repositories designed according to the existing design premises. With these premises, both sites offer possibilities to build and operate a final repository. Comparisons for different siting factors have different outcomes, but overall, Forsmark is judged to offer better prospects for a robust execution. The most important reason is that the low frequency of water-conducting fractures in Forsmark minimizes the risk that intended deposition holes have to be abandoned due to excessive inflows of water. The uncertainties in this respect are much greater for Laxemar.

The rock-related technical execution risks that do exist in Forsmark are above all linked to the occurrence of comparatively high rock stresses. The possibility cannot be ruled out that this will lead to overloading and some spalling of the rock nearest the deposition holes. However, there are good opportunities to adapt the layout of the repository so that this risk is reduced. It is judged unlikely that spalling would have great consequences for the availability of usable deposition positions.

A repository in Forsmark can be made much smaller in extent and volume than a repository in Laxemar, essentially because the rock in Forsmark has higher thermal conductivity so that the canisters can be located closer together. A smaller repository means less rock extraction, lower material consumption, lower transport needs etc, which improves execution efficiency and reduces costs.

The outcome of a comparison of the external factors that influence the execution of the final repository project is in Laxemar's favour. The considerable scope of SKB's present-day activities in Oskarshamn would offer certain synergy advantages, especially in the initial phase of the project. Furthermore, a final repository in Laxemar would gather the entire handling chain for the spent nuclear fuel to one place in the country. Besides efficiency gains, this would result in a lower degree of external dependency. The clearest advantage for Laxemar relative to Forsmark is that the need for sea transport of encapsulated fuel from the encapsulation plant is eliminated. This does not entail any differences from a safety point of view and the cost saving is small, but the longer transport chain to Forsmark nevertheless constitutes a possible source of operational disturbances.

The extensive study work during the site investigation phase has verified SKB's judgement that both sites are suitable siting alternatives with respect to *environmental and health issues*. The prerequisite is that the project is adapted to the environment on the particular site and that preventive, consequence-mitigating and compensatory measures are adopted. In the case of Forsmark, the need for adaptive measures mainly concerns the area's high and sensitive natural values. In the case of Laxemar, however, there is a greater need to show consideration for the cultural and residential environment. The natural resources that will be consumed by the final repository project are affected by the choice of site, but not to any significant extent. All in all, a ranking of the sites based on differences in environmental impact cannot be justified.

A similar judgement is made when it comes to *societal resources*. In preparation for the site investigations, SKB made the judgement that both Oskarshamn and Östhammar municipalities are satisfactory alternatives in terms of societal prospects for carrying out the final repository project. The in-depth knowledge that has been accumulated since then has not altered this judgement. There are many indications that interest in the final repository as an industrial establishment has increased during the site investigation phase in both municipalities. Accordingly, SKB sees no societal factors that could seriously hamper an establishment in either of the municipalities. What then remains to take into account is what local and regional resources are available and how this can affect the efficiency of the establishment. SKB's conclusion is that the differences that can be foreseen in this respect are not sufficiently important to influence site selection.

Site selection in relation to the provisions of the Environmental Code

SKB has been able to show that Forsmark is a suitable site with regard to the purpose of the final repository, and that this purpose can be achieved with very limited damage and detriment. The requirement on minimal damage and detriment also means that there may not be any other site that is available and that offers obviously better prospects on comparison.

Even before the site investigation phase, the conclusion could be drawn that the sites chosen for investigations offered significant advantages with respect to environmental impact, prospects for industrial establishment and local societal conditions. This was true both in comparison with other considered alternatives and in a more general sense. The extensive body of data that has been gathered since then has supported this view.

In the case of many geoscientific parameters of importance for repository safety, data from investigation boreholes is required in order to make complete comparisons between sites. With access to the results of the site investigation, the suitability of Forsmark can therefore now be evaluated (aside from the comparison with Laxemar) in relation to other sites where investigations have been conducted as well. Comparisons for this purpose have been made for a number of safety-related site characteristics. The comparison data have largely been taken from the study sites where investigations were conducted before the actual siting procedure for the final repository was started. The conclusion is that Forsmark is a suitable and favourable site in a relative sense as well. No site has been identified that could offer significantly better prospects than Forsmark. This does not mean there are not other sites with equivalent geological conditions. It is also possible that there are sites that offer comparable prospects overall for achieving long-term safe disposal. But it is not possible to see that there could be another site that offers such verifiable advantages over Forsmark that this would warrant efforts to search for such a site.

SKB's overall conclusion is thereby that the siting of the final repository complies with the intentions of the Environmental Code that there should not be any obviously better site that is available with labour inputs that are reasonable in relation to what could be achieved.

Contents

1 Introduction

On 3 June 2009, SKB's Board of Directors decided to select Forsmark as the site for the final repository for spent nuclear fuel. Many years of work aimed at siting a unique facility thereby achieved its objective. The choice stood between Forsmark in Östhammar Municipality and Laxemar in Oskarshamn Municipality. Both alternatives have been subjected to comprehensive investigations in order to collect the data needed to determine and compare their suitability. What decided the choice of site was that Forsmark is judged to offer better prospects than Laxemar for achieving long-term safety.

This document describes the siting work and the procedure behind SKB's choice of site for the final repository. It also presents SKB's reasons for the decisions made during the course of the siting work. The document comprises Appendix PV to applications under the Nuclear Activities Act and the Environmental Code for licences to build and operate an encapsulation plant adjacent to the central interim storage facility for spent nuclear fuel in Oskarshamn, and to build and operate a final repository for spent nuclear fuel in Forsmark in Östhammar Municipality.

Fundamental requirements

SKB's decision on a site for the final repository is the result of a process that began in the early 1990s. The guidelines for how the process was set up can in turn be traced to experience from investigations and development work over a period of more than ten years before that /Johansson 2006/.

There are two fundamental requirements on the siting of the final repository that have guided the work ever since the beginning of the 1990s. One is that suitable bedrock must exist on the selected site. The other is that acceptance and confidence must exist on a local level for both the siting work and an establishment of the final repository.

The properties of the bedrock are of crucial importance for the prospects of accomplishing the purpose of siting, which is to achieve a safe final repository. A good understanding has been developed of what properties are important and how they influence the suitability for a final repository. The safety assessments which SKB and the regulatory authorities have performed in different phases of the nuclear waste programme have been essential in achieving this understanding. Investigations on a number of sites have provided good knowledge of the ranges of variation of essential properties. But data on these properties that are sufficiently detailed to determine the suitability of a specific site require comprehensive investigations, including boreholes to repository depth, on the site. Until such investigations are conducted, evaluations of individual sites must be based on the information that can be obtained from observations and measurements on the surface in combination with general knowledge. Dependence on incomplete information on rock conditions at early planning stages is not unique for the final repository, but is the general rule for underground facilities. However, this is particularly true of the final repository since certain properties of the bedrock can have consequences not only for the layout and construction of the facility but also for the suitability of the site in general. This has occasioned a siting process based on having a broad geological selection pool all the way up to the final phase.

The requirement of acceptance and confidence on the part of those who are affected locally by the final repository project was a lesson learned from the development phase that preceded the siting work initiated in the early 1990s. Those affected locally are decision-makers in the concerned municipalities as well as nearby residents and the general public in these municipalities. Siting and establishing the final repository against the will of a municipality or a strong local opinion is not advisable in SKB's opinion, if even possible. A site where local support is lacking can thus not be regarded as being available for siting, regardless of any other merits.

While the basic governing requirements have remained the same, knowledge has improved and various regulatory frameworks have changed during the more than 30 years the siting work has been going on. In particular, new laws and regulations have been introduced and a number of Government decisions have been made. In a broader societal perspective, changes in public opinion and attitudes have altered the premises for the siting work. The decisions and choices made during the course of the work must therefore be viewed in light of the current premises.

The choice between Forsmark and Laxemar

The evaluation and comparison of the siting alternatives of Forsmark and Laxemar that comprised the final step in the siting work have been based on the aforementioned basic requirements as well as current laws and regulations. SKB has judged the requirement of local acceptance to be well met for both alternatives, so that this has not been a differentiating factor in the final choice. The central factor has been the prospects for achieving long-term safe disposal. Other aspects, such as harmony with the surrounding landscape and efficiency in the execution of the project, have been secondary. SKB's strategy for choosing between Forsmark and Laxemar can thus be summarized as follows:

1. The site that offers the best prospects for achieving long-term safety in practice will be selected.
2. 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 be the most favourable from other aspects for accomplishing the final repository project will be selected.

In order to be able to apply this strategy, the sites have been compared systematically with respect to all factors that can be of importance for the overall evaluation. Extensive analyses have in particular been made of the site-related characteristics that are of importance for long-term safety and the prospects of executing the final repository project in a robust manner so as to take advantage of the characteristics of the site. The choice was made when the analysis work had come to the point that it was clear that the first point in the strategy would swing the decision in favour of Forsmark and that the remaining analysis work could not change this outcome.

This report

Chapter 2 of this report summarizes the regulatory framework that applies to the siting of the final repository in accordance with current laws and government regulations. Chapters 3 and 4 provide an overview of the main phases of the siting work, up to and including the decisions that enabled site investigations to be initiated for two siting alternatives. The emphasis is on the results and decisions – by SKB and other actors – that were decisive for the way in which the siting procedure developed.

Chapter 5 describes the site investigation phase, with the investigations at Laxemar and Forsmark and the work of preparing site descriptions, site-adapted repository solutions, safety evaluations and background material for an Environmental Impact Statement. The sites are described in general terms with an emphasis on conditions of importance for subsequent site selection.

Chapters 6 and 7 deal with how the site selection was made on the basis of the results of the site investigations. Chapter 6 presents factors and methodology employed by SKB for a systematic comparison of the sites. Chapter 7 presents the comparative analyses that were done with respect to these factors, followed by the overall evaluation that led to the choice of Forsmark. In the concluding Chapter 8, the siting is discussed against the background of general knowledge of geoscientific factors that influence the suitability of the site, and arguments are made in relation to the requirements made by the regulatory framework.

The siting of the final repository is also touched upon in other appendices to the applications. A summary is provided in the appendix that explains how the Environmental Code's general rules of consideration have been observed in the choice of site, method and technology, adopted protective measures etc (Appendix AH). The Environmental Impact Statement (Appendix MKB) accompanying the applications gives an account of the history of the siting process plus conditions and prospects on the selected site in Forsmark, and the alternative siting at Laxemar. Appendix MKB also describes the impact, effects and consequences for human health and the environment of an establishment on either of these sites. The reason for presenting the siting work in greater detail in this appendix, in addition to the accounts in the aforementioned documents, is the great scope of the material.

2 Laws and regulations

Requirements governing the siting of the final repository are laid down in the Nuclear Activities Act, the Radiation Protection Act and the Environmental Code. This chapter summarizes these requirements and the further guidelines provided in the Swedish Radiation Safety Authority's (SSM) regulations and general recommendations.

2.1 The Nuclear Activities Act

The Nuclear Activities Act does not contain any specific provisions regulating the siting of a final repository for spent nuclear fuel, but refers to Chapter 2 of the Environmental Code. Siting is dealt with indirectly in SSM's regulations, however, which are issued pursuant to the Nuclear Activities Act. The following direction is given in SSMFS 2008:21, Sections 2 and 3, regarding how safety is to be achieved with the aid of barriers and their function:

"Safety after the closure of a repository shall be maintained through a system of passive barriers. The function of each barrier shall be to, in one or several ways, contribute to containing, preventing or retarding the dispersion of radioactive substances, either directly, or indirectly by protecting other barriers in the barrier system."

Based on these regulations, SSM has also issued general recommendations, where siting is dealt with (SSM's general recommendations on Sections 2 and 3 in SSMFS 2008:21). Here SSM states the following:

"The repository site and repository depth should be chosen so that the geological formation provides adequately stable and favourable conditions to ensure that the repository barriers perform as intended over an adequate period of time. The conditions referred to are primarily temperature, hydrology, and mechanical (for example rock mechanics and seismology) and chemical (geochemistry, including groundwater chemistry) factors. Furthermore, the repository site should be located at a safe distance from natural resources that are exploited today or may be exploited in the future".

The formulation can be said to be based on the purpose of the siting and site-specific factors that are vital to the prospects of achieving this purpose. The general recommendations further state the following regarding barrier functions:

"The barriers or barrier functions that are needed in a repository are dependent on the radioactive inventory of the repository, on the other substances that affect the safety functions of the barriers and on the design and location of the repository."

2.2 Radiation Protection Act

Like the Nuclear Activities Act, the Radiation Protection Act does not contain any specific provisions regarding siting. However, in the regulations pursuant to this law (SSMFS 2008:37, Section 5), SSM has specified quantitative requirements on long-term safety, the co-called risk criterion, which reads:

"A repository for spent nuclear fuel or nuclear waste shall be designed so that the annual risk of harmful effects after closure does not exceed 10^{-6} *for a representative individual in the group exposed to the greatest risk."*

The regulations also provide directions on what types of analyses shall serve as a basis for specifying the final repository's protective capability in different time perspectives.

Siting is dealt with in the guidelines (general recommendations) for these regulations (Guidelines on Sections 4, 8 and 9 in SSMFS 2008:37) where SSM states the following:

"Application of best available technology in connection with final disposal means that the siting, design, construction and operation of the repository and appurtenant system components should be selected so as to prevent, limit and delay releases from both engineered and geological barriers as far as is reasonably achievable. In considering different measures, an overall assessment should be made of their impact on the protective capability of the repository."

In the same regulations, the Swedish Radiation Safety Authority imposes more general requirements that have a bearing on human health and the environment and that are of importance for the general values the siting must be based on (SSMFS 2008:37, Section 3):

"Human health and the environment shall be protected from detrimental effects of ionizing radiation during the time when the various steps in the final management of spent nuclear fuel or nuclear waste are being implemented as well as in the future. The final management may not cause impacts on human health and the environment outside Sweden's borders that are more severe than those accepted inside Sweden."

2.3 The Environmental Code

In contrast to the Nuclear Activities Act and the Radiation Protection Act, the Environmental Code contains express siting provisions. According to the generally formulated requirement in Chapter 2, Section 6, first paragraph, of the Environmental Code (the siting principle), in the case of an activity or measure for whose purposes a land or water area is used, a site shall be selected that is suitable in order to achieve the purpose with minimum damage and detriment to human health and the environment. According to Chapter 2, Section 7 of the Environmental Code, the requirement on minimum damage and detriment can be relaxed if it is unreasonable to meet it. The legal construction can be described as a far-reaching general requirement balanced by a rule that opens up the possibility of reasonableness assessment from case to case.

The site shall thus be suitable both for the purpose of the activity and for the interests of human health and environmental protection in a general sense. By a "suitable site" is meant a site that is suitable with regard to the Environmental Code's objectives according to Chapter 1, Section 1. There the following is stated:

"The purpose of the provisions of this Code is to promote sustainable development that will ensure a healthy and sound environment for present and future generations. Such development is based on the realization that nature is worthy of protection and that man's right to modify and exploit nature carries with it a responsibility to manage natural resources wisely.

The Environmental Code shall be applied in such a way as to ensure that:

1. *human health and the environment are protected against damage and detriment, regardless of whether they are caused by pollutants or other impacts;*
2. *valuable natural and cultural environments are protected and preserved;*
3. *biological diversity is preserved;*
4. *the use of land, water and the physical environment is otherwise such as to secure a long-term advantageous management from an ecological, social, cultural and economic viewpoint; and*
5. *reuse and recycling, as well as other management of materials, raw materials and energy are promoted so that an ecocycle is achieved."*

In assessing whether the site is suitable, Chapters 3 and 4 of the Environmental Code shall also be applied. These chapters deal with fundamental and special provisions regarding management of land and water areas. Chapter 3, Section 1 states that land and water areas shall be used for the purposes for which the areas are best suited, with preference given to use that promotes good management from the viewpoint of public interest. Large land and water areas that are not affected, or are only affected to a small extent, by development projects or other environmental intrusion (Section 2) and areas that are particularly vulnerable from an ecological point of view (Section 3) shall, as far as possible, be protected against measures that may affect or harm the character of the area. Chapters 3 and 4 of the Environmental Code also contain provisions concerning national interests.

3 The run-up to the siting work

Figure 3-1 illustrates the main phases and milestones in the multi-year process that has led to SKB's decision to locate the final repository in Forsmark. The work of developing a method and selecting a site started back in the 1970s, in the wake of a heated nuclear power debate that led a few years later to a national referendum on the future of nuclear power. Development work and investigations done up until the early 1990s generated a knowledge base that was of great importance for the planning and execution of the siting procedure that was initiated after SKB presented RD&D-programme 1992 /SKB 1992/. Efforts and experience up until this time are summarized in this chapter.

3.1 Early studies

A fundamental requirement for final disposal of spent nuclear fuel is that human health and the environment must be protected from the harmful effects of ionizing radiation. Since it takes a very long time before the radioactivity in the spent nuclear fuel has decayed to a level that is comparable to what can be found in nature, the waste must be isolated and stored so that it cannot harm future generations. This requirement led to the conclusion that the waste should be disposed of in some kind of geological formation. In Sweden, the strategy was that the repository should be located in the Precambrian, crystalline rock types that dominate our bedrock. Other countries with other geological conditions have chosen other alternatives, for example disposal in salt or claystone formations.

One of the main tasks in the initial phase was therefore to acquire good knowledge of the Swedish bedrock and what properties the rock must have in order to meet the requirement of safe final disposal. The first concerted effort was made by the AKA Committee (the Swedish acronym AKA stands for spent nuclear fuel and radioactive waste) appointed by the Government at the end of 1972, which presented its final report in 1976 /SOU 1976/. Since then a great deal of work has been done to build up a general knowledge of the bedrock in the country and the conditions that could affect the function of a final repository.

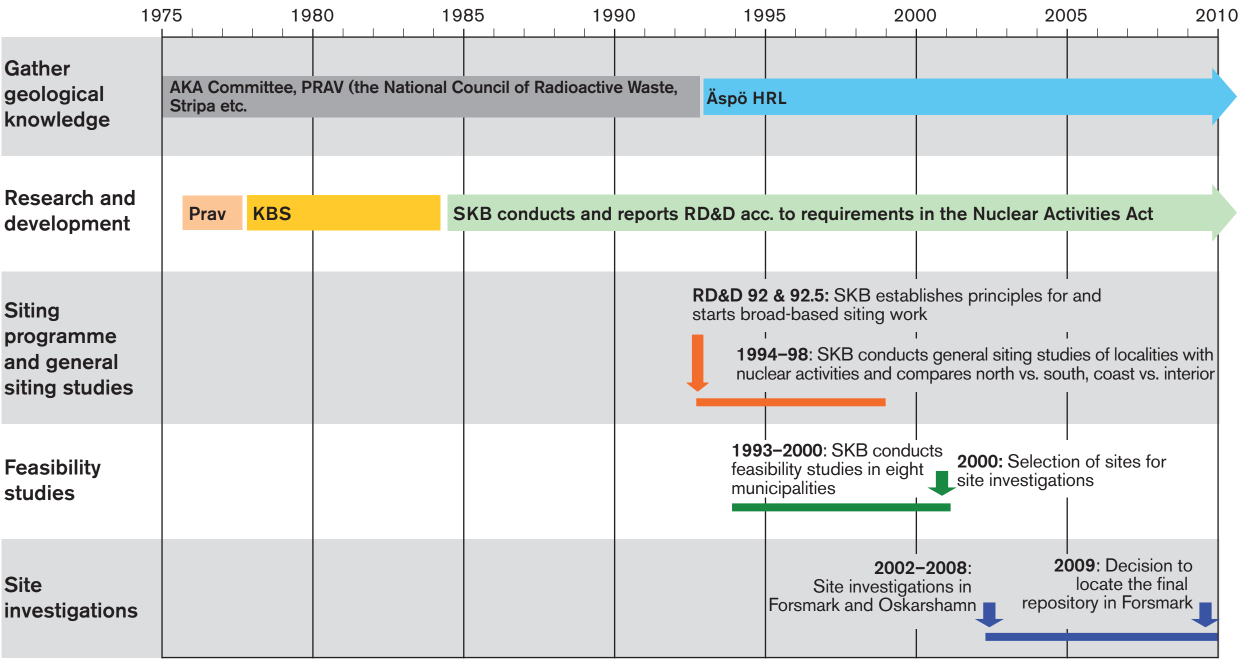

Figure 3-1. *Main phases and milestones in the work leading up to the decision to locate the final repository at Forsmark.*

Geological studies were conducted all over the country and in different geological environments, see Figure 3-2. A large number of possible areas were identified for more detailed investigations with the aid of aerial photos and geological maps. The choice of areas was based primarily on the following criteria:

- flat bedrock topography,
- low fracture frequency on exposed rock surfaces,
- widely spaced major fracture zones,
- uniform composition and structure of the rock mass,
- areas with low seismic activity,
- documented low water flow rate in the rock mass.

The next step was field visits and simple geological mapping. This was followed by more comprehensive investigations of the areas that were judged to have good potential for satisfying the requirements on a long-term safe final repository. At the same time, development of better and adapted investigation methods was being pursued /Johansson 2006/.

3.2 The Stipulations Act and the KBS project

The passage of the Stipulations Act by the Riksdag (Swedish parliament) in 1977 was an important point of departure for the siting work. The Stipulations Act required the reactor owners to show how and where an absolutely safe disposal of the high-level waste (after reprocessing) or the spent nuclear fuel (without reprocessing) could take place in order to obtain Government permits to start the reactors that were planned or under completion. Within the KBS project, the nuclear power companies conducted intensive test drilling and research activities to satisfy this requirement /KBS 1977, 1978, SKBF/KBS 1983, Johansson 2006, SKB 2010a/.

The introductory part of the KBS project's investigation programme consisted of test drilling on five sites representing three different bedrock environments:

- Precambrian granites in northeastern Uppland (Forsmark in Östhammar Municipality and Finnsjön in Tierp Municipality),
- young quartz-rich granite in southeastern Småland (Kråkemåla and Ävrö in Oskarshamn Municipality),
- the coastal gneiss formation in Blekinge (Sternö in Karlshamn Municipality).

After introductory studies, Sternö, Kråkemåla and Finnsjön were selected for more detailed investigations, see Figure 3-2. The programme included test drilling, ground geophysical surveys, outcrop and fracture mapping, evaluation of drill cores, borehole logging, BIPS examination of boreholes, water loss measurements and water sampling for chemical analysis ands dating. The results of these investigations were included in the report to the Government that served as a basis for permits to start the reactors Ringhals 3 and Forsmark 1 /Government 1979/ as well as Ringhals 4 and Forsmark 2 /Government 1980/.

Similar investigations were subsequently conducted on another four sites: Fjällveden, Gideå, Kamlunge och Svartboberget. The KBS project was concluded with the presentation of the KBS-3 method, and the Government granted permits to start the Forsmark 3 and Oskarshamn 3 reactors /Government 1984/.

3.3 Study sites

The sites that were subjected to comprehensive investigations during the KBS project (conducted by SKB or in some cases by the National Council for Radioactive Waste, PRAV) came to be called study sites. Another study site was added following the conclusion of the KBS project, namely Klipperås, see Figure 3-2. In addition to the study site investigations, SKB carried out a special study of fracture zones at Finnsjön /SKB 2010a/.

***Figure 3-2.** Places in the country where investigations were conducted during the period from the mid-1970s until 1990 /SKB 2010a/.*

The choice of areas for investigations was based on the extensive reconnaissance and general assessments that had been going on since the mid-1970s. A total of 85 cored boreholes were drilled with a combined length of more than 45 kilometres. The boreholes were investigated by means of different measurement methods. Special care was taken to determine the permeability of the rock and and the chemical composition of the groundwater at great depth. The results of the study site investigations showed that it is possible to find many places in Sweden where the geological conditions are suitable for building a final repository.

3.4 Hard rock laboratories in Stripa and on Äspö

Research, development and demonstration of a concept and technology for final disposal required testing in a realistic environment. At first the hard rock facilities at the Stripa Mine in Bergslagen were used. Methods for investigating and characterizing the bedrock were developed there during the period 1976–1992. Furthermore, experiments were conducted to study the thermomechanical properties of the rock mass and the function of the bentonite buffer, borehole plugs and tunnel plugs. A large portion of the work was carried out in international cooperation /Fairhurst et al. Gnirk 1993, Gray 1993/.

In the years around 1990, SKB established the Äspö Hard Rock Laboratory (Äspö HRL) near Simpevarp in Oskarshamn. The Äspö HRL has been and is of central importance for development, demonstration and testing of the KBS method, investigation methods etc. During the period 1986–90, extensive geoscientific investigations were carried out before tunnelling for the hard rock laboratory was commenced /Gustafson et al. 1989, Almén and Zellman 1991, Wikberg et al.

1991, Gustafsson et al. 1991/. The Äspö HRL was commissioned in 1995. Planning, construction and operation of the Äspö HRL has yielded important experience that has been used in the site investigations and serves as a basis for the planning of the construction and operation of the final repository /Stanfors et al. 1997a, b, Rhén et al. 1997a, b, c/.

3.5 Conclusions and guidelines for the siting work

A principal conclusion from the study site investigations and other studies of the bedrock was that suitable and less suitable areas cannot be attributed to any particular part of the country or any special geological environment within the crystalline bedrock. It is instead local conditions that are of the greatest importance. Another lesson was, as already mentioned, that the siting work must be based on the acceptance and confidence of the local population. The investigations met with local resistance and protests in many quarters. SKB saw no point in continuing the siting work in such a hostile community climate. These conclusions were the main points of departure for the programme for siting of the final repository that was developed in the early 1990s, and they have guided the work since then /SKB 1994/.

4 The feasibility study phase

The real work of finding suitable sites for the final repository began when SKB formed a siting project in the autumn of 1991. This was the start of a phase that included feasibility studies where the siting prospects in eight municipalities were studied, leading to identification of the siting alternatives that were later the subject of site investigations.

4.1 Focus and programme

SKB presented plans for a broadly conceived siting process in RD&D-Programme 92 /SKB 1992/. Based on the knowledge that there are good prospects to find repository areas with suitable geological conditions, SKB said that it was reasonable and realistic to focus interest on municipalities where conditions were suitable and that were themselves willing to participate, or otherwise showed an interest, in further exploring the potential for a siting.

RD&D-Programme 92 was supplemented in response to Government demands /SKB 1994/, after which the Government, in a decision dated 18 May 1995 /Government 1995/, stipulated that "the siting factors and criteria reported by SKB should serve as a point of departure for the continued siting work". It was further stated in the Government decision that the applications for permits to build a final repository for spent nuclear fuel should contain material for comparative assessments showing that site-specific feasibility studies have been conducted at 5–10 sites in the country, and that site investigations have been conducted on at least two sites and give the reasons for the choice of these sites.

4.2 Feasibility studies

During the period 1992–2000, SKB held more or less far-reaching discussions of feasibility studies with some twenty-odd municipalities in different parts of the country, see Figure 4-1. In eight cases – Storuman, Malå, Östhammar, Nyköping, Oskarshamn, Tierp, Älvkarleby and Hultsfred – this led to a feasibility study being conducted. In other cases the discussions were discontinued, either because SKB found that a feasibility study was not warranted, or because the municipality in question chose to decline.

The purpose of the feasibility studies was to determine whether premises existed for further siting studies for a final repository in the municipality in question, at the same time as the municipality and its inhabitants were given an opportunity to form an opinion, without commitments, on the final repository project and their possible further participation. A principal task was to identify areas with bedrock that could be suitable for a final repository. Geological studies were therefore a principal component. The studies were based on existing knowledge, but no drilling was done. Technical, environmental and societal conditions were also studied. Within the framework of the feasibility studies, SKB also carried on an active dialogue with private citizens, the municipality and the county administrative board.

The feasibility studies were carried out according to the programme and with the siting factors that were presented in SKB's supplement to RD&D-Programme 92, which meant that above all the following questions were addressed /Johansson 2006/:

- What are the general prospects for siting a final repository in the municipality?
- Where could suitable sites exist for a final repository with reference to geoscientific and societal conditions?
- How can transportation be arranged?
- What are the most important environmental and safety issues?
- What are the possible consequences, positive and negative, for the environment, the economy, tourism and other business enterprise in the municipality and the region?

The procedure followed was essentially as follows:

- The general conditions in the municipality with regard to the above questions were studied.
- Areas that did not have sufficiently good chances of satisfying the requirements on the bedrock were excluded.
- The remaining areas were preliminarily ranked, based on an overall assessment where technical and environmental siting aspects were also weighed in. Areas were selected for geological field checks.
- The results were presented in a preliminary final report, which was circulated for comment by the municipality along with other study material.
- Geological field checks and other supplementary work was done.
- All results were compiled, whereby viewpoints offered in the review and commentary procedure were taken into account. Siting alternatives were evaluated and ranked in order of priority. The whole feasibility study was presented in a final report.

The first feasibility studies were done in the municipalities of Storuman /SKB 1995b/ and Malå /SKB 1996/, after these municipalities had shown an interest and SKB's preliminary judgements had indicated favourable conditions there. The feasibility studies confirmed these judgements, but local referendums led in both cases to a decision not to participate further in the siting process. According to the points of departure for the siting work, SKB thereby ruled out further studies in these municipalities.

In parallel with the first feasibility studies, SKB studied the possibilities of siting the final repository in one of the municipalities in the country that already have nuclear facilities, i.e. Oskarshamn, Nyköping, Östhammar, Varberg and Kävlinge /SKB 1995c/. In the cases of Oskarshamn, Nyköping and Östhammar, an extensive body of geological data existed that indicated good siting possibilities. SKB proposed and carried out feasibility studies in these municipalities. /SKB 2000a, b, c/. SKB also recommended a feasibility study of Varberg Municipality, but the municipality declined. In the case of Kävlinge Municipality, SKB found that a feasibility study was not warranted in view of the geological conditions, among other things.

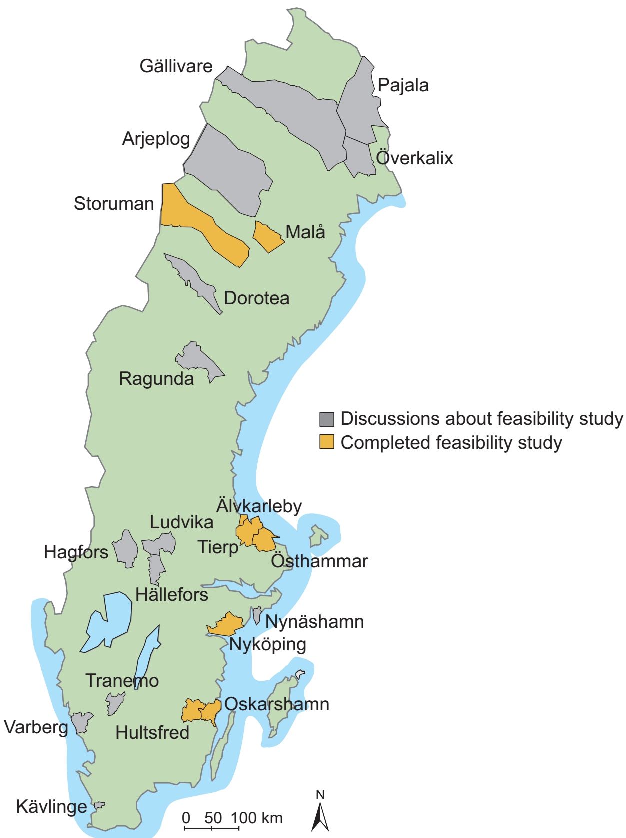

Figure 4-1. *Municipalities where SKB has conducted or held discussions about a feasibility study.*

Three additional feasibility studies were conducted in the municipalities of Tierp /SKB 2000d/, Älvkarleby /SKB 2000e/ and Hultsfred /SKB 2000f/, see Figure 4-1. The reasons were, as in the previous cases, that SKB's preliminary judgements pointed towards potentially favourable conditions, in combination with an interest on the part of the municipalities.

4.3 Supplementary studies

In parallel with the feasibility studies and after the Government's decision regarding RD&D-Programme 95 /SKB 1995a/, other siting studies were also performed in order to supplement the background material. At the end of the 1990s, SKB presented regional general siting studies for all counties (except Gotland) /SKB 1998–1999/. The studies focused on long-term safety and thereby on bedrock conditions, but also included general surveys of environmental factors, existing industry and transport infrastructure. The main conclusion was that there is bedrock in all the counties studied that could warrant further studies concerning siting of the final repository, see Figure 4-2. At the same time, large areas were identified that are probably unsuitable.

Questions relating to the possible advantages and disadvantages of siting the final repository in northern versus southern Sweden, and on the coast versus in the interior, were given particular attention /Leijon 1998/. The conclusion was that these factors are not of any decisive importance. Assessments of suitability must instead be based on studies of local conditions. Questions concerning more general differences between coastal and inland alternatives have also been raised at later stages, for example by the then authorities SKI (the Swedish Nuclear Power Inspectorate) and SSI (the Swedish Radiation Protection Authority) in connection with the selection of sites for site investigations. Such questions have concerned whether or not long flow paths (and long circulation times) for groundwater from inland locations can offer advantages from a safety viewpoint. Results and conclusions of the analyses done by SKB in response to this question are dealt with in Section 8.2.

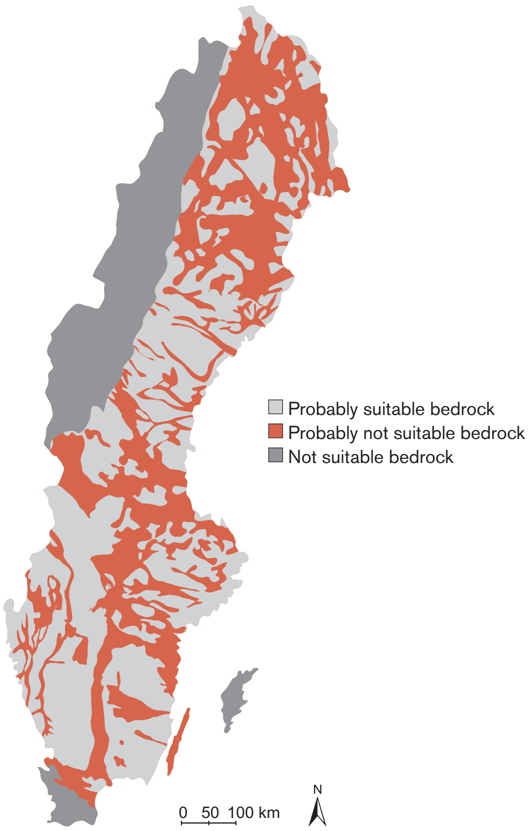

Figure 4-2. *SKB's county-specific general siting studies included all counties except Gotland. For each county, a rough classification was made with respect to the judged suitability of the bedrock for a final repository.*

4.4 Selection of sites for site investigations

4.4.1 Selection pool

Based on the results of the feasibility studies and other studies, SKB concluded in 2000 that enough data were available to proceed to the next phase of the siting work: site investigations for priority siting alternatives. SKB described site selection and the programme for the site investigation phase in the supplement to RD&D-programme 2000 that was presented in the autumn of 2000, known as the RD&D-K report /SKB 2000g/.

As a result of local referendums after the feasibility studies, the municipalities of Storuman and Malå had declined further participation in the siting process (Section 4.2). The pool from which SKB could choose sites for further investigations thereby included the six municipalities of Hultsfred, Oskarshamn, Nyköping, Tierp, Älvkarleby and Östhammar, see Figure 4-1.

SKB concluded there that there were areas in all these municipalities except Älvkarleby where the bedrock is potentially suitable for a final repository. In the case of Älvkarleby it was concluded that the geological conditions were too difficult to judge and that the probability of finding sufficient volumes of suitable bedrock was too low to warrant further investigations. As far as technical and environmental conditions were concerned, the feasibility studies showed good prospects in all cases. SKB also made the judgement that it was possible in all municipalities and regions to gain the support among politicians and private citizens that was necessary to continue the siting work.

The feasibility studies had identified areas with potentially favourable bedrock and had produced rough proposals as to how construction and transport issues could be solved in the event the final repository were sited in one of these areas. The procedure used to arrive at these results is described in Section 4.2. In order to decide which siting alternatives could be included in a selection pool for the selection of sites for site investigations, the results were evaluated with respect to:

- Bedrock: The properties of the bedrock determine the prospects for long-term safety and the technical prospects for building and operating the underground parts of the final repository. The safety requirements and resulting requirements on the rock distinguish the final repository from other rock facilities.
- Industrial establishment: The final repository project must be able to be implemented as an industrial undertaking. This means that construction and operation must be technically feasible, that resources must be available, and that all requirements on occupational safety and protection of man and the environment must be met. In these respects the final repository does not differ essentially from any other industrial activity.
- Societal aspects: In order for the final repository project to be realized, it must have political and popular support. SKB must deem it likely that the concerned municipality, the environmental court and the Government will accept the siting. In practice, this means that SKB and the nuclear waste programme must enjoy broad confidence in the community.

The review resulted in the identification of eight siting alternatives in five municipalities. Evaluated individually and from all aspects, these alternatives were judged to be sufficiently promising to warrant further study. Figure 4-3 shows their names and locations, and Table 4-1 summarizes the fundamental characteristics of the alternatives.

The question then was whether these eight alternatives provided a pool of sufficient breadth and quality to proceed and prioritize a smaller number for site investigations. This question was analyzed based on the same factors that used for the evaluation of the individual siting alternatives, i.e. the properties of the bedrock and industrial, environmental and societal prospects.

In a geological sense, the sites represented several types of crystalline bedrock. In Northern Uppland there are mainly gneissic granites (Forsmark and Hargshamn) and massifs of younger granite (Tierp). Nyköping Municipality is dominated by gneissic granites and veined gneisses of sedimentary origin. The identified alternatives in Oskarshamn and Hultsfred were situated within large contiguous granite areas. Experience from investigations and safety assessments of other sites with in many respects comparable geological environments was an important reason for SKB's assessment that all eight identified alternatives offered favourable geological prospects. The considerable geological breadth was seen as an asset in view of the fact that the material from the feasibility studies did not permit a ranking of the alternatives. SKB's conclusion was that the selection pool was quite sufficient for selecting sites for further investigations.

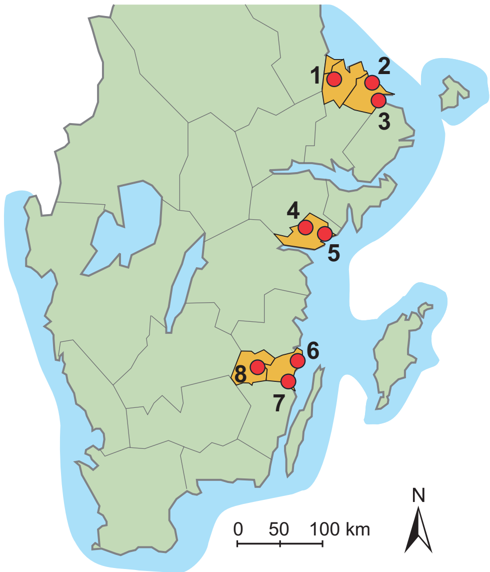

Figure 4-3. *Selection pool prior to the site investigation phase. The feasibility studies resulted in eight siting alternatives that were judged to be sufficiently promising to warrant further study. The alternative of Simpevarp also included the area designated Laxemar during the site investigation phase (reworked from Figure 11-1 in /SKB 2000g/).*

Table 4-1. Fundamental characteristics of the eight siting alternatives that comprised the selection pool /SKB 2000g/.

Siting alternative	Fundamental characteristics (type of bedrock, environment for above-ground facilities, transport infrastructure for spent nuclear fuel)
Tierp north/Skutskär Tierp and Älvkarleby municipalities	Large granite massif north of the town of Tierp New establishment on forest land Transport by rail from Skutskär harbour in Älvkarleby Municipality
Forsmark Östhammar Municipality	Gneissic granite (tectonic lens) southeast of Forsmark Nuclear Power Plant Establishment on industrial land adjacent to the nuclear power plant Transport by road from Forsmark harbour
Hargshamn Östhammar Municipality	Gneissic granite (tectonic lens) Probably new establishment on forest land near Hargshamn Transport by road from the harbour in Hargshamn
Skavsta/Fjällveden Nyköping Municipality	Sedimentary veined gneiss in the Fjällveden/Tunsätter area north of Nyköping Establishment possibly adjacent to Skavsta Airport Transport by rail or road from Oxelösund harbour
Studsvik/Björksund Nyköping Municipality	Gneissic granite in the eastern coastal area of the municipality, west of the Studsvik facility Establishment adjacent to the Studsvik facility Transport by road from Studsvik harbour
Simpevarp Oskarshamn Municipality	Granite (Småland granite) towards the west from the Simpevarp Peninsula (includes the area now called Laxemar) Establishment on industrial land adjacent to the nuclear power plant and Clab main alternative Possibly short transport by road from planned encapsulation plant
Oskarshamn south Oskarshamn Municipality	Granite (Småland granite) south of Oskarshamn Establishment adjacent to the harbour in Oskarshamn Transport by rail or in tunnel from the harbour in Oskarshamn
Hultsfred east Hultsfred Municipality	Granite (Småland granite) east of Målilla New establishment on forest land Transport by rail from the harbour in Oskarshamn

The evaluation of the selection pool with respect to prospects for industrial establishment was based in part on proposed layouts of a final repository on the identified sites. The selection pool included alternatives with special prospects in the form of limited transport needs, availability of industrial land and closeness to nuclear industry. This was essential, since these conditions offer obvious advantages from e.g. an environmental viewpoint. Other alternatives required greater labour inputs for transportation or establishment on the site, but the feasibility studies showed a good potential for achieving technically and environmentally acceptable solutions for these alternatives as well.

As far as the societal prospects are concerned, SKB concluded that the municipalities included in the selection pool had participated actively in the feasibility study work, and that there were good prospects for continued confidence in the next phase. At the same time there was more or less express interest from other municipalities in the country as well. SKB's assessment was, however, that a broadening of the selection pool would not further strengthen society's support for the final repository project.

Based on these results and considerations, SKB arrived at the following conclusion regarding the selection pool /SKB 2000g, p. 187/:

"SKB concludes that the siting work should proceed with site investigations, since the selection pool contains sufficiently many alternatives for which the prospects of satisfying the safety requirements and implementing the final repository project with the support of the community are good."

4.4.2 Comparative evaluation and choice

The next step in the process was to make a comparative evaluation and ranking of the eight siting alternatives included in the selection pool. The evaluation was based on the structure for siting factors used in the feasibility studies. In parallel with the feasibility studies, the methodology for evaluation of the background material for siting had also been further improved, based on the latest knowledge from e.g. geoscientific research and safety assessment /SKB 1999/. The methodology was presented in conjunction with the completion of the last feasibility studies /Andersson et al. 2000/ and in SKB's integrated account prior to the transition to the site investigation phase /SKB 2000g/. There a set of guiding requirements and preferences for different siting factors was presented. By *requirement* was – and is – meant absolute conditions that must be satisfied. If a requirement cannot be satisfied for a site, the site must be judged unsuitable. *Preferences* are conditions that ought to be, but do not have to be, satisfied. Many preferences can be formulated, and satisfying all of them is not realistic. The final repository may very well turn out to be safe even though several preferences are not satisfied, but a satisfied preference can offer advantages such as larger safety margins, simplified repository construction or lower costs.

The set of requirements and preferences was primarily intended as a tool to guide the site investigations and to clarify how the results of the investigations would be evaluated, see further Chapter 5. Certain requirements and preferences could, however, be used as support in the comparative evaluation of the alternatives in the selection pool from the feasibility studies. Since all alternatives were judged to satisfy the requirements that could be checked at this stage, the evaluations were primarily concerned with evaluating the uncertainties in these assessments as well as determining to what extent the alternatives satisfied the preferences that had been formulated.

The bedrock

Each siting alternative in the selection pool included an area judged to have potentially favourable bedrock for a final repository. With few exceptions, these judgements were based on observations from the ground surface in combination with general knowledge. They therefore had the character of predictions of what a site investigation could be expected to reveal and were associated with uncertainties of varying nature and degree. The methodology for site evaluation that had been developed /Andersson et al. 2000/ included a number of requirements and preferences regarding the bedrock. Which of these could be taken into consideration in the feasibility study phase, and how this was done, is summarized in /SKB 2000g, Table 11-1, p. 153/.

The limited body of data did not permit a ranking of the alternatives according to the geological prospects of satisfying the safety requirements. On the contrary, a ranking could be misleading, in part because the knowledge level and reliability of available data varied from case to case. The comparative analysis was therefore focused on evaluating the quality of the data and identifying site-specific questions and uncertainties that were judged important to clarify in a future site investigation. Table 4-2 summarizes the results of these evaluations.

Table 4-2. Summary of data on the bedrock for the selection of sites for site investigations (from /SKB 2000g, Table 12-1/).

Area	Distinguishing characteristics	Available data	Important questions and uncertainties
Forsmark	Gneissic granite. Tectonic lens with homogeneous, fracture-poor rock. Small area.	Data from nearby rock facilities and boreholes. Relatively high proportion of exposed rock.	Importance of surrounding shear zones. Extent of lens in depth and size of favourable area at repository depth. Occurrence of gently-dipping fracture zones. High rock stresses. Bedrock with ore potential at depth.
Hargshamn	Gneissic granite. Tectonic lens with homogeneous, fracture-poor rock. Relatively big area.	Only surface data. Relatively high proportion of exposed rock.	Location in a tectonic lens leads to same questions as in Forsmark. No other site-specific questions can be identified, since only surface data are available.
Tierp	Isolated massif of younger granite. Homogeneous bedrock with granite dykes. Flat soil-covered area. Few interpreted fracture zones. Big area.	Only surface data. Few outcrops.	Frequency and permeability of granite dykes. Depth of granite. No other site-specific questions can be identified due to limited surface data.
Björksund	Gneissic granite. Homogeneous bedrock with low fracture frequency. The area has relatively many fracture zones. They have a dominant direction that gives he rock blocks an elongated shape. Relatively big area.	Only surface data. High proportion of exposed rock.	Size of favourable area at repository depth and adaptation of repository to fracture zones. Access tunnel to repository must pass several regional fracture zones, can cause construction problems. No other site-specific questions can be identified, since only surface data are available.
Fjällveden-Tunsätter	Sedimentary veined gneiss with some gneissic granite Homogeneous bedrock. Big area.	Extensive database from study site. Safety assessment. KBS3 (good forecast). Relatively high proportion of exposed rock.	Occurrence, size and location of suitable bedrock blocks outside study site. Access tunnel to repository must pass several regional fracture zones, can cause construction problems.
Simpevarp	Large coherent massif of younger granite. Homogeneous bedrock with inclusions of other rocks and dykes. Fracture zones divide the bedrock into distinct rock blocks. Big area.	Extensive data available from Äspö and Laxemar. Relatively high proportion of exposed rock.	Size and location of bedrock blocks with favourable properties at repository depth. Occurrence and importance of granitic dykes and fracture zones, particularly with respect to permeability.
Oskarshamn south	Large coherent massif of younger granite. Homogeneous bedrock with few granitic dykes. Big area.	Only surface data. Relatively high proportion of exposed rock.	Size and location of bedrock blocks with favourable properties at repository depth. No other site-specific questions can be identified, since only surface data are available.
Hultsfred east	Large coherent massif of younger granite. Homogeneous bedrock with few granitic dykes. Big area.	Only surface data. Relatively high proportion of exposed rock.	Size and location of bedrock blocks with favourable properties at repository depth. No other site-specific questions can be identified, since only surface data are available.

Industrial establishment

The feasibility studies produced a general but comprehensive body of data on establishment prospects in the form of environmental conditions, transport infrastructure, land availability, etc. This permitted comparative evaluations and some ranking of siting alternatives in the selection pool.

The requirements and preferences formulated for the final repository as an industrial establishment are presented in /SKB 2000g, Tables 10-7 and 10-8/. As mentioned, all alternatives satisfied legal and other fundamental requirements, so the comparisons were largely concerned with the advantages and disadvantages of the alternatives in relation to preferences.

In general, alternatives where existing industrial land could be utilized were considered more favourable than those where new land areas needed to be utilized. A location with few competing land use interests and/or few landowners was regarded as favourable. Siting possibilities in connection with existing nuclear activities were judged to offer special advantages. The preference of availability of local resources for execution of the final repository project (labour, services, etc) was judged to be well satisfied for all alternatives and was therefore not taken into account in the evaluation. The possibilities of arranging transportation for the final repository were also evaluated. Transport chains with few links, short transport distances and existing transport infrastructure were considered advantageous.

Table 4-3 summarizes the evaluations of establishment prospects that were made, as well as special advantages and disadvantages, for the different siting alternatives. The transport needs indicated in the table pertain to encapsulated spent nuclear fuel. Transport of backfill material, rock spoil etc is additional.

Table 4-3. Summary evaluation of the siting prospects with respect to establishment of the final repository, preceding the choice of sites for site investigations (from /SKB 2000g, Table 12-2/).

Alternative	Prospects for establishment	Special advantages (+) and disadvantages (–)
Forsmark	Existing industrial area. Existing harbour. No overland transport outside industrial area. Few landowners. High nature protection values.	+ Industrial area with nuclear activity. + Low environmental impact. – Site investigations in area with high natural values.
Hargshamn	Existing industrial area or establishment of new one. Existing harbour. No, or short, overland transport outside industrial area. Few landowners.	+ Good harbour. – Uncertainty regarding possibility of establishment within existing industrial area.
Tierp north/ Skutskär	Establishment of new industrial area and transport connection (forest land). Site not specified. Harbour and parts of facility in Skutskär. Overland transport, existing railway and new branch line. Preliminary few landowners.	+ Big area – flexibility. + Harbour and industrial area in Skutskär. – Overland transport. – Establishment of new industrial area.
Studsvik Björksund	Existing industrial area. Existing harbour. No overland transport outside industrial area. Few landowners.	+ Industrial area with nuclear activity. + Low environmental impact. – Uncertainty regarding nature and culture protection interests. – Uncertainty regarding land availability.
Skavsta/ Fjällveden	Establishment of new industrial area in Skavsta (land intended for industry), plus small operations area (Fjällveden, site not specified). Harbour in Oxelösund. Overland transport – existing railway and new branch in the first-choice alternative to Oxelösund – Skavsta, tunnel Skavsta-Fjällveden. Few landowners within Fjällveden area.	+ Good harbour. – Establishment of new industrial area and transport routes. – Considerable environmental impact. – Long distance between facility parts.
Simpevarp	Existing industrial area first-choice alternative. No overland transport outside of industrial area. Many landowners.	+ Industrial area with nuclear activity. + No transport of encapsulated spent fuel. + Low environmental impact. – Many landowners can be affected by site investigations.
Oskarshamn south	Existing industrial area or establishment of new one. Existing harbour. No, or limited, overland transport outside of industrial area. Relatively few landowners.	+ Good harbour. – Uncertainty regarding availability of existing industrial area.
Hultsfred east	Establishment of new industrial area and transport connection (forest land). Site not specified. Existing harbour in Oskarshamn. Overland transport, existing railway and new branch line. Relatively few landowners.	+ Big area – flexibility. – Overland transport. – Establishment of new industrial area.

In the overall evaluation and ranking of the siting alternatives with respect to the prospects for industrial establishment, SKB concluded /SKB 2000g, Section 12.3.2/ that:

"As far as environmental impact is concerned, SKB concludes that the establishment and operation of the final repository can be arranged and conducted in an environmentally acceptable way for all alternatives. This judgement is based on the fact that the activities generally cause little environmental impact compared with other industrial activities of equivalent size" ... "An establishment at Simpevarp offers the shortest and simplest handling chain, since the encapsulated fuel can be driven directly from the encapsulation plant to the deep repository without transshipment. In the other alternatives, transshipment and sea transport are required, and in three cases overland transport as well. The siting alternatives that involve overland transport require laying of new railway and utilization of new land for industrial purposes.

SKB concludes that a siting in areas where nuclear activities already exist is advantageous, since infrastructure that suits the needs of the final repository already exists there. In SKB's judgement there are two alternatives that offer obvious advantages. These are Forsmark and Simpevarp, both of which have harbours, available industrial land, and nuclear activities. SKB finds that this offers particularly good prospects for satisfying the requirements of the Environmental Code that industrial sitings shall take place so that the purpose is achieved with the least possible intrusion and detriment. Overland transport of spent nuclear fuel on public roads/railways is avoided with these alternatives.

In the case of the other alternatives, the prospects for establishment of the final repository are deemed to be comparable, except for Fjällveden and Björksund, where the uncertainties are deemed to be greater than for the other alternatives."

Society

The requirements and preferences identified with respect to societal aspects that must be satisfied in order for an establishment of the final repository to be possible are presented in /SKB 2000g, Table 10-10, p. 144/. SKB concluded that many of these were difficult to apply in view of the time perspective for the siting process and possible changes of the conditions. The requirement of confidence on a local level was the factor that was accorded the most importance in the choice of alternatives for site investigations. Furthermore, an uncertainty was noted regarding local acceptance for overland transport of radioactive waste on public transport routes.

The comparative evaluation of the alternatives resulted in the following conclusions /SKB 2000g, Section 12.3.3/:

"SKB concludes that in all feasibility study municipalities included in the selection pool, there is support among elected officials and the public that provides good prospects for proceeding with site investigations. This judgement is based on e.g. the opinion surveys that have been conducted for SKB's account.

SKB considers that the siting alternatives can be ranked with respect to societal prospects, insofar as Simpevarp and Forsmark offer better prospects than the others. One reason for this is that confidence in SKB's activities is deemed to be most stable in those localities where nuclear activities have long existed. Stable local confidence, gained by practical action, is seen as a positive factor that can strengthen the prospects of implementing the final repository project in both the short and long term.

Further, SKB concludes that a siting of the deep repository in Forsmark or Simpevarp is regarded by many as a natural choice. A common argument for this is that provided that the safety requirements can be satisfied, and that the bodies whose job it is to determine this can be relied on, it is difficult to see any rational arguments for other choices than the sites where nuclear installations are already located. An exception is Studsvik/Björksund, where several reviewing bodies have offered critical viewpoints.

Other siting alternatives entail establishment in localities that do not have any nuclear activities. SKB's opinion is that this requires prolonged discussion in the municipality in question and among nearby residents to determine their attitude to such an activity. Against the background of results from opinion surveys and the interest shown by elected officials and the public during the feasibility *studies, SKB believes there is sufficient support to proceed with site investigations. The municipality and other stakeholders will not have to make a decision on an establishment for another eight years or so, which means there is plenty of time for them to look deeply into the matter."*

Selection of sites for site investigations

SKB's strategy for the choice of sites for site investigations was based on the overall goal of being able, after completed site investigations, to present a site that satisfied all requirements for establishment of the final repository. The alternatives included in the selection pool all exhibited good prospects. At the same time, questions remained for all alternatives that had to be answered before their suitability could be established. The uncertainties mainly concerned the bedrock, where data from repository depth were lacking in most cases and the assessments were preliminary. It was therefore possible that test drilling might reveal such conditions that a site would have to be abandoned. For SKB, this meant that the programme for the site investigation phase had to be so robust that negative results from a site investigation or other changes in the siting prospects could be handled without the overall goal being jeopardized. This spoke in favour of a broad programme with investigations on many sites, since the probability that at least one or two sites would eventually satisfy the requirements should increase with the number of alternatives. This, however, had to be weighed against the requirement of reasonable inputs of labour and time.

Based on these considerations and the evaluations of the alternatives, SKB first concluded /SKB 2000g, Section 12.4/ that:

"…SKB concludes that Forsmark and Simpevarp have clear advantages from an establishment and societal viewpoint. They have a good prognosis when it comes to the bedrock as well. With these advantages, it is difficult to see any reason why not to proceed with these alternatives. SKB's conclusion is thus that these two alternatives must be included in the next phase."

Thus, Forsmark and Simpevarp stood out in all respects as clear favourites for site investigations. A programme of that scope would also satisfy the expectation expressed by the Government that the background material for siting should include material from site investigations on at least two sites /Government 1995/. However, SKB found that the requirement on robustness warranted a broader programme, with continued studies of additional alternatives with good prospects but with different conditions than Forsmark and Simpevarp. Interest was mainly focused on sites representing other geological conditions and located in other municipalities. SKB made the following assessment of the available alternatives /SKB 2000g, Section 12.4/:

"Of the siting alternatives, Tierp north and Fjällveden can contribute towards broadening the geological range of alternatives. These sites should therefore be included among the alternatives that are studied further, in SKB's opinion. Tierp north, together with Skutskär, offers good industrial establishment possibilities. SKB judges this alternative to be fully realistic from all aspects. There is a greater degree of uncertainty for Fjällveden with regard to feasibility.

Other siting alternatives do not offer any obvious advantages from the geological breadth aspect. However, there is no good reason at this point to either dismiss or commence site investigations for any of these alternatives. Hargshamn is the leading alternative if it should not be possible to commence site investigations in Forsmark or if the investigations show that the bedrock does not meet the requirements. Similarly, Oskarshamn south and Hultsfred constitute possible alternatives to Simpevarp."

From this, SKB drew the conclusion that a site investigation was also warranted in the granite area of interest in Tierp Municipality. The main uncertainties for the Fjällveden alternative had to do with the prospects for transportation and industrial establishment. Data on the bedrock in the area in question were available from drilling done in the 1980s. SKB's plan for Fjällveden was therefore to further investigate the feasibility of an establishment and to evaluate existing geoscientific data with the aid of modern methodology for safety assessment.

In summary, SKB's programme for the site investigation phase included the following:

- A site investigation in the Forsmark area in Östhammar Municipality.
- A site investigation in the Simpevarp area (including the area that later came to be designated Laxemar) in Oskarshamn Municipality.
- A site investigation in an area in the northern part of Tierp Municipality.
- Further study of the siting prospects in the Fjällveden area in Nyköping Municipality.

4.4.3 The decision process leading up to the site investigation phase

SKB presented the choice of sites plus a general programme for the site investigation phase in the supplement to RD&D-Programme 98 /SKB 2000g/. The programme was thereby subjected to regulatory review and a Government decision in accordance with the established procedure for the RD&D programmes. Further, SKB had clarified that the site investigations were conditional on the consent of the concerned municipalities.

In its review statement regarding the RD&D supplement, the then Swedish Nuclear Power Inspectorate (SKI) summarized both what the other reviewing bodies had said and its own evaluation of SKB's choice of areas for site investigations. In /SKI 2001, pp. 49-50, in Swedish only/ SKI presented the following summary assessment of SKB's choice of sites for site investigations:

"SKI concludes that SKB has carried out feasibility studies in six municipalities (a total of eight including Storuman and Malå) which together provide a broad coverage of geological and geoscientific properties that can be expected in Swedish crystalline bedrock. SKI thereby considers that SKB has presented a sufficient selection pool for selection of sites for siting of a final repository and for commencement of site investigations.

SKI considers that SKB has shown, as far as is possible based on the feasibility studies, that the siting alternatives of (western) Simpevarp in Oskarshamn Municipality, Forsmark in Östhammar Municipality and Tierp north in Tierp Municipality have good prospects of satisfying the regulatory authorities' requirements on safety and radiation protection. SKI also considers that it is reasonable to take into consideration the advantages offered by Simpevarp and Forsmark as regards industrial establishment and societal aspects in the manner SKB has done in its choice. SKI therefore supports SKB's wish to commence site investigations in these two areas.

As far as the choice of Tierp north is concerned, which is not associated with a nuclear facility, SKI considers, with the support of several reviewing bodies, that there are weaknesses in the arguments. SKB cites as a main reason for the choice of Tierp north that this alternative adds geological breadth to the selection pool. However, SKI considers that SKB ought to offer a better explanation of how Tierp differs from other alternatives in this respect. SKB's should clarify the reasons for the choice of Tierp north in the consultation procedure mandated by the Government on 19 December 1996. SKI does not, however, have any objections to SKB's conducting site investigations in Tierp as well.

SKI would also like to point out that there are other factors besides bedrock geology that can add geoscientific breadth. Experience from safety assessments shows, for example, that hydrogeological and geochemical conditions are of great importance for long-term safety. SKI therefore recommends that SKB should not strike Hultsfred from the programme until questions concerning recharge/discharge and salinities etc have been further studied.

Moreover, SSI has pointed out shortcomings in the account of SKB's site selection as far as biosphere issues are concerned, e.g. dilution and accumulation effects in ecosystems, and their importance for long-term radiation protection and safety."

SKI thus agreed on SKB's choice of sites, and in addition had viewpoints concerning the importance of geographic location in relation to groundwater flow and geochemical conditions.

KASAM (the Swedish National Council for Nuclear Waste) also submitted a review statement to the Government (in Swedish only) /KASAM 2001/. KASAM supported SKB's choice of sites for site investigations and, for the most part, the arguments for these choices as well. Shortly before KASAM submitted its review statement, Nyköping Municipality had announced its intention not to let SKB continue with its investigations in the municipality. One reason given by the municipality for its decision was the uncertainty and unclear role that would exist for the Nyköping alternative during the time SKB was carrying out site investigations in Tierp, Östhammar and Oskarshamn, since only after these site investigations were completed would the municipality know whether SKB was still interested in nuclear waste disposal in the municipality /SOU 2002, p. 204/.The decision entailed that Fjällveden was no longer an alternative. Against this background, KASAM said that the possibility of adding one or two more alternatives to the selection pool, with bedrock similar to that of Fjällveden, should be considered.

On 1 November 2001, the Government made a decision on the matter, giving the go-ahead to SKB to continue the work according to the account that had been submitted /Government 2001/. The Government had no objections to SKB's initiation of site investigations in the three areas Simpevarp, Forsmark and Tierp north and assumed that SKB would consider the viewpoints that had emerged from the review of SKB's supporting material for the choice of sites. In the case of Nyköping, the Government observed that SKB's programme was no longer relevant, since the municipality had already declined further participation in the siting process. The Government also deemed that the KBS-3 method should be used as a planning premise for the site investigations.

Following the Government's go-ahead for the site investigations, it was up to the concerned municipalities to decide. In Östhammar, the municipal council decided in December 2001 to consent to a site investigation in Forsmark. A similar decision regarding a site investigation in Simpevarp was made by the municipal council in Oskarshamn in March 2002. In April 2002, however, Tierp Municipality declined further participation in the siting process for the final repository. The neighbouring municipality of Älvkarleby, which would be affected by shipments to a final repository in Tierp, took a positive stand on the site investigation.

The outcome of the decision process was thus that SKB was able to initiate site investigations in Simpevarp and Forsmark. SKB saw this as a fully acceptable basis for continuing the siting work.

5 The site investigation phase

The decisions in 2001 and 2002 that gave the go-ahead to site investigations in Oskarshamn and Forsmark also marked the transition from the feasibility study phase to the site investigation phase. An integrated account of the programme for the site investigation phase was provided in RD&D-K /SKB 2000g/. This chapter summarizes the execution of the site investigations and important results. The sites and the results are also presented in the Environmental Impact Statement /SKB 2011b/. Appendix VP describes how the activities during the site investigation phase as a whole were organized and managed.

5.1 Focus and programme

The overall goal of the site investigation phase was to prepare applications with supporting material for licensing under the Nuclear Activities Act for the final repository and under the Environmental Code for the KBS-3 system. This has required investigations that have furnished material comprehensive enough to:

- show whether the selected site satisfies fundamental safety requirements and whether construction-related conditions are fulfilled,
- permit comparisons between the investigated sites in Forsmark and Oskarshamn as a basis for selecting a site for the final repository,
- serve as a basis for adaptation of the final repository to the characteristics of the site with an acceptable impact on society and the environment.

When all decisions required to commence the site investigations had been made, the technical preparations had proceeded for many years and been described in a series of reports. The type of information SKB intended to gather on the site and how the information was to be used to evaluate the suitability of the site for a final repository was described in /SKB 2000h/. /SKB 2001a/ provided a more in-depth and detailed description of the plans for investigations of the bedrock and the surface ecosystems. This report specified what would or could be measured, what methods would be used, and how site-descriptive models would be set up. The geoscientific parts of the programme were based on the requirements and preferences on the rock formulated in /Andersson et al. 2000/. Based on these general programmes, SKB prepared site-specific investigation programmes for Forsmark /SKB 2001b/ and Simpevarp /SKB 2001c/. The ambition was that the site-specific information should be sufficient for the site-descriptive account and the safety assessment. The programmes were reviewed by the regulatory authorities within the framework of the consultation process that was established in accordance with the Government's decisions regarding RD&D-Programme 95 /Government 1996/ and RD&D-K /Government 2001/.

In response to the partly unique needs, strategies, methods and instruments for surface-based investigations have been developed and applied ever since the start of the nuclear waste programme. The foundation was laid during the study site investigations, and the technology was updated for the construction of the Äspö HRL. Investigation and analysis methods were further developed and improved in preparation for the site investigations. The site investigations were therefore able to build on a solid knowledge base regarding geoscientific investigations. The discipline of surface ecosystems was not included in either the study site investigations or the investigations for construction of the Äspö HRL. Extensive work was therefore done prior to the site investigations to identify which conditions and properties of the surface ecosystems needed to be determined, possible characterization methods and suitable modelling tools /Lindborg and Kautsky 2000, SKB 2001a/.

5.2 Methodology

The work during the site investigation phase was pursued in project form. The most important activities were:

- to carry out investigations in Oskarshamn,
- to carry out investigations in Forsmark,
- to produce descriptions of the investigated sites as a basis for site-adapted repository solutions, safety assessments, environmental studies and environmental impact assessments,
- to design facilities, systems and infrastructure for final repositories on the investigated sites to a level that can serve as a basis for the facility descriptions and safety assessments that are to be included in the applications,
- to produce safety analysis reports for the long-term safety of the final repository and the operation (including transportation) of the facility on the investigated sites,
- to carry out studies as a basis for assessing the impact on environment, human health and society of planned facilities and activities,
- to carry out the prescribed consultations and other communication with concerned parties and the public,
- to devise a programme for the construction phase,
- to produce the Environmental Impact Statement that should accompany the applications.

In the final part of the site investigation phase, an integrated evaluation of all background material was made in order to be able to:

- select a site for the final repository and justify this choice,
- compile the licence applications.

Figure 5-1 shows, with Forsmark as an example, the connections between the most important subprojects and the control of the information flow.

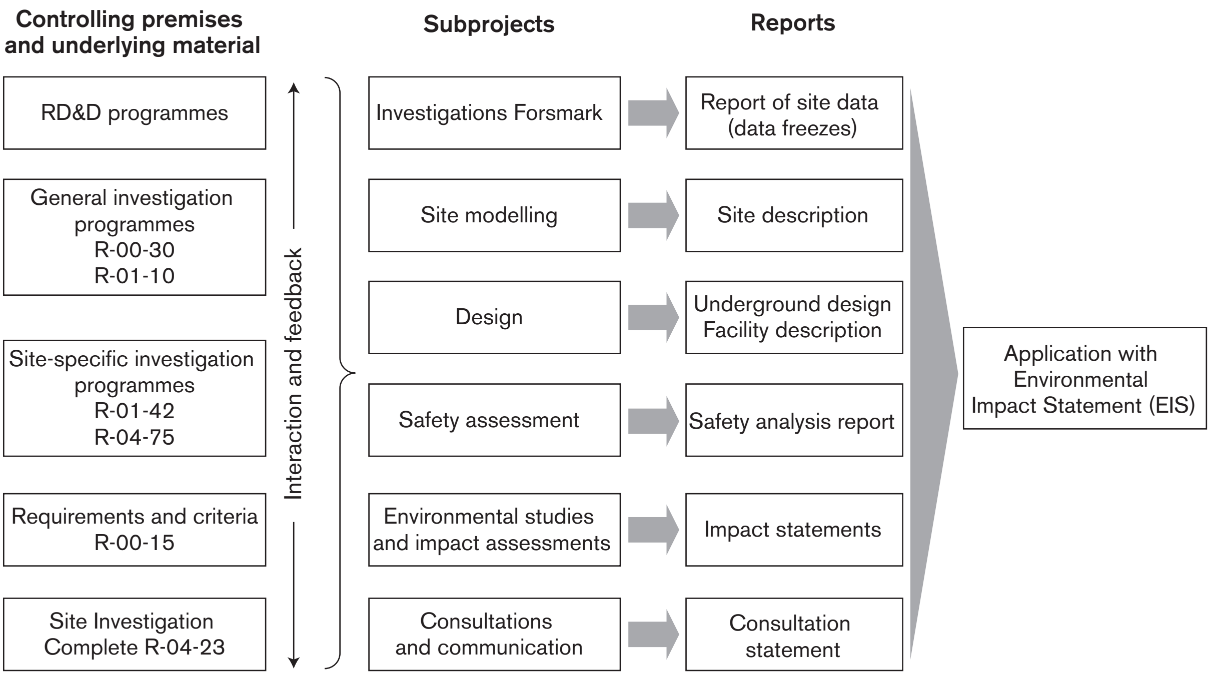

Figure 5-1. *Simplified diagram of the information flow during the site investigation phase, with Forsmark as an example (the figures in the left-hand column refer to relevant SKB reports).*

The project was carried out in two main stages: initial site investigation (ISI) and complete site investigation (CSI). In a similar manner, the design of a site-adapted repository has been carried out in two stages, called D1 and D2. After the initial stage, a preliminary safety evaluation was made of the site in question, which included comparing the data collected on conditions on the site with pre-established criteria /Andersson et al. 2000/. An essential goal was to evaluate the assessment that had justified the choices of candidate sites, i.e. to ensure that these sites have good prospects of meeting the requirements for a final repository. Another goal was to give feedback to the continued investigations and the work with the repository layout and to identify geoscientific questions that might require particular attention in the continued work.

5.2.1 Investigations, site modelling, design and safety assessment

Most of the work during the site investigation phase has been done within four technical main activities: investigations, site modelling, design and safety assessment.

Investigations

Surface- and airborne investigations have included surveys of the biosphere and geological conditions as well as geophysical surveys. The bedrock at depth has been investigated with boreholes, many down to repository depth or deeper. Extensive measurements have been performed in the boreholes. Investigations of the biosphere, mainly meteorology and surface water, have been done recurrently, providing long time series. The investigation methodology has been the same at both sites. But to focus on the issues that were of interest on each site, site-specific investigation programmes were prepared. An important example of a site-specific adaptation is the choice of locations for different boreholes.

The site investigations were conducted in steps with investigations and reporting of site data (data freezes) followed by analyses and feedback. Such an iterative approach was necessary in order to maintain an overview of the state of knowledge and manage the work in such a way that the investigations were focused on questions where the site models indicated a need for more information.

Site modelling

The information from the investigations has been analyzed and interpreted into a useful description of the site. This site description with associated models is necessary in order to understand how a final repository would affect the environment around the site in the short and long term. It provides necessary information for design and safety assessment. Site modelling is done both discipline-specifically and integrated over all disciplines. The result is a three-dimensional site descriptive model of rock, soil and biosphere, see Figure 5-2.

In simplified terms, site modelling is about understanding the properties of a site and interpreting and translating the point-related measurement values from the site investigations so that they apply to areas and volumes. Evaluations of uncertainties in individual parameter values and assessments of the reasonability of geometric subdivisions are important steps in the work. General background knowledge and data from other investigated sites provide support for the analyses.

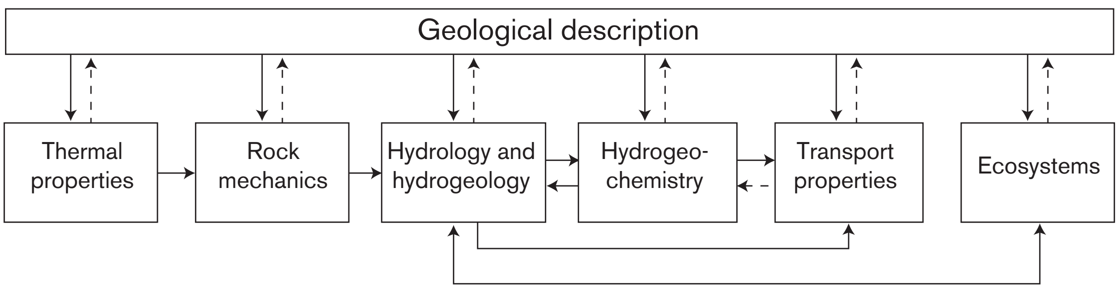

Figure 5-2. *The discipline-specific site models are linked to each other. The geological description serves as a basis for other models.*

The point of departure in site modelling is the rock's lithological structure (distribution of rock types) and the occurrence of deformed rock volumes. This is presented in the geological description, which covers distributions of rock types and their properties as well as the location, geometry and properties of the deformation zones. Based on the geological description, similar models can be constructed for other disciplines. The mechanical and thermal properties of the bedrock are, for example, closely linked to the composition of the rocks and the occurrence of fractures. In a similar manner, the distribution of rock stresses is linked to the mechanical properties of rocks and deformation zones.

The bedrock's fracture structure is also the basis for the hydrogeological model. Only those fractures with high enough permeability to permit groundwater flow are of importance. The water's patterns of movement, residence times and flows are dependent on how permeable the fractures are, how they are interlinked and what driving force the groundwater is subjected to. By examining which minerals cover the fracture surfaces it is also possible to get an idea of what chemical conditions have prevailed during different periods of time and to estimate the ability of the rock to retard the transport of radionuclides. It can be seen during which periods oxygen-rich water has penetrated down into the bedrock and how deep it has reached.

Design

The design work has included producing a site-adapted layout for the repository and a facility description. The work has been based on the site descriptive model. The design work has also included assessments of the consequences of the construction activities.

The design process has been carried out in two steps. After the initial site investigation and based on the resultant preliminary site description, preliminary layouts were developed (layout D1). The purpose of this preliminary design work was /SKB 2004a/ to:

- test and evaluate the design methodology,
- determine whether the final repository can be accommodated within the studied site,
- identify site-specific facility-critical issues and thereby provide feedback to the continued design and development work,
- provide supporting material for preliminary safety evaluations and the SR-Can safety assessment /SKB 2006a/.

After the complete site investigation, facility layouts were developed for each site (layout D2). The goals of this design step were to /SKB 2007/:

- demonstrate a site-specific adaptation of the repository that satisfies the design premises regarding safety, functionality and reliability,
- demonstrate the feasibility and efficiency of a stepwise construction of the repository,
- identify and evaluate site-specific technical risks and the need to address them in the next design step,
- provide a basis for environmental impact assessment and safety assessment.

Safety evaluations and safety assessment

In the safety assessments, long-term safety has been evaluated on the basis of the site descriptive model and the proposed repository layout. An initial evaluation was done after the initial site investigation, involving preliminary safety evaluations. The goals were to evaluate, with a limited labour input, whether the feasibility study's assessment of the suitability of the candidate area from a safety viewpoint was still valid in the light of then-available site investigation data, to provide feedback to the continued work on the repository layout and to identify site-specific issues that might need to be elucidated. The safety evaluation mainly entailed comparing knowledge on the site with the requirements and preferences previously presented by SKB /Andersson et al. 2000/.

A much more comprehensive assessment of the safety of a repository in Forsmark or Laxemar was done in the SR-Can safety assessment /SKB 2006a/. SR-Can was also based on data from the initial site investigation and corresponding site descriptions.

The site-comparing evaluations of safety on which the selection of Forsmark is based (described in Chapters 6 and 7) were based on the results of the complete site investigation.

5.2.2 Environmental studies

Data from the investigations have, together with the design results, been used to study environmental issues and assess environmental impact during the different phases of the project. The studies describe the consequences of construction, operation and transportation for the residential environment and health, the natural and cultural environment, the landscape, recreation and outdoor activities. The studies also include preventive and compensatory measures aimed at minimizing the impact.

5.2.3 Quality control and review

Data from the site investigations have undergone extensive quality control before being entered into SKB's databases. In conjunction with the site modelling, the data used were checked regularly for reasonableness. This was necessary in order to ensure good quality in the final model. An example is the discovery of a non-systematic error in data on the orientation of the boreholes and drill cores, which led to extensive revisions of the analysis work.

Before publication of reports from the investigations, they have been reviewed internally by SKB. The most important ones have also been reviewed for SKB by an independent panel (SIERG) of internationally renowned experts. This peer review procedure has constituted an essential part of the quality assurance of site descriptions and site models and has greatly contributed to ensuring that reports and other documents are of the quality striven for by SKB.

After publication, many of the reports have also been reviewed by the regulatory authorities' international review panels: SKI's review panel INSITE /Chapman et al. 2005/ and SSI's OVERSITE. In addition, SKB's plans and ongoing work have been presented to the regulatory authorities and their review panels at workshops held about twice a year.

5.2.4 Information and consultations

Responsibility for carrying out the site investigations has rested with two separate site organizations within SKB. They have also been responsible for local information and public relations activities. A large number of visitors of all categories have come to see the activities. Great importance has been attached to contacts with landowners and nearby residents who are directly affected by the investigations in order to reconcile the activities with other interests, settle compensation matters etc.

Contacts with the local municipality and county administrative board have also been vital tasks. Ever since the start of the site investigations, the municipalities of Oskarshamn and Östhammar have actively followed SKB's activities through their own organizations and working groups. The municipalities have also conducted – and are still conducting – their own competence building and information activities.

5.2.5 Supplementary studies

In conjunction with the selection of sites for site investigations, then-SKI (the Swedish Nuclear Power Inspectorate) raised the question of the possible advantages and disadvantages of locating the final repository on the coast versus in the interior. More specifically, the question was whether or not long flow paths (and long circulation times) for groundwater from inland locations can offer advantages from a safety viewpoint. Results and conclusions of the analyses done by SKB during the site investigation phase in response to this question are dealt with in Section 8.2.

5.3 Forsmark

Forsmark is located in Östhammar Municipality in Northern Uppland, just over 70 km from Uppsala, see Figure 5-3. The nuclear power plant with its three reactors and associated infrastructure is situated on the industrial area in Forsmark. SKB's final repository for short-lived radioactive waste (SFR) is located next to the harbour.

5.3.1 Investigations

Investigations in Forsmark were initiated in 2002 and concluded in the summer of 2007. Prior to the start, an investigation programme was prepared that mainly covered the initial part of the site investigation /SKB 2001b/. The focus of the initial investigations was on answering general and site-specific questions that were regarded as crucial for assessing the suitability of the site. The initial investigations covered an approximately 6 km long and 2 km wide area known as the candidate area, see Figure 5-4. It comprises the northwestern part of an elongated "tectonic lens", where the bedrock was expected to have been preserved relatively undisturbed in a region with large deformation zones.

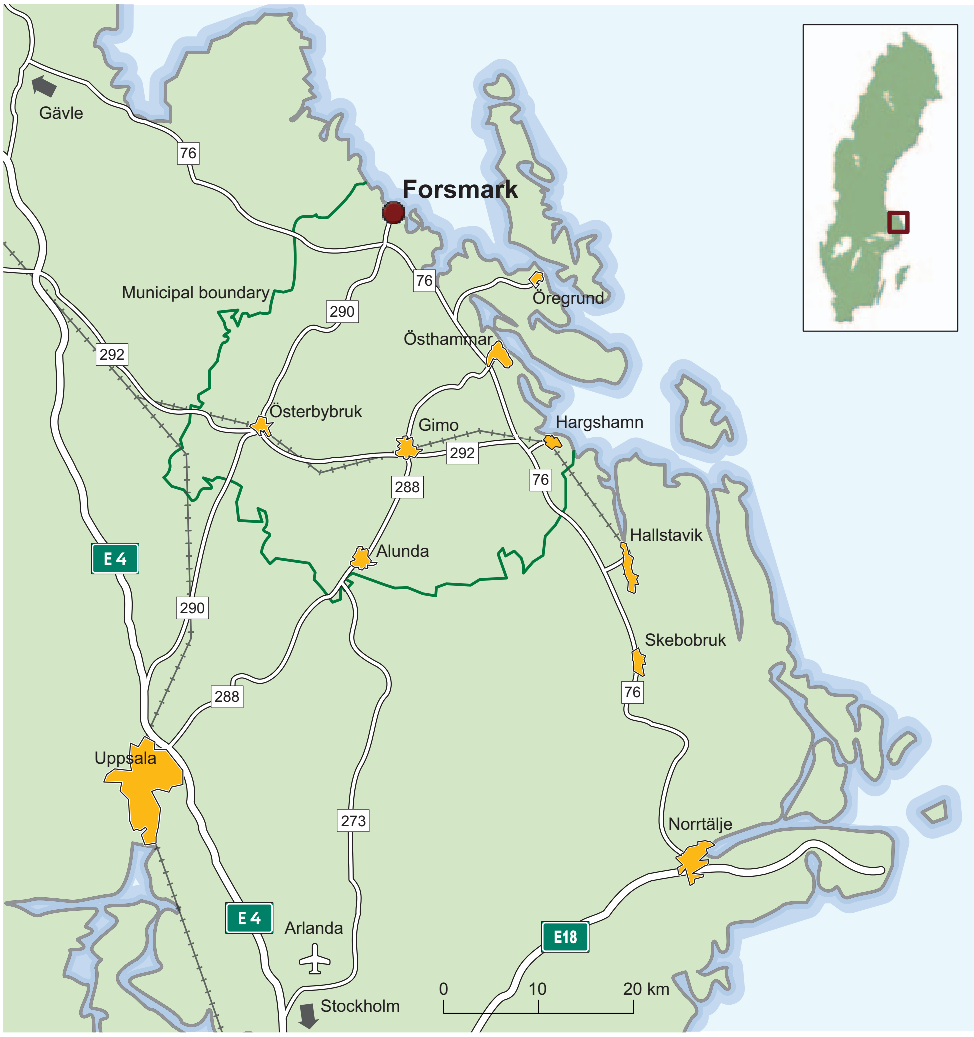

Figure 5-3. Key map: Forsmark, Östhammar Municipality and parts of Uppland.

The investigations had already at an early stage indicated that both the northwestern and the south-eastern parts of the candidate area had bedrock that warranted further investigations. The difference that could nevertheless be noted was a higher frequency of gently-dipping, permeable fracture zones in the southeastern part. The main reasons for prioritizing the northwestern part of the candidate area (Figure 5-4) at that time were that:

- Preliminary studies of space requirements and possible locations showed that a repository could in all probability be accommodated within the northwestern part.
- The location partly beneath the industrial area permitted a repository layout with surface facilities that could be accommodated on existing industrial land. This was deemed to offer a number of technical and environmental advantages.

A programme for the concluding portion of the site investigation was prepared /SKB 2004b/. The aims of the investigations included in this programme were to:

- Determine the geological boundaries of the available rock volume suitable for deposition at repository depth.
- Characterize the available rock volume to the required extent and level of detail.
- Characterize the northwestern part's hydraulic boundary areas.

In all the site investigation has included 25 cored boreholes, 19 of which go down to repository depth or deeper, and a large number of other boreholes (more than 38 percussion boreholes and 100 soil wells), plus a thorough geoscientific and ecological survey on the surface /SKB 2008a/.

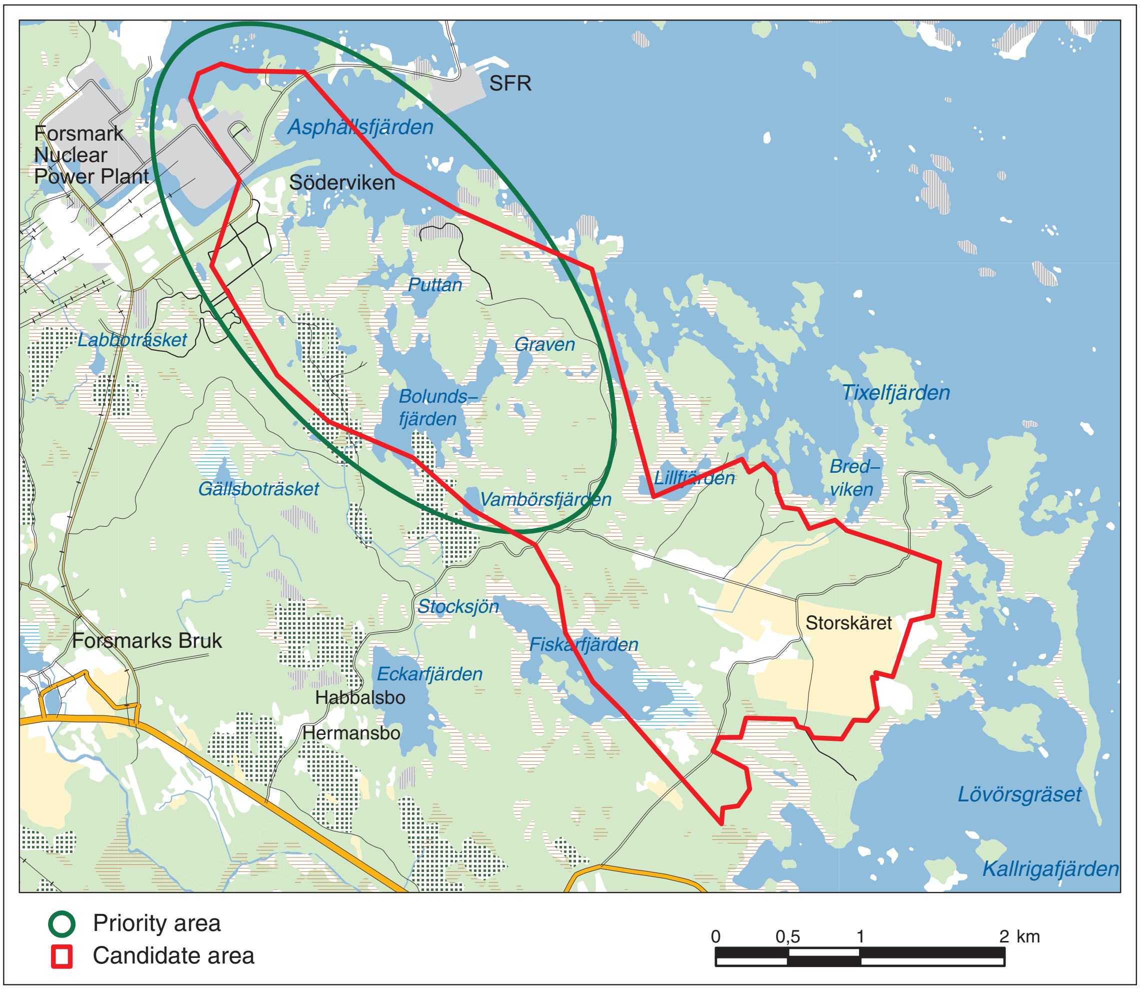

Figure 5-4. Candidate area and priority area in Forsmark.

5.3.2 Site descriptions

Four site descriptive models for Forsmark have been published /SKB 2004c, 2005a, 2006b, 2008a/. The preliminary site descriptive model, version 1.2 /SKB 2005a/ was based on the results of the initial site investigation and served as a basis for design step D1, preliminary safety evaluations /SKB 2005b/ and the SR-Can safety assessment /SKB 2006a/. Three modelling steps were carried out during the concluding part of the site investigation. The main purpose of this first step (version 2.1) was to provide feedback to the investigations in order to ensure effective information gathering during the remainder of the site investigation. In addition, the geological model for lithology and deformation zones was updated, but no complete integrated site descriptive model was constructed. After that, modelling step 2.2 was executed with updated models for site geology, rock mechanical and thermal properties as well as hydrogeology and transport properties. These models were the point of departure for design step D2 and modelling step 2.3, which resulted in the final integrated site descriptive model /SKB 2008a/. Together with the results of design step D2 /SKB 2009a/ it has served as a basis for the comparative safety evaluation in support of site selection /SKB 2010b/ and for the SR-Site safety assessment /SKB 2011a/.

5.3.3 Safety evaluations

When the initial investigation phase had been completed and a preliminary site descriptive model had been constructed, the state of knowledge of the properties of the site was cross-checked against the fundamental requirements and preferences in /Andersson et al. 2000/. The conclusion of this preliminary safety evaluation /SKB 2005b/ was that the site satisfied the requirements that could be checked and that further investigations were therefore warranted. This was subsequently verified by the SR-Can safety assessment /SKB 2006a/. The cross-check also provided material for identifying remaining data needs, along with a strategy and programme for further investigations.

Based on information from the complete site investigations and design step D2, SKB has performed comparative safety evaluations of a repository at Forsmark and one at Laxemar /SKB 2010b/, see Chapters 6 and 7.

5.3.4 Bedrock

The investigated bedrock is geologically homogeneous and is dominated, from the surface down to a depth of at least 1,000 metres, by metagranite with a high quartz content, see Figure 5-5. The rock has high thermal conductivity. A deformation zone that dips gently towards the southeast divides the candidate area into two main parts. The repository area is located northwest of this zone and is intersected by steeply dipping zones.

From the surface down to about 200 metres depth, the frequency of conductive gently-dipping fractures is relatively high. The fractures are hydraulically interconnected over large distances. Together with the gently dipping zones, these fractures constitute the main flow paths. The frequency of conductive fractures is much lower at greater depth. At depths greater than 400 metres, the average distance between conductive fractures is more than 100 metres. The rock stresses are higher than is normal in the Swedish bedrock but increase only slowly with depth.

The salinity and age of the groundwater increases with depth. The water composition in the repository area differs from that in the gently dipping zone in the southeast. The reason for this is judged to be that the water in the repository rock has been isolated from superficial water for a long time, while the water in the weakly sloping zone contains traces of water from the Littorina Sea, which covered the area between 9,500 and 5,000 years ago.

5.3.5 Repository design

The site-adapted layout of a final repository in Forsmark is based on the principle of placing the repository itself within the priority area (Figure 5-4), while surface facilities and activities can mainly be accommodated within the existing industrial area. Different proposals have been formulated and evaluated, resulting in a repository at a depth of about 470 metres with an extent as shown in Figures 5-7 and 5-8. The surface facilities are gathered in an operations area at Söderviken, see Figures 5-6 and 5-8.

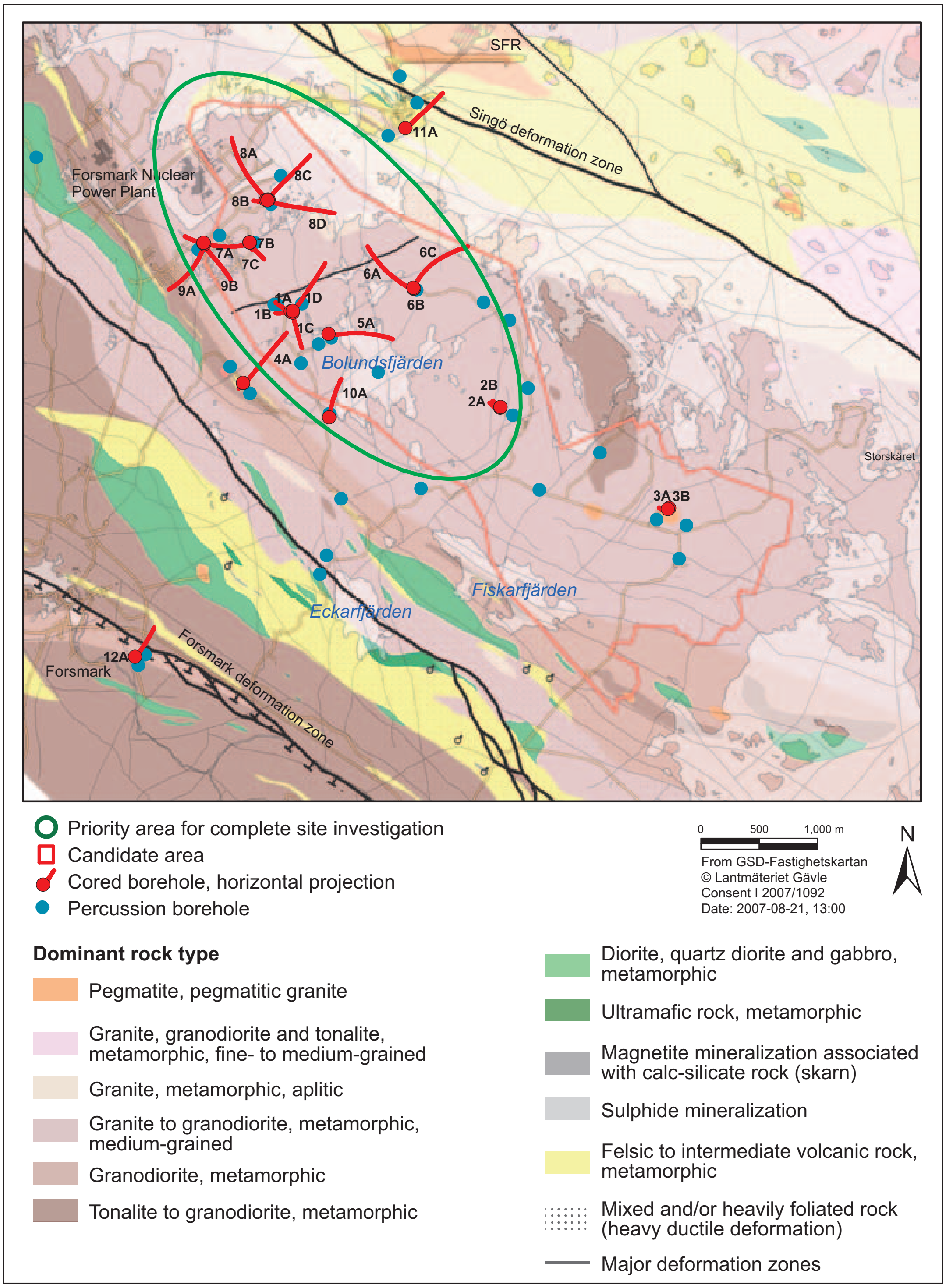

Figure 5-5. *Geology and boreholes in Forsmark.*

The design work in phase D1 resulted in a preliminary layout for a repository at a depth of 400 metres. Two alternative locations for surface facilities were studied. In one alternative, most of the facilities were located adjacent to SFR. In the other alternative, the facilities were gathered in an operations area east of the roundabout at the entrance to Forsmark, on the south part of the industrial area. After a comparative evaluation /SKB 2006c/, the location at the entrance was prioritized. An important argument was that this area is favourably located in relation to the repository's central area so that rock haulage can take place via a vertical skip shaft. This provides substantial operational advantages in comparison with a layout where all heavy goods have to be transported via a ramp. Other arguments in favour of this choice were better availability of areas for handling of rock spoil and smaller total transport needs.

Figure 5-6. Aerial photo of Forsmark. Söderviken is located to the left of the nuclear power plant, with the cooling water channel visible between them. In the foreground is the SFR facility.

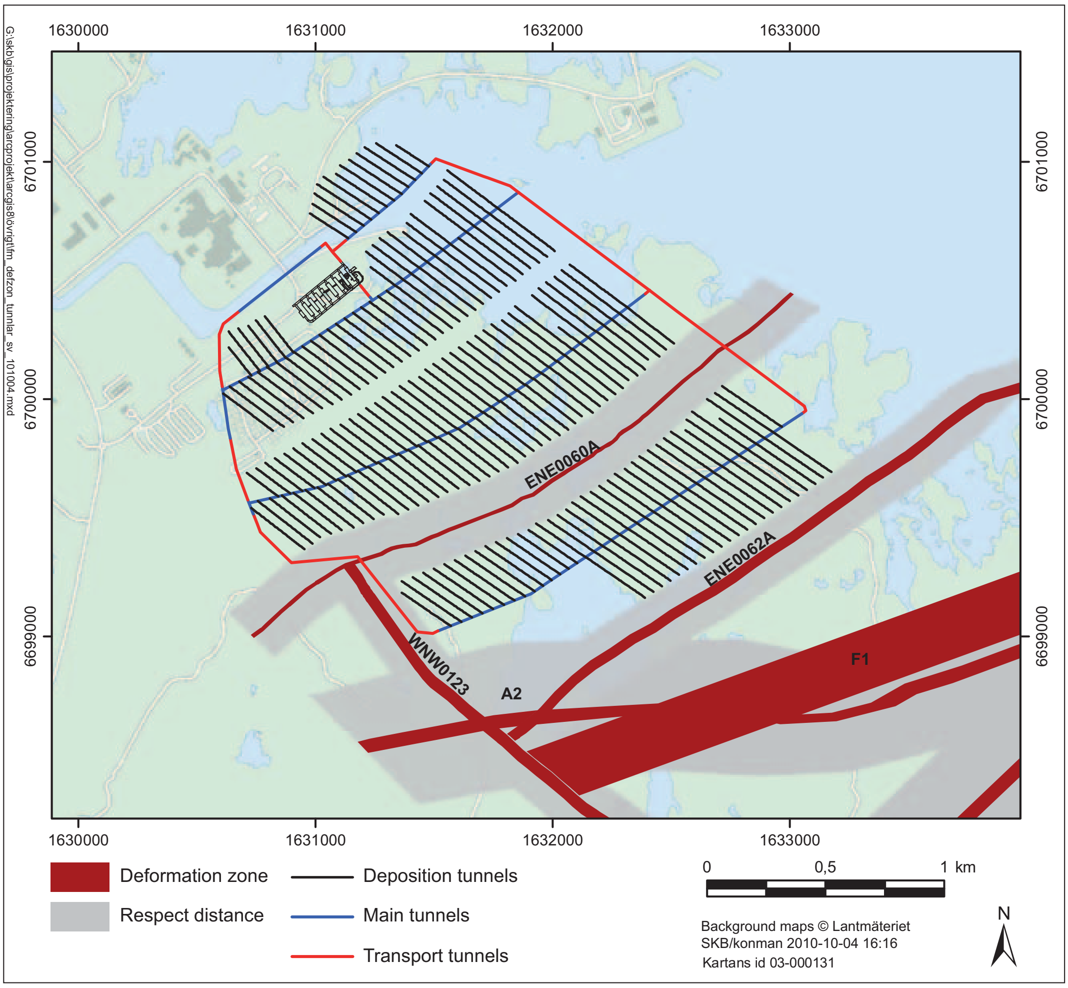

***Figure 5-7.** Layout of final repository in Forsmark. The figure also shows deformation zones with such properties that a specified minimum distance (respect distance) is required between these zones and deposition tunnels. From layout D2 Forsmark /SKB 2009a/.*

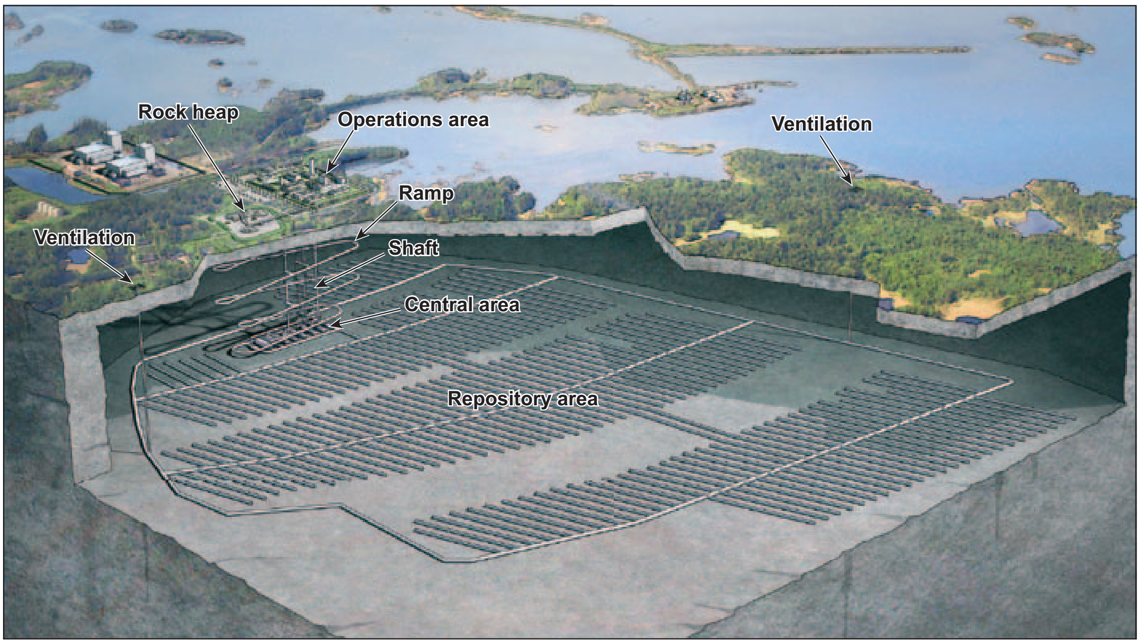

Figure 5-8. Final repository for spent nuclear fuel in Forsmark, fully built.

In design stage D2, all parts of the repository were revised and designed in detail based on the information obtained during the CSI. Based on the system design that had been chosen and the repository layout that was devised, alternatives for fine-adjusting the locations of the surface facilities and the descents, taking into account both rock conditions and other aspects. The alternatives and reasons for the chosen layout are presented in the Environmental Impact Statement /SKB 2011b/. The repository depth was increased from about 400 metres to about 470 metres, since the site investigations showed that the already low frequency of water-conducting fractures is further reduced at depths below 400 m. At the same time, the investigations showed that the rock stresses did not increase as rapidly with depth as had previously been assumed, so that a greater repository depth does not entail any problems. The results of the design work during stage D2 are presented in /SKB 2009b/.

5.3.6 Physical planning

The municipal council in Östhammar Municipality has adopted planning regulations for Forsmark including both changes in the existing detailed development plan and detailed development planning of new areas. Together, these regulations permit a final repository for spent nuclear fuel to be built in the planned manner.

5.3.7 National interests and protected areas

The area being considered for the final repository's facilities has been identified as being of national interest for final disposal of spent nuclear fuel and nuclear waste. A large part of the area is also of national interest for energy production, and part of the area is of national interest for nature conservation. The whole area is of national interest according to the special management provisions for highly developed stretches of coast. Farther to the southwest is Forsmarks bruk, which is of national interest for cultural heritage preservation. Areas of national interest for wind power are located both on land and at sea. In the southeast, bordering on the candidate area as shown in Figure 5-4, is the Kallriga Nature Reserve, which has also been designated a Natura 2000 site /Allmér 2010/.

5.3.8 Infrastructure

Road transport to and from the final repository mainly involves national highway 76 towards Östhammar and Hargshamn, county roads 288 and 290 towards Uppsala and to a lesser extent highway 76 towards Gävle, see Figure 5-3. Canisters for deposition will be transported by sea from

Oskarshamn to the Port of Forsmark and by terminal vehicle from there to the final repository's operations area. Clay material for buffer and backfill will be shipped to the harbour at Hargshamn and from there by truck to Forsmark /Fors and Klingenberg 2008a/.

5.3.9 Existing development

Existing development is sparse; the nearest clustered housing is located around Forsmarks bruk, see Figure 5-4. There are no dwellings within 1 km of the operations area; scarcely 100 people live within 5 km, and around 500 within 10 km /SCB 2009/.

5.3.10 Natural environment

The Forsmark area is low-lying with a convoluted coastline and a number of small islands offshore. The forest goes all the way down to the shoreline. The key words to describe the landscape type are small-scale and pristine. The natural environment has a wilderness character that is atypical of the region and consists for the most part of forested moraine lands with occasional rock outcrops. Numerous protected and valuable areas are located nearby, including around Kallrigafjärden Bay. The area has a rich bird life, with many breeding raptor species, and also numerous rich fens scattered with meres (ponds), where the pool frog can be found /Allmér 2010/.

5.3.11 Cultural environment

Outside of the present-day industrial area, Forsmark bears strong traces of the ironworking era lasting from the end of the 16th century to the end of the 19th century, when Forsmarks bruk's needs shaped the landscape and the built environment. With its well preserved buildings, Forsmarks bruk is one of the foremost examples of mill towns in the country. The district around Forsmark has been dominated by one large landowner.

5.3.12 Recreation and outdoor activities

For a long time the land around the nuclear power plant was poorly accessible, so outdoor activities in the area are less extensive than in many other parts of the east coast. The main value for outdoor activities lies in the pristine countryside and the animal and bird life. Recreational activities such as hunting and fishing are also popular /Ternström 2008a/. A sports centre, a tennis court, illuminated trails and even bathing areas are located within the industrial area there are /Ottosson 2007/.

5.3.13 Environmental consequences

Several valuable natural attractions are affected directly or indirectly by the final repository. The Forsmark-Kallrigafjärden area of national interest lies partially within the repository's impact area, which could lead to consequences for this area of national interest. There are a large number of valuable natural attractions within the area that could be affected by surface facilities and possible groundwater lowering, such as a couple of ponds harbouring a protected species, the pool frog. There are also a number of other protected plant and animal species that could be affected. In all cases it is possible to eliminate or at least mitigate the consequences by preventive and compensatory measures /Allmér 2010/.

Since all radioactive material is encapsulated, construction and operation of the final repository is not expected to lead to any changes in the radiation environment.

The land that is needed for the final repository is owned today by SKB and Forsmarks Kraftgrupp AB. No privately owned properties need to be bought. This fact, plus the fact that the final repository is being located within an existing industrial area relatively far from residential areas means that there are few people whose residential environment will be adversely affected by the establishment of the facility.

Vibrations from the blasting and the heavy transport is not expected to cause damage to buildings, nor will the vibrations be perceived as disturbing to residents in the area.

Due to noise from construction activities and facility operation, some of the area of national interest for recreation and outdoor activities will have sound levels above the guideline values. Otherwise the consequences will be small. Noise from road traffic already causes high sound levels, above the guideline values. Transport to and from the final repository will result in more people being disturbed than at present, but this is not expected to lead to a deterioration in health for more people /Zetterling and 2008a/.

Emissions of air pollutants from transport, heavy equipment and handling of rock spoil add very little to existing emissions. Moreover, very few people are affected by the emissions. All in all, this means that the risk of health consequences due to air pollution is very low /Fridell et al. 2008a/.

Road transport also causes other nuisances in the form of accident risks, increased traffic congestion, and impacts on recreation and outdoor activities etc. These impacts are dependent on the transport volumes, but also a number of other factors such as road standard, weather conditions and commuting patterns.

5.4 Simpevarp/Laxemar

The area in Oskarshamn Municipality that was recommended for site investigation as a result of the feasibility study phase (see Section 4.4) is located about 20 km north of the city of Oskarshamn. The smaller subarea that was prioritized for site selection after the site investigation is called Laxemar and is situated northwest of county road 743 and about two kilometres west of the NPP and Clab on the Simpevarp Peninsula, see Figure 5-9. The Äspö Hard Rock Laboratory (HRL) is located about three kilometres to the northeast.

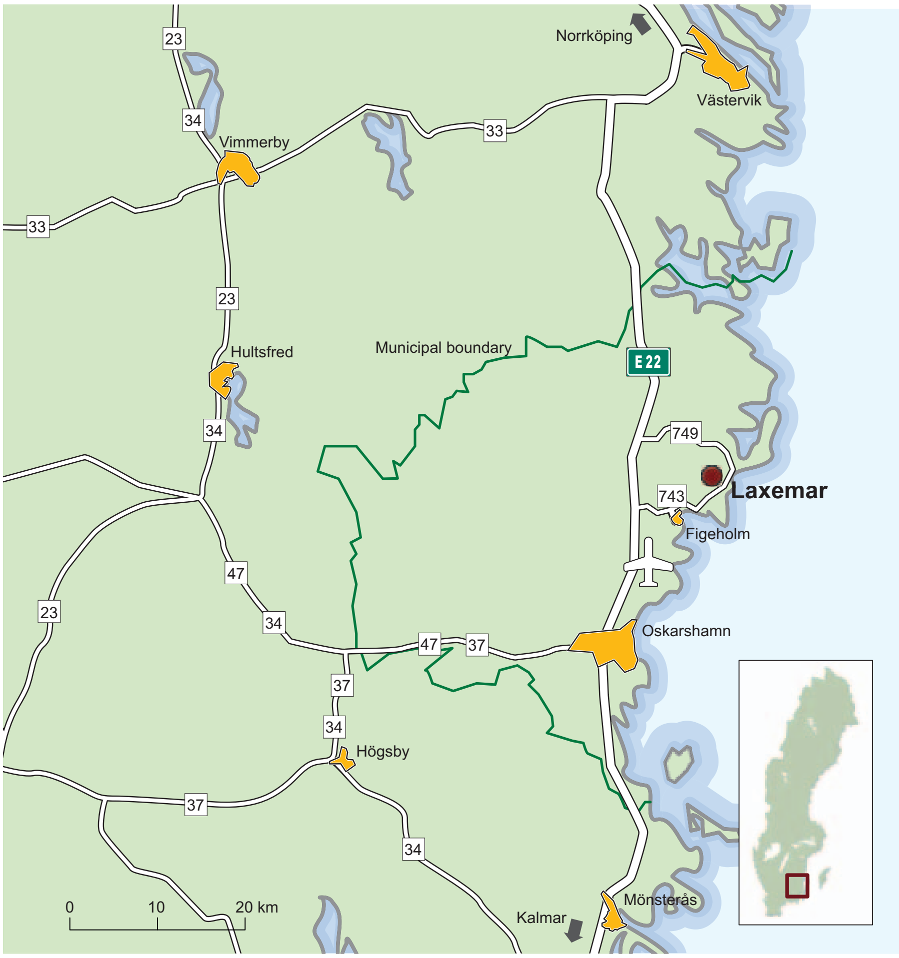

Figure 5-9. *Key map: Laxemar, Oskarshamn Municipality and eastern Småland.*

5.4.1 Investigations

The investigations in Oskarshamn started in 2002 and were concluded during the first quarter of 2008. Prior to the start, an investigation programme /SKB 2001c/ was prepared which mainly covered the initial stage of the site investigation on the approximately 60 square kilometre area that had been identified as being of interest for a site investigation as a result of the feasibility study phase, see Figure 5-10.

The investigations, including drilling, were initiated in an area consisting mainly of the Simpevarp Peninsula (hereinafter called the Simpevarp subarea), plus surface ecological inventories in the regional environs. Furthermore, geoscientific surface investigations were carried out, including geophysical helicopter surveys, within the entire candidate area. It became clear at an early stage that the Simpevarp Peninsula provides limited flexibility in repository layout due to its limited area. The investigation area was therefore expanded to include Ävrö, Hålö and nearby water areas.

Based on the results of these investigations, in March 2003 SKB submitted more precise plans, prioritizing continued investigations in the two subareas Simpevarp and Laxemar /SKB 2003/. Starting in early 2004, an initial site investigation of the Laxemar subarea was conducted, after an agreement had been reached with the concerned landowners.

The initial investigations were completed in the Simpevarp and Laxemar subareas in the autumn of 2004. Based on their results, SKB gave preliminarily priority to Laxemar for further investigations. The reason given was that the area was larger and therefore offered greater flexibility. When additional comparison material was available (site descriptions, design results and safety evaluations), the preliminary assessment was confirmed and SKB made a final decision to proceed with investigations in the Laxemar area.

The investigations within the Laxemar subarea were gradually focused on the area's southern and western parts (see the right-hand part of Figure 5-10). These parts are dominated by quartz monzodiorite, which has proved to be more homogeneous and fracture-poor than the bedrock that dominates the northern and eastern parts of the area. Furthermore, the water-conducting properties of the rock were judged to be more favourable in the southern and western parts /SKB 2005c/.

In all the site investigation has included 46 cored boreholes, 19 of which go down to repository depth or deeper, and more than 200 other boreholes (43 percussion boreholes and just over 190 soil wells), plus a thorough geoscientific and ecological survey on the surface.

5.4.2 Site descriptions

Site descriptions with associated models based on the initial site investigations were presented for the two subareas Simpevarp and Laxemar /SKB 2005d, 2006d/. These models (version 1.2) served as a basis for preliminary site-adapted repository layouts (version D1) and preliminary safety evaluations /SKB 2005e, 2006e/. Two modelling steps were carried out during the concluding part of the site investigation of the Laxemar subarea. The main purpose of the first step (version 2.1 /SKB 2006f/) was, in the same way as in the Forsmark case, to provide feedback to the investigations to ensure effective information gathering during the remainder of the site investigation. In addition, the hydrogeochemical and thermal models were updated, but no complete integrated site descriptive model was constructed. The final modelling work was therefore carried out with revised models for the site's geology, rock mechanical and thermal properties as well as hydrogeology and transport properties. These models served as a basis for design step D2 and for the final integrated site descriptive model /SKB 2009c/. Together with the results of design step D2 /SKB 2009d/, this model served as a basis for the comparative safety evaluation in support of the choice of site /SKB 2010b/.

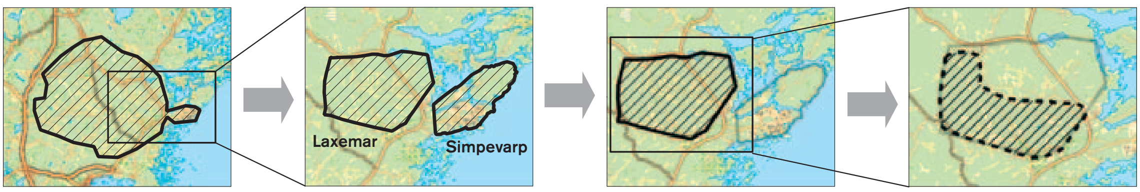

Figure 5-10. *The gradual narrowing of the investigation area at Simpevarp and Laxemar – from the 60 km² candidate area to the priority area in Laxemar.*

5.4.3 Safety evaluations

Cross-checks of the state of knowledge against the fundamental requirements stipulated before the site investigations were begun were done for both subareas, Simpevarp and Laxemar /SKB 2005e, 2006e/. These safety evaluations were based on version 1.2 of the site descriptions and the version D1 of the repository layout. The conclusion was that both subareas satisfied the requirements, but that the possible suitable deposition volumes beneath the Simpevarp Peninsula were limited.

The SR-Can safety assessment was performed based on the same body of material /SKB 2006a/. It showed that a repository in Laxemar satisfied relevant risk criteria but emphasized that the assessment was preliminary and that more representative data were needed for a more complete assessment. The cross-check also identified remaining data needs and enabled a strategy and a programme for further investigations to be established. Based on information from the complete site investigations and design step D2, SKB has performed comparative safety evaluations of a repository at Forsmark and at Laxemar /SKB 2010b/, see Chapters 6 and 7.

5.4.4 Bedrock

The bedrock in the southern and western parts of the Laxemar area (see Figure 5-11) is dominated by quartz monzodiorite and granite with a low quartz content. These rock types are characterized by low thermal conductivity and varying strength. The priority area is bounded by steeply dipping deformation zones. No major gently dipping deformation zones have been identified.

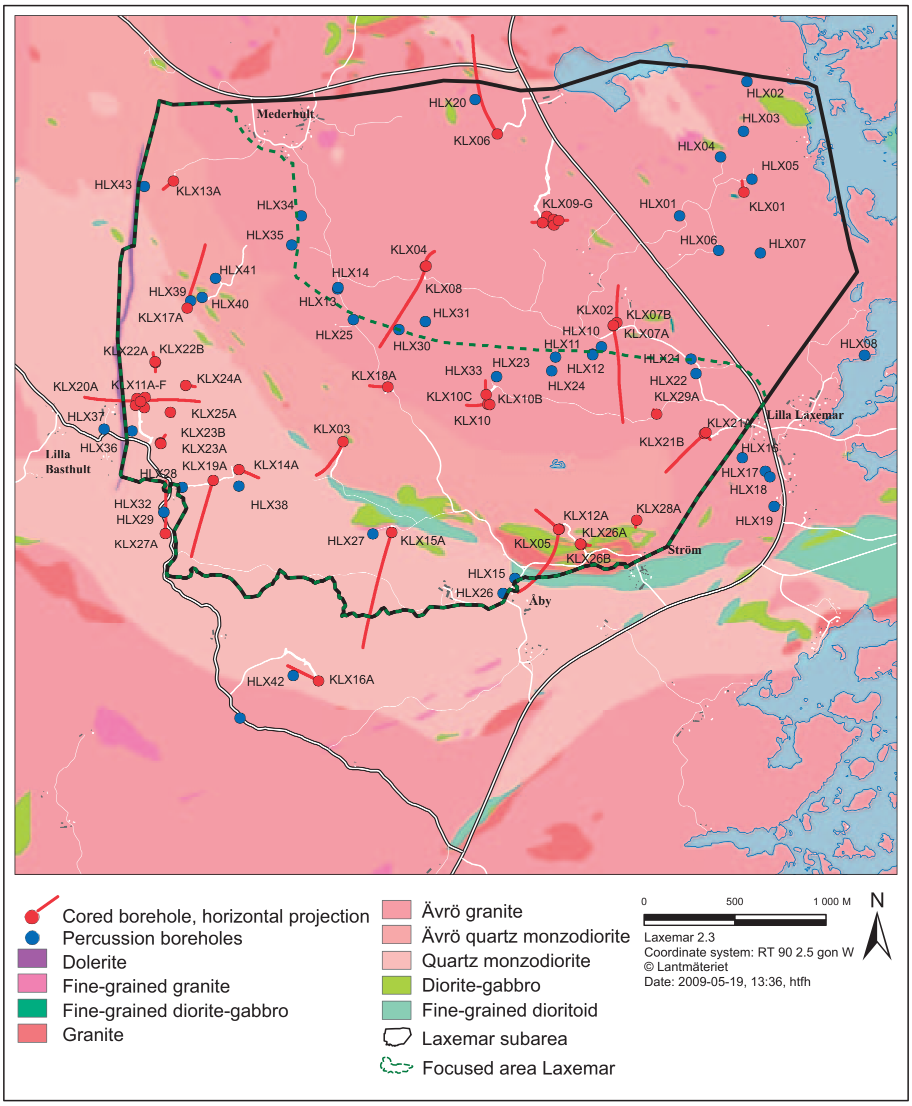

Figure 5-11. *Geology and boreholes in Laxemar.*

The uppermost 150 m of the rock has a relatively high frequency of water-conducting fractures (average distance about 1 m), but the frequency decreases with depth. At between 400 and 650 metres depth, the average distance between such fractures is 5–10 m. At even greater depth (tentatively around 700 m), the frequency of such fractures is judged to be very low (average distance more than 100 m), but this estimate is uncertain. The salinity and age of the groundwater increase with depth. The rock stresses are normal for Swedish bedrock and comparable to those measured at the Äspö HRL.

5.4.5 Repository design

In the site-adapted layout of a final repository in Laxemar that resulted from evaluation of a number of alternative proposals, the repository was located at a depth of about 520 metres with an extent as shown in Figures 5-13 and 5-14. The surface facilities were gathered in an operations area at Oxhagen, about two kilometres west of Simpevarp, see Figures 5-12 and 5-14. The location and layout of the operations area was optimized to obtain good rock conditions for construction of accesses and so that the operations area could be located above the central area. In addition to the geological conditions, other factors that influenced the placement of the facilities are the natural and cultural environment, existing infrastructure and industrial considerations.

At earlier stages, SKB studied several possible locations for the repository's surface facilities on the Simpevarp Peninsula and Hålö. When the decision was made to prioritize Laxemar, these alternatives were eliminated.

Figure 5-12. *Aerial photo of the Laxemar area, with the nuclear power plant and Clab in the background and Oxhagen in the middle of the picture.*

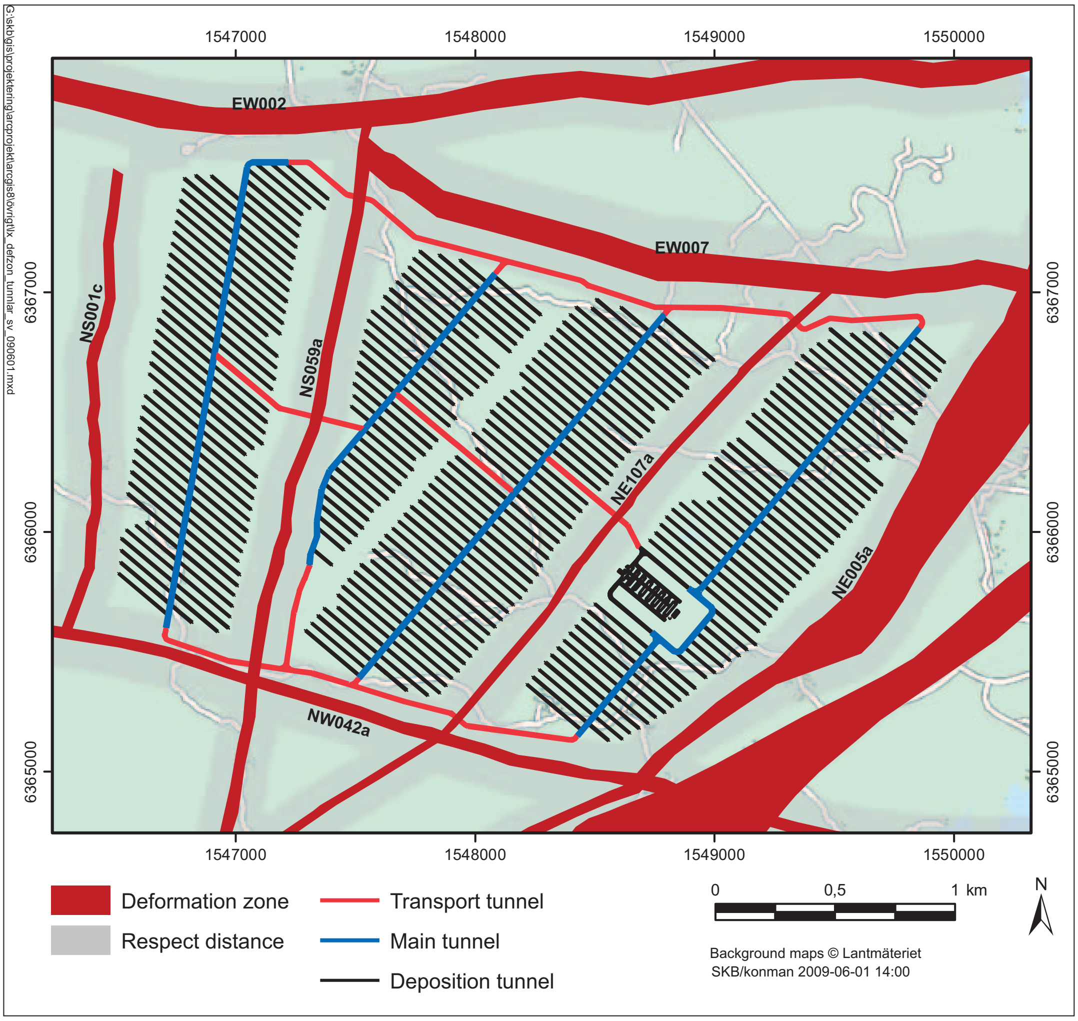

Figure 5-13. *Layout of final repository in Laxemar. The figure also shows deformation zones with such properties that a specified minimum distance (respect distance) is required between these zones and deposition tunnels. From Layout D2 Laxemar /SKB 2009d/.*

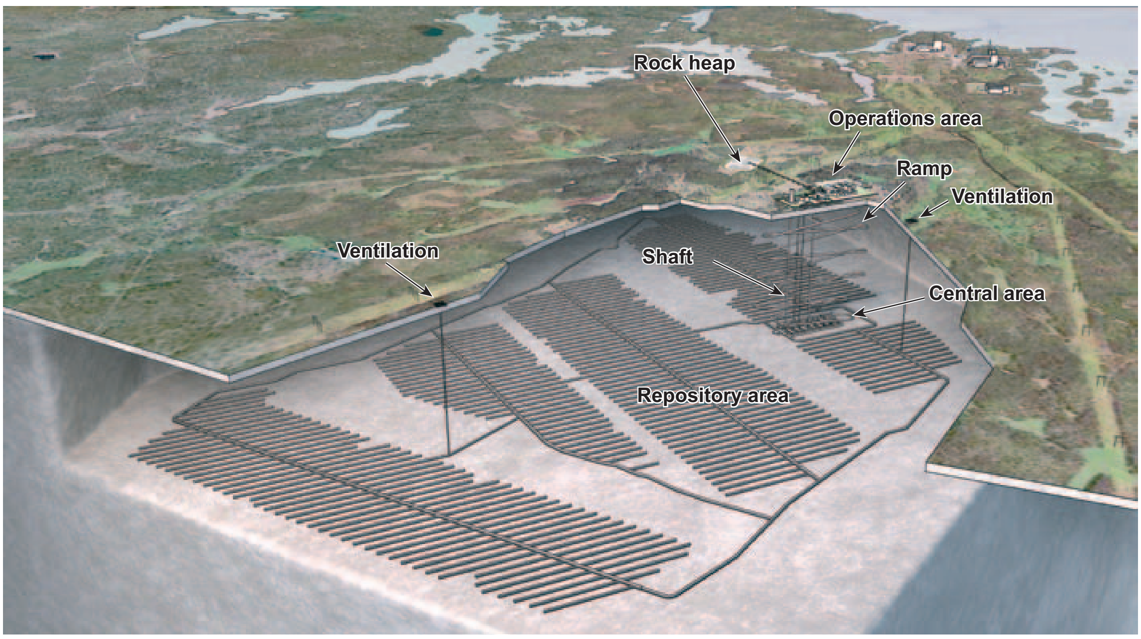

Figure 5-14. *Final repository for spent nuclear fuel in Laxemar, fully built.*

5.4.6 Physical planning

In October 2007 the municipal council in Oskarshamn Municipality adopted an in-depth version of the comprehensive plan, Comprehensive Plan 2000, for the Simpevarp and Laxemar areas. The purpose was to begin physical planning according to the Planning and Building Act for a possible final repository in the Laxemar area.

5.4.7 National interests and protected areas

The area for the planned final repository's facilities has been identified as being of national interest for final disposal of spent nuclear fuel and nuclear waste. The Simpevarp Peninsula, most of Äspö, parts of Hålö and Äspö and certain delimited water areas are of national interest for energy production. Two areas out at sea southeast of Ävrö are of national interest for wind power. The entire coastal and archipelago area is an area of national interest under the special management provisions for highly developed stretches of coast in Chapter 4 of the Environmental Code. The part of the coastal and archipelago area that is not covered by the detailed development plan is of national interest for nature conservation and outdoor activities.

5.4.8 Infrastructure

Road transport of encapsulated fuel from the encapsulation plant at Clab would require a new road connection, from Simpevarp to Oxhagen. Other road transport would mainly involve European motorway 22 and county road 743, see Figure 5-9. Transport of clay material is assumed to take place by truck from the Oskarshamn harbour /Fors and Klingenberg 2008b/.

5.4.9 Existing development

The villages of Mederhult, Ärnhult, Lilla Laxemar, Stora Laxemar, Ström and Åby are located near Laxemar. Approximately 15 people live within a kilometre of the operations area, approximately 150 within 5 kilometres and approximately 2,000 people within ten kilometres /Oskarshamn Municipality 2009/.

5.4.10 Natural environment

The landscape is characterized by a convoluted coastline and flat terrain with exposed bedrock and numerous narrow joint valleys. The relatively small fields, which have been used for pasture and haymaking and in more recent times for growing crops, have been an important resource for the resident population in this part of Småland. The archipelago offers a clear contrast to the more closed forest region. The outer archipelago is not much exploited and ranges from shoals and skerries to wooded islands with a narrow shore zone. There are few buildings and the flat coastline offers few landmarks.

The countryside bears strong traces of former and current farming and forestry activities. Older hardwood trees can be found in densely wooded areas. Most natural values are associated with the agricultural landscape, especially along the valley of the Laxemarån River /Nilsson 2010/.

5.4.11 Cultural environment

The district has historically been typically rural and coastal with agriculture and forestry and with an archipelago environment and fishing. When the nuclear power plant was established the landscape on the Simpevarp Peninsula underwent a total transformation. The power lines with their cleared corridors bring the impact of the industrial landscape into the Laxemar area. The impact on the cultural environment in the area is otherwise relatively limited.

5.4.12 Recreation and outdoor activities

The entire area is used for hunting and other recreational activities. The near-coastal parts offer excellent conditions for bathing, fishing, boating and diving. The area is also used for hiking and cycling. Kråkelund and the Simpevarp Peninsula are very rich in bird life and popular with birders /Dahlström 2007/. Östkustleden (the East Coast Trail), an approximately 160 km long hiking trail, passes through Lilla Laxemar village /Ternström 2008b/.

5.4.13 Environmental consequences

Aside from a valuable hardwood forest area, the final repository's impact area does not contain any natural attractions with high protection values, and there are few protected species or species with high conservation value. The area of national interest, the Västervik and Oskarshamn archipelagos, is affected by discharges of polluted water, but the consequences are deemed to be insignificant /Nilsson 2010/.

Since all radioactive material is encapsulated, construction and operation of the final repository is not expected to lead to any changes in the radiation environment.

The land that is needed for the final repository is for the most part privately owned and divided among a large number of properties. For current landowners, but also for others living in the area, establishment of the final repository would entail a significant change.

Vibrations from blasting and heavy transport activities are not expected to cause damage to buildings; nor will the vibrations be perceived as disturbing by residents in the area. Due to noise from construction activities and facility operation, a slightly larger portion of the area of national interest for recreation and outdoor activities will have sound levels above current guideline values. Otherwise the consequences will be small. Noise from road traffic already causes high sound levels, above the guideline values. Transport to and from the final repository will result in more people being disturbed than at present. But this is not expected to lead to a deterioration in health for more people /Zetterling and 2008b/.

Emissions of air pollutants from transport, heavy equipment and handling of rock spoil add very little to existing emissions. Moreover, very few people are affected by the emissions. All in all, this means that the risk of health consequences due to air pollution is very low /Fridell et al. 2008b/.

Road transport also causes other nuisances in the form of accident risks, increased traffic congestion, and impacts on recreation and outdoor activities etc. These impacts are dependent on the transport volumes, but also a number of other factors such as road standard, weather conditions and commuting patterns.

6 Factors and methodology for site selection

The site investigations have resulted in the two siting alternatives Laxemar and Forsmark. The task in the concluding step of the siting process has been to systematically compare these alternatives in order to obtain the material needed to select a site, in keeping with the established strategy. The factors compared and the methodology used are presented in this chapter.

6.1 Siting factors

In the same way as for the selection of sites for site investigations, siting factors were defined as a basis for comparing the two siting alternatives for site selection. Figure 6-1 shows the factors that formed the basis for the comparison. The factors are divided into the four main groups "Safety related site characteristics", "Technology for execution", "Health and environment" and "Societal resources". This subdivision is a further development of the structure that has been applied in previous stages, adapted to the purpose of comparing two alternatives and the currently available body of data. The results of the site investigations provide knowledge of the sites that is on a completely different level than in previous stages. This applies in particular to the rock conditions at depth, where it has now been possible to base the comparisons on parameters of direct importance for safety and technical feasibility.

The following sections explain the different factors in Figure 6-1 and SKB's points of departure and methodology for evaluation of the siting alternatives with respect to these factors. The factors in themselves do not offer any guidance as to what SKB considers more or less important, what has decided the site selection, or in what way. The siting factors should be regarded as a framework for structured comparisons between the sites, where different aspects are compared individually and in a systematic fashion. These comparisons provide a comprehensive basis for an integrated evaluation and selection based on the strategy presented in Chapter 1.

SKB's siting factors

Safety-related site characteristics
- Bedrock composition and structure
- Future climate
- Rock mechanical conditions
- Groundwater flow
- Groundwater composition
- Solute transport
- Biosphere conditions
- Site understanding

Technology for execution
- Flexibility
- Technical risks
- Technical development needs
- Functionality, operational aspects
- Synergies
- Costs

Health and environment
- Occupational safety and radiation protection
- Natural environment
- Cultural environment
- Residential environment
- Resource management

Societal resources
- Suppliers, human resources
- Public and private services
- Transport and communications

Figure 6-1. *Factors that have served as a basis for comparisons of the siting alternatives leading up to the site selection.*

6.2 Safety-related site characteristics

According to the principles adopted by SKB for site selection (Chapter 1), it is necessary to assess the safety of a final repository adapted to a specific site. What is meant by long-term safety is ultimately defined in acts and ordinances, and has been concretized in the Swedish Radiation Safety Authority's regulations.

Safety for the final repository is evaluated with the support of safety assessments. In a safety assessment, various integrated calculations and evaluations are performed of how the repository system – broadly defined as the deposited spent nuclear fuel, the engineered barriers surrounding the fuel, the host rock and the biosphere outside the final repository – may evolve over time. The future state of the system will depend on its initial state (i.e. the state when the spent fuel and the engineered barriers are in place in the repository), a number of thermal, hydraulic, mechanical and chemical processes that act in the repository system over time ("internal" impact) and the "external" impact of possible events outside the repository system, for example climate change, seismic activity or human intrusion.

An overall safety assessment, called SR-Site /SKB 2011a/, has been done for a final repository on the selected site and is included in the applications. In parallel with the preparation of SR-Site, SKB conducted a study called "Comparative analysis of safety related site characteristics" /SKB 2010b/, in support of the selection of a site. The site selection was made when the analyses on which this study is based (and comparisons with respect to other factors according to Figure 6-1) had come to the point where it was clear that Forsmark was the more suitable site and that the remaining analysis work could not change this outcome. The study presents:

- analyses and calculations of importance for the suitability of the sites with respect to long-term safety,
- evaluations of the possibilities of drawing conclusions about the differences in the suitability of the sites based on these analyses, and
- evaluations of differences in the suitability of the sites with respect to long-term safety.

The analyses that are presented and evaluated in the study are based on SKB's experience from previous safety assessments, most recently SR-Can /SKB 2006a/. This experience shows that there is a set of site characteristics that are of essential importance for safety /SKB 2010b, Chapter 1/. These are the factors listed under the heading "Safety related site characteristics" in Figure 6-1 and described in greater detail in the sections that follow. Based on the data and models obtained from the site investigations, the sites were first evaluated with respect to the different individual factors. Then the factors were weighed together, the central question being how each factor influences the overall safety assessment for the site. The same approach was used for both sites. In the case of Forsmark, the studies that were done also comprise a subset of the body of data for SR-Site.

6.2.1 Bedrock composition and structure

The composition and structure of the bedrock determine the rock mechanical and hydrogeological conditions and also influence the composition of the groundwater and the rock's ability to retard solute transport. These factors are important and are dealt with separately, see below. The rock conditions also determine whether it is possible to configure and adapt the deposition area and the deposition tunnels so that they meet the requirements on long-term safety. Such requirements are derived from the design premises for long-term safety /SKB 2009e/ and include respect distance to major deformation zones in order to manage the risk of future major earthquakes. Other requirements are concerned with maximum acceptable water inflows in deposition holes to ensure that buffer material is not washed away (eroded) with the inflowing water at installation, and properties of the rock that permit the deposition tunnels to be built without a contiguous "excavation-disturbed zone" (EDZ) being created with high permeability over a long distance. It is also important to ensure that a reasonably large portion of the available repository volume remains to be used after the requirements have been applied, but this is primarily an issue related to feasibility rather than safety and is dealt with in Section 6.3. From a safety viewpoint, a judgement is made as to how successfully these requirements can be applied. Another question that needs to be assessed is the possible occurrence of minerals that could lead to future exploitation at the sites. This may have a bearing on safety, since it may affect the risk of inadvertent future intrusion in the repository.

6.2.2 Future climate evolution

The climate can affect both the rock at repository depth and the function of the barriers. An ice sheet on top of the repository affects the groundwater pressure, the pressure gradient (which drives the groundwater flow) and the composition of the water that can penetrate the rock. Future ice ages could therefore have a great impact on the evolution of the composition of the groundwater, which could in turn affect the barrier functions of buffer and canister. Another question is whether there is a risk of freezing at repository depth during periods of extreme permafrost, since this could also affect the barrier functions of backfill, buffer and canister.

6.2.3 Rock mechanical conditions

Present and future loads (rock stresses), together with the mechanical properties of the rock, could affect long-term safety. This applies in particular if the loads are so high that the rock is overloaded locally around the deposition holes, causing spalling. The risk and consequences of future earthquakes must also be analyzed. Predictions have been made of the risk of spalling. Assessments have also been made of the risk that future major earthquakes could damage deposited canisters. However, this risk is managed by adapting the layout of the repository to deformation zones and fractures, so no great differences are expected between the sites.

6.2.4 Groundwater flow

Hydrogeological conditions, especially the frequency and permeability of conductive fractures, control the groundwater flow in the repository volume. These conditions influence solute transport to and from the buffer and thereby also the function of the buffer and the canister and, if the canister has been damaged, how much radioactivity can be released from the spent nuclear fuel and be spread via the groundwater. A low frequency of water-conducting fractures is generally an advantage, along with low permeability of the fractures, since these properties lead to low groundwater flow. More specific measures are calculated in the safety assessment: the transport resistance, F, and the equivalent flow, Q_{eq}, which permits quantitative evaluations and comparisons. High transport resistances and low equivalent flows are advantageous.

6.2.5 Groundwater composition

The present and future composition of the groundwater are of great importance for safety. This applies particularly to substances that affect the canister and the buffer, such as salinity, redox conditions (whether there is dissolved oxygen in the groundwater), and concentrations of other substances that can adversely affect the buffer and the canister. The groundwater composition is well known today from the site investigations, but the evaluation also includes predicting how the composition will be affected in the future due to groundwater flow, climate change and chemical reactions in the rock. The evaluation and the site comparison are based on how the predicted future groundwater composition affects the barrier functions of the buffer and the canister.

6.2.6 Solute transport

The ability of the site to retard released radionuclides if canisters should be damaged is also an important safety function. This retardation depends on conditions linked to the groundwater flow and to the ability of the rock to retard the release by matrix diffusion (radionuclides are retarded when they migrate into the pores in the rock) and sorption (radionuclides are retarded when they adhere to accessible surfaces on the rock). Data on flow-related transport properties and the rock properties determined in the site investigations are used in the evaluation.

6.2.7 Biosphere conditions

The consequences if radioactive substances from the repository escape into the environment depend on, among other things, the hydrological situation at and near the ground surface and the future ecosystems. The biosphere in itself is not considered to contribute to safety. However, it may be important for site selection to ascertain whether great differences in radiation dose due to differences in biosphere properties can be expected between the sites.

6.2.8 Site understanding

In order to assess the safety of a final repository on a given site, we have to be confident that the site descriptions are accurate, since the forecasts in the safety assessment are based on them. The degree of confidence depends in part on how much data and investigations are available from the site, but also on how clearly these data can be interpreted and provide an overall understanding of the site.

6.3 Technology for execution

"Technology for execution" (see Figure 6-1) refers to the prospects offered by the sites for executing the final repository project as robustly, functionally and efficiently as possible. Differences between the sites can be measured in time and cost, but uncertainties in technical execution and associated technology development needs to achieve a safe repository also need to be evaluated. The site that offers the most favourable and reliable prospects for adapting the repository layout and the activities so that the repository meets the safety requirements is also the most suitable one.

6.3.1 Flexibility

By "flexibility" is meant here:

- possibilities to adapt the repository to actual rock conditions, within the areas that have been prioritized as a result of the site investigation, so that the repository's layout meets the requirements for achieving long-term safety,
- allowing space for the planned waste quantity of around 6,000 canisters, plus
- allowing for changed premises for total waste quantity.

A site-specific design and layout has been developed for each site, based on the site descriptive model, that conforms to the stipulated design premises (requirements) for achieving long-term safety, /SKB 2009a/ and /SKB 2009d/, respectively. The layouts are presented in Chapter 5, Figures 5-7 and 5-13. Proposed site adaptations of the layout have mainly been based on:

- knowledge of conditions that affect layout, mainly deformation zones that require respect distances and rock domain boundaries,
- knowledge of the rock's thermal conductivity, which determines the minimum distance between deposited canisters in order to meet requirements on maximum temperature in the buffer, and
- knowledge of rock stresses and rock strength, which is primarily used to adapt and orient the deposition tunnels to obtain mechanical stability in both deposition tunnels and deposition holes.

Of principal interest is comparing the prospects of the site for accommodating the repository, with the assumed waste quantity, within the areas prioritized for complete site investigation on each site. Of secondary interest is comparing the prospects for handling increased waste quantities, since future changes in the Swedish nuclear power programme may entail increases in the quantity of waste to be disposed of. The options that may exist to increase the capacity of the repository are to change the design (for example by changing the thermal design of the repository or building it in two levels) or making use of areas outside of the priority area. All such alternative courses of action require new studies and investigations. The comparison between the sites from this aspect can therefore only be based on general assessments.

6.3.2 Technical risks

Since the *exact* conditions in the bedrock can never be determined completely in advance, there must be a method for gathering detailed information during the construction process, continuously adapting the construction work to this information and managing uncertainties and possible technical risks. This is done by means of the Observational Method /SKB 2010e/. This entails in simpler cases that rock support and sealing are adapted to the actual conditions observed during the construction work. A more complex but vital application of the Observational Method is site adaptation to meet requirements on long-term safety.

Risk analyses are performed as a part of the design process to shed light on the technical risks. The purpose of the risk analyses is to determine whether identified risks and planned methods to manage them are acceptable or whether additional measures are needed. These analyses entail the following in brief:

- Based on uncertainties regarding the characteristics of the site, identify geological conditions that could influence the construction or layout of the repository.
- Assess the probability that risk-related geological conditions actually exist.
- Assess the consequences of the existence of the risk-related geological conditions.

The analyses include all conceivable risk-related geological conditions that can be identified with the aid of geological and rock mechanical specialist knowledge and considering the uncertainties in the site models. Risk is defined as a combination of probabilities and consequences. The different risks are then divided into two categories according to the table shown in Figure 6-2:

- Risks that can be neglected or accepted: The consequences lie within what has already been accepted in the design process or what can be managed during construction by means of the Observational Method, or where the probability that the risk-related geological condition exists is so low that it can be neglected.
- Risks that require extensive measures: The consequences are so great and so probable that extensive measures are required, for example a change in the design, and where plans are therefore needed already now for how these risks are to be managed.

Risks that are judged to negligible/acceptable do not influence site selection other than in the form of increased costs and/or delays. This aspect is taken into account when costing the project. However, risks that have such great consequences and high probability that they require extensive remedial measures, for example changes in repository layout, affect the prospects of achieving a safe final repository and are therefore of greater importance for site selection.

Probability	Consequences: Insignificant	Small	Moderate	Great
Very probable	Negligible/ acceptable	Negligible/ acceptable	Extensive measures	Extensive measures
Probable	Negligible/ acceptable	Negligible/ acceptable	Negligible/ acceptable	Extensive measures
Improbable	Negligible/ acceptable	Negligible/ acceptable	Negligible/ acceptable	Extensive measures
Extremely improbable	Negligible/ acceptable	Negligible/ acceptable	Negligible/ acceptable	Negligible/ acceptable

Figure 6-2. *Methodology for evaluation of technical risks. The probabilities and consequences of identified risk-related geological conditions are first evaluated individually and then weighed together in accordance with the matrix. The resulting estimates are arranged in two risk classes ("negligible/acceptable" or "extensive measures") with respect to the need for remedial measures.*

There are primarily three types of risks associated with uncertainties regarding geological conditions that can have such great consequences and are so probable that they require extensive measures and site adaptation of the layout:

- The risk of spalling problems in deposition holes, to an extent that cannot be accepted with a view to the long-term performance of the repository, or the risk of stability problems on a scale that affects occupational safety or lays claim to large resources.
- The risk that tightness requirements in the deposition area cannot be met with currently proven technology, or that the remedial measures required cannot be accepted with a view to the long-term performance of the repository. Alternatively, the risk that other parts of the repository are judged to require complicated and difficult-to-predict sealing measures that could lead to great delays or the risk of major environmental impact.
- The risk that site adaptation to conditions of importance for long-term safety, such as long deformation zones or very permeable fractures, will lead to the rejection of many deposition positions.

The risk analyses cover all facility parts under ground. In the case of accesses and the central area, risks are evaluated in terms of delays or impact on function. In the case of the deposition area, estimates are made of the total fraction of deposition positions that risk being rejected. These estimates are based on statistical descriptions of the fracture frequency, hydraulic properties and strength of the rock domains, as well as evaluations of rock stress data.

6.3.3 Technology development needs

The technical risks can as a rule be managed by technical solutions. Spalling problems in deposition holes can, for example, be minimized by orienting the deposition tunnels favourably in relation to the rock stress field. Extensive development of new methods and materials to seal the rock is being conducted. A changed design of the buffer and backfill could possibly mitigate the requirements on limiting the seepage of groundwater. Technology development also relates to other methods for detailed characterization /SKB 2010e/, inspection and geotechnical design of the final repository.

In order to be able to evaluate the technical risks prior to site selection, it has also been important to determine what technology development is needed to manage them. Then an assessment must be made of the chances that the technology development will achieve its goals, what resources are needed and how uncertainties can be managed. Risks that are judged to be manageable by technology development are thereby valued lower than risks that are judged to be difficult to manage by technology development.

6.3.4 Functionality

The term "functionality" is not clearly defined, but is often used to describe how smoothly and efficiently a facility functions in the technical sense. A variety of factors enter in, for example reliability and redundancy of subsystems, material flows, and internal and external transport.

In the case of the final repository, functionality aspects are evaluated as a part of the design work. The functionality of rock facilities is determined in part by different factors than that of conventional industrial facilities. An important reason is the necessity of being able to adapt the execution of the facilities to varying rock conditions throughout the construction process. Flexibility, technical risks and ways to manage them are therefore important components in the evaluation of functionality as well.

Underground facilities also involve strict physical limitations on the spaces available for flows of goods, traffic, utilities (power supply, ventilation, water) etc. This creates a sensitivity to disturbances that must be taken into account from the viewpoint of functionality. In the case of the final repository, construction and deposition activities will take place in parallel during the entire operating period. A construction sequence that permits this, without risks of capacity problems or mutual disturbances between the activities, is therefore vital. How well this can be achieved is dependent on the number, size and relative locations of deposition areas, transport routes etc. These factors are controlled by geological conditions and are accordingly site-dependent.

The functionality of the above-ground part of the activities is affected to some extent by site-dependent factors such as disposition of facility parts, logistics etc, but the site characteristics are of far less importance with respect to this factor than is the case for the underground facilities. The exception is external transport to and from the final repository, which is of great importance.

The greatest transport needs arise during the construction phase. Goods transport in this phase is dominated by surplus rock, which needs to be hauled away for reuse, and shipments of building material to the site. The scope of the transport activities decreases when the repository is put into operation. Additional types of goods are casks with canisters from the encapsulation plant to the final repository and clay material for buffer and backfill from supplier to repository. In terms of transport activity, canister transport accounts for a very small fraction, but it comprises a part of the nuclear handling chain in the final repository system and therefore takes place under completely different conditions than conventional transport. Clay transport from harbour to final repository is also limited in scope. Local passenger transport is the dominant type of transport by far in terms of the number of vehicles involved.

Both transport needs and transport conditions are site-dependent. The needs have been calculated based on the location of the site, the planned repository design, goods volumes, organization and activities. The conditions have been evaluated with respect to available infrastructure in the form of roads and harbours, distances to population centres, assumed commuting patterns for personnel, etc. The consequences of transport for safety, functionality, environmental impact and costs have been taken into account.

6.3.5 Synergies

The final repository for spent nuclear fuel will, in terms of the scope of the activity, be the largest component in the entire system for management of radioactive waste in the country. Relationships and links between the final repository and other parts of the system depend in part on which site is selected. For SKB's part, the siting of the final repository will eventually influence all the company's operations. Since SKB already has facilities and activities in both Oskarshamn and Forsmark, there is potential for synergies. Other aspects to consider are technical links between the parts of the waste system, for example between the encapsulation plant and the final repository.

The technical links between *the encapsulation plant* and the final repository consist of delivery and reception of canisters. The requirements on the canister are independent of the choice of site for the final repository. But operational disturbances in either facility can affect the other facility if the disturbances are too great to be absorbed and evened out by the flexibility that exists in transport and handling between them. For this and other reasons the transport chain is of importance – see the section on functionality above.

The links between *the research facilities* and the final repository mainly have to do with the Äspö HRL. SKB's strategy is that vital parts of the disposal technology should as far as possible be developed, demonstrated and fine-tuned at the Äspö HRL, and then transferred to the final repository. The practical implementation of the technology at the final repository can then take place when rock facilities become accessible at repository level, i.e. during the commissioning phase. In other words, there will be strong links in terms of technology and know-how between the Äspö HRL and the final repository, at least up until the operating phase.

When it comes to *the interim storage facility for spent nuclear fuel (Clab)* and *the final repository short-lived radioactive waste(SFR)* there are no direct links to the final repository, aside from the transportation system which serves all waste facilities. Another two facilities remain to be sited before the waste system is complete. One is the *canister factory*, which does not have any direct links with the final repository. The other is the future *final repository for long-lived radioactive waste (SFL)*. The siting of SFL lies far in the future and does not affect the choice of site for the final repository for spent nuclear fuel. The requirements for the siting of SFL also remain to be developed, in parallel with the development of the repository concept. All that can be said now is that SKB's current establishment localities may of course be considered for the siting of SFL, that there is therefore reason to preserve data and other knowledge from the site investigations, and that the area that is used for the the final repository for spent nuclear fuel will be "occupied" when it comes time to site SFL.

The organizational consequences and synergies entailed by the site selection process for SKB are factors that influence the efficiency of both the execution of the final repository project and SKB's operations as a whole. Evaluating such effects in time and money is scarcely possible, and the comparisons that have been made are therefore qualitative. In general, concentrating available resources to as few activity localities as possible usually improves efficiency.

6.3.6 Costs

The costs of executing the whole final repository project including establishment, operation and winding-up have been calculated for the two siting alternatives. Some of the costs are site-dependent. This applies above all to the extensive rock excavation works and backfilling of the underground facilities.

The costs are important for site selection since they reflect the efficiency and in many ways also the robustness of its execution. Relative cost comparisons also provide a good picture of the proportions between the work inputs that are required during different phases.

6.4 Health and environment

The factors for assessment and comparison of the two sites with respect to impact on the environment and health according to Figure 6-1 are derived from the provisions of the Environmental Code, the Nuclear Activities Act and the Radiation Protection Act. The Environmental Code provides the framework for which siting factors must be taken into account when it comes to impact on health and the environment during construction and operation of the final repository. Environmental and health aspects relating to nuclear activities are dealt with in the regulations issued by the Swedish Radiation Safety Authority pursuant to the Nuclear Activities Act and the Radiation Protection Act.

The field of health and environment has been divided into five factors: occupational safety and radiation protection, natural environment, cultural environment, residential environment and health, and management of natural resources.

6.4.1 Occupational safety and radiation protection

Regardless of which site is selected, construction and operation shall be carried out in accordance with relevant occupational safety requirements. The measures that are required and the technology that is most suitable for meeting the requirements may differ between the sites and thereby entail differences in cost. The measures that need to be adopted above ground are the normal ones for industrial facilities. Below ground, reinforcement of the rock openings (rock support) is done to prevent falling rock, and measures are adopted to reduce the fire risk and prevent flooding in excavations. Furthermore, a reliable power supply is arranged to systems that are important for personal safety. Measures may also be needed to limit exposure to radon gas and blasting fumes. Any differences in conditions between the sites and the measures they entail can be expressed in technology inputs and costs.

The canisters are the only units in the final repository that contain radioactive material. The facility is designed so that the canister will remain intact through the handling process, which means that free radioactivity from the spent fuel cannot occur. The structures and measures needed to protect the canister and prevent direct radiation from the canister are the same for both sites and are thus not site-distinguishing. The rock contains radioactive isotopes of uranium, thorium and potassium in varying quantities. When these substances decay they form radon, which can pose a health risk if ventilation is not sufficient. Radon is also emitted in the repository's underground openings from rock surfaces, inflowing groundwater, crushed rock and the tunnel floor, as well as rock heaps. Radon emissions are so great that exposure to radon is always a potential health risk. Adequate ventilation is the primary means of limiting the radon concentration. Possible differences between the sites therefore have to do with different ventilation needs.

6.4.2 Natural environment

There are areas of national interest and protected areas at both sites, see Sections 5.3.7 and 5.4.7. There are also other areas worthy of protection or ecologically sensitive areas, such as key habitats, classified meadow- and pasturelands, calcareous forests, natural attractions, swamp forests and other areas with special natural values.

Development that affects a species listed in Appendix 1 or 2 in the Species Protection Ordinance requires an exemption by the County Administrative Board. The "Red List" is a list of species judged to be in danger of extinction in a region, a country or the world. The species are grouped in categories according to the risk of extinction, but the categories say nothing about preservation value or priority of measures. A red-listed species enjoys formal protection if it is listed in Appendix 1 or 2 of the Species Protection Ordinance.

During both construction and operation there will be effluents consisting of rock drainage water, sanitary sewage, storm water and leachate from rock heaps. Prior to discharge to receiving waters, the various types of waste water will be treated to the necessary extent. Treatment and environmental impact of rock drainage water, sanitary sewage and leachate from rock heaps have been studied as a basis for the Environmental Impact Assessment. The differences that exist between the different sites have to do with environmental impact and costs.

6.4.3 Cultural environment

Landscapes, land use and the built environment have evolved and changed over the centuries. With knowledge of the history of the landscape, it is possible to single out specific cultural environments that are important for protecting the historical qualities of the landscape and developing them in a sustainable fashion. Particularly important cultural environments are those that have been afforded some form of protection, for example areas of national interest for cultural heritage preservation, historic buildings, landscape protection and archaeological remains.

6.4.4 Residential environment and health

In order to determine the number of people that could be disturbed by noise, atmospheric emissions and vibrations, data have been gathered on population, schools and healthcare facilities at various distances from disturbing activities (rock crushers, transport routes etc). The data are presented for distances of 1, 5 and 10 kilometres from the final repository's operations area.

The construction work for the final repository and transport to and from the facility will cause noise. Noise is the single most important factor when it comes to impact on humans and the residential environment. Noise during construction and operation of the final repository has been calculated and compared with existing guideline values for acceptable sound levels. Noise from stationary noise sources (crushers, fans etc) and from road traffic is of varying character, which is why calculation methods and guideline values differ. The two types of noise are therefore dealt with separately. Noise can also affect the fauna in the area.

Besides noise, rock drilling and blasting also causes vibrations and air shock waves. Heavy transport can cause vibration. If vibrations and air shock waves are high enough, they can cause damage to buildings and equipment and be an annoyance to people who live nearby.

Transport activities and dust from rock crushers and handling of rock spoil cause emissions to air. Transport gives rise to emissions of particulates, hydrocarbons, carbon monoxide, sulphur dioxide and nitrogen oxides. Handling and storage of waste rock can give rise to dust in the immediate vicinity, especially in dry weather. The concentrations of nitrogen oxides and particulates (PM10) have been calculated as a basis for the Environmental Impact Assessment. Atmospheric emissions can also affect plants.

Hiking, cycling, mushroom and berry picking, bathing, hunting, fishing, bird-watching, canoeing, kayaking and sailing are examples of activities included in the siting factor recreation and outdoor activities. Noise and other disturbances from the planned activity can affect the prospects for recreation and outdoor activities in the area.

Exposure to air pollution, noise and vibration can have an impact on human health. Furthermore, the project in itself, final disposal of radioactive waste, can arouse anxiety and fear in people. As a basis for the Environmental Impact Assessment, experts in environmental medicine have assessed the risk of health effects caused by air pollution and noise. The risk of psychosocial effects caused by the final repository has been studied in SKB's programme of societal research.

6.4.5 Management of natural resources

Consumption of natural resources can be expressed both as physical consumption and as costs. The latter is included in the cost estimates for the final repository. In order to get a clear picture of the differences between the sites when it comes to management of natural resources, a special comparative accounting has been compiled where the consumption of natural resources is expressed in other units than kronor, such as tonnes of rock, GWh of electrical energy, GWh of fuel, etc. While the cost calculation includes all activities and all resource consumption, the calculation for management of natural resources has been focused on factors with high resource consumption and where there is a difference between the sites.

The land requirement measured in land area does not differ much between the sites. The differences in terms of what type of land is used affect the natural environment and the cultural environment and are described under these headings.

Water supply refers to means of supplying the final repository facilities and activities with fresh water and the impact on private wells due to the fact that the water table is expected to be lowered in the immediate area when the final repository is built. Groundwater lowering, or drawdown, can also affect wetlands and the plants and animals that are dependent on this environment for their survival. This is described under the siting factor "Natural environment".

In connection with construction and operation of the final repository, large volumes of rock will be extracted and hauled away from the site. Surplus rock will be sold for other use as far as possible. This means that other extraction of rock and gravel within the regions in question can be replaced with rock material from the final repository. For establishment of operations areas and rock heaps, it may be necessary to bring in rock and soil from the outside.

The need for clay for buffer is dependent on the number of canisters to be deposited and therefore does not differentiate the sites. All deposition tunnels and a large portion of other openings will be backfilled and sealed with clay. The volumes to be backfilled are different for the sites and equal to the volume of rock extracted. Different types of land and sea transport, extraction of clay for buffer and backfill, and construction and operation of the facility require energy in the form of electricity and fuel.

6.5 Societal resources

SKB evaluates the societal aspects of the choice of site based on its responsibility for ensuring that the final repository project is executed in the best way. In order for the final repository to be realized, the confidence and acceptance of the community at the particular site and locality must be won. Dependence on local support is nothing new; voluntary participation has been and is one of the cornerstones of the entire siting process. The prospects of gaining local acceptance were accorded great importance in the prioritizations made prior to the site investigation phase, see Chapter 4. The judgement that has been made now is that there is strong and stable local support for and interest in the final repository project. This is true in both Östhammar and Oskarshamn, on the political arena as well as among the general public. That is why SKB regards the basic prerequisites of political acceptance and availability as being amply fulfilled at both sites and thereby not a factor to take into account in the comparative evaluation.

The socioeconomic prospects of establishing the final repository offered by a given locality, and what consequences an establishment would have for the community, are questions that have been fully explored. Probably no other industrial project in the country has been as fully illuminated with respect to these aspects. As the contractor for the project, SKB is primarily interested in what the community has to offer the project. The question that is posed is thus what resources are available and will be available in the form of suppliers, services, skills, recruitment base, communications and other factors that are needed for the establishment of a major industrial facility. The sites have been compared in these respects.

The other side of the question is what SKB's activities and the final repository project will mean for the community in the form of e.g. demographics, jobs, service needs, and traffic. Here SKB can furnish information, but how the consequences are evaluated is essentially a matter for other actors to determine, mainly the municipality in question and its inhabitants.

7 Comparative evaluation and choice

This chapter begins by describing the comparative evaluations of Forsmark and Laxemar that have been performed with respect to siting factors described in Chapter 6. It then gives SKB's overall evaluation of the sites and finally the reasons for selecting Forsmark as the site for the final repository.

7.1 Safety-related site characteristics

A comparative evaluation of the prospects of the sites for long-term safe disposal has been carried out using the methodology presented in Section 6.2 and in greater detail in /SKB 2010b/. As regards the factors bedrock composition and structure, future climate evolution, sensitivity to major earthquakes, biosphere conditions and site understanding, the conclusion is that both sites are suitable and that the differences between the sites are small. As regards certain rock mechanical conditions, groundwater flow, future groundwater composition and ability to retard released radionuclides, the differences are judged to be of greater importance for safety.

7.1.1 Bedrock composition and structure

Adaptation of the repository to bedrock composition and structure

Based on the analyses and evaluations presented in the Rock Line Report /SKB 2010c/, it was concluded in /SKB 2010b, Chapter 2/ that it is possible to design and adapt deposition areas and deposition tunnels so that they satisfy the stipulated requirements at both sites. However, such adaptation leads to differences in how straight-forward and robust the technical execution of the project will be. The risk analyses that have been done for technical execution are presented in Section 7.2. Furthermore, the design work for the two sites /SKB 2009a/ and /SKB 2009d/ shows that the following differences can be expected:

- In Laxemar, the majority of the accepted deposition holes are expected to be intersected by a water-conducting fracture, while this is only true of a few (<6%) of the deposition holes in Forsmark.
- In Laxemar, grouting is expected to be needed in a large proportion of the deposition tunnels in order to meet inflow requirements, while this proportion is considerably lower in Forsmark.
- In Forsmark, parts of the walls of the deposition holes are expected to crack due to overloading ("spalling") after having been bored. However, the damage is expected to be limited and lie within accepted tolerances. This can be checked before a decision is made to use the deposition hole.

These differences mainly influence the proportion of the repository rock volume that can be used for deposition, see Section 7.2, but the fact that a large fraction of the potentially approved deposition positions in Laxemar are also expected to have high flows may also have a bearing on long-term safety, see Section 7.1.9.

Mineral resources

The site models include possible areas with mineral resources that could be of interest for future extraction.

In Forsmark there is an area with iron mineralizations southwest of the candidate area, but the mineralizations are very small and are not judged to warrant future exploitation /SKB 2008a, Section 11.2.4/. Further, the possibility cannot be excluded that there are iron mineralizations in an area north of the candidate area. In Laxemar, completed studies show that the whole regional area in Simpevarp may be regarded as sterile with regard to ore and metallic mineralizations /SKB 2009c, Section 11.2.4/. In summary, the assessment is made in /SKB 2010b, Chapter 10/ that there are no mineral resources that would warrant future exploitation at any of the sites.

7.1.2 Future climate evolution

A future climate characterized by global warming delays the onset of periods with permafrost and glaciation. A rise in the sea level due to melting ice sheets on Greenland and/or in the Antarctic is not deemed to have a negative effect on the repository.

However, both sites are expected to be subject to future glaciation. This can affect the groundwater flow, since the ice sheet alters the conditions controlling groundwater flow in the rock. This also affects the future composition of the groundwater, since the meltwater from the ice is assumed to have a high dissolved oxygen content and a very low salinity. The importance of this is discussed in the sections on hydrogeology and groundwater composition.

Forsmark is located further north than Laxemar, which, during cold dry periods, results in a more favourable climate for permafrost growth. Moreover, the rock in Forsmark has a higher thermal conductivity than the rock in Laxemar. The thermal conductivity of the rock in Forsmark is about 3.5 W/(mK), while in Laxemar it varies between 2.6 W/(mK) and 2.9 W/(mK) for the different rock domains. This means in principle that Forsmark is more sensitive to future impacts of permafrost.

If the climate evolves in a way similar to during the last ice age, calculations show that the groundwater could freeze down to a depth of several hundred metres. But the freezing does not reach all the way down to repository level, not even for an unrealistic case where all uncertainties are combined so that the chances of the permafrost reaching deep are maximized. Furthermore, the bentonite buffer only freezes at temperatures below – 4 °C, and analyses show that the buffer can freeze and thaw, and then regain its original properties. This is also true of the backfill in the deposition tunnels. Backfill material in the accesses, at higher levels, will freeze, but it is judged that the clay materials here as well will regain their function when the temperature once again rises.

7.1.3 Rock mechanical conditions

Thermally induced spalling

Rock mechanical conditions – rock stresses and the strength of the rock – vary between the sites, see Chapter 7 in /SKB 2008a/ and /SKB 2009c/. Forsmark has relatively high rock stresses compared with typical values for Swedish bedrock. According to interpretations of the measurements that have been done, the maximum average horizontal stress is about 41 MPa at a depth of 500 m. Laxemar exhibits more typical values, with a maximum horizontal stress of about 22 MPa at a depth of 500 m, see Figure 7-1. The maximum horizontal stress is in both cases nearly identical to the maximum principal stress. The strength of the rock expressed as uniaxial compressive strength is, on the other hand, generally higher in Forsmark (mean values 226 and 370 MPa for dominant rock types) than in Laxemar, where the strength varies between different rock types (167 MPa to 225 MPa).

A rock mechanics analysis has been carried out to determine the effects of temperature increases in the rock due to the heat emitted by the deposited canisters /Hökmark et al. 2010/. The thermal expansion the rock increases the rock stresses, causing a risk that the strength of the rock will be exceeded some time after the canisters have been deposited. The analysis shows that:

- there is a risk of thermally induced spalling of the walls of the deposition holes at both sites,
- the risk is lower and the scope of such spalling is less in Laxemar.

It is noted in /SKB 2010b/ that spalling can greatly increase the exchange of solutes between buffer and water in fractures in the rock, but despite this increase the exchange is lower in Forsmark than in Laxemar, since the groundwater flow around the deposition holes is much higher in Laxemar.

Earthquakes

The probability of future earthquakes of sufficient magnitude (i.e. greater than about M5) to be of importance for the integrity of the canister is very small at both sites, but cannot be completely neglected. The risk that movements induced by earthquakes could damage deposited canisters is greatly reduced or eliminated by adapting the repository to deformation zones and fractures.

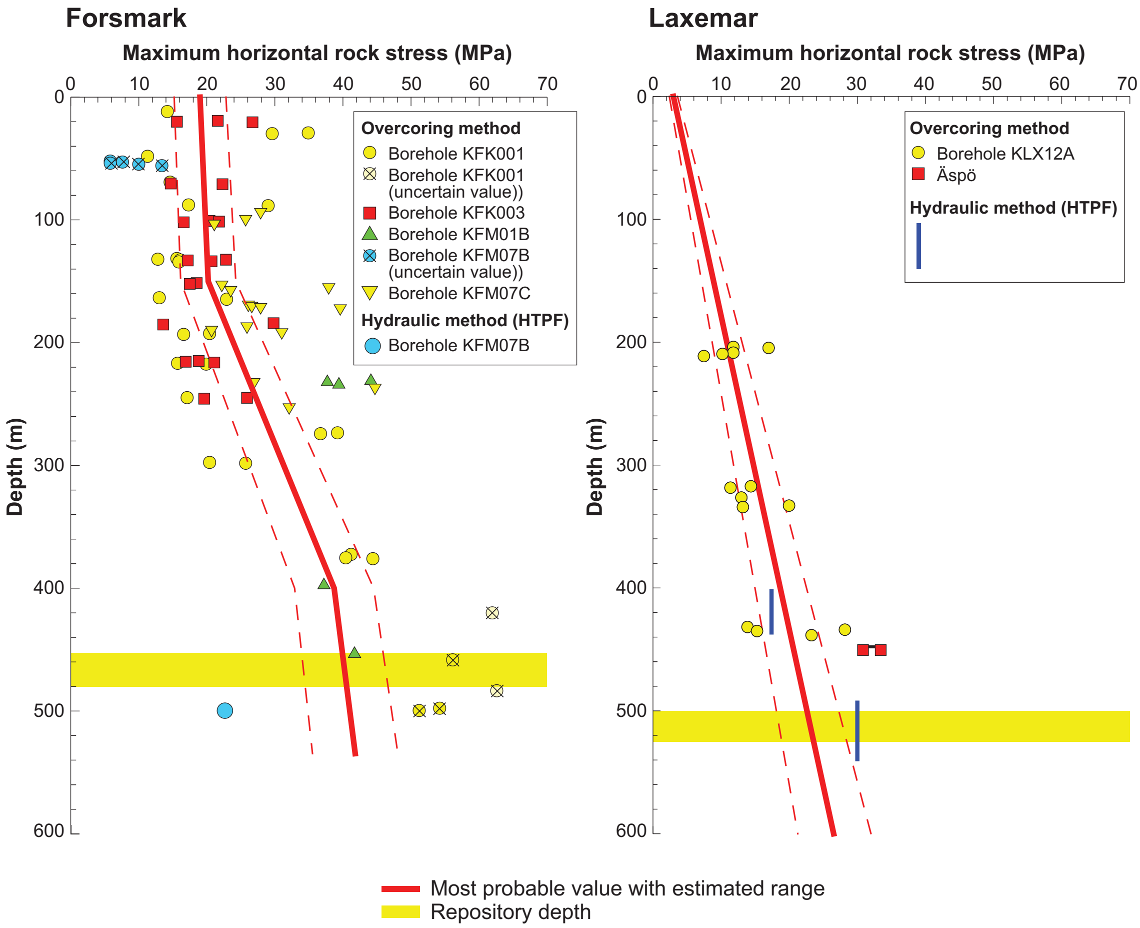

Figure 7-1. Data from rock stress measurements and interpretation of rock stresses in Forsmark and Laxemar.

Completed analyses show that such adaptation can be done successfully at both sites and that the sites are equivalent in this respect. At both sites there are large regional deformation zones where major earthquakes could occur in the future, but the repository is positioned with such a great respect distance from these zones that they do not pose a problem.

7.1.4 Groundwater flow

Hydrogeological conditions, especially the frequency of conductive fractures and their permeability in the repository volume, differ between the sites. In Forsmark water has only been encountered at a few points below the 400 m level in the nearly 1,000 m deep boreholes, while water is much more common in the boreholes in Laxemar down to at least the 650 m level (see Figure 7-2). In the site models, these data are interpreted as indicating that there are very few conductive fractures below the 400 m level in Forsmark, while this only occurs below the 650 m level in Laxemar. The level in Laxemar is uncertain, however, and may be deeper. At 500 metres depth, the average distance between conductive fractures is more than 100 m in Forsmark, while it is about 9 m in Laxemar, except in an even more conductive area in the northern part of the repository area, where the average distance is about 4 m.

As a part of the underground design work, it was deemed that the repository should lie at a depth of about 500 m (highest level about 450 m in Forsmark and about 500 m in Laxemar) at both sites. If the repository in Laxemar were located at levels below 700 m, the frequency of conductive fractures would probably be lower, but locating the repository at such great depth is deemed unsuitable with a view to present knowledge of the site at that depth, safety-related technical specifications, higher temperature in the rock etc.

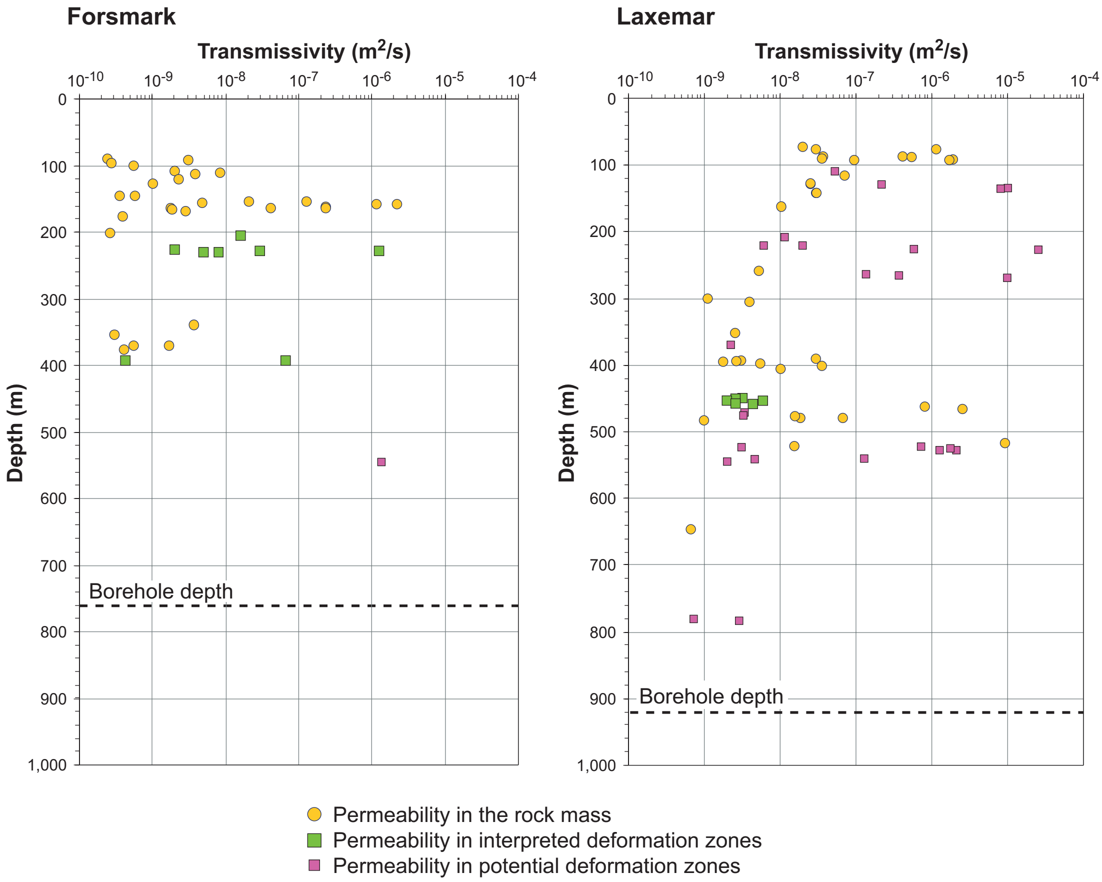

Figure 7-2. *Permeability (expressed as transmissivity) of the conductive fractures encountered in typical boreholes in Forsmark (borehole KFM08A) and Laxemar (borehole KLX011A). Measurements have been made from about 80 m depth to the end of the borehole. Each point represents the individual conductive fractures that have been identified.*

The higher frequency of conductive fractures at repository level in Laxemar than in Forsmark means that there are more potential deposition positions that may be intersected by conductive fractures and thereby a higher fraction of positions linked to high groundwater flow around the deposition holes and low transport resistance. The analyses show that the equivalent flow is on average about 100 times higher and the transport resistance is more than 10 times lower in Laxemar. The difference in the fraction of unfavourable deposition positions will be less if positions intersected by highly conductive fractures are avoided. However, this leads to less efficient utilization of the available rock, see Section 7.2. All in all, the hydrogeological characteristics of the site are therefore much more favourable in Forsmark than in Laxemar.

The groundwater flow is also affected by the future evolution of the climate. Groundwater flow ceases in the frozen portions of the rock during periods of permafrost. This is judged to be generally favourable for safety, but the impact is presumably small. However, during periods when the margin of a melting ice sheet is located on the site, the driving force for groundwater flow may increase dramatically due to the large differences in the thickness of the ice at the ice front. Analyses show that the increase in groundwater flow during such extreme conditions is similar at the two sites and that the relative advantage for Forsmark is retained in this situation as well.

7.1.5 Groundwater composition

The site investigations show that the main features in the composition of the groundwater are similar at both sites. Near the ground surface the water is affected by precipitation, which has very low salinity. The salinity increases at greater depth, indicating that the water derives in part from the Littorina Sea, which was formed after the last ice age. Residues of meltwater from the ice sheet are also encountered, even at levels equivalent to repository depth. At even greater depths the salinities are even higher and the water is deemed to be much older.

There are important differences between the sites, as well as in how the composition of the groundwater is expected to change in the future. In Forsmark, the impact of surface water is restricted to relatively shallow depths, while this impact reaches much greater depths in Laxemar, see Figure 7-3. The difference is mainly due to the fact that the rock below 150 m depth is much less permeable in Forsmark than in Laxemar, plus the fact that Forsmark has been above sea level for a much shorter time than Laxemar.

The depth of penetration of the more dilute water will increase at both sites up until the next ice age, but the impact is expected to be less in Forsmark than in Laxemar. During the next million years, when several ice ages are expected to occur with intervening periods of temperate climate, Forsmark will be covered by a sea similar to the Littorina Sea or today's Baltic Sea for a much longer time than Laxemar. These and other differences between the sites affect the long-term safety of the repository.

The groundwater's salinity and calcium content affect the stability of the bentonite clay. Low concentrations can entail problems in this respect. Even if the salinities decline in the future, it is likely that the low permeability of the rock in Forsmark will keep the salinity at repository level relatively unaffected. In Laxemar the salinity is already lower today and is expected to decline further. Generally, this means that there is less of a risk in Forsmark than in Laxemar that the bentonite clay will erode and disappear to an extent sufficient for the buffer in some deposition holes to lose its protective function.

The groundwater's sulphide content is also important, since sulphide can corrode copper and thereby damage the canister. If the bentonite buffer is intact, however, extremely high sulphide concentrations are required in order for this to be a problem. However, if the buffer is damaged the sulphide content becomes more important. Today the sulphide concentrations are generally low under undisturbed conditions in both Laxemar and Forsmark. Relatively similar conditions exist on both sites in order for microbes to convert sulphate to sulphide. The future evolution of the sulphide concentrations is also expected to be similar on both sites. There are no clear differences between the sites in this regard.

The groundwater at repository level must not contain dissolved oxygen, since oxygen corrodes copper. Today the oxygen in infiltrating precipitation is consumed by microbial processes very near the surface and this requirement is thereby met, but for long-term safety it is also important to assess the future capability of the rock to consume the oxygen in infiltrating water. The future capacity of the rock to buffer pH is also important. At both sites the fractures contain different minerals, mainly calcite, which indicates a good capacity for buffering pH. The occurrence of iron minerals, Fe(II), is important for reducing oxygen. The rock in Laxemar has roughly twice as high a concentration of Fe(II) as that in Forsmark, but in view of the fact that permeability is so much lower in Forsmark, the total capacity of the rock to prevent infiltration of dissolved oxygen is much better in Forsmark.

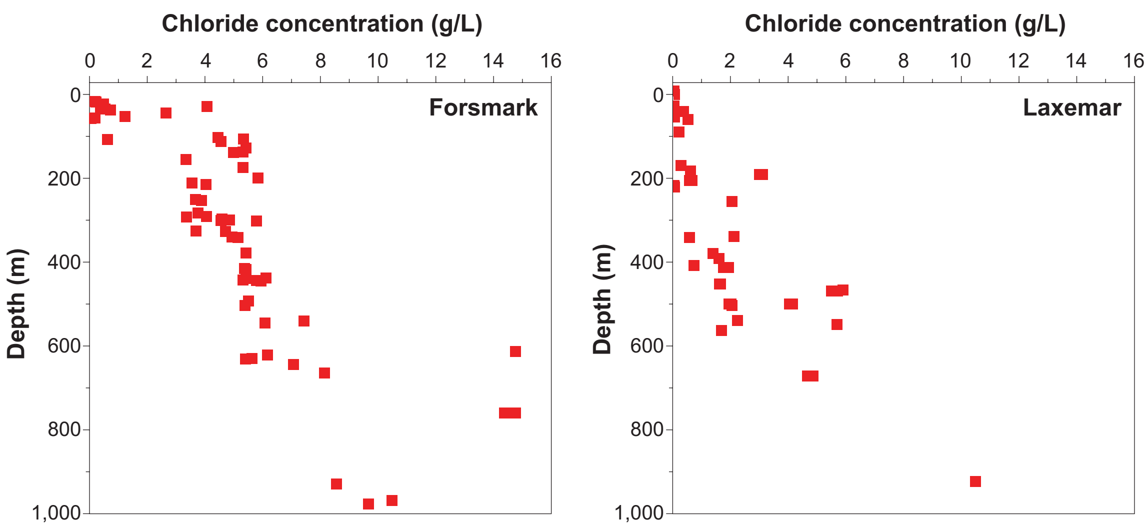

Figure 7-3. *Measured chloride concentration at different depths at Forsmark and Laxemar.*

The composition and future evolution of the groundwater exhibit great similarities between the sites, but are judged to be more favourable overall in Forsmark. In particular, the present-day salinity is more favourable for the stability of the buffer. This is largely due to the fact that the rock is less permeable in Forsmark than in Laxemar. On the other hand, the tighter rock in Forsmark also means that there is slightly lower confidence in the geochemical description there. It has been difficult to obtain water samples in Forsmark because the rock is so tight.

7.1.6 Solute transport

An evaluation has been made of the rock's ability to retard released radionuclides in the event of canister damage. The analysis is based in part on the site-specific flow-related transport properties that have been determined and in part on an evaluation of the rock's ability to retard the release by matrix diffusion and sorption, based on site-specific data.

The data show that conditions in the rock for matrix diffusion and sorption are good and similar for both sites, although the potential for retardation via matrix diffusion is slightly greater in Laxemar. In general, the rock's ability to retard released radionuclides is better in Forsmark, since the flow paths there have much greater transport resistance.

7.1.7 Biosphere conditions

A quantitative comparison has been made of the dose consequences under temperate conditions for a hypothetical release to soil, lakes and streams at the two sites /SKB 2010b, Section 9/. The comparison shows that the differences between the sites are small compared with the uncertainties in such assessments. An evaluation has also been made of future biosphere conditions on the sites. It shows that Forsmark, due to its more northerly location, will probably lie beneath an ice sheet or the sea for considerably longer periods than Laxemar. During these periods the doses from any releases of radioactive substances will be very small.

7.1.8 Site understanding

There is great confidence in the site descriptions at both sites, see Chapter 11 of the site descriptions /SKB 2008a/ and /SKB 2009c/. This assessment is based on the fact that a large quantity of data are available from the sites and that these data can be interpreted unambiguously and with a high degree of agreement between different disciplines.

At the same time, it can be noted /SKB 2010b, Chapter 11/ that the Laxemar area is more geologically heterogeneous than the Forsmark area. This means that there are greater uncertainties in Laxemar regarding exactly where a given rock type or conductive fracture is located. The only method to further significantly improve confidence and detailed knowledge is to continue the investigations under ground while the repository is being built.

7.1.9 Expected risk and summary assessment

Previous analyses of long-term safety at the sites have shown that the phenomena that can possibly damage canisters in the very long term are corrosion if the buffer is lost and possibly also by major earthquakes near the repository.

Many safety-related site characteristics are relatively equal for the sites. This applies, for example, to the probability of future major earthquakes, which is small and is judged to have small consequences at both sites. However, the differences in groundwater flow and also the future composition of the groundwater lead to differences in the assessment of long-term safety. We cannot today rule out the possibility that the bentonite clay in the buffer will be eroded if the surrounding groundwater has too low salinity. During a future glaciation the salinity could become too low on both sites, although this is less likely in Forsmark. Since the flows are lower in Forsmark, fewer deposition holes will be affected there. If enough of the bentonite clay in the buffer disappears, the canister may after a very long time be damaged by corrosion caused by sulphide. The corrosion rate, and thereby the number of canisters that would be damaged, is directly dependent on the groundwater flow. In Forsmark, analyses show that the groundwater flow in most deposition holes is so low that only a few canisters could be damaged, and only after more than a hundred thousand years. The much higher flows in Laxemar mean that more canisters may be damaged there.

The difference in the prospects of future canister damage gives great differences in the calculated risk to a final repository built in accordance with the adopted reference design at Forsmark versus Laxemar /SKB 2010b, Section 10/. Figure 7-4 shows the calculated mean annual effective dose that results from such canister damage, for Forsmark and for Laxemar. The first releases in Forsmark occur in the reference scenario after about 114,000 years, when the first canister is expected to fail. During the analyzed period of a million years, the margin up to the dose that is equivalent to the the limit value stipulated by the Swedish Radiation Safety Authority's regulations (SSMFS 2008:37, Section 5, known as the risk criterion) is at least a factor of 100. In Laxemar the first canister failure occurs far earlier; the dose exceeds the limit value after about 100,000 years and then increases to a level that approaches the level of today's natural background radiation. The curves for both Forsmark and Laxemar in Figure 7-4 have an irregular shape during a stage corresponding to about 50,000 years after canister breakthrough. The explanation is that the total dose that is shown consists of the sum of the contributions of several radionuclides with varying half-lives that are released when the canisters fail. A complete account with the proportions of contributing radionuclides is provided in /SKB 2011a/ for Forsmark and /SKB 2010b/ for Laxemar.

The results in Figure 7-4 assume that the technical execution of the final repository meets the design requirements, i.e. that the intended initial state is achieved. What this is judged to mean in terms of the proportion of theoretically available deposition positions that cannot be utilized, for example because they do not satisfy tightness requirements at deposition, is dealt with in Section 7.2. In the comparative assessment of safety /SKB 2010b/, a hypothetical case is evaluated in addition where the consequence of also being able to avoid deposition holes with future high groundwater flows is analyzed. The analysis shows that if such selection criteria are used, it could be possible to reduce the calculated dose considerably, although at the price of a very large loss of deposition holes and the necessity of developing and verifying technology that shows that such a selection actually works.

In summary, the analysis results referred to above entail that the prospects of achieving a safe final repository are deemed to be much more favourable in Forsmark than in Laxemar. The complete body of evidence for this conclusion is presented in /SKB 2010b/.

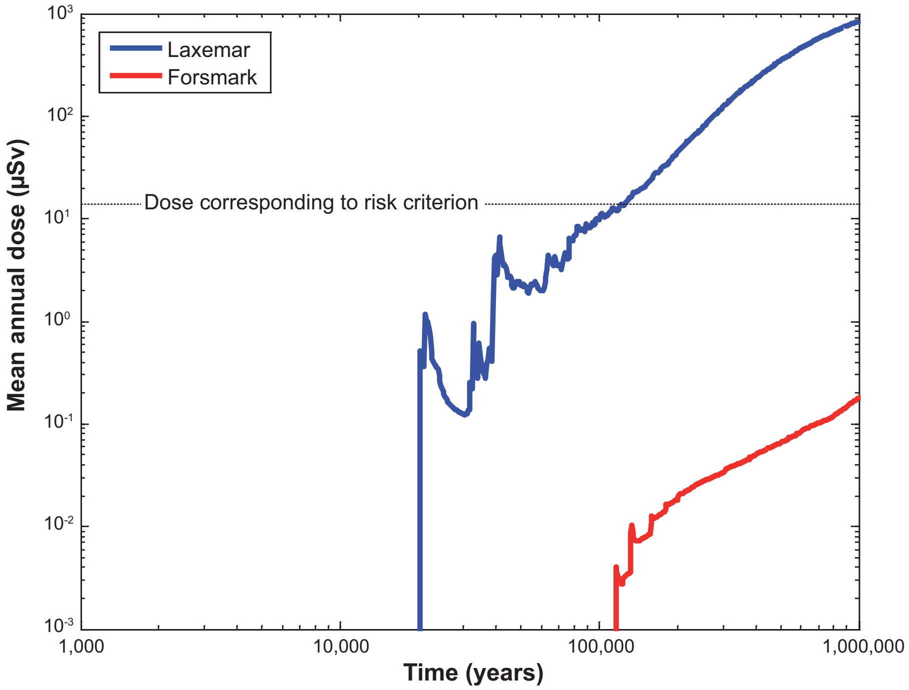

Figure 7-4. *Mean annual effective dose for the corrosion scenario, for Forsmark and Laxemar (modified from Figures 10-5 and 10-6 /SKB 2010b/).*

It is conceivable that further research will show that we are treating bentonite erosion much too pessimistically today. The relative advantage for Forsmark could thereby be considerably diminished. But it is difficult to imagine that the safety ranking between the sites would be changed by additional knowledge. The low groundwater flow and the high transport resistances in the rock in Forsmark are in any case positive for safety, partly because this makes the rock a more effective barrier to radionuclide transport.

7.2 Technology for execution

7.2.1 Flexibility

Operations area and accesses

In **Forsmark**, surface facilities and accesses in the form of shafts and ramp from the surface facility to the repository's central area have been located at Söderviken. In the report on the design premises for the repository /SKB 2008b/ it is noted that the accesses will have to pass varying rock conditions. Near the surface, down to 50-200 metres depth, there is a high frequency of water-conducting gently dipping fractures and minor fracture zones (fracture domain FFM02). The zones can be up to 10 m wide and contain sediment-filled and highly conductive fractures. Below that and down to repository depth the rock is fracture-poor with only a few fractures that conduct significant quantities of water (fracture domain FFM01). The rock stresses at great depth are relatively high, which means that spalling cannot be ruled out if tunnel orientations are unfavourable.

The final report from the design of Layout D2 Forsmark /SKB 2009a/ shows that construction of shafts and ramp is feasible in the planned area in Forsmark. The following needs to be considered, however:

- The location and disposition of the operations area permit only minor adjustments of the exact location of the mouths of the shafts and ramp, if this should be warranted in the detailed design work.
- The passage through the upper water-conducting parts of the rock near the surface makes great demands on sealing, especially if there are environmental requirements on limiting groundwater lowering in the area.
- In order to simplify the sealing work, the route of the ramp must be adapted as much as possible to the orientation of the water-conducting fractures. The available rock volumes are sufficient to make such an adaptation.
- In order to minimize the risk of spalling, the central area's rock caverns – and as much as possible of the lower parts of the ramp – need to be oriented in essentially the same direction as the maximum horizontal stress. The available rock volumes permit this.

The overall conclusion is that there are good prospects for building the repository's accesses in accordance with the planned layout in Forsmark and that there is sufficient flexibility to make continuous adaptations during detailed design and construction.

In **Laxemar**, surface facilities and accesses in the form of shafts and ramp to the repository's central area have been located in an area called Oxhagen. The report on the design premises for the repository in Laxemar /SKB 2009f/ notes that the overburden in the area is very limited and the rock stresses are relatively moderate. The accesses will have to pass through a number of conductive fractures and minor deformation zones, which will have to be sealed by grouting. Their frequency declines slightly at depths below 200–250 m.

The final report from the design of Layout D2 Laxemar /SKB 2009a/ shows that construction of shafts and ramp is feasible in the planned area. The following needs to be considered, however:

- The available land area and the location and disposition of the operations area permit some adjustments of the exact location of the mouths of the shafts and ramp, if this should be warranted in the detailed design work.
- In order to simplify the sealing work, the route of the ramp must be adapted as much as possible to the orientation of the water-conducting fractures. The available rock volumes are sufficient to make such an adaptation.

The overall conclusion is that there are good prospects for building the repository's accesses in accordance with the planned design and that there is sufficient flexibility to make continuous adaptations during detailed design and construction.

Both sites are thus judged to offer good potential for building the repository's accesses according to the planned design and good flexibility for whatever adjustments may be necessary in connection with detailed design and construction. The degrees of freedom for adjusting the positions of the accesses are more limited in Forsmark due to physical restrictions on the ground surface. On the other hand it is difficult to see any need for major changes. Both sites may require some adjustments of the position of the ramp and the execution of the central area with respect to rock conditions.

The deposition area

In **Forsmark**, adaptation of the deposition areas to the rock conditions has been based on the following /SKB 2008b/:

- The repository depth should lie within the interval 450–500 metres, since the frequency of conductive fractures declines dramatically at depths below 400 m. Greater depth has disadvantages in the form of higher initial temperature of the rock, which necessitates a larger repository since the distance between deposited canisters must be increased. The rock stresses do not appear to increase significantly with depth below a level of 300 metres /Martin 2007/.
- The repository's external boundaries are adapted to the boundaries of the tectonic lens.
- The layout is adapted to the established respect distances to four deformation zones inside and near the repository volume.
- According to thermal design calculations, the minimum distance between deposition holes in order to meet requirements on maximum temperature in the buffer is 6.0 m and 6.8 m, respectively, in the two rock domains that occur in the repository volume, provided that the deposition tunnels are spaced at a distance of 40 metres.
- In order to minimize the risk of failure in intact rock (spalling), the deposition tunnels should be oriented nearly parallel (within ±30°) to the direction of the maximum horizontal stress. Any spalling problems in other tunnels are handled with rock support and adaptation of the shape of the tunnels.

Based on these premises, a site-adapted layout (Figure 5-7) at a depth of 470 metres has been devised /SKB 2009a/. With applicable canister spacings and restrictions according to the layout, the gross capacity is 7,818 canisters within the investigated area. The space requirement for about 6,000 canisters means that a loss of up to 23% (1818/7818) can be handled.

In **Laxemar**, adaptation of the deposition areas to the rock conditions has been based on the following /SKB 2009f/:

- The repository should be located at a depth greater than 400 m, since hydrogeological data /Rhén et al. 2008/ show that the frequency of conductive fractures is relatively constant in the depth interval 400 m to 650 m. The repository should, on the other hand, not be located too deep since the initial temperature of the rock increases by about 1.5 °C per 100 m. This means that fewer canisters can be accommodated at greater depths, despite the fact that the available area increases between 400 and 650 m depth due to the orientation of the deformation zones that bound the deposition area. Hydrogeological advantages of greater depth are only achieved if the repository is located below 700 metres depth. However, such great depths have significant disadvantages in the form of e.g. a larger footprint area (greater canister spacing due to higher initial temperature) and construction-related uncertainties (high groundwater pressures, possible stability problems). The repository should therefore be located at a depth of about 500 m.
- The repository is located within a number of identified rock domains.
- The layout is adapted to the established respect distances to deformation zones.
- According to thermal design calculations, the minimum distance between deposition holes in order to meet requirements on maximum temperature in the buffer is between 8.1 and 10.6 m, depending on in which rock domain they are located, and provided that the deposition tunnels are spaced at a distance of 40 metres.

- In order to minimize the risk of failure in intact rock (spalling), the deposition tunnels should be oriented nearly parallel (within ±30°) to the direction of the maximum horizontal stress. Any spalling problems in other tunnels are handled with rock support and adaptation of the shape of the tunnels.

Based on these premises, a site-adapted layout (Figure 5-13) at a depth of 500 metres has been devised /SKB 2009d/. With applicable canister spacings and restrictions according to the layout, the gross capacity is about 8,050 canisters in the priority area. The requirement on space for about 6,000 canisters then means that a loss of up to 25% (2050/8050) can be handled.

In summary, it is concluded that the site-adapted repository layouts developed for both sites provide gross capacities that exceed the need for available deposition positions according to the reference design (about 6,000 positions) by more than 20%. The risk situation with regard to loss of deposition positions is discussed in Section 7.2.2.

Possibilities to increase capacity

In **Forsmark**, there are possibilities to increase capacity, both within the areas that have been well investigated and by extending the repository to adjoining areas, mainly towards the southeast. The latter applies subject to reservation for the fact that knowledge of the rock conditions in these areas is incomplete and investigations are required to confirm their suitability. The capacity of the repository can also be increased by carrying its thermal design further so that the repository area is utilized more efficiently. All in all, it is estimated that thermal optimization can reduce the footprint area by about 20% and thereby increase the repository's gross capacity by about 1,500 positions, but at the price of greater canister spacing, requiring more deposition tunnels /SKB 2009a/. Another possibility is to build yet another repository level, about 100 metres below the first one. The site descriptive model /SKB 2008a/ indicates similar hydrogeological and thermal properties as at the currently proposed repository level, but the slightly higher initial temperature of the rock at greater depths means that the distance between the deposition holes must be increased. The heat output from the upper level must also be taken into consideration, i.e. the deposition process on the upper level can affect the thermal design of the lower level. The rock stresses are not judged to increase significantly, but the uncertainties for this parameter increase with depth.

Laxemar offers comparable or better possibilities to increase capacity by improving the thermal design. If, for example, the tunnel spacing is reduced from 40 m to about 30 m, the gross increase in disposal capacity could be up to 2,000 deposition positions /SKB 2009d/, but at the price of greater canister spacing and more deposition tunnels. Another possibility is to build yet another repository level, about 100 metres below the first one. The site descriptive model /SKB 2009c/ indicates similar hydrogeological and thermal properties as on the currently proposed repository level. The higher initial temperature of the rock at greater depths and the heat output from the upper level must also be taken into consideration, in the same way as described for Forsmark. The rock stresses are not judged to increase significantly, but the uncertainties increase with depth. A third alternative is to expand the repository to the west and south.

Regardless of site, any measures to optimize the thermal design must be adopted at an early stage to have good effect. Extensions in depth or expansion of the repository area should be regarded as hypothetical possibilities in the long term. In summary, there are no decisive differences between the sites with regard to gross capacity for a repository within the areas that are well investigated, or future expansion possibilities.

7.2.2 Technical risks and need for technology development

Technical execution risks have been analyzed in the manner described in Section 6.3.2, with a focus on facilities and activities under ground.

Accesses and central area

The risk analysis that was done in connection with the design of Forsmark /SKB 2009a/ shows that the construction of accesses and central area do not entail any risks that are deemed to require special action plans. Attention should, however, be devoted to the risk of significant delays due to extensive sealing work (grouting) in the upper parts of the accesses. A similar risk analysis was done in connection with the design of Laxemar /SKB 2009d/. There as well the conclusion is that there are not any significant risks that are deemed to require special action plans, but that the risk of delays due to extensive grouting needs should be noted.

The risks involved in construction and operation of the final repository's accesses are thus judged to be limited for both Forsmark and Laxemar. The differences that exist concern the type of risks, but the potential consequences for the final repository project are deemed to be comparable and are, as mentioned above, limited in both cases. The same applies to the central area. The risk situation for accesses and central area is therefore not regarded as a significant factor in the comparison of the sites.

The deposition area

The risk analysis done for the deposition area in connection with the design of a repository in **Forsmark** /SKB 2009a/ is summarized in Figure 7-5. The table follows the classification shown in Figure 6-2. The projected consequences of different risks are expressed as the estimated number of theoretically available deposition positions that cannot be used because they do not satisfy all stipulated requirements /SKB 2009e/.

The deposition area in Forsmark

Probability	Insignificant (< 500)	Small (500–1,000)	Moderate (1,000–1,800)	Great (> 1,800)
Very probable				
Probable	Geological boundaries of rock and fracture domains differ from those assumed.			
Improbable	The rock type distribution differs from that assumed. The thickness of the minor deformation zones (MDZ < 1 km) is greater than assumed. The rock mechanical properties of major and minor deformation zones are much poorer than assumed in connection with design.	The orientation of the maximum principal stress varies more than ±15°. The spatial distribution of the thermal rock domains differs from that assumed. Bedrock units containing mafic rocks with low thermal conductivity occur more frequently than assumed.	New deformation zones in the length interval 1 km to 3 km are discovered. The maximum horizontal stress is greater than the most probable value, but not greater than the improbable maximum value.	
Extremely improbable			Higher frequency than expected of water-conducting fractures with flows that exceed what is permitted in deposition holes and deposition tunnels.	Higher frequency than expected of large fractures. New deformation zones that require respect distances are discovered. The maximum horizontal stress is greater than the improbable maximum value.

Consequences (loss of deposition positions)

Figure 7-5. *Risk analysis for the deposition area in Forsmark. The consequences of the risks that have been identified are expressed as estimated loss of theoretically available deposition positions. In the weighing-together of probability and consequence, all risks have been classified as negligible or acceptable, i.e. manageable within the framework of the planned construction process (green field). None of the risks is deemed to require extensive measures (beige field), /SKB 2009a/.*

Comments on risk analysis for Forsmark, Figure 7-5:

- While there is high confidence in the orientation of the rock stresses and relatively high confidence in the strength of the rock in Forsmark, confidence in the magnitude of the maximum horizontal stress is lower /SKB 2008a/. Analyses have been done to evaluate the risk of spalling in deposition holes prior to deposition /SKB 2009a, Appendix C/. The analyses show that fewer than 400 deposition holes are expected to suffer breakouts that exceed the tolerance requirements, even with very pessimistic assumptions for the rock stresses. At very high rock stresses, however, this assumes that the deposition tunnels are oriented completely parallel to the maximum horizontal stress. It is therefore essential to determine the stress situation better before the final layout of the deposition area is determined. A sufficiently reliable determination cannot be done until the repository's accesses, primarily the sunk shaft, have been built down to repository depth.
- Thanks to the low occurrence of water-conducting fractures within the deposition area in Forsmark, a very limited loss rate of possible deposition holes is expected, about 6% or 500 positions, due to high inflows in the deposition holes. It is furthermore probable that the few deposition holes that could have too high flows would have been rejected anyway because they are intersected by long fractures, see below.
- In order to ensure that the repository is not adversely impacted by any major future earthquakes, only deposition holes that are not intersected by long fractures are accepted. The estimated loss rate is in the range 10 to 25 percent (700 to 1,900 positions), depending on which fracture model is assumed. The criterion that is used today to determine whether a deposition position is intersected by a long fracture is, however, unnecessarily restrictive, and it is therefore deemed to be extremely improbable that the loss would be as great as 1,900 positions.

The risk analysis done for the deposition area in connection with the design of a repository in **Laxemar** /SKB 2009d/ is summarized in Figure 7-6.

Comments on the risk analysis for Laxemar, Figure 7-6:

- The relatively high frequency of conductive fractures within the deposition area in Laxemar is expected to cause considerable loss of deposition holes due to excessively high inflows of groundwater. The problem is greatest within the hydraulic domain that is located in the northern part of the repository area and that with the current repository layout accounts for about 2,000 deposition positions, but the loss rates are relatively great (20–30%) in other domains as well. The inflow to deposition tunnels must also be restricted in order to ensure that the backfill can be installed, which makes it more difficult to use the domain with the highest permeability. If this domain cannot be used, the total potential loss is estimated to be up to 4,000 positions.
- The rock stresses in Laxemar are low compared to the strength of the rock. Rock mechanical calculations for the design of Laxemar /SKB 2009d/ show that the uncertainties in the stress model do not entail a risk that the current repository layout could lead to extensive spalling in deposition holes prior to deposition.
- In order to ensure that the repository is not adversely impacted by any major future earthquakes, only deposition holes that are not intersected by long fractures are accepted. The estimated loss rate is in the range 10 to 25 percent (800 to 2,000 positions), depending on which fracture model is assumed. The criterion that is used today to determine whether a deposition position is intersected by a long fracture is, however, unnecessarily restrictive, and it is therefore deemed to be extremely improbable that the loss would be as great as 2,000 positions.

The deposition area in Laxemar				
Probability				
Very probable	Geological boundaries of rock and fracture domains differ from those assumed. Boundaries of deformation zones differ from those assumed.			
Probable	Rock type distribution differs from that assumed. New deformation zones in the length interval 1 km to 3 km are discovered. The spatial distribution of altered rock is not well defined. The spatial distribution of thermal rock domains deviates clearly from what has been assumed in connection with design.			Higher frequency than expected of conductive fractures or minor deformation zones (MDZs) with flows in excess of what is permitted in deposition holes and deposition tunnels.
Improbable	The strength of major and minor deformation zones is lower than assumed. The orientation of the maximum principal stress varies more than ±15°. The maximum horizontal stress is greater than the most probable value, but not greater than the improbable maximum value.	The thickness of the minor deformation zones (MDZ < 1 km) is greater than assumed. The transmissivity and complexity of deformation zones are underestimated. Thermal conductivity is lower than assumed.		
Extremely improbable		The maximum horizontal stress is greater than the improbable maximum value.	Higher frequency than expected of large fractures.	New deformation zones that require respect distances are discovered.
Consequences (loss of deposition positions)	**Insignificant** (< 1,000)	**Small** (1,000–1,500)	**Moderate** (1,500–2,000)	**Great** (> 2,000)

Figure 7-6. *Risk analysis for the deposition area in Laxemar. The consequences of the risks that have been identified are expressed as estimated loss of theoretically available deposition positions. In the weighing-together of probability and consequence, a risk has been identified that is judged to require extensive measures (beige field). Other risks are judged to be manageable within the framework of the planned construction process (green field), /SKB 2009d/.*

A comparison of the risk analyses for Forsmark and Laxemar reveals significant differences between the deposition areas, expressed as risks of loss of deposition holes and resulting development need to manage these risks. These risks affect the prospects of achieving a safe final repository in practice. The following overall assessment is made of the risk situation:

- The risk analysis for **Forsmark** shows that the available gross capacity of about 7,800 deposition positions is more than enough to permit a repository according to the reference design with about 6,000 approved deposition positions. There is, however, a small but not entirely negligible risk of stability problems (spalling) in deposition holes due to high loads (rock stresses), see Figure 7-1. In the unlikely event that the rock stresses are so high that this occurs far too frequently, calculations indicate that the problem can be managed without extensive changes in the layout of the repository, mainly by further adapting the orientation of the deposition tunnels to the stress field. It is therefore important to conduct rock mechanics tests on a relevant scale and at relevant depth as soon as possible during the construction of the repository's accesses so that the need for measures, if any, can be determined. Furthermore, occupational safety issues and maintenance needs must be taken into account, above all in the construction of the main tunnels. This does not require any technology development, however.
- The risk analysis for **Laxemar** shows that the available gross capacity of about 8,000 deposition positions cannot be considered enough to permit a repository according to the reference design with 6,000 approved deposition positions unless additional measures are adopted. The reason is that the water inflows to many deposition holes risk being too great for the holes to be accepted as deposition positions. The problem is greatest within the hydraulic domain that is located in the northern part of the repository area and that with the current repository layout accounts for about 2,000 deposition positions, but the loss rates are relatively great (20–30%) in other domains as well. In order to manage this risk, the layout should be revised so that the northern domain is completely avoided. This can primarily be done by means of a thermal optimization that permits the remaining deposition area to be utilized more efficiently, but this means that more deposition tunnels must be built. It may also be necessary to utilize additional rock volumes for deposition. Further development and production adaptation of the technology for fine sealing of tunnels is also needed.

Furthermore, an adaptation is necessary at both sites so that possible movements in connection with major future earthquakes do not risk damaging deposited canisters. This is done by avoiding deposition positions that are intersected by fractures that are long enough – or might be long enough – to cause movements that can affect the canister's integrity. With today's criteria, this can result in a loss rate in the interval 10 to 25 percent at both sites, but the actual loss rate is expected to be considerably lower. The preparations for the investigations that will be performed of each deposition tunnel and deposition position will be aimed, for example, at developing more efficient methods for determining the size of fractures that might intersect possible deposition positions /SKB 2010e/.

7.2.3 Functionality

It must be possible to build out the repository at the same time as deposition is proceeding. Build-out must be able to proceed so that access to work faces, separated transport routes etc can be guaranteed. The site-adapted layouts that have been devised are judged to meet these requirements and permit a flexible build-out where excavation of new tunnels can co-exist with the deposition activities without great risks of conflicts between these activities /SKB 2009a and SKB 2009d/. Tunnelling and deposition work can proceed in different parts of the same deposition area, provided they are separated and accessed via different transport routes. This applies to both sites to roughly the same extent, even though the layouts have completely different geometries.

The site differences that can be seen with respect to functionality are instead the result of both the reported technical risks with the accompanying need for remedial measures and the fact that a repository in Forsmark can be made much smaller in extent than a repository with equivalent capacity in Laxemar. The fundamental reason is differences in the thermal conductivity of the rock, which determines the spacing between the deposition positions and thereby the required deposition area. Measured in total excavated rock volume up to concluded operation (fully built-out repository) and with the current repository layouts, a repository in Forsmark will be approximately 30% smaller than a repository in Laxemar. Figure 7-7 illustrates one effect of this, namely the differences in transport performance to build the various repository tunnels.

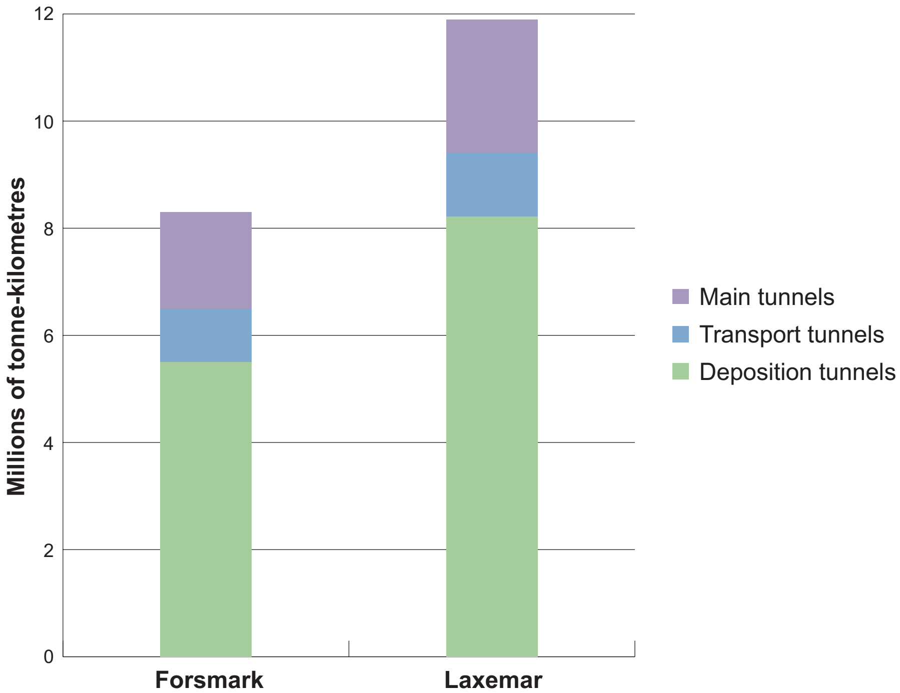

Figure 7-7. *Transport performance in tonne-kilometres required to build the final repository's tunnels in Forsmark and Laxemar.*

A more compact repository reduces inputs of labour and material, goods flows, maintenance etc. All of this contributes to better functionality, due to higher efficiency and reduced risks of operational disturbances. This is, of course, provided that working efficiency is not inhibited by a lack of space, but this is not expected to be the case.

Both Forsmark and Laxemar offer good and very similar conditions for the off-site transport that will be required locally for the final repository project. The similarities include, for example, the standard of the local road network, commuting distances from nearby residential localities, and distances to the harbours (Hargshamn and Oskarshamn) that may be used for importing clay material for buffer and backfill /Fors and Klingenberg 2008a, b/.

The transport needs differ in two respects:

- Laxemar requires larger volumes of bulk material to be transported, due to the fact that the repository will be bigger there than in Forsmark. This includes outbound transport of surplus rock for sale and inbound transport of clay for backfilling. The volume differences affect the costs and the environmental impact of the transport. However, they are not expected to have any consequences for operational reliability.
- Forsmark requires sea transport of encapsulated fuel from the encapsulation plant at Simpevarp. The total transport chain includes overland transport by terminal vehicles from the encapsulation plant to the port at Simpevarp, from there sea transport by m/s Sigyn (or a successor with comparable capacity) the approximately 450 km to the port at Forsmark, and finally overland transport the short distance from the port to the repository. In the Laxemar alternative, canisters only have to be transported approximately 2 km by road on terminal vehicles. This transport, whether by sea or by land, takes place in a similar manner to the transport of spent nuclear fuel that has been taking place for a long time from the nuclear power plants to Clab. The additional sea transport for the Forsmark alternative does not affect the radiological safety in the system. It does, however, entail an extra cost and additional energy consumption (see Section 7.3.5). Over the years, sea transport has proven to be very reliable, but this additional link in the handling chain in the case of Forsmark must nevertheless be regarded as a possible source of operational disturbances.

7.2.4 Synergies

A siting at Laxemar would mean that the entire handling chain for spent nuclear fuel from today's interim storage to a closed final repository would be gathered at one place in the country. This offers a number of advantages. The most obvious one (in comparison with Forsmark) is that the need for sea transport of canisters is eliminated. How SKB evaluates this is discussed in Section 7.2.3. In general, concentrating an activity reduces external dependency. In view of the fact that the project will extend over more than a half a century in a changeable world, SKB considers this to be a significant advantage, although impossible to evaluate quantitatively.

SKB's activities in Oskarshamn today employ some 200 people, divided between Clab, the Äspö HRL, the Canister Laboratory, and investigation and information activities. In other words, SKB has a considerable internal resource base and in-house infrastructure to start with for establishment of the final repository (and the encapsulation plant). In Forsmark, SKB's activities currently employ about 25 people (SFR, investigations, information). This figure will increase in connection with the planned extension of SFR, but a siting of the repository for spent nuclear fuel in Forsmark would nonetheless entail more of a new establishment than it would in Laxemar. This difference entails clear efficiency advantages for Laxemar, which however are difficult to translate to savings in time or money. For this and other reasons, general synergies of this type have not been taken into account in the following cost comparison.

It is also important to evaluate differences in SKB's own local capacity in relation to the total offering of resources at the localities in question. It can for example be noted that in both Oskarshamn and Östhammar the nuclear energy sector – with the nuclear power companies and their local suppliers – employs well over 1,000 people. Furthermore, the advantage of having a pre-existing operation is greatest in the initial phase when the project is established, but then declines with time. Experience from other establishment projects shows that organization and resources are eventually adapted to the needs.

The Äspö HRL is a "supplier" of unique technology and expertise for the needs of the final repository. Transferring this technology and expertise from development to operations would be facilitated by a siting at Laxemar, due to proximity.

In summary, SKB's already extensive operation in Oskarshamn offers synergies and efficiency gains if the final repository is sited at Laxemar, especially in the establishment phase of the final repository project. Forsmark does not offer the same advantages in this respect. Furthermore, the implementation of the technology developed at the Äspö HRL is facilitated by a siting at Laxemar due to the geographic proximity. Finally, selecting Laxemar would entail gathering the entire handling chain for the nuclear fuel at a single location, which would simplify execution and reduce external dependency. The synergies between the nuclear power plants and the final repository are judged to be similar for the two sites.

7.2.5 Costs

The calculations that have been carried out in conjunction with the site-adapted design of the final repository show that a repository in Laxemar would cost approximately SEK 4.5 billion, or 15%, more than a repository in Forsmark. The difference in cost is due above all to the difference in repository size. A final repository in Laxemar requires much more tunnelling, which has a great impact on the total cost since rock excavation and backfill material are large cost items. The extra costs for canister transport by sea and slightly longer transport distances for clay material in the case of Forsmark have been taken into account, but represent only about 1% of the total cost of the project.

The calculations have been executed carefully, but the uncertainties for many site-distinguishing items are nevertheless considerable in this early stage of the project. Predicted differences in, for example, rock support and sealing needs in conjunction with rock construction have been taken into account as far as possible, but not the possible consequences of the more important execution risks described above. As mentioned, synergies with other facilities and the overall organizational consequences of the choice of site also lie outside the calculations, since they cannot be translated into resource measures. These uncertainties can have a considerable impact on total costs and relative differences, but are not judged to be able to change the ranking between the sites from a cost viewpoint.

7.2.6 Conclusions

Both sites are deemed to offer the necessary conditions for building and operating the final repository in a robust manner. Comparisons have different outcomes for different siting factors, but the overall judgement is made that Forsmark offers better prospects. The main reason is that the rock conditions in Forsmark offer a much lower risk that extensive remedial measures will be needed beyond what is planned. This has a direct bearing on the feasibility of achieving a repository that meets the safety requirements.

The rock-related technical execution risks that do exist in Forsmark are linked to the occurrence of relatively high rock stresses. But the stability problems, with related loss of usable deposition positions that this could entail, are judged to be both improbable and relatively simple to manage if they should nevertheless occur. The uncertainties in the case of Laxemar are greater and concern the availability of deposition positions with acceptably low inflows and good prospects for building deposition tunnels that meet the tightness requirements, given the comparatively high frequency of conductive fractures. Considerable modifications in the layout of the repository are judged to be necessary in order to deal with these problems. Furthermore, there is a need for continued development of methods to seal the rock to the extent that would be required.

The rock conditions in Forsmark offer great advantages in terms of efficiency as well. The reason is that a repository in Forsmark can be made much smaller and more compact than is possible in Laxemar. This is because the higher thermal conductivity of the rock in Forsmark permits denser canister spacing and thereby a smaller total deposition area. The smaller volumes are reflected in lower transport needs, material consumption, labour needs etc, which taken together entail a more efficient execution of the project.

If external factors are instead taken into account, the outcome of a comparison is in Laxemar's favour. One main reason is that SKB's existing facilities and extensive operations in Oskarshamn would provide synergies, especially in the initial phase of the final repository project. This applies particularly to the implementation of the technology and expertise that is being developed at the Äspö HRL and can be applied to the final repository. The other main reason is that selecting Laxemar would gather the entire handling chain for the spent nuclear fuel at one place in the country. Besides efficiency gains, this entails less external dependency. The clearest advantage relative to Forsmark is that the need for sea transport of encapsulated fuel from the encapsulation plant is eliminated. The extra cost this entails for Forsmark is marginal, but the longer transport chain to Forsmark nevertheless constitutes a possible source of operational disturbances.

7.3 Environment and health

7.3.1 Occupational safety and radiation protection

Construction and operation of the final repository will be carried out in accordance with relevant occupational safety requirements. This is true regardless of site. Any differences between the sites lead to differences in required measures and thereby costs.

All radioactive material deposited in the final repository will be encapsulated. The structures and measures required for protection of canister integrity and against direct radiation from the canister are the same for both sites.

The natural uranium concentrations in the rock are low – normally less than 10 ppm – in both Forsmark and Laxemar. The biggest contribution to the radon concentrations comes from inflowing groundwater. The in-leakage is greater in Laxemar than in Forsmark. A much higher air exchange rate is therefore needed for a repository in Laxemar in order to meet the legal radon limits. However, the planned ventilation capacity is sufficient to keep the radon concentrations at acceptable levels /Jelinek 2008/. Radon is therefore not expected to have any adverse impact on the health of the personnel.

From the radiation protection viewpoint the sites are thus equivalent.

7.3.2 Natural environment

There are a number of areas of national interest at both sites. The area of national interest in Forsmark is Kallrigafjärden, which is partially located within the repository's impact area. The consequences for the area of national interest are judged to be noticeable, but can be reduced to small by damage-mitigating and compensatory measures /Hamrén et al. 2010a, Allmér 2010/. In Laxemar the area of national interest that is affected is "the archipelagos of Västervik and Oskarshamn", due to discharges of contaminated water. The consequences are judged to be insignificant /Nilsson 2010, Hamrén et al. 2010b/.

There are several natural attractions with high values in Forsmark, above all a couple of ponds with pool frogs (a protected species that was released in the Forsmark area in the 1990s, see Figure 7-8), within the area affected by the surface facilities. SKB will submit proposals on how to compensate for the loss of the pool frog's habitats by creating new ponds in suitable environments. With the planned measures, it is believed there will be no negative consequences for the local pool frog population. The Forsmark area also harbours additional species that are protected under the Species Protection Ordinance as well as a number of red-listed species which could be impacted. With suitable measures, and provided they are successful, it should be possible to limit the consequences for protected species and species worthy of protection in Forsmark. No natural attractions with national or regional values are affected in Laxemar, so the consequences are much smaller there than in Forsmark. The number of protected species and species worthy of protection is also much smaller.

There are many wetland areas, which can be sensitive to groundwater lowering, within the area in Forsmark that could be affected by groundwater lowering /Allmér 2010, Hamrén et al. 2010a/. Roughly half of the seventy or so identified valuable wetland sites, ponds and surface bodies of water around Forsmark will be affected by the calculated groundwater lowering. Another fifteen or so sites will be affected by a changed groundwater balance. The possible consequences vary /SKB 2011b/. In the case of the most important wetland environments it is possible to arrange for infiltration of water, which would reduce the consequences. In Laxemar the consequences of a groundwater lowering would be less, since most valuable natural attractions are not assessed to be sensitive to groundwater lowering /Nilsson 2010, Hamrén 2010b/.

Figure 7-8. *There are ponds with the pool frog within the area affected by the surface facilities in Forsmark.*

Provided that rock drainage water, leachate and sanitary sewage are purified and treated before being discharged, the consequences are assessed to be small to noticeable in both Forsmark and Laxemar. There is one well in Forsmark and a large number of wells in Laxemar that could be affected by groundwater lowering. However, affected property owners can be compensated by supplying their properties with water.

The strict protection afforded certain species that would be affected by an establishment in Forsmark requires that measures be taken so that these species are not greatly affected. SKB has begun the work of devising suitable measures. Regarding the local population of pool frog, the results show that there are good prospects for creating new ponds so that the population is not adversely affected. Similarly, the impact on the area's most valuable wetlands due to groundwater lowering can be limited by infiltration. The conclusion is that Forsmark is a sufficiently good site with respect to impact on the natural environment. This is largely due to the fact that the facilities will for the most part be built within the existing industrial area, which limits the consequences. But this will require caution, adaptation and preparedness for different types of measures: preventive, consequence-mitigating and compensatory.

With some reservation for the fact that the siting at Oxhagen entails intrusion in a valuable hardwood forest area (see Figure 7-9), it is difficult to see any objections to the conclusion that Laxemar is a suitable site from the viewpoint of the natural environment. This is true in spite of the fact that a final repository entails a "greenfield establishment" without any direct link to an existing industrial activity. The main reason is that the area that would be affected, or at least is perceived to be affected, has long been used for human activities. Consequently, impact and intrusion are primarily regarded as a matter for affected humans, not as an "occupation" of the natural environment.

In summary the impact on natural values is much greater in Forsmark than in Laxemar. Species-rich and sensitive rich fens, the occurrence of the pool frog etc are examples of high natural values that could be affected. Measures must therefore be taken to prevent this. In Laxemar it is above all the landscape with hardwood forests and aquatic environments along the coast that are impacted. From a Swedish perspective, the natural values in Forsmark are uncommon while the environments around Laxemar are relatively common.

Figure 7-9. *There are valuable hardwood environments within the area affected by the surface facilities in Laxemar.*

7.3.3 Cultural environment

An establishment at Oxhagen in Laxemar entails a greater impact on the cultural environment and the landscape than an establishment at Söderviken in Forsmark. At Forsmark the landscape with the open coast outside is affected. This impact is, however, softened by the fact that the development is directly adjacent to existing industrial facilities. At Oxhagen the cultural environment and the agricultural landscape are affected. However, the impact is assessed to be moderate, since a large part of the area consists of production forest and clear-cut areas without any high cultural values. There are no known archaeological remains at either Söderviken or Oxhagen. At Oxhagen there are cultural remains in the form of stone walls, farm roads and clearance cairns associated with the agricultural land. Neither Oxhagen nor Söderviken contains any cultural environmental values of an indispensable character, which means that a siting of the final repository can in both cases be done with an acceptable impact on the cultural environment and landscape. Oxhagen, however, contains values with some conservation value. The conclusion must be that Forsmark (Söderviken) is the site that is most advantageous for siting of the final repository from a cultural environmental and landscape viewpoint /Ternström 2008a, b/.

7.3.4 Residential environment and health

A final repository in Forsmark entails establishment within an existing industrial area relatively far from housing, with temporary housing within the industrial area as the only exception. In Laxemar there are more permanent residents within the area (see Section 5.3.9 for Forsmark and 5.4.9 for Laxemar). There are also considerably more vacation homes around Oxhagen than around Söderviken /SKB 2011b/. There are therefore considerably more people in Laxemar than in Forsmark who would be affected and could perceive a deterioration in their residential environment.

A factor that is closely linked to the residential environment is land ownership. In Forsmark the land needed for the final repository has long been industry-owned – today by SKB and Forsmarks Kraftgrupp AB. In Laxemar the land is mainly privately owned and divided into a number of properties with owners who in many cases live in or have ties to the district. A prerequisite for an establishment of the final repository is that power of disposition over the land is transferred to SKB. In the case of Laxemar, this would entail a big change for many people, since homes as well as livelihoods and recreational activities are directly associated with land ownership. How such a change is perceived and valued can differ radically from case to case, but it nevertheless entails replacing a generations-old way of life with something new.

Due to noise from construction activities and operation in both Forsmark and Laxemar, parts of areas of national interest for recreation and outdoor activities will have sound levels above current guideline values. Otherwise the consequences will be small on both sites /Zetterling and Hallberg 2008a, b/.

As far as transport to and from the final repository is concerned, the differences are that in the case of Laxemar there are more people who live and are affected along the transport routes, and the goods volumes to be transported are greater. During the construction phase the number of residents along the route Forsmark–Hargshamn exposed to sound levels above the existing guideline value (55 dBA) will increase from around 160 to around 180 (+20) and during the operating phase from around 175 to around 195 (+20). Along the route Oskarshamn–Oxhagen, the equivalent figure during the construction phase is an increase from 290 to 310 (+20) and during the operating phase an increase from 290 to 345 (+55). Noise from road traffic thus already causes disturbances today. Additional noise from transport to and from the final repository will result in more people being disturbed than at present, in the operating phase more in Laxemar than in Forsmark. However this is not expected to lead to a deterioration in health for more people /Zetterling and Hallberg 2008a, b/.

Emissions of air pollutants from transport, heavy equipment and handling of rock spoil will add very little to existing emissions. Moreover, very few people are affected by the emissions. All in all, the risk of health consequences due to air pollution is very low in both Forsmark and Laxemar, despite the differences in transport volumes /Fridell et al. 2008a, b/.

Road transport also causes other nuisances in the form of accident risks, increased traffic congestion, and impacts on recreation and outdoor activities etc. These impacts are dependent on the transport volumes, but also a number of other factors such as road standard, weather conditions and commuting patterns. With the exception of the volumes, which are greater for Laxemar, it is not possible to distinguish the alternatives in these respects. Neither in Forsmark nor in Laxemar are vibrations from blasting and heavy transport activities expected to cause damage to buildings; Nor are they expected to be perceived as disturbing by residents in the area.

In summary, the impact on the residential environment is expected to be slightly greater in Laxemar than in Forsmark. The differences that exist are that the acquisition of land that is needed in Laxemar would also affect the residential environment; that more people live in the immediate vicinity of Laxemar than in the immediate vicinity of Forsmark; that in the case of Laxemar more people live along the stretch of road where clay material and rock spoil will be transported; and that in the case of Laxemar there are larger quantities of rock spoil and clay material to be transported.

7.3.5 Management of natural resources

The quantity of excavated rock is greater for a final repository in Laxemar than in Forsmark. Altogether approximately 8.7 million tonnes of rock are excavated in Laxemar and about 6.4 million tonnes in Forsmark – about 2.3 million tonnes more in Laxemar. The larger excavation volume also means that there is a greater need for clay for backfilling and closure of the repository's rock openings in Laxemar. In Laxemar a total of about 5.2 million tonnes of clay are needed for buffer, backfilling and closure. In Forsmark about 3.6 million tonnes are needed /SKB 2010d/.

In Forsmark about 200,000 m^3 of fill material is needed during the construction phase to prepare the land area where the surface facility will be built. Most of the fill material is needed before excavated rock can meet the need. In Laxemar the need for fill material is much less /SKB 2010d/.

The pie chart in Figure 7-10 shows the relative distribution of energy consumption for the nuclear fuel system, divided between canister and final repository. The entire chain from the mine until the canister leaves the encapsulation plant filled with spent nuclear fuel is included for the canister. This portion is completely independent of the site of the final repository and accounts for more than half of the energy input for the whole system.

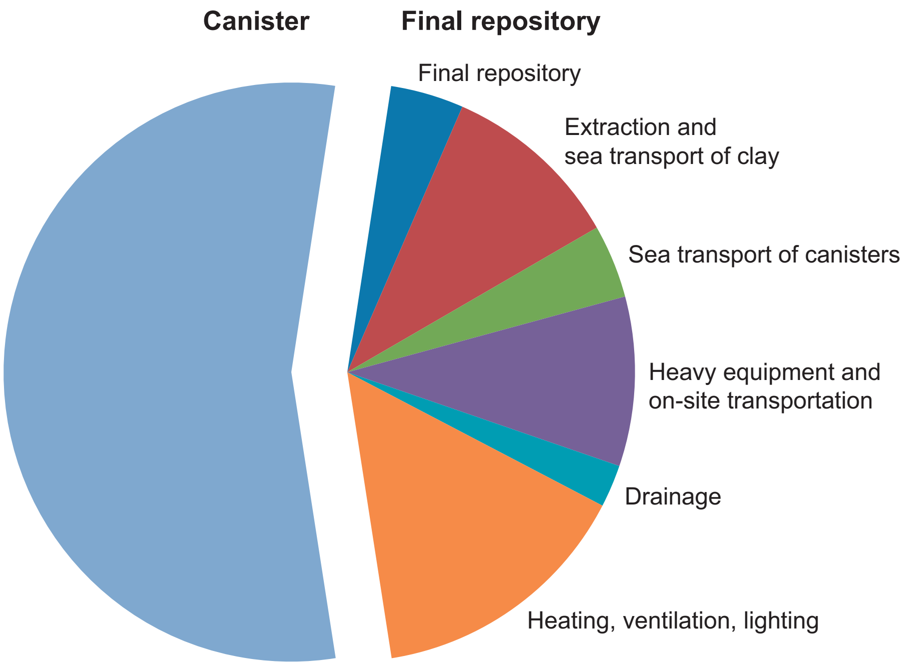

Figure 7-10. *Distribution of energy consumption in the nuclear fuel system. The left-hand sector represents the fraction for the canister (total for the entire chain from raw material production to sealed and controlled canister) while the right-hand sector is for the final repository (construction, operation and decommissioning), divided into activities that contribute to energy consumption. The example concerns Forsmark.*

The final repository portion of energy consumption (less than half of the total) is thus somewhat site-dependent. The components that represent the largest fractions are extraction and sea transport of clay, energy for heavy equipment and on-site transportation, and heating, ventilation and lighting.

Figure 7-11 shows a comparison of energy consumption for a repository in Forsmark versus in Laxemar. Since the quantity of excavated rock is much greater for a final repository in Laxemar, energy consumption is higher and the transport need is greater. The transport distance by sea for the clay materials is slightly longer for Forsmark than for Laxemar. But since the need for clay is so much greater in Laxemar, the total energy need for extraction and transport of clay is nevertheless greater for Laxemar than for Forsmark. The difference is roughly equivalent to the energy need for transport of encapsulated nuclear fuel from Simpevarp to Forsmark. Due to greater water inflow in Laxemar, the energy need for drainage is greater /SKB 2010d/. All in all, energy consumption is greater for Laxemar than for Forsmark, but the difference is not great and is even smaller when considered in relation to energy consumption for the whole system, including the canister.

7.3.6 Conclusions

With respect to environmental and health issues, both of the sites are suitable siting alternatives for the final repository. The same conclusion was drawn in the early stages of the siting work, and the extensive body of data produced by the site investigation phase has not altered this judgement. A comparison of the alternatives reveals great similarities in some respects. This includes, for example, the distances for passenger and goods transport. In other and essential respects there are clear differences. It is nevertheless difficult to rank the sites, since the environmental consequences of an establishment differ in type of impact rather than scope.

In the case of Forsmark, the surroundings are characterized by a sensitive natural environment with high conservation values. A far-reaching adaptation to these values is necessary and possible, but some measure of intrusion in the natural environment is nevertheless unavoidable. On the other hand, people's residential environment in the final repository environs would be affected to a very small extent, for the simple reason that very few people live or work in the area (with the exception of activities and temporary housing within the industrial area).

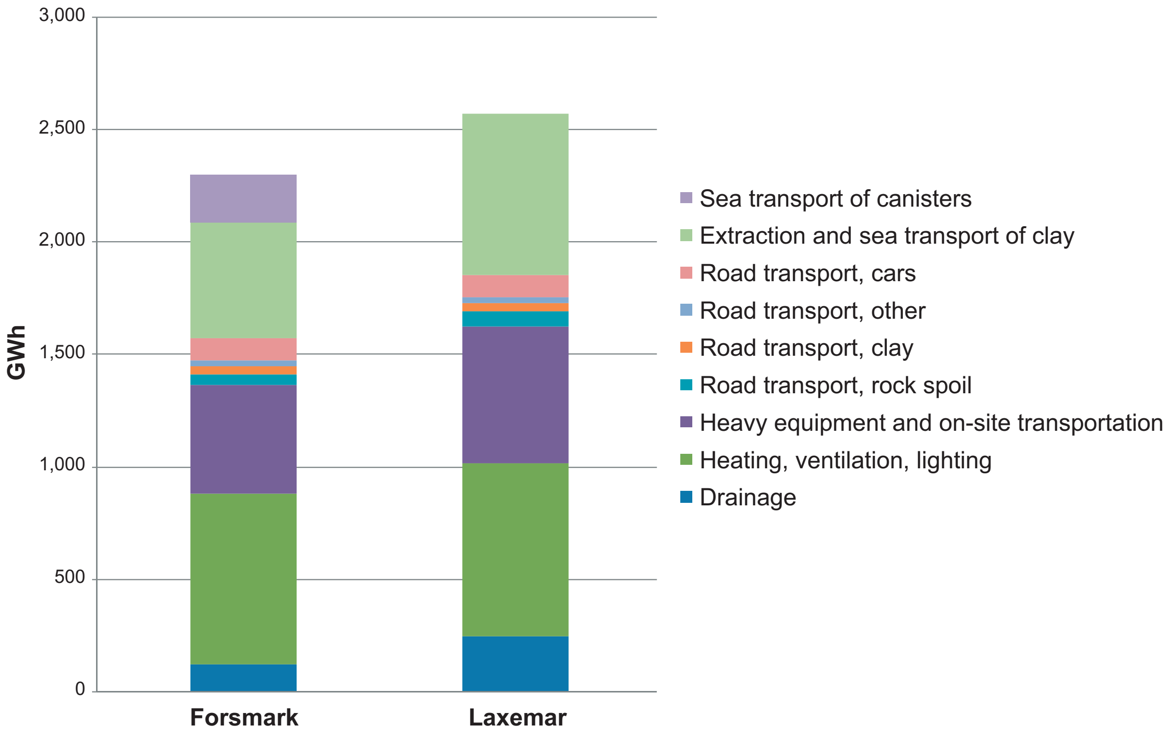

Figure 7-11. *Comparison of energy consumption (GWh) for construction, operation and closure of a final repository in Forsmark and in Laxemar.*

The opposite is true in the case of Laxemar. Even though it is a question of a “greenfield establishment” there, the impact on the natural environment is of little importance. Of greater importance is the fact that people live and work in the Laxemar area, and have done so for a long time. Privately owned land and land-based industries are important features of the picture. An establishment will entail a change in land ownership, but does not have to entail a significant change in land use. Establishing a new large-scale industrial activity quite different from that which characterizes, and has characterized, the area nevertheless entails an intrusion and requires adaptation.

A siting at Forsmark is slightly less energy-demanding than a siting at Laxemar. Based on the siting factor “Management of natural resources”, Forsmark is thus the more suitable site. The difference is small, however, and the assessments are associated with uncertainties.

In summary, the conclusion is that both sites are suitable siting alternatives with respect to environmental and health issues. Important prerequisites are that the final repository project is adapted to the environment at the site and that preventive, consequence-mitigating and compensatory measures are implemented. A ranking based on differences in environmental impact is not meaningful, since it would require comparisons of factors that cannot be compared. Differences in energy consumption are included in the cost calculation and are therefore not evaluated here. From this it follows that the siting factor “Environment and health” scarcely influences the overall evaluation for site selection.

7.4 Societal resources

Prior to the selection of sites for site investigations, SKB made concluded that both Oskarshamn and Östhammar municipalities are satisfactory alternatives with respect to the societal prospects for executing the final repository project. Studies during the site investigation phase have since contributed detailed data on the socioeconomic prospects for, and consequences of, a final repository in Östhammar versus Oskarshamn. Summaries of these data and references to individual studies are provided in /SKB 2008c/ and /SKB 2008d/.

The additional knowledge gained has, in SKB’s opinion, confirmed the previous assessment that both Oskarshamn and Östhammar offer good prospects for executing the final repository project. It is also difficult to imagine any changes in the local communities that could adversely alter this assessment. On the contrary, interest in the final repository seems to have been gradually strengthened during the site investigation phase in both municipalities.

Accordingly, there are no factors that could seriously hamper an establishment in either of the municipalities, during either the construction or the operating phase. There are, however, some differences that may be worth taking into account in the overall assessment of efficiency in the execution of the final repository project.

Oskarshamn’s advantages include a comparatively stronger local supplier capacity and recruitment base. Contributing causes are a generally strong industrial tradition and a long-standing heavy SKB presence. The municipality is also characterized by a generally high preparedness to incorporate the final repository in its already extensive industrial activities. The disadvantages that can be seen with the Oskarshamn alternative are above all associated with its geographic location, far from any of the country’s resource-strong population centres. Together with the neighbouring municipalities, Oskarshamn forms a region that is in many respects dependent on its own resources. This puts restrictions on local delivery capacity and human resources recruitment, particularly in the long term and against the background of the current trend of increasing concentration of the country’s resources to already dominant population centres.

In the case of Östhammar, the situation can be said to be the reverse: The local capacity in the form of recruitment base and supplier capability is comparatively weaker, but if the whole region is taken into account the picture is quite different. The municipality lies within reach of daily commuting to resource-strong Uppsala and Gävle, and to some extent also to the Stockholm region. It can be assumed that the advantages this offers for long-term human resources recruitment will grow with time due to improved communications and regional development.

Conclusions

To put it simply, Oskarshamn has advantages in terms of societal resources on the local scale and Östhammar on the regional scale. Weighing these advantages and disadvantages against each other in a relevant manner is hardly possible. Furthermore, the similarities as a whole are much greater than the differences. The differences can therefore not be accorded any decisive importance in the overall comparison of the alternatives for site selection.

7.5 SKB's overall evaluation and choice

7.5.1 Summary comparison of the sites

Safety-related site characteristics

Assessments of the long-term safety of the sites have shown that the processes that could damage canisters in the very long term are corrosion if the buffer is lost and possibly major earthquakes in the vicinity of the repository. If all canisters remain intact, no releases of radioactive substances will occur.

For many of the factors that could affect safety, the outcome of the comparative analyses that have been done for the sites is relatively similar. This applies, among other things, to the probability of future earthquakes, which is small and is judged to have small consequences at both sites.

However, the differences in frequency and permeability of conductive fractures, and to some extent also the differences in the future composition of the groundwater, lead to big differences in the assessment of long-term safety. Based on current knowledge, we cannot today rule out the possibility that the bentonite clay surrounding the canisters will be eroded if the surrounding groundwater has too low salinity. During a future glaciation, the salinity on both sites could fall so low that this occurs, but this is less likely in Forsmark than in Laxemar, partly because the rock in Forsmark generally has lower permeability, and partly because fewer deposition holes are intersected by water-conducting fractures. If the bentonite clay in the buffer disappears, the canister could be damaged after a very long time due to corrosion caused by the sulphide dissolved in the groundwater. The corrosion rate, and thereby the number of canisters that would be damaged, is dependent on the groundwater flow. In the case of Forsmark, analyses show that the groundwater flow in most deposition holes is so low that only a few canisters could be damaged, and only after more than a hundred thousand years. The much higher flows in Laxemar mean that considerably more canisters may be damaged, and that this could occur earlier.

These differences in potential for canister damage have a great impact on the overall risk calculations for the final repository. In the case of Forsmark, the calculations show that the quantitative limit value for annual effect dose stipulated by the Swedish Radiation Safety Authority (the so-called risk criterion, see Section 2.2) is met with a margin of roughly two powers of ten. The outcome for Laxemar is much worse. This does not necessarily mean that a safe final repository cannot be achieved in Laxemar, but this would require changes in layout and design that could be difficult to to achieve in practice.

Technology for execution

Both sites are deemed to offer the necessary conditions for building and operating a final repository designed in accordance with current design premises. Comparisons have different outcomes for different siting factors, but the overall judgement is made that Forsmark offers better prospects. The main reason is that the rock conditions in Forsmark offer a much lower risk that extensive remedial measures will be needed beyond what is planned. It is therefore easier to achieve a repository in practice at Forsmark.

The rock-related technical execution risks that do exist in Forsmark are linked to the occurrence of relatively high horizontal rock stresses. It is, however, deemed unlikely that this would have great consequences for the availability of usable deposition positions.

The uncertainties for Laxemar are greater and pertain to the availability of deposition positions with acceptably low inflows and the necessary conditions for building deposition tunnels that meet the tightness requirements. Considerable changes in repository layout are judged to be necessary in order to deal with these problems. Furthermore, there is a need for continued development of methods to seal the rock to the extent that would be required.

The rock conditions in Forsmark offer significant advantages in terms of efficiency as well. The reason is that a repository in Forsmark can be made much smaller and more compact than is possible in Laxemar. This is in turn essentially due to the fact that the higher thermal conductivity of the rock in Forsmark permits denser canister spacing and thereby a smaller total deposition area. The smaller volumes are reflected in lower transport needs, material consumption, labour needs etc, which taken together result in a more efficient execution of the project.

The differences in rock conditions, material consumption, transport needs etc mean that a repository in Forsmark would be about SEK 4.5 billion, or 15%, cheaper than a repository in Laxemar. Even though the calculation contains uncertainties, they are not great enough to alter the assessment that the costs of a repository in Forsmark would be lower than in Laxemar.

If external factors that affect execution are instead taken into account, the outcome of the comparison is in Laxemar's favour. One reason is that SKB's existing facilities and the large scope of the activities in Oskarshamn would provide synergies, particularly in the initial phase of the final repository project. Another reason is that with a final repository in Laxemar, the entire handling chain for the spent nuclear fuel would be gathered at one place in the country. Besides efficiency gains, this would result in a lower degree of external dependency. The clearest advantage relative to Forsmark is that the need for sea transport of encapsulated fuel from the encapsulation plant is eliminated. The extra cost this entails for Forsmark is marginal, but the longer transport chain to Forsmark nevertheless constitutes a possible source of operational disturbances.

Environment and health

With respect to environmental and health issues, SKB finds that both of the sites are suitable alternatives for the final repository. The prospects for passenger and goods transport are equivalent. In other respects there are clear differences, but it is nevertheless difficult to rank the sites. The reason is that the environmental consequences of an establishment differ in type rather than degree.

Forsmark is characterized by a sensitive natural environment with high conservation values. A far-reaching adaptation to these conditions is necessary and possible, but some intrusion in the natural environment is nevertheless unavoidable. The cultural environment and the human residential environment in the environs of the final repository would, however, be very marginally affected, since so few people live in the area.

The situation in Laxemar is the reverse. The impact on the natural environment is judged to be very limited. Of greater importance is the fact that people live and work in the Laxemar area, and have done so for a long time. Privately owned land and land-based industries are important features of the picture. An establishment will entail a change in land ownership, but does not have to entail a significant change in land use. Establishing a new large-scale industrial activity quite different from that which characterizes the area nevertheless entails an intrusion and requires adaptation.

The conclusion is that both sites are suitable siting alternatives with respect to environmental and health issues. Regardless of site, the final repository project can and should be adapted to the local environment. The natural resources that will be consumed by the final repository project are marginally affected by site selection. Thus, environmental and health issues have not influenced the choice between Forsmark and Laxemar.

Societal resources

In preparation for the selection of sites for site investigations, SKB made the judgement that both Oskarshamn and Östhammar municipalities are satisfactory alternatives with respect to the societal prospects for executing the final repository project. The in-depth knowledge that has been accumulated since then has not altered this judgement. It is also difficult to imagine any changes in the local communities that could adversely alter this assessment. On the contrary, interest in the final repository seems to have been gradually strengthened during the site investigation phase in both municipalities.

Accordingly, there are no societal factors that could seriously hamper an establishment in either of the municipalities. What then remains to take into account are what local resources are available and how this can affect the efficiency of the establishment. SKB's conclusion here is that the differences that can be foreseen with regard to local supplier capacity, human resources recruitment etc are not sufficiently important to influence site selection.

7.5.2 Conclusion

The strategy established by SKB for choosing between the siting alternatives Forsmark and Laxemar was formulated in the following two points:

1. The site that offers the best prospects for achieving long-term safety in practice will be selected.
2. 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 be the most favourable from other aspects for accomplishing the final repository project will be selected.

The background and reasons for this strategy are presented in the report's introductory chapter (Chapter 1).

The analyses and comparisons of the sites that have been done, and that are summarized in Sections 7.1 through 7.4, have, in SKB's opinion, provided the information that is required to apply this strategy. SKB's conclusion is that Forsmark is the site that clearly offers the best prospects for achieving long-term safety in practice. In keeping with the first point in the strategy, SKB has therefore chosen to locate the final repository at Forsmark. The rock conditions in Forsmark also offer prospects for a more robust and efficient execution of the final repository project than in Laxemar.

The individual factors that contribute most to Forsmark's advantages are the great differences in frequency and permeability of water-conducting fractures. These differences have a clear impact in the comparative safety evaluations /SKB 2010b/. There are also clear differences with respect to the adaptations and technical measures that would be required to achieve a repository that satisfies the relevant design premises /SKB 2009a, d/.

The industrial prospects for establishing and operating the final repository in a satisfactory manner are judged to be very good at both sites. The differences that do exist cannot be accorded any decisive importance for site selection. The same applies to the environmental impact which the project will cause.

The selection of a site for the final repository is a decision that entails considerable commitments for the nuclear fuel programme. It is then important to minimize the risk of making a decision that later turns out to be wrong. The site investigations and the subsequent analyses have therefore been carried out with a high level of ambition in order to achieve sufficiently good site understanding. SKB considers that the body of data that has been accumulated has permitted a well-founded choice. Of crucial importance for this judgement is that both sites are thoroughly investigated, that the comparative analyses that have been made of the prospects for achieving long-term safety have arrived at clear outcomes, and that the site is judged to be suitable in itself. What remains are uncertainties that can only be reduced by obtaining access to underground openings for investigations. The knowledge that is then obtained will in all likelihood require further modification of the repository's layout, but not to an extent that is expected to fundamentally affect the assessment of the suitability of the site.

8 The siting in a national perspective

Chapters 3 through 7 have described and explained the reasons for the investigations, analyses, prioritizations and decisions that have led up to the selection of Forsmark as the site for the final repository for spent nuclear fuel. This chapter explains the reasons for SKB's conclusion that there is no other site that is obviously better than the selected one and that can be made available with reasonable labour inputs.

8.1 Background

The Environmental Code's general rules of consideration state as a general siting requirement that a site shall be selected that is suitable in order to achieve the purpose of the activity with a minimum of damage or detriment to human health and the environment (see Chapter 2). The requirement of minimum damage or detriment means that there may not be any other site that is available and that offers obviously better prospects on comparison. According to the general rules of consideration, these requirements shall be weighed against the requirement that the labour input that is required to prepare the site shall be reasonable in relation to the benefit obtained. The purpose of the final repository is to protect human health and the environment from the harmful effects of ionizing radiation from the spent nuclear fuel, now and in the future. SKB has shown that the selected site, Forsmark, is suitable for this purpose /SKB 2011a/ and that disposal on this site can be achieved with very limited damage and detriment /SKB 2011b/.

Forsmark has been selected following a procedure that has included comparisons of sites and priorities in several steps, ranging from relative evaluations of a large number of siting alternatives in the feasibility study phase /SKB 2000g/ to the detailed comparative analyses of Forsmark and Laxemar that preceded the selection /SKB 2010b/. The comparisons have included all aspects of the siting, i.e. prospects for safety and execution plus environmental and societal aspects. Which individual factors have been evaluated at different stages, and how, has been adapted to the available body of data. In the case of some factors, it was possible to make both general and site-specific evaluations, as well as to rank the sites, in the final part of the feasibility study phase (cf. Section 4.4), since comprehensive and sufficiently detailed data for this was available. These factors include transport matters, land availability, natural and cultural environmental considerations and local societal aspects. The evaluations that were then made with respect to these factors indicated great advantages for the sites chosen for site investigations.

For other factors, investigations on the site are required in order to obtain data that permits reliable comparisons between the sites. This is particularly true of the geoscientific parameters, which have to be determined by investigation drilling to repository depth. Until such investigations have been done, evaluations of sites with respect to these parameters are based on the information that can be obtained from observations on the surface in combination with general knowledge. This is the main reason why SKB has striven for a broad geological selection pool at early stages of the siting work.

This dependence on data from drilling for reliable site evaluation means that sites where drilling has been done can be compared on a completely different level than is otherwise possible. With access to data from the site investigation in Forsmark, geoscientific properties that are essential for the suitability of Forsmark can thereby be evaluated (aside from the comparison with Laxemar) in comparison with corresponding properties on other sites where drilling has been done earlier. Comparative analyses for this particular purpose have been reported by /Winberg 2010/. The comparison material has largely consisted of results from the study site investigations that were conducted before the actual siting procedure for the final repository was started /SKB 2010a/ and that included extensive drilling.

The analyses include, where available data permit, those factors that are introduced in Chapter 6 under the heading “safety-related site characteristics” (see Figure 6-1), i.e.:

- Bedrock composition and structure
- Future climate
- Rock mechanical conditions
- Groundwater flow
- Groundwater composition
- Solute transport
- Biosphere conditions
- Site understanding

These characteristics are crucial for achieving a safe repository and are also of importance for its technical execution. The analyses reported by /Winberg 2010/ are necessarily general, since there are considerable differences between the body of data from Forsmark and the body of data that is available for comparisons. The differences include what parameters have been determined, investigation technology, the size of the areas that have been investigated and, above all, the level of ambition of the investigations, where the site investigations are unparalleled in Sweden. Data on biosphere conditions are lacking from the study sites, so this factor is not included in the analyses reported by /Winberg 2010/.

Important results from /Winberg 2010/ are summarized in the following sections, along with SKB’s comments and conclusions. In addition, supplementary analyses presented by /Ericsson and Holmén 2010/ regarding the importance of groundwater flow on a regional scale for the protective capability of a final repository are summarized and commented on.

The reported results and comments do not alter or influence the above conclusions concerning the suitability of Forsmark as a site for a final repository. The sole purpose is to provide an idea of the merits of Forsmark with regard to a number of safety-related siting factors, in relation to available knowledge concerning these factors from other sites. This may help to shed some light on the question of whether there may be another site that is obviously better than Forsmark, and that is available with reasonable labour inputs.

8.2 Comparisons with regard to safety-related site characteristics

8.2.1 Reference areas

Comparison material regarding safety-related site characteristics has mainly been taken from sites investigated during the period 1975–1985, see Section 3.2–3.3. Of the sites where borehole investigations were performed at this stage, data have been utilized from Sternö, Klipperås, Fjällveden, Finnsjön, Svartboberget, Gideå and Kamlunge, see Figure 8-1. The remaining two sites – Kråkemåla and Taavinunnanen – were excluded because the drilling done there was too limited to permit relevant comparisons with Forsmark. Äspö is also included in the comparison material. The sites that comprise reference areas thereby fulfil the following conditions:

- They have not been included in the selection pool within the site selection process and are thereby a source of fresh reference material.
- They represent several basement rock settings that are relevant in the context.
- They have been investigated with a number of cored boreholes (more than three) and have been subjected to borehole investigations to relevant depths.

For specific comparisons between Forsmark and Laxemar, see Chapter 7 and /SKB 2010b/. Certain data from Laxemar are presented below together with data from Forsmark and reference areas where this may be of special interest.

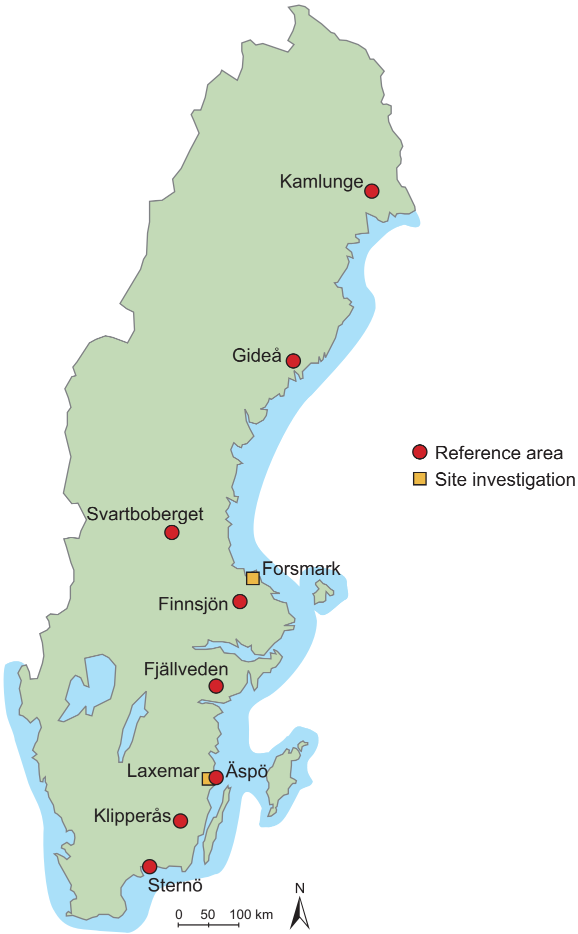

***Figure 8-1.** Locations of reference areas, and sites for site investigations.*

8.2.2 Bedrock composition and structure

The implications, direct and indirect, of the bedrock composition and structure on the safety of the repository is described in Section 6.2.1. Comparisons with reference areas regarding the thermal conductivity of the rock, the frequency of open fractures and the possibility of repository adaptation to major deformation zones are presented below.

Thermal conductivity of the rock

The thermal conductivity of the rock is determined by its mineralogical composition, particularly its quartz content, and is of crucial importance for the minimum spacing required between deposition positions to meet temperature requirements for the buffer. In other words, it is an important parameter in designing the repository to meet the safety requirements.

Figure 8-2 shows mean values and approximate ranges of variation in the results for thermal conductivity, based on laboratory measurements, for sites where data are available. In the case of Forsmark and Laxemar, values have been calculated for identified rock domains. In the case of Forsmark, the values roughly agree with those for the study sites, all of which have rock of mainly granitic composition. According to Section 7.2.1, the coefficients of thermal conductivity for Forsmark and Laxemar give canister spacings of 6.0–6.8 m and 8.1–10.0 m, respectively. Thus, the difference in thermal conductivity has considerable consequences for the design of the repository.

Open fractures

The occurrence of open fractures has a direct and indirect influence on safety in a number of respects, see Section 6.2. Large and/or water-conducting fractures can prevent deposition positions from being utilized. Groundwater movements in the rock take place via open fractures, which is why the fracture situation is of crucial importance for the long-term function of the engineered barriers.

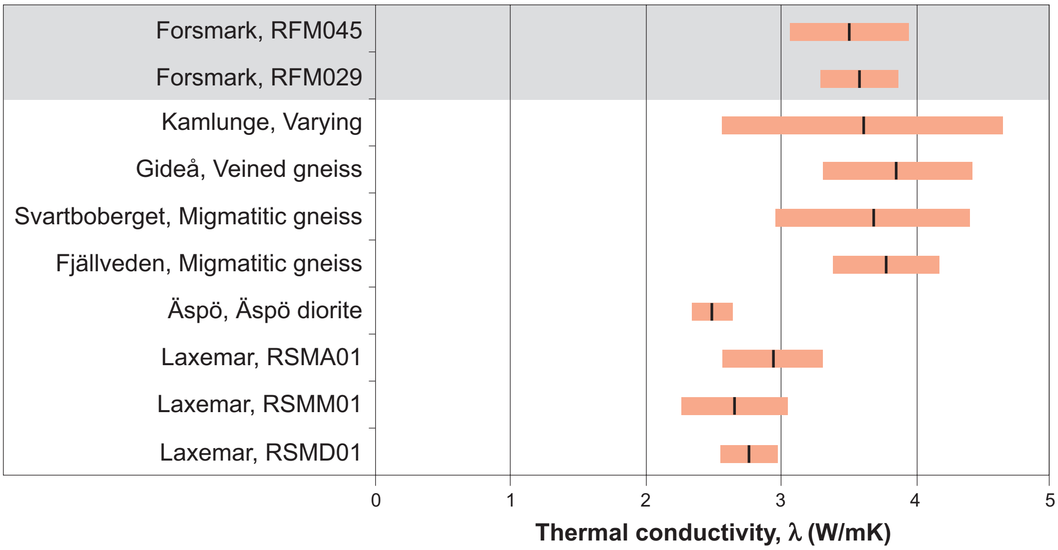

Figure 8-2. *Data on thermal conductivity from Forsmark, Laxemar and reference areas (see /Winberg 2010/ for references).*

By "open fractures" is meant here fractures that split the drill core and that are not judged to be caused by drilling or other handling. They may be coated with fracture-filling minerals and they have the potential to conduct water. Data on the frequency of open fractures in the depth range 400–700 m from Forsmark, Laxemar and reference areas have been compiled by /Winberg 2010/. The results are summarized in Table 8-1. Reported fracture frequencies apply to the rock mass between identified deformation zones (in the case of mapped sections marked as "crushed zone" or "core loss", a fracture frequency of 50 fractures/m has been assumed).

Data have been taken from different sources, and there are differences in the methods used for investigation, data processing and evaluation that to some extent influence the comparability of the calculated fracture frequencies. But even with this reservation, the inescapable conclusion is that Forsmark exhibits a very low frequency of open fractures at repository depth in relation to other investigated sites. The only reference area with a comparable fracture frequency is Sternö. The frequency of open fractures is roughly a factor of 3–12 higher for other reference areas and Laxemar than for Forsmark.

Table 8-1. Frequency of open fractures in the rock mass between deterministically modelled deformation zones, within the vertical depth interval 400 m to 700 m (for borehole designations, calculation methods and sources, see /Winberg 2010/).

Area	Fracture frequency (open fractures metres)
Forsmark	0.6
Kamlunge	2.5
Gideå	3.6
Svartboberget	2.4
Finnsjön	6.8
Fjällveden	1.6
Klipperås	4.1
Sternö	0.8
Äspö	3.4
Laxemar	3.1

Repository adaptation

According to the criteria for facility design applied during the site investigation phase, a minimum distance of 100 metres is required between deposition areas and deformation zones with an interpreted length greater than 3 km. Based on this criterion, the layout of Forsmark has been adapted to four deformation zones, one of which divides the repository area into two deposition areas, see Figure 5-7. In the case of Laxemar, adaptation to several zones has been necessary, and the repository area has been divided into three deposition areas, see Figure 5-13. No layout work has been done for the reference areas with comparable assumptions regarding repository size and criteria for adaptation to zones. However, an rough assessment can be made that none of the reference areas has so few major deformation zones as to make it unnecessary to divide the repository into two or more deposition areas. More detailed comparisons are not meaningful, however.

Conclusions

The rock in Forsmark, as at many other places, has good thermal conductivity, which facilitates the design of the repository. Comparisons with reference areas verify the perception that Forsmark is characterized by a very low frequency of open fractures. This has a number of essential advantages with respect to long-term safety. Furthermore, Forsmark has been shown to offer good flexibility for adapting the repository to major fracture zones. More favourable conditions could hypothetically be a site where the repository area is not intersected by any deformation zones that require division into several deposition areas. However, available data do not suggest that such a site exists. It is furthermore doubtful whether this would provide any significant advantages.

In summary, comparisons with reference areas do not indicate conditions that could make any of these areas obviously better than Forsmark with respect to the studied factors pertaining to rock composition and structure.

8.2.3 Future climate

The possible impact of the evolution of the climate on the safety of the repository is summarized in Section 6.2.2. The geographic variation of the climate in Sweden is mainly governed by latitude and altitude. It is difficult to evaluate what these geographically related differences in climate could mean for a final repository in general terms, since the effects of the climate are closely related to site-specific rock and groundwater conditions. /Winberg 2010/ has reported comparisons with reference areas, based on the assumed climate evolution that constitutes SKB's reference scenario for SR-Site and the assumption that relative differences between different places will continue to exist even during a future glacial cycle. The comparisons relate to maximum permafrost depth, maximum ice thickness during a future glaciation and the length of periods when the site lies beneath the sea. This latter factor influences the salinity of the groundwater. Since analyses that integrate the effects of climate and local rock and groundwater conditions have not been done for the reference areas in the same way as for Forsmark and Laxemar, the comparisons are mainly qualitative.

Permafrost

During periods with permafrost, the duration and depth of the permafrost are generally greater towards the north and less towards the south. Other parameters also affect permafrost depth, such as the thermal conductivity of the rock. Based on the reference scenario for climate evolution, the permafrost in Forsmark is expected to reach down to 260 m and in Laxemar to 160 m /SKB 2010b/. The permafrost will only have a significant impact on safety if it reaches down to the repository so that the buffer freezes, which occurs at about –4 C. This will not happen at either Forsmark or Laxemar, not even if very pessimistic assumptions are made concerning climate evolution. In the case of more northerly sites, greater repository depth is probably required in many cases to avoid freezing with certainty. The disadvantages of greater repository depth, if any, are dependent on local rock conditions.

Glaciation

Glacial cycles have an extensive impact on loads and groundwater conditions, even at repository depth. The duration of the glaciation and the thickness of the ice sheet are dependent on the geographic location. The more northerly location of Forsmark means that glaciations will have greater duration and the ice sheet will be thicker than in Laxemar. The comparative calculations that have been done for Forsmark and Laxemar show that the differences with respect to groundwater pressures and pressure gradients that drive groundwater flow do not have a significant impact on an integrated evaluation of safety. Differences in how the glacial cycle affects the chemical composition of the groundwater can have greater effects.

The maximum groundwater pressure at repository level during a glaciation is proportional to the maximum thickness of the ice sheet. For the different climate evolutions for Forsmark that are analyzed in SR-Site, /SKB 2011a, Section 12.7/, the conclusion is drawn that this pressure could amount to about 35 MPa. Adding the swelling pressure from the buffer, yields a maximum pressure on the canister of nearly 50 MPa. More northerly sites or inland sites give higher pressures, since the ice thickness will be greater there. However, the site differences are small compared with the uncertainties in such predictions. A highly conceivable value for the thickness of a future ice sheet is, however, believed to be the maximum ice thickness that has been measured today in Antarctica, which is about 4,500 m. This would be equivalent to a total pressure on the copper canister of about 60 MPa. Even this extreme value is well below the pressure the canister has been calculated to withstand (90 MPa).

Periods beneath the sea

The fact that the site for the final repository is beneath the sea is positive for safety, since it counteracts the penetration of fresh water from precipitation or deglaciation to repository level, which could otherwise have an adverse effect on the function of the barriers, see Section 6.2. Site differences when it comes to the extent of the future sea cover are affected by altitude, but also by geographic differences in the thickness and duration of the glacial ice sheet. This latter factor affects the depression of the bedrock during glaciation and the subsequent post-glacial land uplift. The parts of the country situated above the highest coastline have not been beneath the sea for any period during or after the last ice age. Data on the composition of the groundwater from sites situated above the highest coastline show a markedly greater presence of surface water with low salinities that has penetrated to greater depths than data from sites below the highest coastline. This could entail considerable disadvantages for sites situated above the highest coastline.

Conclusions

The future evolution of the climate is important in many respects for the long-term safety of the final repository. The outcome of different scenarios for climate evolution during the next 100,000 years is closely connected to rock and groundwater conditions on the repository site. Geographically related differences in climate are as such of minor importance, as long as critical limits are not exceeded. This includes, for example, the effects of differences in permafrost depth and ice sheet thickness during expected future glacial cycles. Groundwater composition exhibits geographic variations that are of great importance for the safety of the final repository. These variations are to some extent related to differences in climate, but are to an even higher degree related to height above sea level. These questions are discussed in 8.2.7.

All in all, Forsmark has a favourable location with respect to climate factors, something which is also true of Laxemar and large parts of the rest of the country. There is nothing to suggest that there are sites which, in relation to Forsmark, would offer essential advantages related to differences in expected climate evolution.

8.2.4 Rock mechanical conditions – rock stresses

Rock mechanical conditions influence both the long-term safety of the repository and its technical execution, see Sections 6.2.3 and 6.3.2. As regards long-term safety, two aspects in particular must be taken into account. One is the possible instability of the rock nearest deposition holes and deposition tunnels due to local overloading (spalling). The other is possible movements in fractures or fracture zones in conjunction with future earthquakes. Stability questions linked to local conditions around deposition openings are dealt with here. Earthquakes and their possible consequences are discussed in the following section.

Strength

The stability of underground openings is generally determined by the strength- and deformation properties of the rock, the loads (the rock stresses), and the geometry of the excavated openings. According to the extensive tests that have been done, the rock types that dominate at repository level in Forsmark have strengths that can be described as normal to high in relation to both the scanty strength data available from the reference areas of Gideå, Finnsjön and Sternö /Winberg 2010/ and general data for granitic rock types.

The mechanical properties of the rock mass on a larger scale are also dependent on the fracture situation. In the case of Forsmark, the low occurrence of open fractures contributes to a rock mass with high strength and favourable properties for rock construction. This is clearly evident from the predictions that have been made of the need for rock support in the underground openings in the final repository /SKB 2009a/.

Rock stresses

During the site investigation at Forsmark, a number of methods were used to obtain knowledge on the rock stresses. This means that an extensive body of data is available, but also that uncertainties remain due to limitations in available measurement methods. The measurements indicated relatively high rock stresses, which means that the state of stress is of great importance for the design of the repository. Intensive interpretation efforts have therefore been devoted to obtaining the best possible prediction as a basis for designing the repository and evaluating the possible consequences of the remaining uncertainties /Martin 2007/. Interpretations and results are summarized in Section 7.1.3.

Of the reference areas, only Äspö has been subjected to rock stress measurements to any great extent. There it has also been possible to conduct investigations from underground openings. Data from other areas are restricted to limited and somewhat uncertain measurements in Gideå and Finnsjön /SKB 2010a/. A better basis for comparison than the scanty measurement results from the reference areas can be obtained from databases that gather many of the results of rock stress measurements in the Scandinavia countries, among other places. Figure 8-3 shows data for the maximum and minimum horizontal stress components, along with the best interpretations for Forsmark according to /Martin 2007/ (cf. also Figure 7-1). Background data have been taken from a database that includes measurement results from Sweden, Norway and Finland up to around 1986 /Stephansson et al. 1991/, plus most of the measurements done in Sweden after that time (including data from the reference areas and Laxemar).

It should be pointed out that background data are by no means free of error. Examples of sources of error are deficiencies in measurement methods or the fact that the stress field where the measurements were made may have been affected by nearby excavations, something which is common in e.g. mines. But if individual measurement points are disregarded and the data are regarded as a whole, a good idea is obtained regarding normal values and ranges of variation for the horizontal stresses in Scandinavia bedrock.

A comparison with the interpretations for Forsmark then shows the following:

- The maximum horizontal stress, σ_H, in Forsmark is clearly higher than the average for the background data, but falls within the range of variation.
- The minimum horizontal stress, s_h, in Forsmark is also higher than the average, but not to the same degree as σ_H.

Figure 8-3 does not show any stress directions or vertical stresses, but the directions observed in Forsmark agree well with the general trends for all of Scandinavia. The same applies to the magnitudes of the stresses in a vertical direction /Martin 2007/.

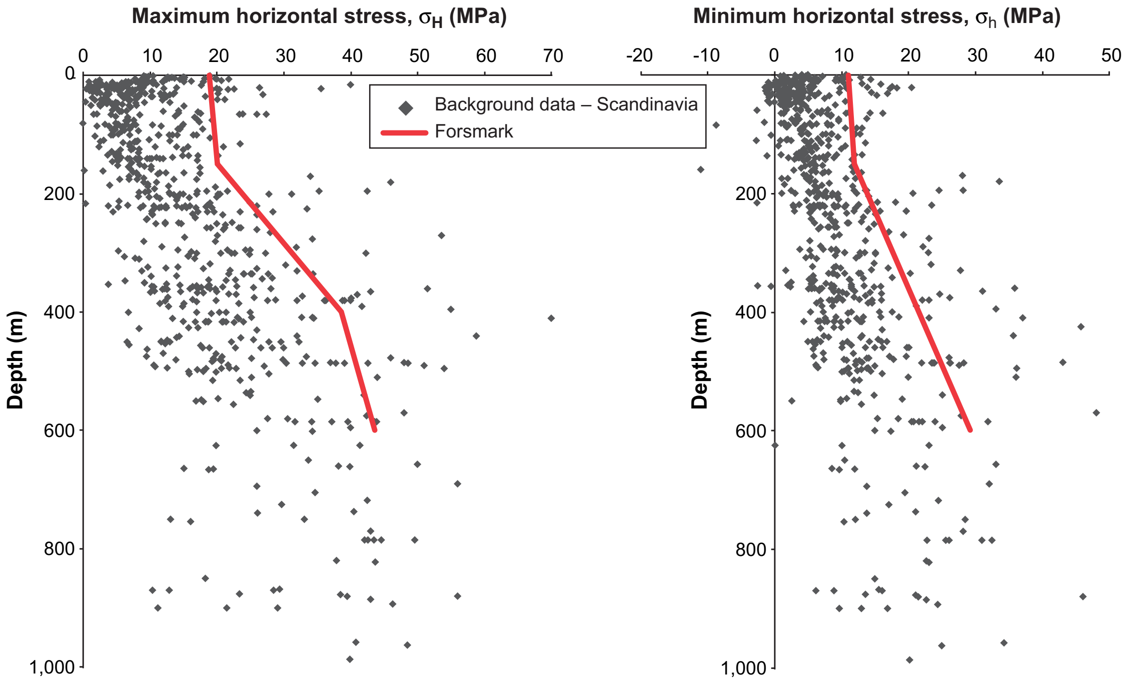

Figure 8-3. *Maximum and minimum horizontal stress as a function of depth /Winberg 2010/. Background data represent measurements in Scandinavia. Data for Forsmark (solid red line) are represented by summarizing interpretations according to /Martin 2007/.*

The conclusion is thereby that Forsmark is distinguished by high – but not uniquely high – horizontal stresses, and otherwise normal stress conditions. It is these conditions which, in combination with additional thermal loading, can give rise to overloading and spalling around deposition holes, requiring adaptation of the repository layout. This is dealt with in Sections 7.1.3 and 7.2, and in greater detail in /SKB 2010b/.

Considering the geological conditions in Forsmark, the occurrence of high rock stresses at great depths is not surprising. The bedrock inside the tectonic lens where the repository is planned to be located is characterized by relatively stiff and high-strength rock types, but above all by a low frequency of open fractures (cf. Table 8-1), which taken together make for a rock mass with high stiffness. Experience from mines and hard rock facilities in various locations around the world show that bedrock with a low frequency of open fractures and high stiffness in relation to its environs tends to have elevated stress levels. The generally accepted theoretical explanation is that when a material with locally varying stiffness is subjected to an external load, the transfer or load inside the material will be distributed so that parts with high stiffness transfer higher loads than parts with lower stiffness. This agrees well with the situation in Forsmark. The correlation that has been demonstrated between fracture frequency (fracture domains) and stress levels within the investigated rock volume also supports this explanatory model.

Conclusions

The elevated rock stresses documented in Forsmark entail disadvantages in the form of special requirements on adaptation of the layout of the repository in order to avoid overloading around deposition tunnels and deposition holes. The possibility that overloading and spalling will occur can nevertheless not be entirely dismissed. It is also clear that there are sites where these risks are less pronounced or non-existent due to lower stresses.

The rock stresses and their possible consequences must, however, be evaluated as a part of the overall geological conditions in Forsmark. There is support for the conclusion that the elevated stresses are directly related to the distinguishing characteristics of the rock, especially the low frequency of open fractures at depth. These characteristics afford several essential advantages, the most important being that there are few fractures that can conduct water, which is of crucial importance for the prospects of achieving long-term safety (see Section 7.1). Construction and operation are also facilitated, e.g. due to small needs for rock support and sealing during tunnelling.

In an integrated evaluation, elevated rock stresses can be seen as the "price" that is to be paid for bedrock with crucial beneficial properties in other respects. Since the problems that follow from the rock stresses can be handled by adapting the layout and design of the repository and the uncertainties that remain after these measures are judged to be small, this is not, all things considered, a disadvantage for Forsmark in relation to other sites.

8.2.5 Rock mechanical conditions – earthquakes

Movements in conjunction with major future earthquakes could possibly damage the integrity of individual canisters and thereby cause releases of radionuclides. The frequency of earthquakes is today, and has historically been, low in Sweden. The earthquakes that do occur are geographically unevenly distributed and their magnitudes are low, with few exceptions < M3.5 /SKB 2010b/. Considerably larger earthquakes, probably M8-9, occurred in northern Sweden in conjunction with the retreat of the last glacial ice sheet. No traces of similar earthquakes have been found in the investigations conducted in conjunction with the site investigation in Forsmark /SKB 2008a/. During the next million years, when several ice ages are expected, one or more quakes with a magnitude of 5 or more can, however, be expected to occur.

The methodology that has been developed to adapt the layout of the repository to these possible movements is outlined in Section 7.1.3 and described in detail in /SKB 2010b/. This methodology has been applied in designing the repository layouts for Forsmark and Laxemar, in both cases with the result that the risks that canisters could be damaged by movements in conjunction with earthquakes are very small and comparable for the two sites.

Conclusions

The Forsmark region exhibits a low frequency of earthquakes, and it has not been possible to find the traces of any major earthquakes since the last deglaciation more than 10,000 years ago. This does not mean that the possibility of major earthquakes can be completely ruled out, either in Forsmark or at other sites. The repository must therefore be designed so that major deformation zones are avoided, along with canister positions with a potential for secondary movements in fractures that could damage canisters. This has been done for Forsmark with good results.

In general, the differences in observed earthquake frequency between different parts of the country cannot be used as a basis for ranking regions or sites with respect to suitability for a final repository. Local conditions and how the repository is adapted to them is of crucial importance. The documented occurrence of major earthquakes at the time of the retreat of the ice sheet in northern Sweden could possibly be regarded as a disadvantage for this region, in relation to southern Sweden.

8.2.6 Groundwater flow

The factors that control groundwater flow and how they affect the safety of the repository are summarized in Section 6.2.4, while conditions in Forsmark and Laxemar are compared in Section 7.1.4. In the sections that follow, a comparison is first presented of borehole data on the hydraulic conductivity of the rock mass in Forsmark with data from reference areas. This is followed by a summary of the discussion previously carried on between SKB and the regulatory authorities (then SKI and SSI) regarding the possible importance of groundwater flow on a regional scale for the siting prospects for the final repository, based on supplementary analyses performed on SKB's behalf.

Hydraulic conductivity

/Winberg 2010/ has compared data on the hydraulic conductivity of the rock mass from the site investigations in Forsmark and Laxemar with equivalent data from investigations of reference areas at earlier stages. The comparison bears similarities to the analysis of fracture frequency in Section 8.2.2: it concerns the depth interval 400–700 m and is limited to the rock mass between identified and deterministically modelled deformation zones. The parameter studied is hydraulic conductivity at approximate repository depth and in the part of the rock where canisters could be placed in a hypothetical repository.

Comparative data on hydraulic conductivity for Forsmark, eight reference areas and Laxemar are presented in the same graph in Figure 8-4. The data are from injection tests on a measurement scale of 20–25 m. The curves in the figure show cumulative distributions, i.e. the percentage that can be read for a given conductivity value indicates the fraction of the measurements on the site that have yielded conductivities less than this value. Note also that the scale for hydraulic conductivity is logarithmic.

The distributions in Figure 8-4 represent measurements made over a period from the late 1970s (Sternö, Finnsjön) to the site investigations in 2002–2008. The measurement technology was developed considerably during this period, particularly with regard to measurement limits. What this means for the data processing and the comparability of the distributions in Figure 8-4 has been evaluated by /Winberg 2010/. Two effects should be observed: One follows from the fact that the lower measurement limits in the earliest measurements were considerably higher (in other words poorer) than in later measurements. The effect is that the distributions for the earliest investigated sites – Sternö and Finnsjön – are shifted to the right relative to the other ones (since low conductivities could not be registered). Sternö and Finnsjön can therefore not be compared directly with other sites, with the possible exception of the uppermost percentiles of the distributions (high conductivities). This also explains Sternö's apparently high conductivities, despite a documented very low frequency of open fractures able to conduct water (cf. Table 8-1). The other effect is that differences in measurement limits can to some degree also affect distributions for other sites, but then limited to very low conductivities, i.e. the parts of the distributions at the bottom left in Figure 8-4. This is less important in this context, since it is the occurrence of much higher conductivities (at the top right in the figure) that sets the limits for the suitability of the rock.

With these reservations, it can be concluded that Forsmark exhibits a distribution that corresponds to very low conductivities, and above all a very low fraction of measurement sections with high conductivity. The distribution for Kamlunge is for the most part nearly identical to that for Forsmark, and Gideå, Svartboberget and Fjällveden also conform to the same trend. Klipperås and Laxemar exhibit a completely different type of distribution, with conductivities evenly distributed over a wide range. Finally, Äspö conforms to Klipperås and Laxemar at conductivity values greater than 10^{-9} m/s, but not otherwise.

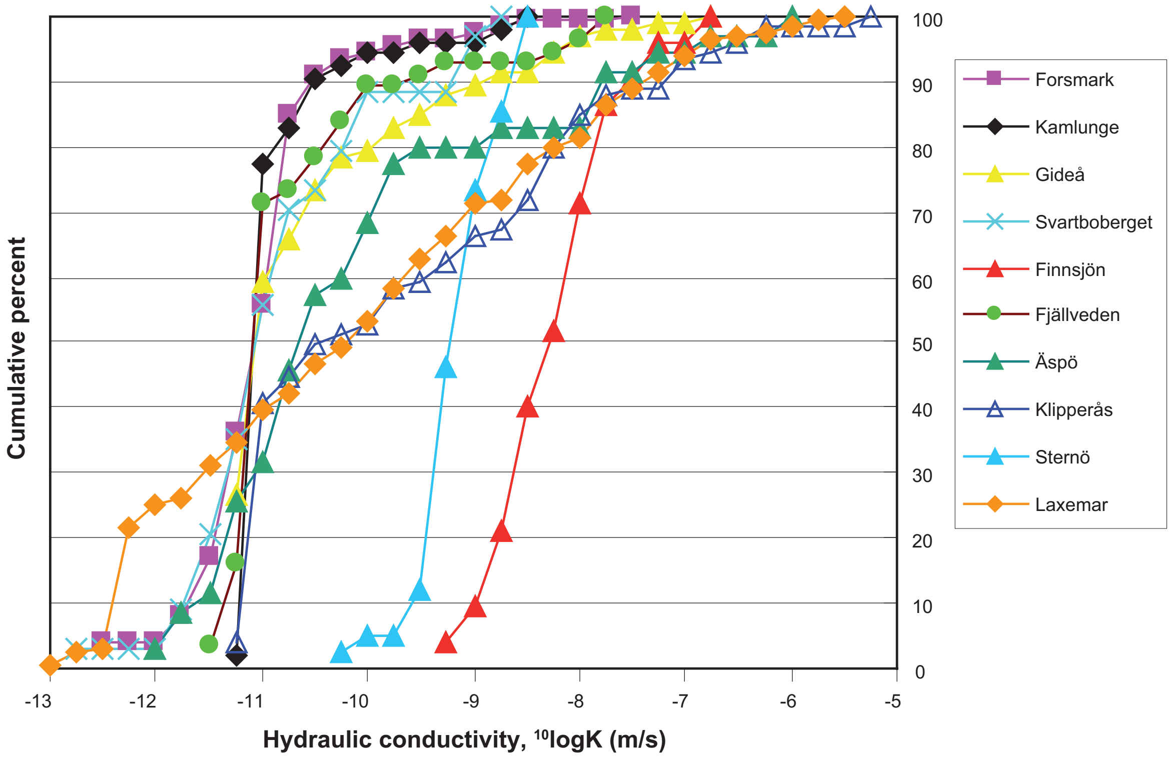

Figure 8-4. *Cumulative distributions for measured hydraulic conductivity (K) on a scale of 20–25 metres, for Forsmark and reference areas. The data represent the rock mass between deterministic deformation zones in the depth interval 400 to 700 m.*

Table 8-2 shows the comparison from another viewpoint. The table shows the number of data for each site and the percentage of conductivity values ≤ $3 \cdot 10^{-10}$ m/s (Sternö and Finnsjön have been excluded for the reasons given above). The value $3 \cdot 10^{-10}$ m/s has been chosen because it can be linked to the acceptance criterion for water seepage into deposition holes. The maximum permitted inflow to a deposition hole is 0.1 L/min /SKB 2009e/. This is equivalent to a fracture transmissivity of $3 \cdot 10^{-9}$ m^2/s /Smith et al. 2009/, which can be roughly translated to a hydraulic conductivity on a ten-metre scale (equivalent to the deposition hole) of about $3 \cdot 10^{-10}$ m/s. The percentage of measurement results ≤ $3 \cdot 10^{-10}$ m/s can thus be roughly assumed to correspond to the percentage of the rock mass that satisfies the criterion and can thereby be utilized for deposition, i.e. the degree of utilization. In the case of Forsmark and Laxemar, this gives estimated degrees of utilization of 97% and 63%, respectively (solely with respect to inflow into deposition holes and without respect to sealing measures). These values are on a par with the degrees of utilization that have, according to Section 7.2.2, been calculated based on the site models and the site-adapted repository layouts. The estimates should then provide reasonable values of the degree of utilization for reference areas as well.

Table 8-2. Hydraulic conductivity – number of data and percentage of results ≤ $3 \cdot 10^{-10}$ m/s (measurement scale 20–21 m).

Site	Number of data	Percentage of results ≤ $3 \cdot 10^{-10}$ m/s
Forsmark	151	96.7
Kamlunge	53	96.2
Gideå	93	85.0
Svartboberget	34	88.2
Klipperås	74	59.5
Fjällveden	56	91.1
Äspö	35	80.0
Laxemar	172	62.8

Conclusions – hydraulic conductivity

Comparisons of Forsmark with reference areas with regard to the hydraulic conductivity of the rock mass at repository depth and the fraction of the rock that is judged to be able to be utilized for deposition show that conditions in Forsmark are either better than or comparable to conditions in the reference areas. There is nothing to suggest that any other site could offer substantially better conditions than Forsmark with respect to these factors.

Regional groundwater flow

In the feasibility study phase of the siting work, the advantages and disadvantages of locating the final repository in northern versus southern Sweden, as well as on the coast versus inland, were examined /Leijon 1998/. The conclusion was that these geographical factors do not have any decisive importance and that assessments of suitability must instead be based on knowledge of local conditions. One aspect of locating the repository on the coast versus inland has since been further discussed and subjected to analyses. This concerns whether long flow paths (and long retention times) for groundwater from inland locations can offer advantages from a safety viewpoint by contributing to retardation of radionuclides, and if so whether this could be exploited in siting.

In 2005, based on earlier studies and the regulatory authorities' viewpoints on the results, SKB initiated a large modelling project to shed light on these matters /Ericsson et al. 2006/. The study was aimed at evaluating conceptual simplifications and uncertainties in the modelling of groundwater flow on a regional scale, and analyzing regional flow conditions in eastern Småland.

The results of the model analyses improved our understanding of the groundwater flow pattern on different scales and how the flow pattern is theoretically affected by a number of important system characteristics. One conclusion was that most of the groundwater circulation that has to do with repository depth takes place within local flow cells. The fraction of supraregional flow cells was very small, according to the study. The pattern of dominance of circulation on a local scale was strengthened with increased conceptual complexity in the system description which the models represented.

Statistical differences in hydraulic conductivity between different rock types were simulated in the study. The results showed that favourable flow conditions (small flows, long breakthrough times) tend to correlate geographically with rock types with low conductivity. However, it was also pointed out that permeability on a local scale can in reality vary within wide limits, and that the groundwater flow is heavily dependent on these variations. For individual sites, it was judged that this could influence the size and distribution of the flow to a much greater degree than the variations of system parameters that were analyzed in the study. This was an important reason why the study was not considered to permit any conclusions to be drawn regarding the groundwater flow on individual sites. For SKB's part, the study yielded valuable knowledge of the importance of different system parameters for groundwater flow, but it did not alter previous conclusions regarding the importance of regional groundwater flow from a siting viewpoint.

The study, which was reported by /Ericsson et al. 2006/, was reviewed jointly by then SKI and SSI, and more thoroughly by SSI /Dverstorp 2007/. The review lent support to the contention that the work had contributed to a better scientific understanding of the influence of different factors on the flow pattern. At the same time, the review pointed out that the consequences of a number of assumptions and model simplifications were inadequately studied, and that the evaluation of certain results was incomplete. SSI /Dverstorp 2007/ therefore concluded that the study ought to be supplemented in the following respects prior to SKB's planned licence applications:

- Further investigate the significance of assumptions and model simplifications to strengthen the credibility of the calculation results. This includes the influence of model depth, topography, location of the groundwater table, boundary conditions for the sides of the model, discretization, representation of geological structures and determinations of flow paths, which can be suspected of influencing the proportion of calculated long transport pathways and travel times.
- Further develop the statistical evaluation of the model calculations in order to be able to draw more reliable conclusions, including a discussion of the completeness of analyzed conceptual model descriptions and of significant local site characteristics that can be identified from available data.
- Illustrate to what extent site-specific differences in the groundwater's flow pattern, expressed in a number of hydrogeological parameters such as the length and travel times of the transport pathways, influence the results of the safety assessment.

Supplementary studies have been conducted on behalf of SKB with regard to the above points /Ericsson and Holmén 2010/. Sensitivity analyses have been done to illustrate how stipulated model assumptions, boundary conditions etc can affect the conclusions drawn at earlier stages. In summary, these factors do not influence the results enough to alter the general conclusions presented previously in /Ericsson et al. 2006/. Complete analyses and results are presented in /Ericsson and Holmén 2010/.

The supplementary sensitivity analyses also permit a better evaluation of the completeness of the analyzed model calculations. None of the analyzed variation cases resulted in changes of calculated travel times in excess of 10–20 percent. Furthermore, the statistical distribution of flow paths within specific areas was studied in greater detail. Even in areas that generally have more favourable travel times, mainly due to assumed low water permeability, the variation in breakthrough times is extremely large due to the local variation of permeability. There can be a considerable range of variation in the properties of the flow paths within an area. It is therefore not possible to say anything about the distribution of transport pathways from a given area based on a flow analysis of a large area and only general knowledge of the magnitude of the permeability in different areas.

Conclusions regarding how site-specific differences in the groundwater's flow pattern, expressed in a number of hydrogeological parameters such as the length and travel times of the transport pathways, influence the results of the safety assessment can be obtained from sensitivity analyses done in different safety assessments, most recently SR-Site /SKB 2011a/. The most important risk-affecting factors are presented in SR-Site /SKB 2011a, Table 13-13/. They include the specific groundwater flow around deposition holes and the groundwater flow in the rock, expressed as transport resistance. The transport resistance is correlated to the groundwater's travel times (which are dependent on the length of the transport pathways), but the rock's structure and fracture frequency also play a role. The sensitivity analyses show that differences in groundwater flow or transport resistance of several tens of percent are of little importance for the risk.

Conclusions – regional groundwater flow

SKB's overall conclusion is that no systematic difference can be demonstrated between coastal and inland locations with regard to the occurrence of favourable flow conditions. The supplementary analyses presented by /Ericsson and Holmén 2010/ have not altered this conclusion. The main reason is that investigations and analyses have shown that local conditions, mainly the permeability of the bedrock, are crucial in determining whether a site is suitable for a final repository with respect to groundwater flow. The site investigations in Laxemar and Forsmark have confirmed this contention. Notwithstanding this, the groundwater flow from a repository location may include regional components characterized by long and slow flow paths. However, it is not deemed possible by means of reasonable efforts to verify such conditions with sufficient reliability that they could be credited with any safety-enhancing function for a final repository.

8.2.7 Groundwater composition

The present and future composition of the groundwater is of great importance for long-term safety, see Section 6.2.5. This applies particularly to salinity, redox conditions (whether there is dissolved oxygen in the groundwater) and concentrations of other substances that can adversely affect the buffer and the canister. The safety assessment makes estimates of how the composition of the groundwater will be affected in the future due to ongoing land uplift and future climate change.

Sampling and analyses

Sampling and analyses of deep groundwaters have undergone considerable development from the first investigations on Sternö and in Finnsjön in the late 1970s, via the Äspö HRL, to extensive sampling in Forsmark and Laxemar during the site investigations. Early samplings in the reference areas revealed great difficulties in obtaining representative samples /SKB 2010a/. Sites in the interior where samples had been taken in boreholes tend to be characterized by groundwater inflow (groundwater recharge). Such conditions, in combination with difficulties in isolating superficial parts of the boreholes, entail a risk of contamination of samples from greater depths, which has also been observed. Analyses of groundwater from reference areas in the interior are therefore characterized by a lack of representative data from relevant depths for essential parameters /Winberg 2010/.

Sampling is more reliable in environments characterized by groundwater discharge, for example in Finnsjön, Äspö, Laxemar and Forsmark, where in particular samplings of deep groundwaters during the past decade have provided a more reliable picture of the chemistry of deep groundwaters. However, it should be noted that even older data from Finnsjön, which is near the coast, acceptably illustrates the chemical conditions at greater depths on this site. This is not, on the other hand, true of older data from Sternö.

Comparisons

The groundwater at repository level must not contain dissolved oxygen, since oxygen corrodes copper. The presence of dissolved oxygen in groundwater at repository level has not been detected at any of the investigated sites. However, it should be pointed out that most of the dissolved oxygen today is consumed by microbial processes near the ground surface, and it is only at Forsmark and Laxemar that more thorough investigations have been done demonstrating that the rock, with constituent minerals, will also reduce oxygen in infiltrating groundwater.

The groundwater's salinity and calcium content affect the stability of the bentonite clay. Low concentrations can entail problems in this respect. Here a general comparison can be made between a number of sites, since data on salinity are relatively reliable. Figure 8-5 shows typical chloride concentrations at different depths in Forsmark, Laxemar and reference areas. At the near-coastal sites – Forsmark, Äspö and Finnsjön – the chloride concentrations are relatively high (5,500–7,500 mg/l). Considerably lower concentrations have been found at sites located further inland (Kamlunge, Gideå, Fjällveden, Klipperås). Laxemar occupies an intermediate position, with a chloride concentration of 1,700 mg/l. The low value for Sternö, which is situated by the sea, can be ascribed to contamination with surface water.

Conclusions

Groundwater in Forsmark at depths between 400 and 600 m is brackish, with salinity that increases with depth, low tritium content (indicating a limited influence of superficial water), and with some content of glacial water and Littorina water (marine origin). Similar groundwater is found at similar depths at the near-coastal sites of Laxemar and Äspö, and to some extent in Finnsjön, but the salinities are higher in Forsmark. The variations between these sites are linked to variations in permeability and local topography, and thereby varying coverage by the Littorina Sea.

The possibilities of quantitatively comparing analyses of deep groundwaters from reference areas are limited for many parameters, given differences in the reliability of data and geographic location. However, there is a basis for comparing salinities, which are important because low salinities can lead to buffer erosion. The salinities in Forsmark, as well as at other near-coastal sites, are judged to be high enough to prevent buffer erosion. Areas further inland have much lower salinities, and there may be sites there where the salinity is already too low today to ensure the stability of the buffer.

As regards other important hydrogeochemical conditions such as sulphide concentration, pH or buffer capacity, reliable data are lacking from other sites than Forsmark and Laxemar to permit meaningful comparisons. The overall conclusion is thereby that there is no other investigated site that exhibits, in any respect that can be verified, a substantially more favourable situation than Forsmark with regard to hydrogeochemical conditions.

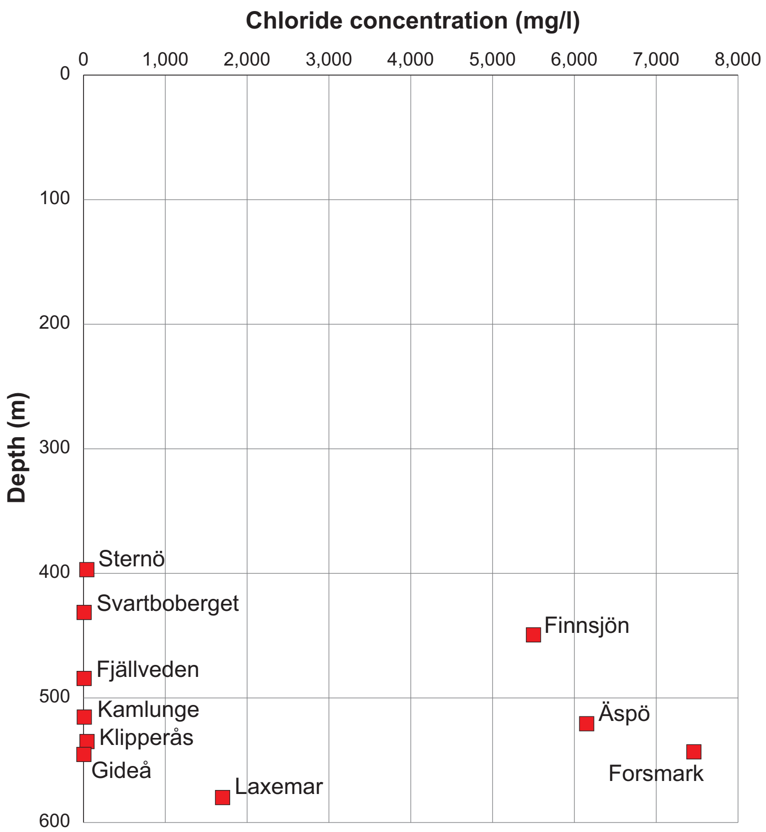

Figure 8-5. *Typical chloride concentration in groundwaters sampled in the depth interval 400–600 m. For a full documentation of representative data, see /SKB 2008a, 2009c/.*

8.2.8 Solute transport

The rock's ability to retard the migration of radionuclides from a damaged canister is determined by material properties in combination with the size and distribution of the groundwater flow, see Section 6.2.6. The material properties determine matrix diffusion (exchange of matter between water in fractures and the rock matrix) and sorption (adhesion of matter to fracture surfaces and internal surfaces in the rock matrix). Experience from the site investigations, as well as from previous investigations in reference areas, indicates small differences between different sites with regard to matrix diffusion and sorption. There are, however, great differences in groundwater flow, see Section 8.2.6. Inasmuch as Forsmark has a very low frequency of conductive fractures at repository depth and a low water flow rate, Forsmark has an essential advantage in this respect compared with the reference areas.

Conclusions

Groundwater conditions in Forsmark also contribute to favourable prospects for retardation of solutes. There is nothing to suggest that another site would offer significantly better prospects in this respect.

8.2.9 Site understanding

In order to be able to assess the safety of a final repository on a given site, we have to have confidence in the accuracy of the site description, since the forecasts in the safety assessment are based on it.

The degree of site understanding that is achieved is determined by the combination of investigation efforts and the natural attributes of the site. As regards investigation efforts, the investigations made of the reference areas cannot be compared to the site investigations, either quantitatively or qualitatively. However, experience from the reference areas, together with other siting studies, have provided good knowledge of what conditions can simplify or obscure the understanding of a site. In general, bedrock with clearly defined and homogeneous lithological units and a regular structural makeup offers advantages. A thin overburden and high degree of exposure is also advantageous, especially in early stages of the investigation.

Forsmark is distinguished by a clear, structurally controlled and relatively homogeneous geology. This is generally reflected in uniform mechanical, thermal and hydrogeological properties. These conditions have proved to greatly facilitate an understanding of the site and compensate more than well for a low degree of exposure, which initially complicated the description of the rock's geometry and properties at depth. The best reference for comparison is Laxemar, where more heterogeneous geological conditions have necessitated greater investigation efforts to achieve an equivalent degree of site understanding, cf. Section 7.1.8. Without being able to refer to any quantitative comparisons, some of the reference areas are generally deemed to offer prospects for site understanding that is on a par with that of Forsmark, while others offer less favourable prospects. The former include Gideå and Fjällveden, while the latter include Kamlunge, Svartboberget and Klipperås.

Conclusions

Site comparisons in quantitative terms of the prospects for site understanding are not possible. Investigations and analyses of Forsmark have nevertheless yielded a good understanding of the site, and the risks of surprises in the construction phase are deemed to be limited, cf. Section 7.2.2.

8.3 Conclusions

Forsmark has proved to be a suitable site with regard to the prospects of achieving the purpose of the final repository for spent nuclear fuel. The properties of the bedrock are decisive for this suitability. Comparisons of these properties with those of other sites where investigations have been done show that Forsmark is a suitable, and favourable, site in a relative sense as well. No site has been identified that could offer significantly better prospects than Forsmark. This does not mean there are not other sites with equivalent or more favourable conditions with respect to individual geological factors. It is also possible that there may be sites that offer comparable prospects overall for achieving long-term safe disposal. But it is not possible to see that there could be another site that offers such verifiable advantages over Forsmark that this would warrant efforts to search for such a site.

Regardless of site, the requirement that the purpose must be able to be achieved with a minimum of damage or detriment to human health and the environment necessitates adaptation to local environmental conditions, conditions for industrial establishment, transport infrastructure, etc. This has been taken into account during the siting work for the final repository, and the conclusion was drawn even prior to the site investigations that the sites chosen for the investigations offered essential advantages in relation to other sites in these respects (see Section 4.4.2). The extensive body of data that has been gathered since then has supported this view.

Against this background, SKB's overall conclusion is that the siting of the final repository complies with the intentions of the Environmental Code that there should not be any obviously better site that is available with labour inputs that are reasonable in relation to what could be achieved.

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