R-01-36

International workshop on site investigation and evaluation based on the siting process in Sweden

Held at Äspö Hard Rock Laboratory, Sweden, April 18–20, 2001

Compiled by

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June 2001

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Preface

Purpose of workshop

SKB's goal is to commence surface based site investigations in 2002. Extensive preparations are now being made for this transition to the next phase in the siting process for the deep repository for spent nuclear fuel. The purpose of the international workshop on site characterisation held at Äspö April 2001 was to:

- present the SKB site investigation and evaluation programme to a group of international experts,
- discuss whether the available toolbox of investigation methods for surface based site investigations is appropriate and state-of-the-art in an international perspective, and
- by working group sessions discuss the level of ambition in the programme for site investigation for each discipline.

SKB conclusions

This report summarises the conclusions of the workshop in general terms. Many of the detailed comments and ideas obtained at the workshop have already inspired and will also directly inspire the on-going planning work for site characterisation. The core activity at the workshop was the work performed by working groups. They addressed what should be considered for a site characterisation programme, based on the generic planning made so far by SKB. The working groups also outlined site specific characterisation programmes for the sites suggested by SKB. The tasks were strictly confined to technical and scientific modelling issues. The working group chairmen presented the working group results at the workshop and have also submitted short memos to SKB. The present document is a compilation of these memos.

The SKB generic programme as presented in the existing top level documents, "Requirements and Criteria" /Andersson et al, 2000/ and "Overall Programme" /SKB, 2000b/, received general endorsement and was appreciated for being comprehensive and systematic. For example, it contains comprehensive lists of parameters to be measured. However, there is need for prioritisation and sequencing. This is actually included in the current planning process at SKB where the generic programme /SKB, 2001/ later this year will be adapted to the site-specific conditions for the three sites of interest.

Most groups agreed that core drilling at a location within what is presumed to be a "block of good rock" should be started as soon as possible. However, to be meaningful it is first necessary to formulate a preliminary structural model of the site such that the results of the bore hole investigations can be properly evaluated.

The suite of investigation methods available to SKB and included in the SKB programme /SKB, 2000b/ was discussed. The working groups only identified a few more site characterisation methods worth considering. Particular consideration was recommended for 3D seismic surveying and long directional drilling.

Most groups pointed out the need for SKB to establish sufficient structure, in terms of decision-making and project management organisation, to enable prioritisation of programme objectives, clear demarcation of programme responsibilities and the positive identification of intermediate programme goals. Several groups suggested quite similar organisations with different teams at each site but combined with a rather strong central evaluation function.

The need for integrating Safety Assessment, Design and Site Investigation was stressed. SKB is presently in the process of changing the organisation to meet the demands of site characterisation work.

Finally, the timing was excellent for having our reports reviewed by a group of international experts and to get comments and proposals at different levels. The summary of the workshop as presented in this report will be essential for the continued planning work.

Anders Ström
Repository Technology Unit SKB

Summary

The Swedish Nuclear Fuel and Waste Management Company (SKB) has held an International workshop on site investigation and evaluation based on the siting process in Sweden, at the Äspö Hard Rock Laboratory, Oskarshamn, Sweden, 18–20 April, 2001. The core activity of the workshop was the work performed by working groups. They addressed what should be considered for a Site Characterisation Programme, based on the generic planning made so far by SKB. The working groups made recommendations on overall strategy of the programme, planning of the programme, measurement techniques, modelling, and overall organisation. The working groups also outlined site specific characterisation programme for the sites suggested by SKB. The tasks were strictly confined to technical and scientific modelling issues.

The SKB generic programme as presented in the existing top level documents, "Requirements and Criteria" /Andersson et al, 2000/ and "Overall Programme" /SKB, 2000b/, was appreciated. It contains comprehensive lists of parameters to be measured. However, most groups recognised the need for prioritisation and sequencing in the next step. However, it should also be noted that the detailed general programme /SKB, 2001/, at the time of the workshop only existed in Swedish and was thus not available to most participants.

Strategy of a site characterisation programme

It was noted that investigating three sites with different characters and different degrees of "prior knowledge" in parallel, and within a tight time scale, to achieve comparable levels of understanding and discrimination is a major challenge. The general programmes need additional prioritisation and site specific adoption. Still the programmes at the different sites need to be comparable.

Most groups stated that top down issues should guide the programme. This approach starts with the future desired goals and then works backwards through the requirements of intermediate stages to arrive at the starting point, the current state of knowledge. Iterative hypothesis testing should be used to guide the investigation. The starting hypothesis needs to be a conceptual understanding and be based on what is already known and what SKB is seeking to determine.

The programme should early seek to determine whether any of the requirements listed in the "Requirements and Criteria report" /Andersson et al, 2000/ would be violated, but this focus must also be balanced against the need to gradually develop and test understanding of each site in a structured way. Clearly developing a soundly based site descriptive model is also crucial in order to properly address to what extent the site fulfils requirements and preferences.

There is also a need to relate the current programme to the needs and objectives of the following detailed (underground) investigations. While site selection and license to start underground exploration (and in fact construction of the repository) must rest on information from surface based investigations, there are several site confirmation and detailed scale issues which can only be addressed from the underground.

Placement of boreholes and borehole testing

Before deciding on where to place boreholes and which measurements to carry out in these boreholes, the overall strategy of the programme needs to be adopted to the specific site. Given the safety related site requirements most groups emphasised the need for the programme to characterise the perceived good rock, with focus on lithology, hydrogeochemistry and rock stress and not only to be driven by an urge to identify and parameterise the fracture zones.

Most groups agreed that core drilling at a location within what is presumed to be a "block of good rock" should be started as soon as possible. However, to be meaningful it is first necessary to formulate a structural model of the site such that the results of the bore hole investigations can be properly evaluated within the format of iterative hypotheses testing.

Also, there should be a common set of tests that are performed at all sites, for example a set of hydraulic tests using the same packer intervals. However, it is recognised that flexibility is required in site characterisation in order to respond to specific conditions at the site. Thus the siting and orientation of boreholes will be site specific, and additional techniques will be employed at some sites.

Baseline and monitoring

Most working groups emphasised the need for establishment of baseline conditions prior to any site disturbance. (Possibly, this emphasis was due to the fact that baseline studies and monitoring is not discussed very much in the overall programme /SKB, 2000b/, although it is much discussed in the detailed general programme /SKB, 2001/, which so far only exists in Swedish). It should also be borne in mind that the programme of monitoring "baseline conditions" should merge smoothly into any monitoring planned as part of a repository retrieval or closure period.

Additional Site Characterisation Methods

The working groups only identified a few more Site Characterisation methods worth considering, in addition to those already discussed in the SKB programme /SKB, 2000b/. Particular consideration was recommended for 3D seismic surveying and long directional drilling.

Site modelling and evaluation

Several working groups noted that a key task for the site investigation programme is to integrate all the data from different disciplines and evaluate it holistically in order to develop a coherent and consistent understanding of the site. There is a need to ensure that specialists in all the various disciplines work together as a team. The integrated modelling should start now.

Most working groups saw a need to further develop procedures for integrated modelling, uncertainty description and iterative improvement of models. This calls for development both of tools and procedures.

Data management and visualisation

All modelling assumptions and parameters should be coordinated through a central database and visualization system such as that described for RVS. Quality control should be maintained both for modelling and for data integration. However, the full functionality of the RVS tool was questioned. Also more extensive use of 3D visualisation technologies presently used in the petroleum and mining industries may be considered.

Site specific issues

Site specific issues at Tierp concern the lack of exposure, lack of modern geological mapping, lack of underground data, the degree of homogeneity, the shape of pluton and the unknown hydrogeology, hydrogeochemistry and rock mechanical conditions. The aim of a site investigation programme must be to quickly clarify a wide range of critical conditions, but at a very basic level. For this site, early deep boreholes are needed primarily to check homogeneity, hydrogeochemistry and rock stress.

The general knowledge of the Simpevarp area is high, due to the presence of the Äspö HRL. Site specific issues concern, distribution of high conductivity features, homogeneity in lithology and anisotropy. The risk of the rock at Simpevarp having a significant ore potential is considered to be low. It was suggested that given the extensive knowledge of this particular region, it was considered prudent to drill the first deep borehole in the centre of the first major block to be investigated, but after updating the geological description of the site.

Site specific issues at Forsmark concern size, ore potential, rock stress conditions and groundwater chemistry. Most of these issues may be resolved by early deep boreholes placed in the "good rock" and focusing on lithology, water chemistry and rock stress.

Quality assurance and Technical audit

The proposed programme contains many complex technical activities that need to be performed correctly but also many decisions concerning which technical activities should be undertaken at all. It was regarded important that the programme includes a number of mechanisms designed to retain alternative thinking and enable such thinking to be implemented if necessary by various means, including independent peer review and technical audit.

Organisation

Most groups pointed out the need for SKB to establish sufficient structure, in terms of decision-making and project management organisation, to enable prioritisation of programme objectives, clear demarcation of programme responsibilities and the positive identification of intermediate programme goals. Several groups suggested quite similar organisations with different teams at each site but combined with a rather strong central evaluation function.

The need for integrating Safety Assessment, Design and Site Investigation was stressed and some raised concern that Safety Assessment and Design might be treated as separate tasks. In contrast, safety assessment should be regarded as an element of design that everyone contributes to.

Contents

1 Introduction

The Swedish Nuclear Fuel and Waste Management Company (SKB) has held an **International workshop on site investigation and evaluation based on the siting process in Sweden**, at the Äspö Hard Rock Laboratory, Sweden, 18–20 April, 2001.

1.1 Background

SKB's goal is to commence surface based site investigations in 2002. Extensive preparations are now being made for this transition to the next phase in the siting process for the deep repository. In November 2000 three sites were proposed to the public /SKB, 2000a/.

One of the principal tasks assigned to SKB is to develop a distinct site investigation programme /SKB, 2000b/. The programme should thus detail what information is intended to be collected from a site and how it is to be used in evaluation of a site's suitability for a deep repository. The programme presented is general and has later been augmented with more detailed technical descriptions /SKB, 2001/. The detailed technical description will be translated into English in late 2001. Later during 2001 the programmes will be adapted to the site-specific conditions for the three sites of interest.

The goal of the site investigation phase is to obtain the permits that are required to site and build the deep repository. The geoscientific work during the site investigation phase is supposed to provide the broad knowledge base that is required to evaluate the suitability of investigated sites for a deep repository. The material must be comprehensive enough to

- show whether the selected site satisfies fundamental safety requirements and whether civil engineering prerequisites are met,
- permit comparisons with other investigated sites, and
- serve as a basis for adaptation of the deep repository to the properties and characteristics of the site with an acceptable impact on society and the environment.

The general site characterisation programme, aiming at fulfilling these needs, defines different characterisation stages, describes the interaction needed between different disciplines and generally describes the investigation methods. The investigation programme aims at determining properties of the surface ecosystems, geology, hydrogeology, hydrogeochemistry, rock mechanics, thermal properties, and radionuclide transport properties of the rock. Measurements will be made from the air, from the ground and in boreholes. The emphasis of the field work will naturally lie on investigations of the rock, since it is there the lack of knowledge is greatest today.

The selection of parameters to be explored during the site characterisation programme rests on several assessments on what is required to be determined for the use of safety assessment and design. Over the years SKB has developed a significant experience, from various field studies, safety assessments and from the work at the Äspö Hard Rock Laboratory (HRL) on what to measure. More directed efforts have also been undertaken. Andersson et al, /1998/ made a preliminary listing of all site specific parameters judged to be needed during site investigation. SKB has recently completed a safety assessment project, SR 97 /SKB, 1999/ using data from different sites in Sweden. Further, Andersson et al, /2000/ formulate requirements and preferences on the rock, from a safety and engineering perspective, drawing upon the analyses and conclusions made in SR 97. Additional data are needed to obtain a geoscientific understanding of the site. The need for ecosystem information was explored by Lindborg and Kautsky /2000/.

The work during the site investigation phase is planned so that a body of knowledge is progressively built up. On the basis of the site-specific information at a given stage of investigations, geoscientific models (descriptions) of the site are setup. These models are used to produce a site-specific facility description with repository layout and to assess the consequences of the construction work. The long-term safety is then evaluated based on specified site models and repository layout. These evaluations affect the planning of the next stage of investigations. When the next stage of investigations is carried out the geoscientific models are updated as well as the design and safety evaluation, if needed.

1.2 Purpose of workshop

The purpose of the workshop was to

- present the SKB plans for site investigation and evaluation to a group of international experts,
- discuss whether the SKB toolbox of investigation methods for surface based site investigations is appropriate and state-of-the-art in an international perspective, and
- by working group sessions discuss the level of ambition in the programme for site investigation for each discipline.

1.3 Setup of the workshop – working groups

At the first day of the workshop SKB presented the current plans. The second day was almost fully devoted to working groups. The last day the working group presented their findings followed by general discussion and conclusions.

The working groups were generally asked to discuss what should be considered in a Site Characterisation Programme. However, in order to focus the discussion it was made within the framework of the sites suggested by SKB. Each group considered one of the SKB suggested sites (i.e. two groups per site). Maps and other basic information of the sites were provided. The information was brief and condensed. Furthermore a potential "prioritised area" (within the suggested sites) for the investigations was indicated on these maps. The working group addressed the following two related subtasks:

- Outline a site specific characterisation programme for the specified site based on the generic programme presented by SKB. Should the generic programme be supplemented or is it partly redundant? Essential site specific needs? Can the needs for safety assessment and repository design be met? The different groups could focus on different scientific topics but should keep the integrated safety case in mind. For assistance there also was a suite of detailed questions each group could address if they wished.
- In relation to the programme, discuss and assess suitable characterisation methods. Again some detailed questions to be potentially addressed were provided.

The tasks were strictly confined to technical and scientific modelling issues. Pure instrument matters were also outside the scope of the task. In particular, questions about site selection, selection of prioritised areas within the municipality etc were not to be discussed within working groups. It should be understood that the prioritised areas provided for the exercise were given as examples only – areas eventually selected in the actual investigation programme may be different. The working groups were asked to address the tasks as stated above, but within these limits be free to approach the tasks in a way they found appropriate as long as they spent significant time on both subtasks.

1.4 Documentation

The working group chairman presented the working group results at the conclusion session of the workshop. After this the chairmen submitted short memos to SKB. The present document is a compilation of these memos.

2 Strategy of a site characterisation programme

A significant part of the working groups was spent on discussing the overall strategy of a site characterisation programme.

2.1 Challenges

There are several challenges facing SKB. Investigating three sites with different characters and different degrees of "prior knowledge" in parallel, to achieve comparable levels of understanding and discrimination is clearly a major challenge. The targeted timescale for the various milestones and decision-making is also very challenging. Apart from the logistical and resource issues, the other challenges identified are mostly concerned site investigation objectives, project management, and dissemination/communication of outcomes.

2.2 Prioritising the programme

The general programmes presented in SKB reports (such as SKB /2000b/) needs additional prioritisation in order for the programme to be completed within the suggested time schedule. Most groups stated that top down issues should guide the programme. This approach starts with the future desired goals and then works backwards through the requirements of intermediate stages to arrive at the starting point, the current state of knowledge. Implicit within this approach is the need to view the planned project as a complete whole and only provide as much detail about individual elements of the project as is necessary to define priority tasks or key activities. Still the programmes at the different sites need to be comparable.

Most groups favoured an iterative approach allowing the conceptual understanding to evolve. Hypothesis testing should be used to guide the investigation. The starting hypothesis needs to be a conceptual understanding and be based on what is already known (or thought to be known) and what SKB are seeking to determine. This approach will help target the site investigation, provide a common focus for different disciplines (thereby helping integration), provide a means of tracking progress (qualify how understanding is developing) and establish links into design.

Some suggested the site characterisation activities need to be evaluated quantitatively in an iterative manner to establish the adequacy of the program using a generalised metric such as "probability of licensing" which reflects technical, social, environmental, and economic uncertainties. The amount of site characterisation necessary after each step may be evaluated based on the marginal improvement in uncertainty reduction and increase to the "probability of licensing".

One working group suggested the following steps in developing the programme:

- Develop a conceptual model of the site.
- Identify factors likely to rule out the site straightaway.
- Consider how to obtain information on these factors.
- Establish the PA/SA modelling needs and the associated requirements for investigation.
- Establish what additional information is required for general confidence building and input into repository design.
- Develop the site characterization procedure based on the previous five items.

Most groups agreed that at early stages the "probability of licensing" is strongly related to the probability of identifying a block of "good rock" of sufficient volume for the repository. The programme should seek to determine whether any of the requirements listed in the "Requirements and Criteria report" /Andersson et al, 2000/ would be violated. Attention could be focused on investigation of these requirements and the outcomes. The strategy for testing these requirements needs to be carefully thought out from the outset of site characterisation. Inadequate measurements that give negative indications against one or more requirements could have undue impact on decision-making.

There is, however, a danger in focusing too strongly on requirements. The view was also expressed that site characterisation should be designed to test conceptual hypotheses about the sites, i.e. to develop and test understanding of each site in a structured way that addresses performance assessment requirements. Thus the strategy has to manage these two types of objectives alongside each other. Clearly developing a soundly based conceptual model of the site is also crucial in order to properly address to what extent the site fulfils requirements and preferences.

Some also pointed out that in case there is a lack of knowledge of the basic features of the investigation area, there could be no attempt to outline a Complete Site Investigation programme at the present time. Instead, one of the main aims of the Initial Site Investigation programme should be to collect and analyse sufficient data to make it possible to plan the Complete Site Investigation. This implies that there must be a specific analysis-integration-planning period inserted between the completion of data acquisition in the Initial Site Investigation phase and the start of Complete Site Investigation data acquisition.

In general it is very important to allow enough time for integration of the results from each site as well as between sites. This is particularly important when the timetable is so tight, otherwise a lot of data may be collected but the true value and meaning of the knowledge will not be realised.

2.3 Relating the Site Characterisation Phase to the Underground phase

Some working groups saw the need to relate the current programme to the needs and objectives of later phases of the programme, i.e. when the programme goes underground. While site selection and license to start underground exploration (and in fact construction of the repository) must rest on information from surface based investigations, there are several site confirmation and detailed scale issues which can only be addressed from the underground. The objectives and the ambition level of the surface based programme should reflect this.

2.4 Quality assurance and Technical audit

The proposed programme contains many complex technical activities that need to be performed correctly but also many decisions concerning which technical activities should be undertaken at all. The programme should not only be seen to do things right but should also do the right things.

There are many aspects of the programme that, apart from requiring to be performed correctly, also require to be seen to be performed correctly, in other words it is important that the programme is carried out in a transparent manner. Additionally, the site investigation for a repository is unusual in that it has to satisfy both the needs of safety assessment and engineering.

According to the experiences of some, complex tightly scheduled projects often find it very difficult to keep up with adequate quality assurance documentation, are slow to recognise and incorporate discovered knowledge and find it impossible to rethink strategy or goals. They suggested it would be valuable to incorporate a number of mechanisms designed to retain alternative thinking and enable it to be implemented if necessary by instituting the following mechanisms:

- appoint an independent review group,
- perform parallel/alternative interpretation/modelling activities to avoid the development of self-reinforcing orthodoxies in the realm of understanding and safety assessment,
- a positive proposal to undertake rapid analysis/evaluation/interpretation of the data from the site investigation. This should be performed as close to real time as possible. The group should be encouraged to think the impossible in order to promote ultimate robustness.

Many groups expressed that timely technical review should be carried out for all investigated sites, in such a manner that reviewer comments can be addressed as the programs progress.

3 Generic Programme

The SKB generic programme as presented in the existing top level documents, "Requirements and Criteria" /Andersson et al, 2000/ and "Overall Programme" /SKB, 2000b/, was appreciated. It contains comprehensive lists of parameters to be measured. However, as discussed in the previous section most groups recognised the need for prioritisation and sequencing in the next step. It should also be noted that the detailed general programme /SKB, 2001/, so far only exists in Swedish and was thus not available to most participants.

3.1 Baseline and monitoring

Most working groups emphasised the need for establishment of baseline conditions prior to any site disturbance. (Possibly, this emphasis was due to the fact that baseline studies and monitoring is not discussed very much in the overall programme /SKB, 2000b/, although it is much discussed in the detailed general programme /SKB, 2001/, which so far only exists in Swedish).

Some participants had experience of other repository and underground laboratory licence applications where much emphasis became placed on the need to be sure that the proponent had adequate knowledge of the undisturbed conditions before major disturbance was permitted. Also the monitoring programme at the site should be defined at the same time as the site investigation programme, to ensure that there are no major conflicts between them. Site characterisation activities need to be carried out to minimise site disturbance and maximise the information, which will be available from monitoring.

Most groups concluded that an adequate baseline study is required prior to any site disturbance. Ideally a baseline study needs to cover significant time in order to capture seasonality of e.g. piezometric data and compositions for groundwaters, and of ecosystems data. A "snapshot" will be inadequate, since most of the functions and parameters have some sort of cyclical variation. Hence measurement of baseline conditions needs to produce an understanding of the rate of change of many factors. It was pointed out that this needs careful thought particularly since some have the experience that protestors will focus on undermining the proponent's proposal on the basis of the points that the proponent understands least well.

Such requirement may conflict with SKB's projected programme, so urgent considerations and action are recommended. From a practical viewpoint, there is merit in starting to measure baseline conditions as soon as possible regardless of where a repository may be sited subsequently. (Indeed the need is recognised by SKB and both planning and activities are underway).

Examples of typical baseline information include:

- climate,
- ecosystems surveys,
- shallow groundwater and surface water hydrology with typical seasonal fluctuations (in both recharge and discharge areas, i.e. high and low topographic positions),
- chemical compositions of shallow groundwaters, streams and especially of groundwaters discharging in topographic lows; analyses to include key solutes, isotopes, trace elements including natural radionuclides, dissolved gases,
- radiochemical and radiological survey of soils and soil gas emissions, also other soil gases e.g. helium, that might characterise groundwater upflow zones,
- microseismic activity.

It should also be borne in mind that the programme of monitoring "baseline conditions" should merge smoothly into any monitoring planned as part of a repository retrieval or closure period. Ongoing baseline studies after deep drilling has started would include monitoring for earth tide effects, groundwater heads, etc in undisturbed (i.e. recovered) instrumented boreholes.

3.2 Size of investigation area

Some groups noted that the physical dimensions of the investigation area (i.e. the 5 to 10 km^2 area) may not contain the boundaries for the hydrogeology and ecosystem. Hence, while there is the requirement to keep the site to a fixed dimension provision must be provided for investigating boundary conditions that exceed those physical dimensions. (This will also be the case since the characterisation programme also concern the regional environment to the investigation area).

With regard to bedrock geological mapping, it was emphasised that, in particular in regions with little present knowledge, important inputs were seen also from detailed regional studies of surrounding areas, even though these may be at quite a distance from the investigation area. Examples of such studies may include neighbouring, better exposed parts of the rock, and detailed analogue (or "proxy") studies of, for instance, fracturing in similar rock types, wherever exceptionally good outcrop conditions occur.

3.3 Placement of boreholes

Before deciding on where to place boreholes and which measurements to carry out in these boreholes, the overall strategy of the programme needs to be adopted to the specific site, as discussed in section 2.2. Hypothesis testing should be used to guide the investigation. The starting hypothesis needs to be a conceptual understanding and be based on what is already known (or thought to be known) and what SKB are seeking to determine.

In light of this, and given the safety related site requirements /Andersson et al, 2000/, most groups emphasised the need for the programme to characterise the perceived good rock, with focus on lithology, hydrogeochemistry and rock stress and not to be driven by an urge to identifying and parameterizing the fracture zones. While recognising that during a site investigation it is inevitable that the geological and geophysical studies will eventually concentrate on identifying the disposition of the fracture system it was judged essential, for all the sites, to obtain early data from deep boreholes in the rock between zones. Such data is judged essential for judging whether the site may be in jeopardy with any of the requirements of the rock. It was also judged essential that there are some hydrogeological (and possibly nuclide transport) measurements that positively identify less permeable rock suitable for the environs of the deposition regions.

Most groups agreed that core drilling at a location within what is presumed to be a "block of good rock" should be started as soon as possible. However, to be meaningful it is first necessary to formulate a structure model of the site such that the results of the borehole investigations can be properly evaluated within the format of iterative hypotheses testing. Only a few argued that such a hole could be drilled without any preliminaries. The depth of such pre borehole analysis would be site specific, but at most sites the modelling may require some additional preliminary (airborne) geophysics, possibly combined with 3D seismic and re-interpretation of other surface based structure data. It was also made clear that it will be essential that the preliminary boreholes are be located, designed and tested to the highest standards (i.e. they should not be regarded as "reconnaissance" boreholes) and that data should have high reliability because decisions of site suitability could be based on them.

In addition to the "show stopper" factors already discussed, there is a variety of information required for the PA/SA requirements, repository design and confidence building. Thus, knowledge on this second set of factors is already required at an early stage.

Also, there should be a common set of tests that are performed at all sites, for example a set of hydraulic tests using the same packer intervals. However, it is recognised that flexibility is required in site characterisation in order to respond to specific conditions at the site. Thus the siting and orientation of boreholes will be site specific, and additional techniques will be employed at some sites.

One group raised concern that the potential repository region should be disturbed as little as possible by the site investigations, especially if this results in hydraulic connections to major zones and the surface. This arises because of uncertainties about the longevity of borehole seals. In view of this, careful consideration should be given to whether cored boreholes should pass through the centre of the good rock block, and whether hydraulic fracturing should be used to measure stresses.

3.4 Data for understanding the site

Data required to perform a palaeohydrogeological reconstruction of the site is planned to be acquired in the geological, hydrogeological and hydrogeochemical programmes /SKB, 2000b/. The various strands of information and understanding will need to be brought together by an integration team.

3.5 "New" technology

The working groups only identified a few more Site Characterisation methods in addition to those already discussed in the SKB programme /SKB, 2000b/.

3.5.1 3D seismic surveying

Some working groups discussed the potential for valuable detailed information on geological structure to be obtained from 3D seismic surveying. Some felt that this technology was poorly exploited in radwaste site investigations relative to the enormous advances that have been made in the oil industry. It was recognised, however, that the method is more speculative and less developed for crystalline rocks than for sedimentary rocks. In crystalline terrain its applicability and added value may not be possible to realise. The potential importance of this surveying method for mapping structure more comprehensively than other methods still suggests that it needs to be fully evaluated before being discounted. (SKB is also currently evaluating the use of this method).

3.5.2 Directional drilling

Some working groups noted that advanced directional drilling has made tremendous advances over the last decade, allowing for the drilling of long sub-horizontal holes.They suggested that the site characterisation program should not be limited to a particular drilling methodology if the site characterisation program can be improved by adopting newer drilling techniques. The use of directional drilling may be particularly useful for investigating the major steep fracture zones that may provide boundary conditions for a block. It was recognised that there are particular requirements to drill specific diameter boreholes (also vertical in many cases) to accommodate instrumentation that has been developed. Drilling strategy should therefore encompass both types of borehole as far as possible.

It was suggested that these techniques are now used on a day-to-day basis in the mining and petroleum industries, and a capability should be developed for site characterisation as soon as possible. The Initial Site Investigation phase will last for a couple of years and in this time a direction drilling programme could be developed for general use in the following Complete Site Investigation phase.

3.5.3 Other

There were also some other examples of techniques which may be considered.

- If hydraulic fracturing is to be carried out at the site it would be possible to use induced seismicity techniques to determine fracture patterns and preferential fluid paths.
- Resisitivity tomography should be considered for its role in saline intrusion exploration.
- A new high resolution permeability tool (MDT) should be considered in the hydrogeology investigations.

It was also pointed out that sequencing and coordination of sampling will be vital, especially with regard to hydrogeology and hydrogeochemistry.

4 Site modelling and evaluation

Several working groups noted that a key task for the site investigation programme is to integrate all the data from different disciplines and evaluate it holistically in order to develop a coherent and consistent understanding of the site. This task is aided by comprehensive and easy to access databases and by conceptual, geometric and mathematical modelling techniques.

4.1 Developing confidence in the Site Descriptive model

The content and structure of the Site Descriptive model and the confidence in the Site Descriptive models are crucial input to Safety Assessment. It was noted that a key challenge for the site characterisation programme is to develop an integrated understanding of the site, which means that scientists from a variety of disciplines will have to work closely together. There is a need to ensure that specialists in all the various disciplines work together as a team. One way of facilitating this might be for staff to work together in a project room rather than in separate offices. Another would be to have regular review meetings attended by everyone working on the programme.

It was also suggested that SKB should form an integration and evaluation team with a range of responsibilities including quality checking, interpretation, documentation and presentation of site data and understanding. Team working is considered to be essential for the success of this complex multi-disciplinary programme.

Also the procedures for iterative control and updating of the model, with a staged evaluation of uncertainties in each stage are important means for developing confidence in the models. This aspect is discussed in the subsequent section.

4.2 Iterative control and updating of the models

Most working groups saw a need to further develop procedures for integrated modelling, uncertainty description and iterative improvement of models. This calls for development both of tools and procedures.

Integrated modelling of the site should start now and be updated periodically throughout the programme. In particular, this is crucial for the geological description, including the description of fracture zones and fracture geometry. The first iteration should be based on the current understanding and á-priori hypotheses. A set of alternative conceptual models that are each consistent with the data in order to focus on what measurements might best discriminate between models should be maintained.

The ongoing effectiveness, and success of site characterisation activities should be assessed quantitatively. This will provide the basis for evaluating alternative activities within budget constraints, determining "how much is enough", and providing a basis for prioritizing and possibly abandoning some of the sites. Such procedures require assessing the degree of uncertainty at each stage of characterisation as well as the formulation of which precision is really required.

Consequently, there is also a need to have a systematic procedure for updating models of the site. This should improve the efficiency of the process and produce consistent interpretations. In particular there is a need to make use of data freezes so that information from the wide range of disciplines is used consistently in interpreting the data.

All modelling assumptions and parameters should be coordinated through a central database and visualization system such as that described for RVS. Quality control should be maintained both for modelling and for data integration.

4.3 Modelling techniques

There were several comments made regarding modelling techniques.

4.3.1 Upscaling by modelling or measurements

Some raised the issue whether upscaling should be done by modelling, which is the basic plan now, or if it should also be addressed by measurements. Concern was raised that upscaling of one-dimensional borehole information into three dimensions using Discrete Fracture Network (DFN) models, may overestimate connectivity. Tests that would reduce these tendencies or provide independent verification are transient single hole hydraulic tests, interference tests (either single hole or cross hole) and tracer tests.

4.3.2 Soft data in DFN – modelling

Fractures and fracture zones below a scale in the order of hundreds of metres can only be described statistically during the site investigation phase. According to plan SKB will utilise Discrete Fracture Network (DFN) modelling technique for this description. However, some teams pointed out that the development of Discrete Fracture Network models inevitably requires input of expert judgement in addition to hard data, for example the finite extent of zones and initial and boundary conditions.

The modelling problems are especially challenging when there are few outcrop data. The use of a few "cleared" outcrops and trenches, and the analysis of data from analogue localities, could be critical in this respect (e.g. for supporting the chosen length distributions). Similarly, a genetical understanding of the process and history of brittle deformation at the site and in the region surrounding the site will be essential as a basis for modelling, and should be built up as soon as possible.

4.3.3 Adequacy of the RVS tool

Some working groups considered the possible role of the RVS package in fulfilling SKB's requirements. In the SKB plans RVS is not only an aid to understanding systems involving complex rock geometry. It is also planned to be a system, which would enable and control interactions between different disciplines of geoscientists working on the same site. However, the functionality of these latter uses would require further development both of the software and of procedures. (Such development is also underway).

The timescale for implementation and the demands for data for integration from an early stage may suggest that many data integration needs may need to be handled by other tools in addition to RVS. Some suggested that using an existing package may be an alternative, whereas others noted that also the use of existing packages requires significant adoption. SKB was advised to reconsider the role of the RVS and how to integrate the site information with respect to a realistic view on what RVS and other tools can achieve within the time available. Such reconsideration must be started very soon.

4.3.4 Data integration using 3D visualization tools

According to the experience of some teams the success of developing an adequate geotechnical model for the site in the time frame proposed is a direct function of the availability of the team to integrate their data quickly to provide a self-consistent model. Such a process may be greatly enhanced if use is made of the 3D visualisation technologies presently used in the petroleum and mining industries. An example use of such technology could be the following:

- Setting: All information is projected on a large screen such that with appropriate hardware and software all data is displayed in three dimensions.
- Large-scale digital terrain maps would show the potential site at the regional scale with the overlying geology, topography and drainage system (Satellite images).
- Zooming in to the local scale show the local relief features, the correlation with the surface lineament features in the topography.
- The geological features mapped at the site are shown in 3D along with potential excavations, the ground water flow patterns, the isosurface of ground water chemistry such as salinity, isosurfaces for rock stress magnitudes, etc.
- Then the proposed site is shown along with the local topography (potential recharge and discharge), inferred geological features and correlated surface lineaments. The size, layout and depth of the repository could also have been shown.

Having all the scientific players in the room looking at the model for the site may have facilitated a rapid consensus on the strategy for the site characterization program.

5 The Sites

The working groups outlined site specific characterisation programmes for the specified sites. While this input is gratefully considered in the SKB planning for actual programmes, the documentation in this section rather highlights some specific issues, which need to be addressed at the different sites.

5.1 Tierp

5.1.1 Site specific issues

Lack of exposure, lack of modern geological mapping, lack of underground data

The main characteristic of the Tierp site, which influences the design of a site investigation programme is the sparsity of data on the bedrock geology at the present point in time. This is due to the almost complete absence of bedrock outcrops (5 small outcrops in an area of 36 km^2), and the poor exposure and lack of modern 1:50 000 geological maps in the whole surrounding area. Also, there are no underground facilities in the area or its surroundings, and within the investigation area itself there are few or no boreholes (e.g. in SGU's well archive). These features of Tierp are in strong contrast to Forsmark and Simpevarp, and mean that a site investigation programme in the former area will look quite different to that in the latter two. However, the area is covered by high quality aeromagnetic data, which has been supplemented/confirmed by electromagnetic (VLF) data, on the basis of which the bedrock is thought to be part of a lithologically rather homogeneous pluton (monzonite - quartz-monzonite - monzodiorite), intersected by a few regional fracture zones.

Degree of homogeneity and shape of pluton

Because of the lack of outcrop and underground data, one of the main concerns at present is the degree of lithological homogeneity (mineralogy, grain-size) within the pluton, and the degree to which the pluton was at a late stage of intrusion, or later, intersected by felsic veins and dykes (as seen in the few outcrops). In addition, the investigation area shows an unexpectedly pronounced negative gravity anomaly and a recent gravity model indicates inward-sloping pluton margins and a shallow depth (few kilometres) of the pluton base in and around Tierp. Any investigation programme should aim to throw light on both these features, particularly the question of homogeneity, which could have a direct influence of the fracture patterns.

Fracture system and fracture zones

Again because of the lack of outcrop and underground data, nothing is known today about fracturing below the limit of resolution of the aeromagnetic/VLF data (regional fracture zones). However, there is no reason to believe that the investigation area is unusual in this respect, either in a positive or negative direction. The group members were agreed that an attempt must be made to gather as much data on brittle deformation as possible, as early as possible, in any site investigation programme.

Others – rock mechanics, salinity interface, hydrogeology ore potential, etc

In the course of the discussions, several other themes were aired – all with the same result: nothing is known at present – information has to be obtained as soon as possible. Critical features which various group members thought could turn out to be "show stoppers" included rock mechanical conditions (in situ stress v. rock strength), the depth of the salinity interface, and the question of ore potential (because of the apparent closeness of the investigation area to the pluton margins). The area is very flat so there is little potential energy to "drive" a groundwater system and flush out old sea waters. The hydraulic gradient, and the relation between the hydrogeology of the superficial deposits (Uppsala esker and related shoreline deposits) and the groundater flow in the bedrock, and the question of the necessity of detailed geomorphological studies needs to be addressed.

5.1.2 Implications for characterisation programme

Both groups addressing the Tierp site reached similar conclusions. Site investigations should address the major unknowns identified by the preceding desk studies.

Bedrock and hydrogeological conditions in the Tierp site are practically unknown. Any site investigation programme starts more or less from scratch, and will be strongly hampered by the fact that there is no bedrock exposure and by the area showing a dominant forest cover, with only a widely spaced network of access tracks. The aim of a site investigation programme must be to quickly clarify a wide range of critical conditions, but at a very basic level. It should also include detailed regional studies (e.g. of the whole pluton) to partially compensate for limited amount of data which it will be possible to collect in the investigation area itself.

There was still discussion on how to practically address these concerns. Deep boreholes are needed primarily to check homogeneity, hydrogeochemistry and rock stress. Boreholes intending to characterise fracture zones etc can possibly wait until it is established if the rock blocks have expected and desirable properties. While there was diverging opinions whether additional geophysical measurements would be worthwhile, both groups addressing Tierp suggested that the deep holes should be drilled at an early stage.

5.2 Simpevarp

5.2.1 Site specific issues

Knowledge of the site

The general knowledge of the area is high, due to the presence of the Äspö HRL. A related positive feature of Simpevarp is that there are abundant rock exposures at the surface, making fracture mapping relatively straightforward.

Distribution of high conductivity features

It was noted that the performance assessment of Aberg in SR 97 (TR 99-23) was particularly influenced by transmissive groundwater pathways. It was noted that the Äspö data set suggests that there is locally greater fracture transmissivity than estimated for the other SR 97 sites. Whether that is a feature that extends to the Simpevarp candidate area is clearly an important issue to be resolved at an early stage.

Lithology

The possibility of there being highly conductive dolerite dykes at the site should be investigated. This might be best accomplished using low altitude airborne or hand-held magnetic surveys, which would detect the magnetite content of such dykes.

The rock also contains fine-grained granite. This has a higher quartz content than the rest of the rock and is consequently more brittle. As such it is more prone to the formation of discontinuities, which may be non-planar and increase the connectivity of fracture systems. Consequently, it would be worthwhile to characterise the distribution of fine-grained granite, at least in a statistical sense.

Anisotropy

It is suggested that the flow in the averagely fractured rock at Simpevarp is likely to be highly anisotropic. This arises because the minimum principal stress is approximately perpendicular to the NNW fracture set.

Low ore potential

The risk of the rock at Simpevarp having a significant ore potential is considered to be low.

5.2.2 Implications for characterisation programme

The characterisation programme should address the above issues. It was also suggested that given the extensive knowledge of this particular region, it was considered prudent to drill the first deep borehole in the centre of the first major block to be investigated. However, the first step would be to update the geological description of the site using e.g. 3D seismic and re-interpretation of other surface based structure data. An obvious benefit of an early borehole in the "good rock" is that the general permeability of the "good" rock mass can be established early and compared to the Äspö experience and measurements. The notion being that a repository cannot be designed until a sufficient volume of good quality rock can be identified.

It will be essential that the preliminary boreholes should be located, designed and tested to the highest standards (i.e. they should not be regarded as "reconnaissance" boreholes) and that data should have high reliability because decisions of site suitability could be based on them.

5.3 Forsmark

5.3.1 Site specific issues

A number of issues were raised which would require attention by the site characterisation programme. The list is not intended to be comprehensive, but come out as a result of the different working group assessment of a conceptual model of the site.

Knowledge of the site

A lot of pre-existing data is available at this site together with (fairly shallow) underground access at the SFR facility. This will need to be integrated into the initial conceptual understanding of the site.

Size

The proposed site is considered to be within the tectonic lense but the largest block bounded by major fractures may not be big enough to house the repository. Do the bounding fracture zone locations, strikes and dips allow a sufficiently large volume of rock for the repository? Are there any fracture zones inside the tectonic lens, especially sub-horizontal fracture zones, that would prohibit siting the repository in the lense?

Ore potential

The question of ore potential needs to be addressed. This seem crucial as some significant mining has occurred in the region.

Rock stress conditions

There is not too much knowledge about rock stress conditions at depth in a tectonic lense. Early measurements for characterising the in situ stress seem motivated.

Groundwater chemistry

Given the proximity to the sea the salinity conditions at depth seem important to acquire at an early stage. One group also raised concern about redox conditions and colloid content.

5.3.2 Implication for site characterisation programme

Most of the site specific issues listed may only be resolved by one or two deep boreholes, focusing on lithology, water chemistry and rock stress. The holes should be placed inside the site (i.e. being targeted for the "good rock").

6 Organisation

Most groups pointed out the need for SKB to establish sufficient structure, in terms of decision-making and project management organisation, to enable prioritisation of programme objectives, clear demarcation of programme responsibilities and the positive identification of intermediate programme goals. This is particularly essential in order to have any hope of meeting a very tight schedule. It was recognised that the outputs from the Site Investigation work, Repository Design, Safety Assessment, EIA, and Understanding are not easy to assess in terms of how to direct resources but that getting the balance right is at the core of SKB's function.

6.1 Site organisation and central evaluation

Several groups suggested quite similar organisations with different teams at each site but combined with a rather strong central evaluation function. There was a suggestion that the whole programme should be organised in terms of three separate project teams (or commercial consortia). Each of these teams should work through a system of "tool gates" which would be defined in terms of goals by a specified date. This would still require overall decision-making by SKB but would remove SKB from daily management responsibility at the sites. It was recognised that responsibility for development of the Safety Cases would remain with SKB together with responsibility for assessing and communicating the developing site understanding and hence a major portion of public perception.

Another group suggested that a senior technical SKB team be established to overview the various activities and to ensure that the right questions are being addressed and that a local site team with local management be established early. It was believed that while a site team and presence is important it is more important to ensure that each site receives the best technical direction and review available such that the highest level of technical credibility is achieved for each site.

Yet another group suggested a fairly similar organisation. The overall programme being co-ordinated by an evaluation and integration group at head office, the investigations in the individual areas being planned and executed by separate offices, each with a scientific project manager, and the different disciplines at each office being led by each their principle investigator. The evaluation and integration group will need to be a strong element in such an organisation, so that the area offices can be given the independence they need and still remain mutually compatible.

6.2 Integrating Safety Assessment, Design and Site Investigation

One working group raised concern that Safety Assessment and Design might be treated as separate tasks. In contrast, safety assessment should be regarded as an element of Design that everyone contributes to. While Safety Assessment has to play a separate role in the licensing process it is important to establish a culture whereby everyone recognises that each individual contributes to the Safety Assessment process.

It was also recommended that the site characterisation team contain an engineer responsible for designing the repository footprint and layout. It is important for the investigation team to develop an understanding, early in the site characterization process, of how the information being collected and the associated analyses will impact repository design. The interaction of the repository designers with site investigation team should also ensure that critical design issues are addressed early in the site characterisation process, i.e., location of support infrastructure, depth of repository, emplacement room layout relative to stress field, etc.

6.3 Peer Review

Some working groups recommended that an external senior technical review board should evaluate the Site Characterisation process. The board should have specific terms of reference that ensures the technical program is carried out to adequate technical standards.

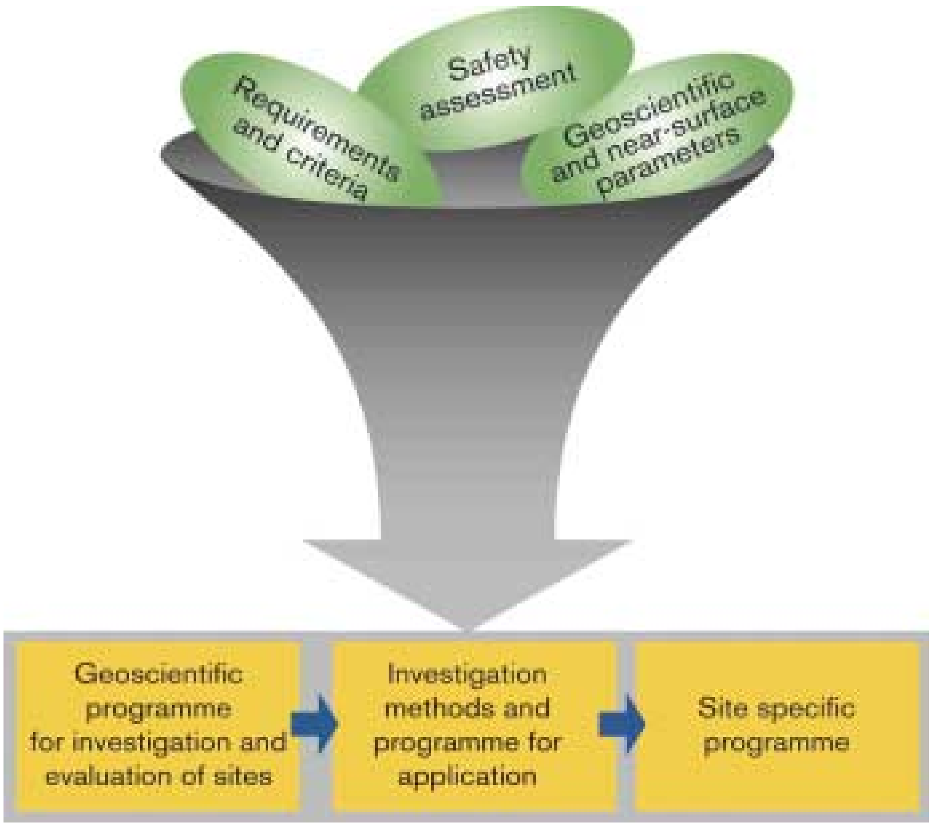
It was also pointed out that it is important that aims and procedures should be transparent and that information collected during the Site Characterisation process be made openly available. The use of the web to make information freely available is an option that SKB could evaluate.

7 Final remarks

The background of the workshop was the current siting process in Sweden and the status of the technical planning work. Many years of planning work resulted in detailed, technical programmes for the site investigation stage made available during 2000 /Andersson et al, 2000/, /SKB, 2000b/. The programme was augmented with more detailed technical descriptions in March this year only available in Swedish and presented at the workshop /SKB, 2001/, see the figure below.

All products so far have been generic, i.e. they still need to be adapted to the site-specific conditions for the three sites of interest. Therefore, it was good timing for having our reports reviewed by a group of international experts and also to get comments and proposals of different kinds and at different levels. The summary of the workshop as presented in this report will be one of the tools providing information for the forthcoming planning work.

SKB's goal is to commence surface based site investigations early 2002.



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