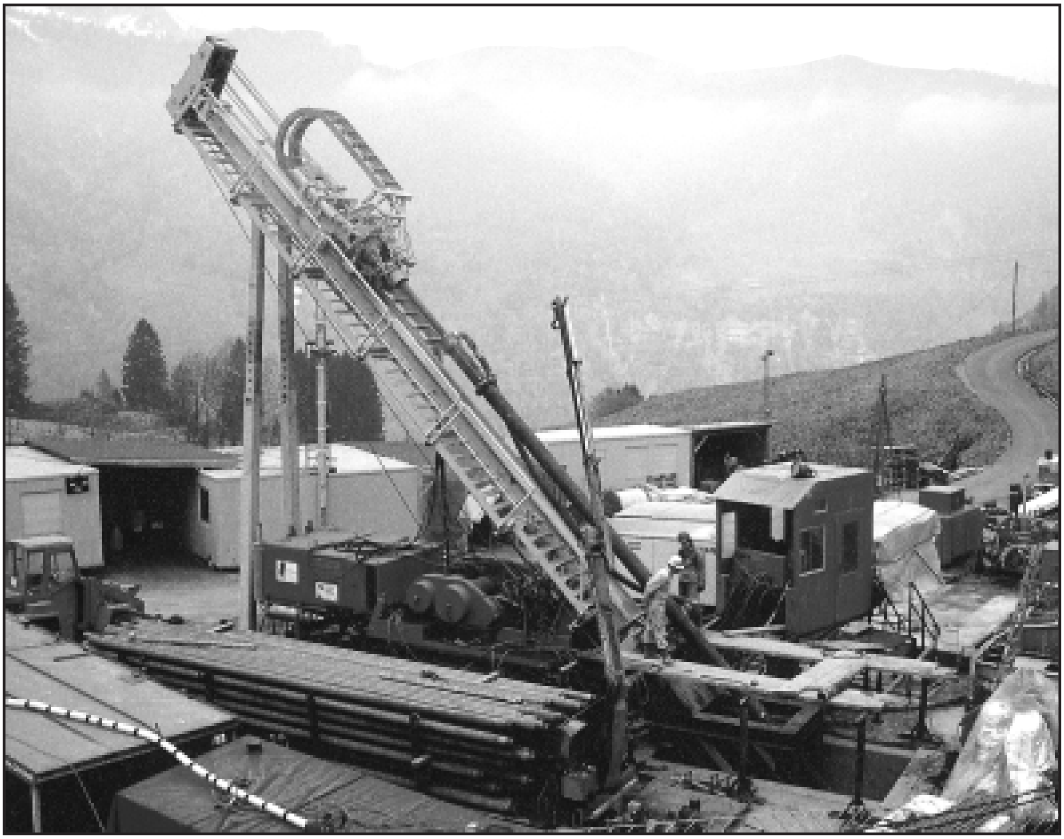

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Hydrogeological Investigation of Sites for the Geological Disposal of Radioactive Waste

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1999

HYDROGEOLOGICAL INVESTIGATION OF SITES FOR THE GEOLOGICAL DISPOSAL OF RADIOACTIVE WASTE

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FOREWORD

There is a far reaching international consensus that high level radioactive waste can be safely isolated in deep geological repositories using a system of engineered and natural barriers. In a normal situation the pathway having the greatest potential for transferring radionuclides to the human environment is transport by groundwater. Therefore, a good understanding of the hydrogeological characteristics of the repository site is important. The range of variation in the properties of potential sites for deep geological repositories is considerable. For example, saturation states can vary from fully saturated to unsaturated conditions. The approaches used to characterize the hydrogeological environment in the various geological media are correspondingly different. However, despite these differences there are certain hydrogeological criteria which must be fulfilled by any potential geological repository.

As part of the subprogramme on radioactive waste disposal, the IAEA has prepared this report which discusses the approaches used in the hydrogeological investigation of repository sites on the basis of experience gained in the Member States on different rock types considered as having the potential to host a repository.

Sixteen experts from the Member States participated in the preparation of this report. The three IAEA staff members responsible for the project are M. Bell, A. Bonne and J.U. Heinonen.

EDITORIAL NOTE

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

A geological disposal system for radioactive waste is a system of natural and engineered barriers whose function is to isolate the waste from humans and the environment. The natural barriers include the host rock and surrounding geological formations, including the groundwater systems and the geochemical systems of the minerals and groundwater. The engineered barriers include the conditioned waste form, the waste package, any external buffer or overpack used to protect the waste package, backfill material (if needed) and seals, placed in the underground openings, boreholes and shafts. Together, these barriers should combine to limit, over sufficiently long time periods, the radiological impact to the levels prescribed by national authorities.

In a geological disposal system, the natural systems provide the environment within which the engineered barrier system must function and also retard the transport of any radionuclides that may be released from the engineered system into the environment. Within the natural system, groundwater plays a major role, since transport in groundwater is generally considered to be the most likely mechanism for radionuclides to reach the human environment. Thus, the hydrogeology is an important factor to be considered in the selection and characterization of a site for a geological repository for radioactive waste.

However, because the time period of concern for isolation exceeds many thousands of years, and since there is no long term past experience to draw upon, the performance of the overall hydrogeological system is addressed using numerical models, which need validation derived from hydrogeological investigations. The decisions regarding disposal, firstly to select a site or sites to be investigated and then to proceed with construction, operation and closure of the repository, will of necessity be made in the face of a number of uncertainties. A hydrogeological investigation programme has to contribute towards progressively reducing these uncertainties and to increase confidence in the understanding of the long term functioning of the disposal system.

Because Member States are considering a variety of geological environments for the disposal of radioactive waste, the hydrogeological systems, the type of uncertainties in the scientific understanding of such systems and the predictions about their future behaviour also differ. Despite these differences, there are certain common criteria that the hydrogeological conditions must fulfil in a geological disposal system. Therefore, similar information regarding the properties of the hydrogeological systems is needed and similar approaches and investigation methods are used to characterize a candidate geological disposal site. Some hydrogeological studies need to be done on a broad regional scale, while others need to be done at the candidate site. This report discusses the approaches followed in the hydrogeological investigation of sites for geological disposal and reflects the experience gained in this matter in a number of Member States.

1.2. OBJECTIVES

The objectives of this report are to describe the functions of the hydrogeological system that are important in the geological disposal of radioactive waste, the major hydrogeological issues being investigated in the different geological media under consideration by Member States and the approaches being taken in Member State waste management programmes to address these issues.

1.3. SCOPE

The scope of this report is limited to hydrogeological investigations for the disposal of high level and long lived radioactive wastes in deep geological repositories. While hydrogeology and the investigation of hydrogeological issues are also of great relevance to the near surface disposal of radioactive waste, these topics will not be treated here.

1.4. STRUCTURE

The report is divided into six sections. Section 2 introduces the multibarrier concept for the achievement of the adequate isolation of radioactive waste from the environment. The specific role of natural and engineered barriers as components of a repository system which as a whole should meet established safety and performance objectives is briefly summarized.

Section 3 discusses the contribution of the geological barrier to repository safety, including the physical and chemical protection of the engineered disposal system (waste and engineered barriers) and radionuclide retardation in the geosphere and dilution in deep and shallow aquifers. It must be ensured that there is enough geological stability to maintain a suitable environment and one that is adequately predictable.

Section 4 provides a focus for hydrogeological investigations which aim to develop an understanding of the overall groundwater regime with the help of conceptual models and to provide input data for performance assessment and for the design of engineered barriers. General guidelines for the development of a methodology for hydrogeological investigations are outlined.

Section 5 reviews the hydrogeological issues specific to different types of potential host formations, namely crystalline rocks, salt formations, argillaceous formations and tuff.

Section 6 identifies particular approaches to the characterization of the hydrogeological system at different scales and at different types of site. The role of underground research facilities, specifically in the four potential host rock formations, is also discussed.

Finally, a compilation of the major issues dealt with in the report is provided in the summary.

2. GEOLOGICAL DISPOSAL OF RADIOACTIVE WASTE

2.1. MULTIBARRIER CONCEPT

To achieve isolation, a multibarrier enclosure concept has been developed. In this concept, several barriers are used to delay or prevent radionuclide migration into the adjacent environment. The multibarrier system as a whole is designed to ensure the isolation of radionuclides in the waste from the biosphere, although the time periods over which particular barriers are of primary importance may differ. Engineered barriers are generally the most important for the initial hundreds to thousands of years, while the natural, geological barriers are of more significance over longer periods of many thousands of thousands of years. The relative importance assigned to each barrier as a function of time depends on the type of waste, the repository design and the site characteristics [1].

2.2. SYSTEMS APPROACH

The concept of multibarrier confinement is based on the use of both natural and engineered components of the repository system to prevent or retard migration of the radionuclides towards the biosphere and to ensure that the protection objectives are met. As stated in Ref. [1], the long term safety of high level radioactive waste disposal must be based on the multibarrier concept and must be assessed on the basis of the performance of the disposal system as a whole.

The multibarrier approach provides defence in depth because the performance of the geological disposal system does not rest on a single component or barrier, but rather on the combined performance of several barriers with built-in redundancy. If a single component or barrier does not fully perform its intended safety function, the overall confinement system must still be more than sufficient to meet the protection objectives.

Total system performance assessments should be used to evaluate the safety of repository concepts and designs [2]. In such assessments the uncertainties regarding the performance of each of these barriers increase with time. Total system performance assessment will, to varying degrees depending on the host rock and the repository design concept, establish the degree of confidence for both the engineered and natural barriers. Performance models should take into account the possible mechanisms through which the engineered barriers may limit the rate of radionuclide release into the natural barrier. These mechanisms could include slow dissolution of the waste form and the physical and chemical control of the immediate environment.

2.3. NATURAL BARRIERS

The existence of natural barriers that can isolate radionuclides from the environment and the long term stability of these barriers are the principal advantages of the geological disposal of radioactive waste. The characterization of a potential disposal site is directed at establishing the favourable and potentially adverse aspects of the geological environment as they relate to the performance of both the natural and engineered barriers. The key characteristics of the geological environment that need to be considered in determining the effectiveness of natural barriers are as follows:

— Physical protection of the disposal system for long periods of time,
— Longevity of the engineered barriers and restriction of radionuclide release from the repository,
— Radionuclide retention on the rock due to sorption and matrix diffusion within the rock,
— Dilution of contaminated water in aquifer and surface waters.

The biosphere is not considered here to be part of the system of natural barriers, although several processes in the biosphere contribute to the retardation or dilution of radionuclides.

Transport in groundwater is an important mechanism for the migration of radionuclides to the biosphere and therefore disposal concepts generally rely on the existence of a geological environment in which the fluxes and/or velocities of groundwater in the vicinity of the repository are sufficiently small to provide adequate isolation. This can be achieved by locating the repository in appropriate geological formations, such as crystalline rocks, salt formations, argillaceous formations and volcanic tuff in the unsaturated zone.

Many of the attributes of such formations and their adjacent geological formations can contribute to providing the required isolation of a radioactive waste repository built in them.

2.4. ENGINEERED BARRIERS

Engineered barriers are components of the disposal system made during construction, operation or closure of a repository. They include the waste form or matrix, the waste container or package, the buffer mass or backfill, and the seals. These engineered components are designed to provide confinement of the waste radionuclides for a period of several hundred to a few thousand years. After that time they are likely to be degraded, allowing penetration of groundwater to the waste material.

To predict the effectiveness of the engineered barriers quantitatively, as a function of time, information is needed about their physical and chemical properties as well as the geological processes that may cause changes in those properties. Important hydrogeological data needed for the design of engineered barriers include the flow characteristics and chemistry of groundwater in their vicinity.

3. FUNCTION OF THE GEOLOGICAL BARRIER IN A DISPOSAL SYSTEM

3.1. INTRODUCTION

The direct contribution of the geological barrier to repository safety can be briefly summarized as:

— Protection of the engineered disposal system (waste and engineered barriers)
— Radionuclide retardation in the geosphere and dilution in deep and shallow aquifers.

When disposal is considered in an environment that currently satisfies these requirements, it is necessary that containment will not be compromised in the future. This requires geological stability sufficient to ensure that the future geological environment remains suitable and is adequately predictable.

3.2. PHYSICAL PROTECTION OF THE ENGINEERED DISPOSAL SYSTEM

Protection of the disposal system from external influences is ensured in suitable geological formations by the following factors:

— The thickness of the overburden protects the repository from intentional or accidental human intrusion (minimized by the absence of extractable resources in the host rock), from sabotage and from other external influences (e.g. acts of war).

—The deep location of the repository protects the technical barriers and the waste from the effects of erosion by water and ice, and also minimizes the effects of extreme events such as earthquakes.
— Siting of the repository in a tectonically inactive area enhances the long term mechanical integrity of the engineered barriers and the stability of the geological barriers.

In general, the effectiveness of isolation increases with depth. However, the depth chosen for a repository must be balanced against practical constraints related to engineering considerations, operational safety and cost.

The potential for various natural events and processes also has a major influence on the depth chosen for a repository. Where a return to glacial or periglacial conditions is likely during the period of interest for a repository, glacial erosion could remove some thickness of the overlying rocks, or permafrost could extend to a considerable depth. Climatic changes in general can have major effects on the groundwater flow system, including increases in precipitation and recharge, a rise in the elevation of the groundwater table, a lowering of the sea level and the alteration of the groundwater recharge patterns because of partial or permanently frozen ground. For these reasons, disposal at a depth sufficient to prevent exhumation of the repository by glacial action or other erosional processes and to reduce the influence of climatic changes on the groundwater flow system can be an important consideration. For repositories sited in the unsaturated zone, the timing and magnitude of climate induced changes in water table elevation are important factors in depth selection.

Apart from large scale and gradual natural events, such as uplift and erosion, there are some other kinds of natural event that could influence the long term stability of the geological environment, and hence the performance of the repository system. Igneous activity and its associated heating are examples of events that could cause direct and peripheral disruptions to the repository system. Knowledge to date indicates that the occurrence of such events will be limited to certain areas during the time period of concern. Therefore, it is considered that the impact of such events could be avoided or minimized by careful siting of the repository.

Other tectonic phenomena of particular importance to physical isolation for the near surface parts of a repository are vibratory ground motion and surface fault movement. They can also have an effect on engineered barriers. It has been well established in Japan and elsewhere that damage caused by seismic events generally decreases with depth [3]. However, uncertainty remains about the effect of seismic events on the groundwater flow system and about the time needed for the system to return to its previous state following an event.

Neotectonic deformation and its potential effect on erosion are also considerations in evaluating physical isolation. In many areas, uplift or subsidence is occurring now or could occur in the future, for example as a result of general tectonic deformation or glacial unloading. The effects of uplift or subsidence depend on the location of the site and the local topography, but could include flooding and either an increase or decrease in the rate of erosion. Thus, the depth to the repository could change and the groundwater flow system could be affected. Sea level changes could have similar effects.

The information needed to evaluate the above factors for a specific site can be obtained through site characterization.

3.3. CHEMICAL PROTECTION OF THE ENGINEERED DISPOSAL SYSTEM

The geochemical conditions and processes in the host rock serve as a barrier by providing an environment that slows or prevents the degradation of engineered barriers and limits the rate of mobilization and transport of radionuclides when they are released from the repository.

In general, the engineered components of the repository are designed to be compatible with the geochemical conditions in the host rock. This is particularly important for ensuring that the engineered structures will perform as expected for long periods of time. For those materials being considered for the engineered components of the repository in most countries, the most favourable geochemical conditions include a relatively high pH, a reducing environment, buffering by minerals in the rock and low concentrations of complexing organic compounds.

Work is progressing on the expansion and rationalization of geochemical databases [4] and on the verification of codes [5] for modelling both rock–water interactions and radionuclide speciation and solubility. These models have yet to be validated, but international co-operation efforts in this respect are under way.

Recently, software programs have been developed and are being further extended for coupling geochemical and transport codes [6]. Although existing codes are adequate for modelling transport, coupling would represent an improvement in the realism of the model.

3.4. RETARDATION IN THE GEOSPHERE — THE ROLE OF HYDROGEOLOGY

The IAEA Safety Guide on Siting of Geological Disposal Facilities [7] provides guidance for identifying and selecting suitable geological disposal sites. Site features will provide a natural barrier that, together with the engineered barriers, isolate the waste from humans and the environment. The Guide recognizes the particular importance of the natural barrier in the disposal of long lived waste. At the same time it is emphasized, however, that the system of natural and engineered barriers has to be considered as a whole. Flexibility in the disposal system is seen as an important factor, so that it is possible to compensate for uncertainties in the performance of one component by placing more reliance on another.

Those site selection guidelines that are related to the geological environment refer to the geological setting, future natural changes, hydrogeology and geochemistry. With regard to the hydrogeology, the Guide states:

> "The hydrogeological characteristics and setting of the geological environment should tend to restrict groundwater flow within the repository and should support safe waste isolation for the required times."

In other words, the geological barrier, and in particular the host rock or formation, should provide conditions, by their characteristics and setting, that tend to restrict water flow over long periods of time.

For most geological disposal concepts, the mechanism having the greatest potential for the release of radionuclides into the biosphere is transport by groundwater, and hence the characteristics of the hydrogeological environment in which the repository is located are of prime importance. The preferred hydrogeological environments for waste isolation are likely to be characterized by groundwater flow paths along which flow takes a considerable time. Very long groundwater 'transit times' can result from both short flowpaths with very slow flow as well as very long flow paths with more rapid flow. Ultimately, however, the role of hydrogeology in disposal concepts is to provide a context for describing and predicting the transport of radionuclides.

4. FOCUSING HYDROGEOLOGICAL INVESTIGATIONS

4.1. AIMS

The previous sections have described the general principles of multibarrier containment and the role of the geological barrier in providing a suitable environment. To provide a focus for hydrogeological investigations, broad aims can be identified which illustrate their role in determining the suitability of the potential site:

- Develop an understanding of the overall groundwater flow regime and chemical environment at the site in order to establish the credibility of decisions made on the basis of simplified representations (e.g. in a performance assessment);
- Provide the necessary input to enable groundwater flow within the geosphere to be represented within a performance assessment of the system (these input requirements will be dependent on the methods selected for conducting a performance assessment);

— Provide data on groundwater conditions (hydraulic and hydrochemical) which may affect construction and investigation methods.

All of these aims are interrelated. Figure 1 summarizes the relationship between them. The development of a credible understanding of the groundwater flow regime is of fundamental importance to achieving the other aims in a defensible manner. It requires the development of a set of assumptions regarding the site (conceptual models), mathematical simulations of flow and transport at the site to feed into the performance assessment and a robust database of information. These are outlined in more detail below.

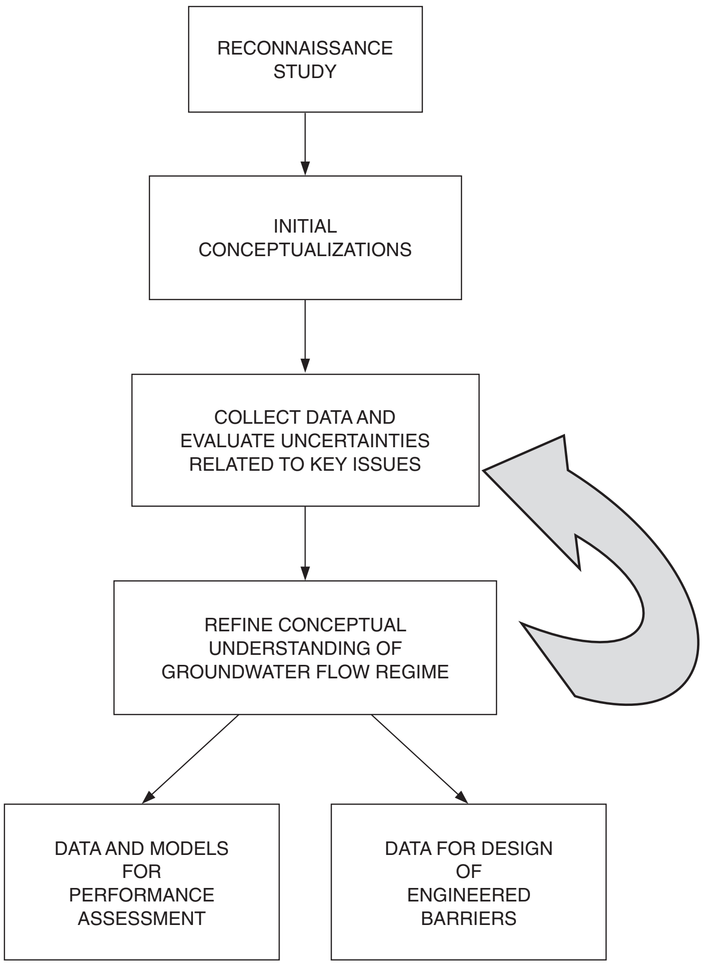

FIG. 1. Flow diagram of hydrogeological investigations and aims.

4.2. UNDERSTANDING THE CURRENT GROUNDWATER REGIME

4.2.1. Conceptual models

4.2.1.1. Application

Conceptualization of the groundwater flow regime is an important aspect of the hydrogeological investigations as it provides a mechanism for structuring views regarding the behaviour of the site. It also permits identification of those aspects of the groundwater flow system where views differ because of high levels of uncertainty. Conceptual models represent an understanding of the groundwater flow regime at any point in the investigations.

Conceptualization can be achieved by developing a series of linked hypotheses for the groundwater flow processes and parameters, geological structures, limits to the regional flow system and boundary conditions considered plausible at the site. These should ideally be consistent with the data available at the time of conceptualization. Relationships (or lack of them) to the geological features and processes observed at the site also form part of this conceptualization. Once an understanding of the groundwater flow system has been structured into a conceptual model, the hydrogeological investigations can be focused in order to test the hypotheses within the conceptual model. Conceptualization may require a range of alternative conceptual models to be established, particularly in the early stages of the investigations, when data and interpretations are sparse.

As the hydrogeological investigations proceed, the range of conceptual models will change to accommodate new data and understanding. In general, this should result in a reduction in the range of plausible conceptual models and increased confidence in the groundwater flow processes, limits and boundaries. The conceptual model, therefore, provides a useful tool for demonstrating increased understanding of the groundwater flow regime as the hydrogeological investigations proceed.

A number of factors are generally considered in describing the current groundwater regime. These relate to the hydrodynamics of the site, the hydrochemical environment and an integrated interpretation, which can improve the plausibility of the conceptual model and enable an assessment to be made of the state of evolution of the groundwater flow regime over time.

4.2.1.2. Hydrodynamic considerations

Assumptions regarding the flow processes in operation at the site need to be established within a conceptual model. These should be sufficiently comprehensive that a numerical simulation of the system or parts of it can be developed. This requires consideration of many aspects, including:

— Overall system evolution and geodynamic processes;
— Driving forces (e.g. gravity, density, osmosis);
— The extent of the flow system and the nature of its boundaries;
— The geometry of different flow units within the overall flow system and any relationship to observable geological features;
— Flow properties (e.g. transmissivity, porosity, flowing fracture frequency) to describe flow within the flow units;
— The nature of flow within the different flow units (e.g. contribution from matrix, role of fractures and joints);
— Patterns and trends in the flow properties within the flow units (e.g. decrease with depth) with a description of the cause;
— The nature of flow between the different flow units;
— The relative contribution to overall flux provided by different flow units.

The range of assumptions established for hydrodynamic phenomena will vary at different scales. This may result in a different level of emphasis or detail being applied to different elements of the conceptualization as the hydrogeological investigations proceed.

4.2.1.3. Hydrochemical considerations

Hydrochemical considerations can be used to establish a number of key elements in the overall understanding of the groundwater flow regime:

— The distribution of major groundwater types within the regional flow system and the mixing relationships between them;
— The provenance of major groundwater bodies (e.g. location of recharge and climatic conditions during recharge);
— The broad chemical environment into which the potential disposal system would be emplaced and the level of chemical equilibration achieved prior to construction;
— The groundwater residence times;
— The heterogeneity arising from different water–rock interaction processes occurring in the fractures and in the matrix;
— The potential perturbations to the chemical system which may have already occurred or which could result from hydrogeological investigations from both surface and underground excavations.

4.2.1.4. Integrated interpretation

Integration of both the hydrodynamic and the hydrochemical considerations can enhance the conceptual understanding, particularly if combined with a general knowledge of the geology. The regional distribution of groundwater types, evidence of residence times and provenance can be used to provide an independent check on the hydrodynamic considerations identified in Section 4.2.1.2. For example, are the hypothesized flow processes supported by chemical indications of mixing lines? Is the division of flow between fractures and matrix corroborated by heterogeneity in groundwater chemistry? Do the inferred groundwater residence times in a particular flow unit support the rate of flux to be inferred from the description of flow properties?

Indications of heterogeneity may be observed in geological, hydrochemical and hydraulic properties. Combining all the evidence of heterogeneity can provide additional information on how physical differences in the rock can control flow patterns. Corroboration of heterogeneity (at whatever scale) can build added confidence in conceptual hypotheses developed on the basis of a single data set.

Combining the chemistry and the hydrodynamics also enables the state of evolution of the site to be assessed. Different aspects of the groundwater flow regime will respond to geological and climatic changes at different rates. In low permeability rocks it is unlikely that all elements of the system will be in equilibrium with the current conditions. The system should be considered as a continually evolving environment, which in some cases may still be responding to events which occurred several tens of thousands of years ago. The current groundwater regime should be understood in the context of this evolution.

Steady state models, based on hydrodynamic properties and features observed under the current conditions, generally represent a transient state (a snapshot in time) between the past and some future condition. Indicators such as pore pressure or hydraulic head may not be in equilibrium with the current conditions and it is commonly found that steady state hydrodynamic models cannot reproduce observations of present day hydrochemistry. The hydrogeological investigations of the site, and the conceptual models which support them, should attempt to evaluate the palaeohydrogeological evolution of the site to the present day and should identify the extent of equilibration of key hydrodynamic and hydrochemical parameters with the currently observed conditions.

4.2.2. Mathematical models

The conceptual models can be used to develop mathematical models to simulate flow and transport processes, given the assumptions presented in the conceptual model. These mathematical models are used in the hydrogeological investigations as tools to develop and quantify the characterization of the groundwater flow regime within a given region, using available measurements. The mathematical models can be used in both an interpretive and a predictive manner.

As an interpretation tool, the models can be used to discriminate between the various plausible concepts in order to interpret data (e.g. could a hydraulic boundary or connection exist in some areas; should hydraulic conductivity values vary strongly with depth?). For predictive modelling, the hydraulic characteristics of the groundwater flow regime are quantified on the basis of assumptions given in the conceptual model (e.g. what is the magnitude of groundwater flow in an area; what are the flow directions and lengths?). These results form the basis for providing input data to the performance assessment of the geosphere barrier.

Mathematical models help to illustrate and quantify the uncertainty that exists at any point in time for critical performance assessment input parameters, as well as the impact of this uncertainty on the predictions. However, confidence in the accuracy of the output is dependent on the ability of the mathematical model to reproduce the conceptual model on which it is based. Additionally, the confidence with which the modellers can structure and input data, and formulate algorithms also affects the adequacy of the mathematical model.

4.3. FORWARD PREDICTIONS

The hydrogeological investigations should aim to provide as much information as possible on the future evolution of the groundwater flow system in terms of its foreseeable consequence on underground circulation and the possible dilution process. On the basis of this information, the performance assessment of the geosphere barrier will have to make predictions about the future evolution of the site and the groundwater flow regime.

Understanding the palaeohydrogeology of the site (Section 4.2.1.3) is important in this respect. The chemistry, and variations in hydraulic head, can therefore be used to understand flow processes and driving forces which could have operated in the past on the sort of time-scales over which a performance assessment will have to predict into the future.

The different factors which may affect the evolution of the groundwater flow system are:

— Climatic changes and their effects, of which glacial/interglacial cycling is particularly important. The effects to be examined include: pluviometry variation, erosion rate, sedimentation rate, base level changes, recharge and discharge processes.
— Different tectonic factors causing overall vertical movements and their combined effects: reactivation of faults and fracture systems, diapirism (in bedded salts) and seismicity.
— Anthropogenic effects due to resource exploitation.

4.4. METHODOLOGY

On the basis of the preceding sections, some general guidelines for developing a programme of hydrogeological investigations can be identified. In particular, the focusing of hydrogeological investigations to address key questions or issues is a useful approach, as it can reduce unnecessary expenditure.

There is a requirement for iteration between the conceptualization of the site and the collection of data to improve understanding. This iteration should be frequent and ongoing and is illustrated in Fig. 1. In this way, key questions can be raised as a result of considering the range of conceptual models and the areas of most significant uncertainty. Detailed data collection or mathematical modelling requirements to address those key issues can be identified. In the absence of this focusing, there is a possibility of collecting inappropriate data, or of not identifying and resolving issues which have an impact on performance assessment.

The use of a conceptual model, or range of models, to evaluate data may influence the way the data are interpreted and the conclusions drawn. For this reason, it is advisable to commence hydrogeological investigations with a wide range of plausible conceptual models. In this way, bias in the interpretation of data can be minimized.

Mathematical modelling of the assumptions identified in any conceptual model provides a mechanism for transferring the hydrogeological understanding into the performance assessment, which can be used to evaluate the risk associated with the hydrogeological uncertainties.

It is important for the credibility of the programme that the understanding of groundwater flow in the immediate vicinity of a proposed disposal facility is placed in its regional and geological context. As a result of this, a range of scales needs to be studied within the hydrogeological investigation programme, as illustrated in Fig. 2.

In order to structure hydrogeological investigations and to facilitate modelling of the system, the range of scales is commonly divided into three categories:

— Regional: the scale on which large scale geological evolution processes are operating.
— Area: the scale which establishes the boundaries to the regional flow system and the location of potential discharges from a repository. This scale is commonly used in the siting process.
— Site: the scale on which the physical characteristics of the potential flow paths from the repository into the regional flow system needs to be established, and the scale on which interaction between the natural and the engineered barriers may occur.

An example of this categorization is given in Fig. 2.

This categorization into three scales can mask the fact that hydrogeological investigations should be conducted on a continuum of scales, and that the actual extent of the geological framework, the regional flow system and the zone of influence of the engineered system will be very dependent on the disposal concept and the nature of the site.

The process of investigating a site needs to ensure the development of understanding and increasingly confident conceptualization, as well as accommodating the

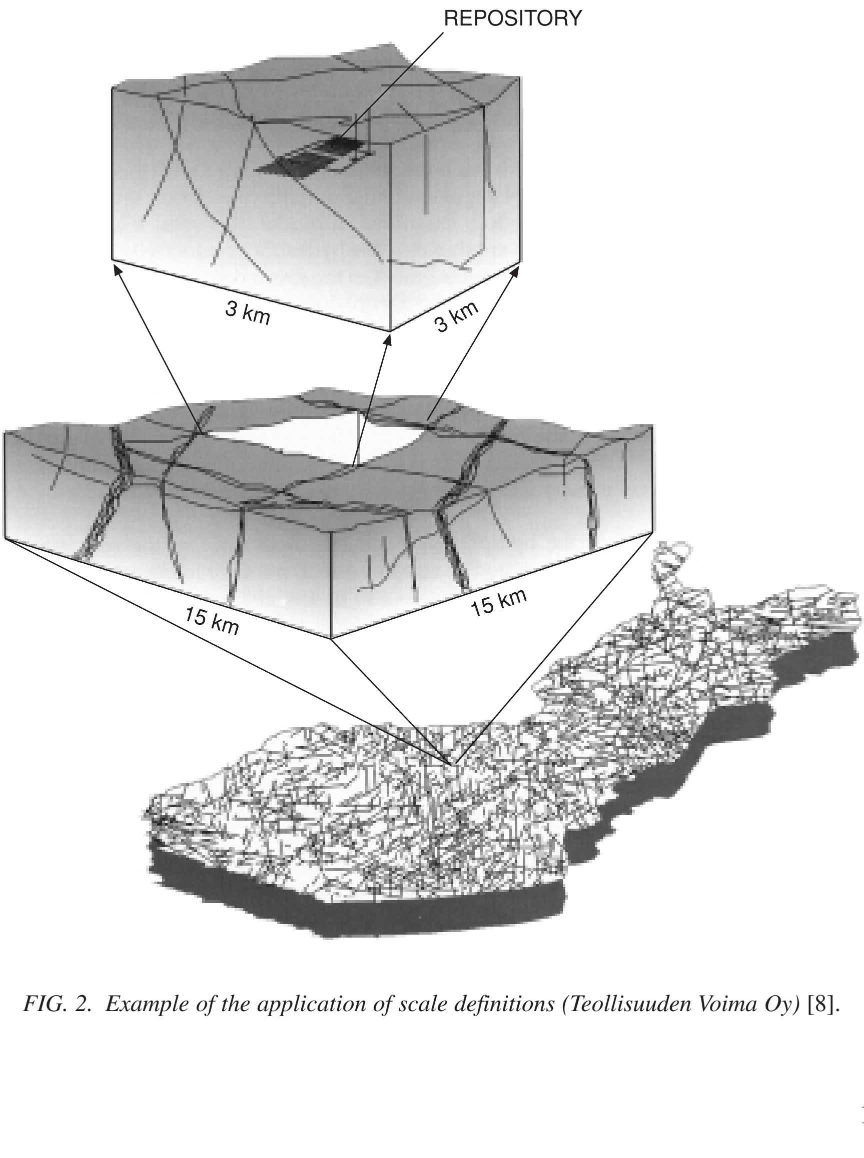

FIG. 2. Example of the application of scale definitions (Teollisuuden Voima Oy) [8].

fact that the process of collecting data may alter the behaviour of the site. A number of sequential steps in the process can therefore be identified:

- — Description of the undisturbed site conditions;
- — Prediction of the induced changes to the site conditions resulting from characterization, construction and operation;
- — Monitoring of the induced changes and the iterative modification of the prediction;
- — Description of the final, disturbed conditions;
- — Prediction of the long term evolution of the hydrogeological system.

The following sections discuss some of the issues specific to different host rock environments and present in more detail possible approaches to hydrogeological characterization activities.

5. HYDROGEOLOGICAL ISSUES IN DISPOSAL SYSTEMS

5.1. INTRODUCTION

Information from hydrogeological investigations is needed for a variety of purposes, all of which are related in some way to achieving the safety objective of the repository. The information is used in:

- — Establishing the baseline hydrogeological and hydrogeochemical conditions at the site,
- — Developing the design of the repository,
- — Developing models of groundwater flow and radionuclide transport for the evaluation of the long term performance of the repository.

As mentioned before, investigations for the characterization of the hydrogeological system are required at different scales and at each of these scales they need to a certain extent to be integrated with other geoscientific studies or approaches such as surface hydrology, structural geology and tectonics, geodynamic studies and palaeoclimatology. An example of the significance of an integrated approach is the fact that the distribution of major structural features and the tectonic forces acting upon a host formation at a particular site could affect the hydrogeological and hydrogeochemical conditions at the site.

There are several issues common to all potential host formations and their surrounding formations that need to be addressed by the hydrogeological investigations at the site:

- The groundwater regime (recharge, discharge and flow) under natural conditions;
- The hydrodynamics (features, processes and boundary conditions controlling flow) under natural and disturbed conditions;
- The hydrogeochemistry under natural and disturbed conditions;
- The transport processes and pathways under natural and disturbed conditions.

Since geological formations with low permeability or low water throughflow are being considered for final geological disposal of radioactive waste, it has been necessary to develop appropriate methods, new interpretation schemes and an understanding of processes which previously were not of great interest in the hydrogeological sciences.

In the following sections the issues more specific to the four host formations (crystalline rocks, salt formations, argillaceous formations and tuff) that are being widely considered for disposal are discussed.

5.2. CRYSTALLINE ROCKS

5.2.1. Favourable properties

Several characteristics of crystalline rock have been recognized as being potentially favourable for disposal.

Crystalline rocks have high mechanical strength. Consequently, stable shaft, tunnel and gallery openings can be excavated at depths appropriate for geological disposal. The areal extent and depth of crystalline massifs are usually extensive and these characteristics provide a wide choice of potential sites for exploration.

In general, crystalline rocks are poorly transmissive. Groundwater flows predominantly through interconnected networks of fractures in the rock. Crystalline rocks contain minerals both in the matrix and as fillings along fractures that sorb radionuclides. Transport of many radionuclides will be significantly retarded by sorption. Crystalline rocks have both low matrix permeability and low matrix porosity. Transport through the rock matrix is primarily by diffusion and migration of radionuclides will be greatly retarded. In addition, transport of large molecules through the matrix tends to be prevented by filtration.

Crystalline rocks have very low solubility. Creation of new pathways for groundwater flow or transport by dissolution is not a concern. However, soluble minerals may have been precipitated along fractures in the rock and these could be redissolved.

Crystalline rocks generally have good thermal conductivity. Consequently, any heat generated by the waste can be dissipated so that thermal effects on both the engineered barriers and the surrounding rock will be minimized.

5.2.2. Geological setting

Crystalline rocks were formed at high temperature and pressure either by cooling from a molten state or by the deformation and recrystallization of pre-existing rocks. They occur as individual igneous intrusions (plutons or massifs) or as extensive igneous or metamorphic terrains whose formation and emplacement occurred during various phases of orogeny. They are strong and brittle and commonly show evidence of at least one period of brittle deformation. Although the rock matrix has low porosity and poor permeability, fractures and faults can have high porosity and high transmissivity. The characteristics of the fracturing in the rock is one of the primary distinguishing features between different volumes with significantly different groundwater flow and solute transport characteristics. Since the fracturing results from the tectonic history of the crystalline rock, a knowledge of the structural history often forms the basis for the definition of 'domains' of similar hydrogeological performance.

The pattern of fracturing in crystalline rocks can be described in a number of ways, ranging from fully probabilistic to strictly deterministic. In a fully probabilistic approach, the fracturing (its density, orientation and extent) is described in terms of a particular pattern. No specific fractures are identified. In the extreme, the fracturing is seen as being fractally organized and there is no scale at which the pattern can be averaged.

A more common approach envisages large features (very often fault zones) which are specifically identified within a background region described probabilistically. An example of such a description is given below.

Three domains of fracturing are identified:

- Fracture zones (faults), which are volumes of intensely fractured rock; these domains usually have significant internal variability of solute transport properties.
- Moderately fractured rock, which are volumes of rock containing a small number of sets of relatively widely spaced, interconnected discrete fractures (joints); these domains would usually have a bimodal distribution of solute transport properties, one peak representing the rock matrix, the other the fractures.
- Sparsely fractured rock, which are volumes of rock containing microcracks and very sparsely distributed discrete fractures that are not very interconnected; these domains can have fairly uniform solute transport properties.

An approach similar to the one above, but based on different structural elements, is given in Fig. 3. This also illustrates the commonly used approach of linking hydrogeological properties to the identifiable structural elements. This can be termed a semi-deterministic approach.

Apart from the pattern of fracturing, other aspects sometimes form the basis for defining useful (subsequently hydrogeologically described) domains. Hydrothermal alteration and near surface weathering come into this category. Previous sub-aerial weathering surfaces should also be borne in mind.

Whatever approach is adopted, it is often based on the ability to recognize the structural elements in boreholes and underground excavations. It should be borne in mind that domains often need to be recognized by various forms of remote sensing. In general, gradational boundaries are not easy to identify and heterogeneity is a function of scale. In the end, the approach used to describe fracture structure in crystalline rocks is a balance between uncertainty in recognition and simplicity for subsequent modelling.

5.2.3. Potential for changes

Because of the high strength and low solubility of crystalline rock, there is little likelihood that major water conducting pathways (e.g. fracture zones) will change after a repository is closed. However, a major change in the in situ stresses could alter their relative importance. Addition of tectonic stresses or significant erosion of the rock overlying the repository could provide such a change in regions that were tectonically active. With the exception of active plate margins, crystalline massifs are not expected to experience additional tectonic stresses for many millions of years. In addition, the high strength will provide protection from significant erosion for millions of years.

Significant stress changes could occur if a site were glaciated (additional load), so this would need to be evaluated for sites that could be expected to be affected by renewed continental glaciation within the time period of concern for safety. Rapid stress changes can also occur at active plate margins, such as subduction zones.

Substantial changes in the hydraulic gradients in the hydrogeological system are also unlikely to occur unless there are changes in the pathways, or the in situ stresses, or the area is glaciated or heating occurs. This stems primarily from the fact that the major hydraulic gradients are usually due to topographic relief, which will not change unless erosion takes place or the site is glaciated.

Examination of most crystalline rock sites shows evidence of mineral precipitation within fractures at different times during the geological evolution. Not only does it yield evidence of how fluid flow may have occurred in the past, but it also indicates some of the possible ways in which the rock may interact with leachate from the waste in the future.

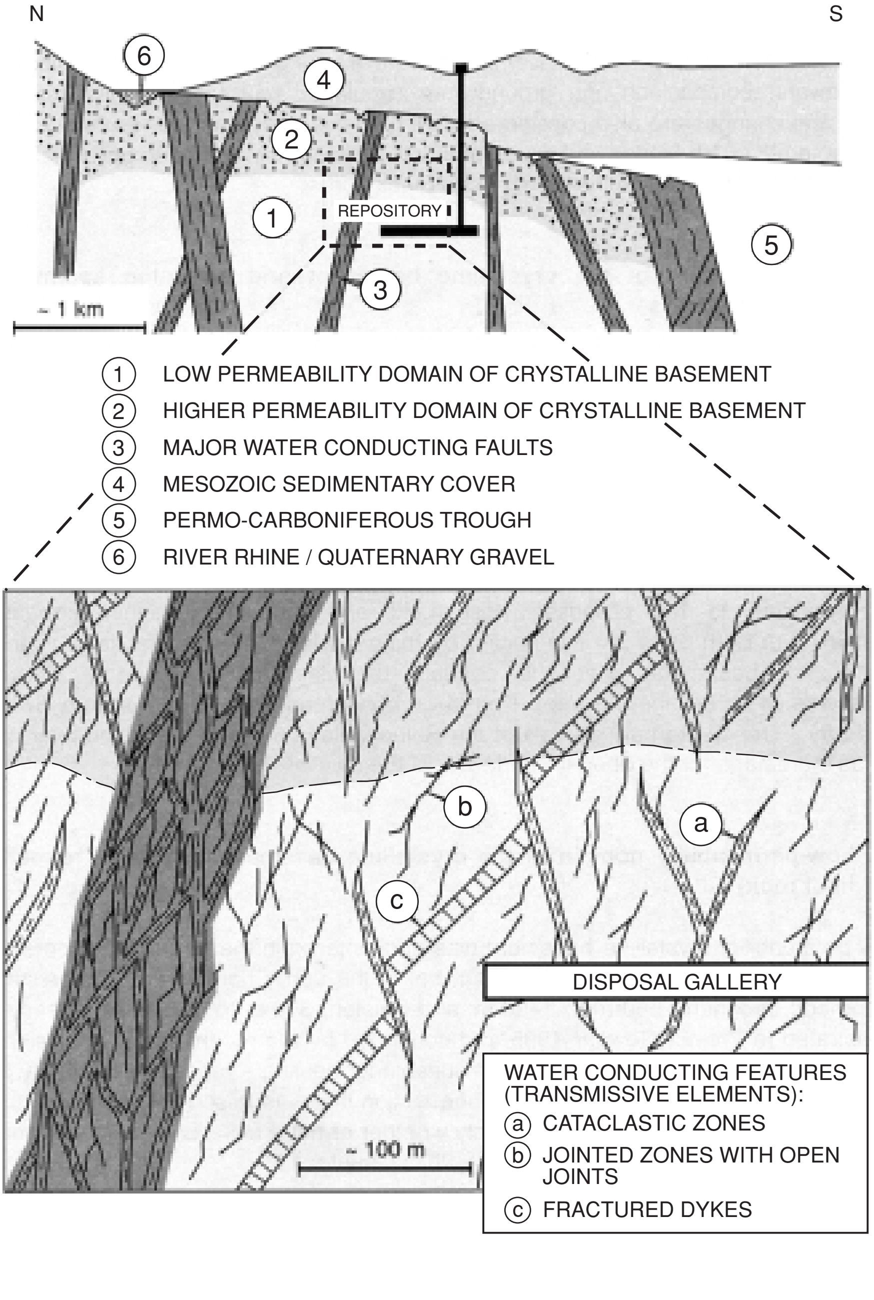

FIG. 3. Conceptual geological model of the crystalline basement of northern Switzerland, area West (Kaisten–Leuggern–Böttstein area) [9].

5.2.4. Specific issues investigated

The major issues for hydrogeological investigations in crystalline rock arise from the presence of fracturing of varying intensity and frequency. It is evident that an assessment of the suitability of crystalline rock sites depends on identifying the different fracture domains, determining the appropriate way to represent flow and transport processes in each domain, and obtaining representative values for the parameters needed to model the processes.

5.2.4.1. Identification of potential flow and transport pathways

The most important pathways for the movement of groundwater in crystalline rock at repository depth are discrete water conducting features (often faults) that cut through the rock and extend over relatively large distances. Intense fracturing is often concentrated in widely spaced, comparatively narrow faults that may extend for distances of several hundreds of metres or even kilometres. These fracture zones may be interconnected with other similar zones. Fracture zones are commonly much more permeable than the remainder of the rock, although significant spatial variations in permeability can occur within them. The permeability variations can cause channel-like patterns of high and low permeability.

Near the surface (200–500 m deep) and adjacent to fracture zones, crystalline rock is also likely to contain networks of individual fractures that are relatively permeable. In some cases, the frequency of joints decreases with depth. At greater depths the rock contains fewer permeable fractures, aside from the large fracture zones and networks of discrete fractures adjacent to them (Fig. 3).

Surface investigations conducted on any scale can generally identify major fracture zones that intersect the surface. Such zones commonly form long, linear or curvilinear topographic depressions or anomalies on geophysical surveys because they represent zones of relative weakness or of different electrical or magnetic properties in the rock. Minor zones may be less readily identified because the topographic depressions associated with them will tend to be narrower and shorter, or completely hidden by overburden. Where there is good exposure, distributions of both moderately fractured and sparsely fractured rock can be readily identified.

At the regional scale, the distribution of major pathways is usually inferred from surface information. On a smaller scale, identification of potential flow and transport pathways at repository depth requires boreholes which should be sited after the completion of preceding geophysical and geological investigations.

Discrete fractures are readily identifiable in core from boreholes and from geophysical surveys run in boreholes. However, identifying specific structural elements, such as fracture zones, requires the establishment of careful, area specific, precise definitions for the examination of borehole evidence. Cross-hole geophysical surveys (either radar or seismic) can identify regions of similar electrical or mechanical properties (usually associated with fracturing) between boreholes. These methods can be effective at interborehole distances of up to about 100 m (radar) and 400 m (seismic), depending on local conditions.

The hydrological properties of features identified can be determined near the borehole by single borehole tests, but continuity of hydrological properties between boreholes must be determined by multiple borehole hydrological interference tests and by longer term observation of variations in hydraulic head with time at many different points in the rock.

5.2.4.2. Representation of flow and transport at different scales

Because the different fracture domains have different hydrological properties, flow and transport within them may need to be represented differently. In addition, the appropriate representation may depend upon the scale of the investigation.

The primary driving forces for flow and transport from a repository in crystalline rock are likely to be the hydraulic gradient, the gradient in solute concentration and the thermal gradient created by the heat generating waste. Other forces resulting from tectonic events may also be significant in some circumstances. The processes that might need to be incorporated in the models representing flow and transport would be advective flow, convective flow, dispersion, diffusion, sorption and radioactive decay. The important parameters would be hydraulic head, transmissivity, temperature, fluid density and viscosity, porosity parameters (total, effective, tortuosity, pore size), sorption parameters and geochemical data.

The transmissiveness and porosity of fracture zones can be highly variable. Although fracturing is intense, alteration of the original rock fragments to clay minerals and shear within the zone can produce regions of low transmissivity. Normal stresses across a zone may also be high, which would tend to minimize fracture apertures. At other locations normal stresses may be very low and effective porosities may exceed 10%. At all scales of investigation, fracture zones would be expected to have a behaviour varying from porous to pipe like.

Fractured rock has two contrasting sets of hydrological properties. The unfractured matrix has a very low effective porosity (<1%) and hydraulic conductivity (10^{-12} m/s). In contrast, discrete fractures have much higher effective porosity and transmissivity, but form a very small proportion of the rock volume. Whether fractured rock can be represented as a porous medium depends on the scale of investigation and the approach to the description of fracture structure. At the regional scale, a porous medium representation is expected to be realistic. At the near field scale, for flow and transport over distances of up to 10 m, it is almost certain that flow and transport should be represented as taking place through a network of discrete fractures. At what point a porous medium representation would become realistic would have to be determined by transport experiments carried out as part of the site specific studies. Transport would be primarily along discrete fractures by either flow or diffusion, depending on the gradients. Diffusion could also take place from the fractures into the matrix.

5.2.4.3. Representativeness of the data (observed values of parameters)

Site investigation methods using boreholes can disturb the natural hydrogeological system at a site. In addition, construction and operation of the repository will disturb the system. An essential component of the site studies would be to determine what the natural system was before it was disturbed significantly and to observe the disturbance as it occurs. This could be achieved by installing instrumentation for monitoring the hydraulic head and by taking water samples in every borehole as soon after drilling as practicable. This would minimize the disturbance caused by the borehole and provide a means of observing the disturbance caused by subsequent boreholes or excavation. The representativeness of the data is dependent on the temporal and spatial sampling density.

5.3. SALT FORMATIONS

Rock salt was the first geological medium to be suggested (1957) for the disposal of high level radioactive waste [10]. Salt formations considered for disposal essentially consist of the mineral halite (NaCl). In spite of their high potential solubility, salt formations exist in huge accumulations, which have remained protected from dissolution by water for millions of years.

5.3.1. Favourable properties

From the hydrogeological point of view, the main advantages of the salt formations are:

- Extremely low permeability to water and gas;
- Very low water content, either in the mineral structure (absence of hydrated crystallization) or in the texture (presence of very small volumes of fluid inclusions);
- Relatively high plasticity that increases with temperature and pressure and provides the possibility for the self-sealing of fractures and void spaces.

The low permeability and water content are due to a very low and discontinuous porosity of salt rocks.

Other favourable properties of the salt include its high thermal conductivity and good mechanical properties, the latter property contributing to the ease of excavation and the production of large cavities.

To these attractive intrinsic properties, it should be added that many salt formations are located in stable geological areas with very little earthquake activity. The considerable thickness of some salt deposits also attests to the stable geodynamic conditions during sedimentation over several millions of years.

5.3.2. Geological setting

Salt formations belong to the evaporite suite of rocks and comprise a class of sedimentary rocks resulting from the evaporation of saline waters. Most evaporites are derived from bodies of sea water, but under particular conditions (very large continental basins), lakes may provide notable accumulations of continental evaporite deposits. However, the most important salt deposits, which provide an adequate thickness for potential use in waste disposal, are of marine origin.

Evaporites of this kind begin to form when sea water is concentrated to about 50% of its original volume. Formation of minerals then takes place by the precipitation of dissolved elements from the saturated brine in the reverse order of their solubility:

— Carbonates: limestone and dolomite
— Sulphates: gypsum and anhydrite
— Halite
— Sodium, potassium and magnesium salts: carnallite, sylvite, kieserite, etc.

Having been generally deposited in large, closed and tranquil basins, evaporite formations therefore comprise a succession of subhorizontal, well stratified layers. The texture and mineralogy of each layer reflects the geochemical and climatic conditions prevailing during sedimentation. Together with the crystallization processes, halitic rocks are always characterized by the presence of fluid inclusions, which generally correspond to remnants of the primary brine, but which may also contain more recent water, a testimony to groundwater migration.

After deposition of the evaporites, according to the geodynamic and geochemical changes in the environment, other sediments such as sands, clays and marls may be deposited on top.

If the difference between the specific gravity of the evaporite layers and the overlying formations is not significant, and if there are no local differences in pressure, the evaporite formation may retain its original subhorizontal shape (bedded salt formations). Conversely, a disequilibrium in the overlying pressure could result in halokinesis effects, which lead to the deformation and uplift of the salt to form pillows, domes and diapirs.

Figure 4 shows a cross-section of the Gorleben salt dome in Germany, which is currently being investigated as a potential site for the disposal of high level waste. Figure 5 shows the stratigraphy of the Waste Isolation Pilot Plant (WIPP) site in the United States of America, which is a bedded salt formation.

5.3.3. Potential for changes

5.3.3.1. Natural evolution

The future evolution of the geological environment and its foreseeable consequences on the underground circulation should be carefully assessed as such evolution could lead to the activation of dissolution processes in the saline formation.

From this standpoint, the possible changes must be studied with regard to the combined effects of climatic fluctuations (i.e. increase of pluviometry and groundwater circulation in the surrounding formations), the general geodynamic evolution and the different tectonic factors which could affect the region and may cause an overall vertical movement of the formation.

5.3.3.2. Induced effects

The disposal of radioactive waste may itself induce effects (heating, radiolysis) in the behaviour of the salt formation, owing to changes in the properties of its constituents. As a consequence, the following are being studied:

— Thermal effects:
  mechanical (creep, diapirism);
  corrosion phenomena;
  brine migration;
— Radiolysis effect and gas generation.

Furthermore, specific problems linked to the construction of the underground facilities must also be considered. Owing to the possibility of dissolution, particular attention must, for example, be given to the construction and isolation of the different facilities (particularly the wells and access shafts) in order to avoid any artificial communication between aquifers through the saline formation.

5.3.4. Specific issues investigated

Salt formations possess very favourable intrinsic properties. Their suitability for radioactive waste disposal will, however, depend on the characteristics of the host rock itself and its surrounding formations. The main problem relating to the siting of

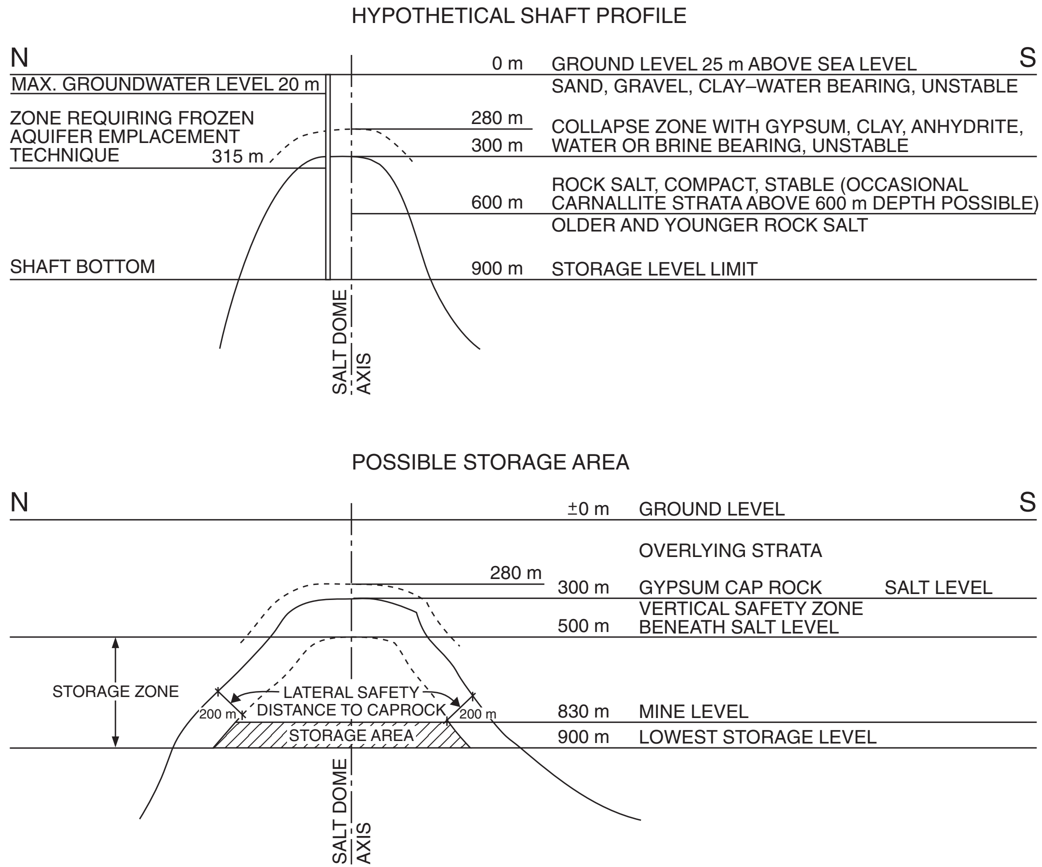

FIG. 4. Cross-section of the Gorleben salt dome in Germany. The dome is made up of a variety of evaporite minerals, e.g. halite, anhydrite and carnallite [11].

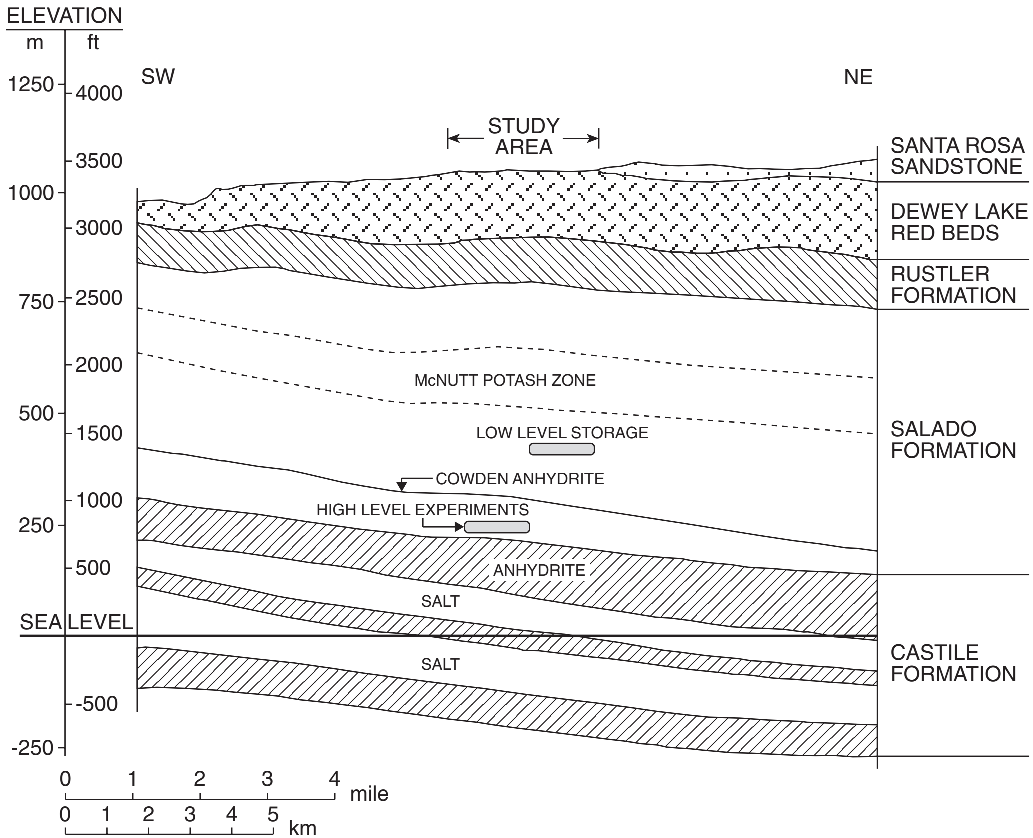

FIG. 5. Geological section showing the stratigraphy of the WIPP area [12].

a salt repository is linked to the dissolution process. Consequently, one of the main issues lies in the demonstration of the present and future isolation of the salt formation from its environment, and particularly from the water which may move in the surrounding and adjacent formations.

The studies should therefore involve not only the salt formation but also, necessarily, the regional hydrogeology as well as the geological structures, in order to assess all the hydrodynamic features liable to affect the salt formation, now or in the future.

At a smaller scale, the composition of the fluid inclusions may serve as an indicator of the crystallization conditions and as a testimony to the past groundwater circulation. The study of fluid inclusions is also of value in the investigation of the fluid migration processes under thermal gradients.

5.3.4.1. Bedded salt formations

It is important to be certain that the bedded salt formation is not currently undergoing dissolution or to be able to demonstrate that dissolution has only affected a small proportion of the total volume of the formation.

(a) Issues related to the saline formation itself:

 (i) Mineral heterogeneities in the formation may locally form particular textures (e.g. phenoblastic) which could play a role in the migration of fluids at a small scale.
 (ii) The presence of well defined interstratified non-saline strata in the evaporite formation may have important consequences on the possibility of underground water flow:

 — Gypsum may provide a significant amount of crystallization water as a consequence of thermal effects.
 — Anhydrite and carbonate rocks, being more brittle and permeable than the halite strata, can be considered as potential pathways for groundwater.
 — Clay and marls, on the contrary, constitute natural barriers to the development of dissolution processes and groundwater flow.

(b) Issues related to the surrounding and adjacent formations:

 (i) The overlying strata should be impervious enough to protect the salt from infiltration by surface water.

 (ii) The first information to be acquired concerns the geometry and lithological nature of the different layers of the overlying formation (aquifers and aquicludes). Detailed data should be obtained on the lateral variability and structural features (presence of faults and fractures).

(iii) The hydrodynamic parameters (porosity, hydraulic conductivity, transmissivity, etc.) and hydrochemistry (including isotopic composition) have to be determined for each aquifer. Particular attention must be given to the first, low permeability layer in contact with the salt formation, taking into account the fact that it provides the hydrological isolation against dissolution processes.

(iv) The past and/or present indices of dissolution must be carefully sought. In spite of the real difficulties in the precise quantification of the dissolution processes, valuable information may be acquired from detailed geological and hydrogeological studies:

— Morphological expressions at the ground surface of dissolution processes in deeper formations (e.g. collapse structures and dissolution pipes) and petrographic relics of dissolution in rocks overlying evaporite deposits, should be sought through geological investigations. Precise localization and measurement of the size of these features will provide a semi-quantitative estimate of the magnitude of the dissolution processes. Furthermore, the interpretation of these figures must be made in terms of the dating and the origin of the dissolution episodes in accordance with the general knowledge of the tectonic and geodynamic evolution of the region.

— Determination of the hydrological balance of the overlying aquifers will be carefully investigated in order to obtain an estimate of the effective infiltration and possible vertical drainage. Hydrogeological studies will also be concerned with all saline aquifers and saline springs in the region. Particular attention will be paid to chemistry and isotopic composition in order to approach the saline balance.

5.3.4.2. Salt domes

The main issues concerning salt domes are generally identical to those for bedded salt formations. In addition to the issues mentioned in the previous section, attention should be paid to the particularly complex internal structure of salt domes and the overlying strata. Detailed surveys of the structure should be carried out in such a way as to recognize major discontinuities which could occur in the dome, as well as to locate the more homogeneous zones in order to avoid strata (e.g. anhydrite and carnallite) that are likely to create flow paths under certain conditions.

Since the caprock plays an important role in the isolation of the salt from the circulating groundwater, its continuity has to be verified. The hydrochemical signature of the caprock enables an understanding to be gained of the dissolution process from the past to the present.

Owing to the effects of halokinesis, the overlying sediments have experienced the effects of condensation, erosion and faulting which can create complex geometrical and hydrogeological conditions.

5.3.4.3. Regional hydrogeological features

In order to assess the problems, a comprehensive review must be made, including:

— Geometry for all formations at the regional level;
— Position and continuity of deep faults;
— Presence of major lithological discontinuities;
— Hydrogeological balance at the scale of each catchment area so as to obtain an estimate of the effective infiltration at the outcrops of the confined aquifers;
— Determination of the recharge and discharge zones;
— Relationships between aquifers;
— Geological characteristics of the aquifers and aquicludes (lithology, morphology, continuity, etc.);
— Distribution of the hydraulic head in the different formations (aquifers and semi-permeable formations);
— Hydrodynamic parameters (porosity, hydraulic conductivity, transmissivity, etc.);
— Hydrochemistry and isotopic content of the different types of water;
— Continuity of the caprock formation.

Owing to the large rise of bedded salt basins, one of the main difficulties lies in the location of the actual zones of recharge and discharge of the different aquifers. Another difficulty is the determination of the hydrogeological conditions at the lateral limits of the saline formation. Bedded saline formations, for instance, are very often located in subsiding sedimentary basins delimited by complex structural features and abrupt variations in lithology (Fig. 5).

5.4. ARGILLACEOUS FORMATIONS

5.4.1. Favourable properties

Depending on the induration and the water content, the formation may consist of plastic or less plastic clays. The favourable hydrological properties are essentially:

very low hydraulic conductivity, high sorption capacity for dissolved cations, effective filtration capacity for colloids and large molecules, low solubility of the clay constituents, and in the case of plastic clays a self-healing property which tends to restore the previous condition after a disturbance.

The remarkably low hydraulic conductivity and high sorption capacity are related to the clay mineral content of the argillaceous formation. Thus, the higher the clay mineral content of the host rock, the better its barrier function. The advantageous host rock properties of clay formations derive from the large specific surface of clay minerals, the small dimensions of the pores and the interaction between the clay mineral particles, water molecules and dissolved chemical species [13].

Most clays, and in particular plastic clays, can be described as continuous porous media, which may be an advantage for the modelling of their hydrological behaviour.

5.4.2. Geological setting

Mostly, the argillaceous formations being considered form part of a sedimentary basin. That is, the particular form of geological structure where thick sequences of argillaceous sediments are usually found. Such sedimentary basins consist of sequences of formations with rather large differences in permeability, related to the nature of the formations, which are often alternating with, or enveloped by, other sedimentary rocks. The sequences may demonstrate continuous lateral extension of the properties of the individual strata and allow for a high level of confidence in the prediction of characteristics in non-sampled positions in between sampled ones [13].

The deeper that such formations are buried in sedimentary basins, the lower the water content and porosity: the rock's characteristics changing from plastic to indurated [14].

5.4.3. Potential for changes

Potential changes to argillaceous formations may be due to external natural forces (i.e. climatic change, erosion and subsidence/uplift), or due to the disturbance induced by the construction of the repository. During deeper burial, the water content and level of induration may change.

5.4.4. Specific issues to be investigated

In the case of strongly indurated clays with a low water content, the existence of open cracks may be a concern and these have to be investigated for their potential to act as preferential pathways.

5.4.4.1. *Identification of hydrogeological pathways*

A distinction has to be made between the hydrology of the surrounding water bearing formations and the argillaceous formation.

On a regional scale, the geology and the hydrological properties of the different geological features has to be known or assessed. On the basis of this information a regional conceptual model can be built. The model can be a layered two dimensional or three dimensional one and has to address any issue relevant to cross-formational flow. The dimensions of such a conceptual model may be of the order of thousands of square kilometres for the surface area covered and a kilometre in depth.

On a local scale, a more detailed hydrogeological investigation has to determine the groundwater flow lines affecting the repository and to identify the possible pathways by which the radioactive waste may return to the biosphere.

In the argillaceous formation considered as a host for the repository, the possible transport of radionuclides has to be studied in much more detail than for the regional scale. In very low permeability formations, transport by advection may be small compared with transport by molecular diffusion.

5.4.4.2. *Flow and transport modelling*

On the basis of the conceptual model, the hydrogeological system can be represented by a mathematical model, which allows the calculation of flow and transport. The conceptual model has to take into account all the physical processes involved. The model parameters needed have to be obtained with sufficient accuracy, and the sensitivity of the different model parameters has to be assessed.

In the surrounding, more pervious water bearing formations, flow and transport may be dominated by advection, but in the less pervious argillaceous formation chosen as the host rock, the flow and transport may be dominated by diffusion.

5.4.4.3. *Applicability of data and models*

For the application of the models and the use of the data and the results of the calculations, it must be borne in mind that the gathered data represent only a snapshot in time. It is most likely that the system will be in a very slow, transient regime. For the assessment of the safety of a possible repository, the evolution over time for both the past and the future have to be assessed by the study of different evolution scenarios.

For modelling on a regional scale, the available data will be less detailed than for local modelling in the immediate vicinity of the repository. Appropriate investigation methods have to be used to obtain representative data for the model calculations.

The fact that extreme parameter values (which were not of the same level of concern in earlier research) have to be investigated and confirmed requires that new techniques and investigation tools be developed for investigations on the margins of what has been studied before. This is particularly true, for instance, in the determination of the hydraulic characteristics (hydraulic conductivity, interconnectivity of pores and pore size).

In the use of the measured data, the possible influence of the method of measurement on the value of the data should be considered.

5.5. VOLCANIC TUFF FORMATIONS

5.5.1. Favourable properties

The attributes of volcanic tuffs that currently make them candidates as sites for nuclear waste repositories can be grouped into three broad categories:

(a) Properties inherent to tuffs that may offer a waste isolation capability:

- (i) Individual tuff layers may be rich in minerals (zeolites and clays) that have a large capacity to sorb most radionuclides.
- (ii) Tuff sequences are frequently internally stratified and the fractures stratabound, so that fracture continuity is generally disrupted, except at major faults.
- (iii) Tuff formations possess high matrix porosity compared with crystalline rocks, enhancing matrix diffusion of radionuclides migrating along fracture pathways.

(b) Properties which, when combined with conditions of partial saturation, lead to enhanced isolation capability:

- (i) Tuff formations located within the unsaturated zone in arid regions have effective permeabilities in existing moisture states that are orders of magnitude less than their intrinsic permeabilities, so that water fluxes are very low.
- (ii) For tuff repositories sited in the unsaturated zone, the greater capillary attraction for water associated with generally smaller pores of the rock matrix tends to draw water from the fractures, making fractures generally non-transmissive to water except in areas of locally high saturation.

(c) Properties which, when combined with unsaturated conditions and judicious repository design, may result in improved isolation capability:

(i) Stratification and tilting of tuff formations at unsaturated zone sites may enable repositories to be situated to take advantage of natural capillary barriers, which may promote shedding of infiltrating water around waste emplacement drifts.
(ii) For tuff formations within the unsaturated zone, location of the waste emplacement drifts within fractured formations allows free drainage of water, minimizing contact time between infiltrating water and the waste packages.

5.5.2. Geological setting

Tuffs are the result of silicic and andesitic volcanism and thus indicate that a region was tectonically active at the time of their deposition. Individual tuff formations may be deposited by ash flow or ash fall mechanisms.

Hot ash flows move downslope in response to local topography. Because they are deposited while hot, glass shards may be welded to varying degrees, depending on their location within the individual flow unit, or the time interval that elapsed between ash flows. Compression of the ash by overlying material may squeeze trapped gases into pockets or cavities. Contraction of the ash while cooling produces a joint system that may be partially or completely filled by minerals that have crystallized from the vapour phase.

Ash fall tuffs are deposited as relatively cool material and are therefore not welded, or only partially welded. Non-welded or partially welded tuffs, including those deposited as part of an ash flow unit, are more porous and generally have greater primary permeability than moderately to densely welded tuffs, unless later alteration by zeolitic or clay minerals clogs the original pore structure. Cooling fractures are sparse or absent in non-welded to partially welded units. Tectonically induced fractures and faults may be superimposed upon this generally stratified system. Additionally, secondary alteration of the primary rock matrix is promoted by the circulation of hot, mineralized fluids associated with the volcanism.

Within more densely welded, less porous stratigraphical units, fractures form the dominant contributors to overall rock permeability. In contrast, secondary permeability is less important in the more porous, non-welded and partially welded tuffs where these have not undergone extensive alteration. Where saturated, the densely welded units may be the principal aquifers and the non-welded units function as aquitards. In the unsaturated zone, the non-welded units may tend to interrupt the continuity of fracture pathways and disperse flow that had been moving downward along fractures in overlying stratigraphical units.

Because many individual fractures are stratabound, faults and fault zones, by virtue of their continuity, represent likely pathways for water and gas through thick, unsaturated, stratified tuff formations. However, individual faults or fault zones may be filled by mineralization or gouge, depending on past water movement and the degree of crushing along the fault surface, or they may be open owing to recurring movement. Faults may also interrupt the lateral continuity of beds by juxtaposing layers of contrasting hydrological properties. Except where disrupted by faults or removed by erosion, there is often extensive lateral continuity of individual ash flow units.

5.5.3. Potential for changes

Tuff formations occur in regions that, at one time or another, have been tectonically active. Depending upon when the tuffs were formed, the region in which a potential repository site is located may or may not continue to be tectonically active. If deposition of the tuffs has been recent, indicating a tectonically active site, renewed volcanism and faulting can compromise the isolation capability of a repository. The potential for renewed fault movement or the development of new faults, and intrusion of the repository by magma bodies or by associated hydrothermal activity should be assessed.

Repositories which rely on the maintenance of unsaturated conditions for their isolation capability need to consider the effect that possible climate changes may have on water table elevation or the development of perched water bodies that could inundate the repository. Either event would nullify many of the advantages associated with unsaturated tuff sites. Additionally, climatic change could increase water fluxes through an unsaturated or saturated tuff site. Repositories in unsaturated tuffs that rely on the present day aridity of the site for their isolation capability, rather than on low host rock permeability, may be more vulnerable to the effects of climatic change than other sites. It is, therefore, important to examine carefully the geological record for evidence of past climatic fluctuations in order to determine the probability of the climate becoming significantly wetter during the intended containment period. Isotopic analysis of mineral infillings in fractures can reveal the periods during which fractures were flowing and may reflect whether the source of water was the ground surface or the result of a higher water table in the past.

Depending on the age of the waste and the spacing of the waste canisters, varying thermal perturbations can be imposed on the repository by waste generated heat. In some cases, these temperature changes will induce the mobilization or deposition of mineral species in pore water, with accompanying changes in matrix or fracture permeability. Changes in the composition or structure of certain minerals may also occur. Temperature changes can induce mechanical stresses in the rock surrounding the emplacement drifts, so that the effects of these coupled thermomechanical stresses on drift stability should be considered. For repositories located within the unsaturated zone, large volumes of water are likely to become mobilized as water vapour is generated from in situ pore water around the waste packages. This vapour will condense in cooler areas of the repository. The redistribution of moisture as vapour and the fate of the condensed water should be considered in assessing the future evolution of a repository located within the unsaturated zone.

5.5.4. Specific issues investigated

Because many of the anticipated benefits of waste isolation in tuffs are associated with partially saturated conditions, the following discussions will focus on aspects of unsaturated zone isolation. Saturated tuffs with very small porosities may exhibit hydrological behaviour quite different from that described below and reference can be made to the relevant sections on crystalline rocks for an insight into their possible hydrological behaviour.

5.5.4.1. Identification of potential flow and transport pathways

At the site scale, water flow paths through stratified tuff sequences that have also been fractured, faulted and tilted may be very complex. At tuff sites, fracture, fault and matrix properties may all vary across stratigraphical units so that water pathways may be quite tortuous. Under unsaturated conditions, the transmissive properties of rock matrix, fractures and faults are functions of the moisture state of the rock, so that the single phase permeability of various strata or structural features does not necessarily reflect which pathways will actually be utilized, only that certain pathways are available given the appropriate moisture conditions. Water flow paths, and whether flow occurs predominantly through the fractures or rock matrix, thus depend on the distribution and magnitude of infiltration, and hence on climate.

In the thick unsaturated zones, there is also the potential for substantial lateral redistribution of moisture as water percolating from the ground surface to the water table encounters strata with contrasting hydrological properties. Water moving laterally along stratigraphical contacts may be intercepted by faults and diverted downward, or accumulate against a fault, depending on the fault's hydrological properties and/or the properties of strata juxtaposed across the fault. If certain strata are identified as being particularly important to radionuclide isolation by virtue of their chemical properties, it is important to determine whether those strata can be bypassed by lateral flow, or short-circuited by faults.

By virtue of their continuity, large faults have the potential to exert substantial control on the flow field, whether extremely permeable or relatively impermeable. Because smaller fractures are often discontinuous across strata, faults that cross many stratigraphical units become possible pathways for the migration of radionuclides and thus obvious targets for investigation and hydrological characterization. They may be identified through surface mapping, geophysical investigations, surface drilling and underground exploration.

Underground excavations, by virtue of the large surface areas they provide for observing seepage through the rock, are particularly important for identifying potential pathways, although mechanical unloading effects and capillary barrier effects may bias observations to some degree.

Isotope information from sampled pore fluids or seeps, particularly those isotopes associated with nuclear testing in the atmosphere, may be especially instructive for determining pathways that have recently been active. Analysis of the spatial distribution and ages of fracture lining minerals may also allow past flow patterns and mechanisms to be inferred, as well as the periods during which the hydrological system was particularly active.

5.5.4.2. Representation of flow and transport at different scales

Because of the general complexity of the flow field at tuffaceous repository sites and, in particular, the non-linear relationship between fracture, fault and rock matrix permeability with moisture state, numerical models assume considerable importance to the understanding of the hydrology of these sites. At unsaturated zone sites in arid regions, where average moisture fluxes are believed to be small, the movement of water as vapour may also be an important component of overall moisture movement. In this case, the effects of the geothermal gradient also need to be considered. The geometrical complexity and coupled nature of the moisture flow problem necessitate the use of multiphase numerical codes that consider the effects of heat if all potentially significant processes are to be taken into account.

Building confidence in these models requires both that controlled experiments be conducted in order to verify that processes are adequately understood and that considerable amounts of site information of both a quantitative and qualitative nature be collected to constrain the conceptual and numerical model results. Because experiments and observations are usually conducted at a variety of spatial scales, numerical models at multiple scales are necessary for their interpretation and for bridging the gap between the experimental and larger scales.

There is also a need to scale observations in time as well as space. Generally, site investigations last only a small fraction of the time required for waste isolation. Processes that may assume importance over geological time-scales, such as mineral precipitation or dissolution, may not be evident during short term experiments. Also, where repositories are to be located in unsaturated zones in arid regions, short term monitoring may not fully capture the full range of climatic variability, even in the absence of major climatic change. As discussed above, the spatial distribution and age of fracture lining minerals may be particularly valuable as indicators of patterns of past fluid movement and may suggest possible modifications to be made to conceptual models. Sampling of pore fluids for environmental tracers can yield information somewhat comparable to that which might be obtained from long duration tracer tests, although the location and timing of inputs is not as well controlled. In addition, although not necessarily site specific, natural analogues may be available for several processes related to the performance of nuclear repositories, including radionuclide migration and the geochemical consequences of waste generated heat.

Although numerical models of flow at unsaturated tuff sites are, at present, uncertain predictors of flow distribution and magnitude, they are valuable in indicating the relative sensitivity of model results to various input parameters, thereby prioritizing the types of data to be collected. Also, they enable the development of better conceptual models that form the basis for hypothesis tests that suggest observable consequences for certain types of system behaviour if certain processes, features or site attributes are present.

Finally, residual uncertainty in conceptual models should be viewed as acceptable if it can be shown that alternative conceptual models do not affect decisions about site suitability, or that processes, although uncertain, are well enough understood to be bounded.

5.5.4.3. Determination of water balances

The performance of repositories located in the unsaturated zone will be sensitive to the net infiltration. Net infiltration, which is the overall infiltration minus the water lost to evapotranspiration, represents the quantity of water that can arrive at the waste packages or engineered barriers, if present. In general, infiltration is variable in time and space at any potential repository setting, but this may be especially true in arid regions, where infrequent but severe rainfall events may be the dominant contributors to recharge of the groundwater system. Because of temporal variability in infiltration and evapotranspiration and because in arid regions significant rainfall events may be infrequent, methods that average net infiltration over longer timescales may be particularly useful. In general, such methods involve the use of natural tracers, such as isotopes of hydrogen and chlorine produced as a result of nuclear testing in the atmosphere, ^{14}C, and natural variations in the stable isotopes of oxygen and hydrogen that have occurred as a result of climatic shifts. Another potentially valuable method, the chloride mass-balance method, accounts for the accumulation of chloride in the soil or rock profile, providing the means of estimating the net infiltration at a certain depth.

Additional methods involve the physical measurement of water potential and temperature over time and the determination of the functional relationships between the transmissivity of the medium to water and the water potential or some other measure of moisture status. These data are then combined to estimate directly water fluxes through the appropriate governing equations. However, uncertainties in the functional relationships and the relatively short periods over which the monitoring is typically performed make these methods less effective for estimating long term behaviour than isotopic methods.

Additionally, although the methods described above have all been used with success in unconsolidated media in which preferential pathways are absent, their usefulness in structured media, such as fractured, volcanic tuffs is not well established. In structured media, within which water may be flowing along relatively isolated pathways, the significance of the isotopic measurements with regard to average recharge rates may not be straightforward.

In structured media, it is sometimes useful to make measurements at depths in which considerable mixing is expected, such as at particular stratigraphical horizons or at the water table. Patterns in the distribution of isotopes at the water table may reflect rates of flux through the overlying media. Additional methods that may be useful include lysimeter studies, where alluvium or soil is deep enough to allow instrument emplacement, and regional groundwater studies that make estimates of recharge during model calibration. These regional studies often have other significant uncertainties and assumptions, so that estimates produced by the models are best used for the corroboration of estimates produced by other methods.

Although a variety of techniques are available for the determination of net infiltration, each one has limitations and uncertainties associated with it. Therefore, several different techniques should be used as a means of cross-checking the estimates.

5.5.4.4. Potential effects of climate change

As stated earlier, repositories that depend on the present day aridity of the site area for their waste isolation capability, rather than on the absence of high permeability pathways, are to some degree vulnerable to the effects of climatic change. Waste repositories in unsaturated tuffs in arid regions rely on the fact that water does not flow through the fractures continuously. Under arid conditions, it can be reasoned that if flow does occur through fractures, these flows will be generally short lived in the absence of continuous water sources at the ground surface. Once the source of the flowing water has been removed, capillary imbibition will tend to draw water from the fractures into the rock matrix, where rates of movement are substantially lower. Although conditions such as perched water bodies in the subsurface may also initiate more sustained flow in fractures, ultimately these too must be replenished by water from the ground surface.

Sensitivity analysis can reveal the consequences of increased rates of net infiltration on the waste isolation capability of unsaturated zone repositories. Such analysis should be done irrespective of the likelihood of climatic change, given that estimates of percolation flux may be uncertain. Once a critical value for net infiltration above which performance standards are not met has been identified, the likelihood that a site will experience that value or greater net infiltration must be assessed, given a knowledge of the infiltration mechanisms and the characteristics of the surface materials, and the probability that the climate will change at some time during the intended containment period. The probability of climatic change will be based on the palaeoclimatic record for the repository site, as inferred from the geological record.

Types of information that have proven useful in identifying palaeoclimatic changes include: stable isotopes of oxygen and deuterium from lake, marsh and playa sediments, or spring deposits; palaeoenvironment reconstructions based on botanical evidence preserved in pack rat middens; and identification of communities of microscopic crustaceans known as ostracoda, preserved sediments and spring deposits, and comparison of those communities with their modern analogues.

5.5.4.5. Repository induced effects

Materials introduced into a repository during its construction and operation have the potential to alter radically the hydrology and geochemical character of a site compared with the pre-development conditions. Some of these changes, such as the introduction of rock bolts and cement for roof support, may change the geochemical environment and the possible unintended consequences should be assessed. Others, such as the introduction of crushed tuff backfill, may be part of the engineered barrier system and would be intended to provide additional containment by preventing water from reaching, or radionuclides from leaving, the near field environment. Although the possible introduction of crushed backfill at unsaturated tuff sites is still being investigated, there is evidence that this backfill can be designed using finer grained material placed over coarser material to function as a capillary barrier, with the finer grained layers holding, and ultimately diverting, water around coarser tuff material placed nearer the waste packages. In this case the coarser grained material would remain relatively dry, so that the major potential transport mechanism from any degraded canisters to more active flowpaths would likely be diffusion through thin water films around the tuff grains, an exceedingly slow process.

Ventilation of repositories located in the unsaturated zone during operations, and before the repository is closed, also has the potential to remove a great deal of in situ moisture. Dryer conditions at the time of repository closure would be beneficial in view of the fact that there is greater storage capacity in the rock matrix for imbibition of water that may be recharged through fractures and that there is less water available to be mobilized by heat generated by the decay of the waste.

Numerical models predict that following waste emplacement, heat generated by radioactive decay of the waste will mobilize a substantial amount of in situ water under most practical emplacement scenarios. Water is removed as vapour from those regions with temperatures above the boiling isotherm, which moves outward from the waste canisters with time. This vapour is predicted to condense in cooler regions above, below and on the perimeter of the repository. While the condensate generated above the repository is not predicted by the models to return to the waste canisters for tens of thousands of years, there is concern that, owing to heterogeneity in the rock or other unmodelled effects, large amounts of condensate may be focused on a small number of waste packages. The same models predict, however, that even when temperatures are kept below boiling, large amounts of moisture can be redistributed by the thermally induced, buoyancy driven flow of gas. Experimental evidence of these effects is being actively sought. Research is still under way to determine the best way to engineer the thermal loads to keep the canisters dry and keep possibly undesirable chemical and mechanical changes to a minimum.

6. APPROACHES TO CHARACTERIZATION OF THE HYDROGEOLOGICAL SYSTEM

6.1. STRATEGY

Section 4 outlined general guidelines for the development of a methodology for hydrogeological investigations. This section identifies particular approaches to the characterization process at different scales and at different types of site.

As discussed previously, hydrogeological characterization needs to be conducted from the scale over which geological processes occur (the regional scale), through the scale of the regional groundwater flow system (the area scale), to the smaller site scale on which a detailed understanding of the physical processes of flow and transport is required (Fig. 6). This hierarchy seems to imply a progression from the large scale to the small scale. However, in some cases the different scales of investigation may be performed at the same time. In other cases, it may be necessary to revert to a regional study in order to solve a site specific problem. The time required for the hydrogeological investigations associated with each scale will depend on the site conditions, the time required for the tests and the proposed repository design.

Figure 1 illustrates the main aims of the hydrogeological investigations and links the development of conceptual models and the acquisition of data into an iterative process. In general, this requires an initial reconnaissance phase of hydrogeological characterization, which is used to develop the early conceptualization of the site on which future investigations will be based.

The initial reconnaissance phase should make maximum use of existing data on all scales for the site. Of particular importance at this stage is the development of conceptual hypotheses for the geological framework and the regional flow system. It may be necessary at this stage to conduct some regional surveys (e.g. surface or air-

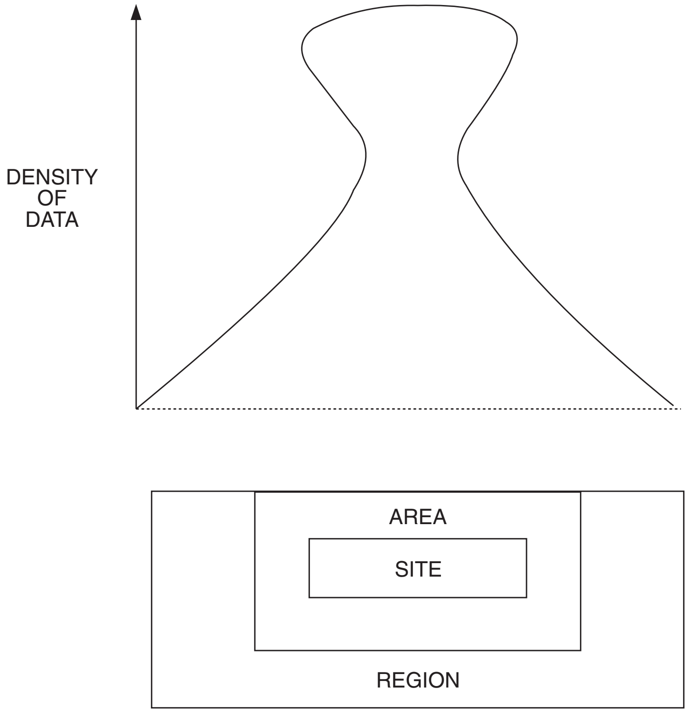

FIG. 6. Scales of hydrogeological investigation.

borne geophysical surveys and surface hydrology studies), to support data available from the literature. In some cases, exploratory drilling may be required to augment the data available from the literature or from remote sensing techniques.

After an initial conceptualization of the site is established the detailed site characterization can comprise frequent iteration between the conceptual models of the site and specifically identified activities (data collection or data evaluation) used to develop understanding on the key issues. Ideally, any data collection should have a key objective that is related to one of the key issues prevailing at the time.

Multidisciplinary investigations should be used and the data should be integrated from all the different specialized fields of hydrogeology and related earth sciences.

Hydrogeological parameters are primarily determined from boreholes or from laboratory tests on field samples. There is a need to optimize the hydrogeological investigations (e.g. for cost and limitation of disturbance). Therefore, maximum use should be made of other characterization methods to meet this need. Such methods include the analysis of satellite imagery and other existing information, geological mapping, and airborne and surface geophysical surveys. Geophysical surveys can provide areal information of the surface and can penetrate to some depth to support hydrogeological investigations.

Boreholes represent a very specific resource from which to conduct hydrogeological investigations. As such, careful consideration needs to be given to the location of any borehole and a borehole siting strategy should be developed on the basis of the proposed disposal system and the initial conceptualization. The data obtained from drilling boreholes, which is often a high cost activity, should be maximized, although without compromising the main objective or cost effectiveness of the borehole.

As an example, once the boreholes have been drilled they should be geophysically logged using a suite of wireline techniques considered appropriate for the geological environment. The borehole geophysical logs can generally help to identify the major hydrogeological units at the site and help in selecting intervals for testing.

For some sites and disposal concepts, the hydrogeological investigation programme can be augmented by the development of an underground facility for testing and research. Such a facility can be regarded as a logical development from studies made in surface boreholes, providing access to a larger volume of rock and permitting different scales of measurement. However, the development of such a facility should be carefully considered and programmed to ensure that the overall investigations are not compromised by major excavation activities.

The representativeness of the hydrogeological parameters increases with the time duration of the test, because a larger volume of rock around the test interval in the borehole is tested. Monitoring from a large number of isolated intervals in surface based boreholes should be available for a minimum of one annual hydrological cycle before underground investigations begin.

6.2. REGIONAL STUDIES

The size of the regional study largely depends on the type of site being considered, the level of knowledge already available and the conclusions of the preliminary regional evaluation, as follows:

— For crystalline rocks, the geographical limit of the regional study is not obvious and depends on the general structural features.
— For salt formations, the regional study should be concerned with the aquifers located around the evaporite formation.
— For argillaceous formations, the regional study may cover a large area — even the whole basin — from the outcrops of the formations to the natural outlets of the different regional aquifers.

— For tuff formations, the limits of the regional study will be defined by the tectonic structure of the volcaniclastic massif.

The regional studies give the general guidelines on the knowledge of the geological context within which the facility will be sited and an understanding of the structural characteristics directing the principal hydrogeological features (location, direction and evolution of the principal regional fractures, etc.).

In order to determine this, regional studies should focus on establishing the large scale geological characteristics of the site, which might affect the determination of the limits of the investigation area indicating, for example, the geometry, the extension and the continuity of the different aquifers. Those hydrogeological properties which average out over a large area should be considered as part of the regional investigations, so that any heterogeneities identified are meaningful on a regional scale.

Such studies could include:

— Information on the long term variation of the hydrological system in the past by assessment of geochemical and isotopic variations in the interstitial water and rock matrix. The studies will provide data on the relationships between surface water and groundwater, the relationships between aquifers, the age of the groundwater and information on past climatic evolution.
— Evaluation of the evolution of the groundwater system by a geoprospective approach which takes into account the effects of climatic evolution and tectonic changes.
— Evaluation of the regional hydraulic head and temperature fields which can provide an indication of regional flow directions and the extent of heterogeneity within the regional flow system.

Regional hydrogeological studies use:

— Regional information already available through other geological and earth science investigations (deep oil exploration wells, remote sensing data) should provide the main characteristics and geometry of the different formations, the stratigraphy and the impact of the principal tectonic features.
— Groundwater supply and geothermal programmes provide general information on regional aquifers and general piezometry.

However, information gained from other sources does not always correspond to the specifications required in regional studies. Consequently, the quality of the available data should be assured.

6.3. AREA STUDIES

The area studies address the area over which the regional flow system operates and within which it is anticipated that future discharges from the proposed repository will occur (Fig. 7). The extent of the area depends very much on the type of environment being considered and on the anisotropy of the system. In many cases, the area studies may be the same as the regional studies, in which case no distinction is necessary.

Area studies provide a more complete understanding and a better representation of all the major phenomena governing water movement in the system. This includes the acquisition of all the relevant hydraulic parameters needed in the simulation of the fundamental processes involved in conceptualizing the site.

A general water balance of the aquifer system, indicating the zone and rate of recharge, and the relationship between the aquifers, the general direction of flow and the natural outlet zone, should be established where appropriate and the boundary conditions for modelling the system should be identified.

A comprehensive description of the host formation and its environment includes:

- An indication of the hydraulic head and thermal fields, perhaps with greater resolution than that provided at the regional scale;
- The geometry, structural features and fracture distribution system (heterogeneity and spatial variability);
- The petrographic and mineralogical nature of the different rocks;
- The continuity and variability of the hydrogeological units;
- The relationship between different hydrogeological units;
- The potential recharge and direction of flow;
- The hydrogeochemical composition.

The area study should provide accurate information on the boundary conditions of the site being considered for the repository (or underground research facility) and should provide the choice of appropriate hydrogeological models and their application (steady state and transient conditions).

The main parameters studied include:

- Distribution and variability of hydraulic conductivity
- Water in storage
- Hydraulic head field
- Temperature and thermal conductivity
- Hydrochemical variations.

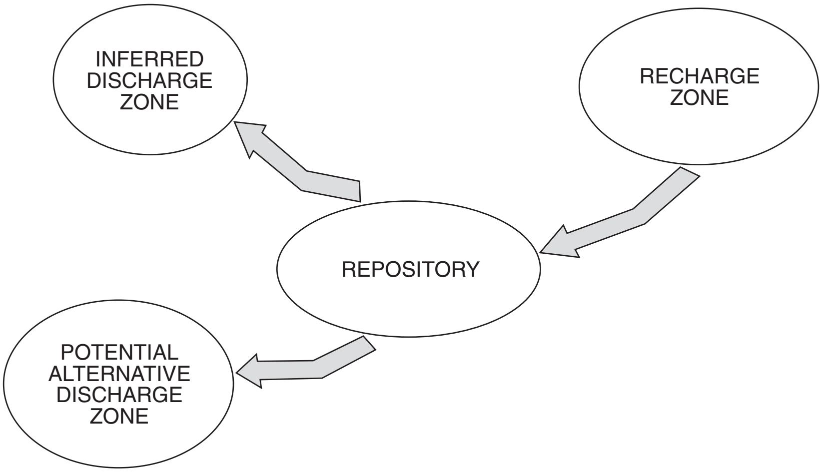

FIG. 7. Area studies: Components of the overall flow system.

Area studies can be developed by a combination of surface based surveys of geological features, surface hydrology and hydrochemistry and can be augmented by the drilling and testing of boreholes penetrating key features of interest in the regional flow system.

It is important to define at this stage of development which parameters are important for the characterization and modelling of the hydrogeological system and for defining the initial stage to take account of possible changes in the system (e.g. by developing an underground research facility and/or repository).

Within the context of the development of hydrological observation networks [15], the following should be considered:

- The design and optimization of the network layout, including the choice of parameters to be determined, the location and frequency of the observations or sampling, and the duration;
- The measuring or sampling devices (methods, design, calibration and installation, data transmission, etc.);
- Data management (databases, documentation, conservation, etc.);
- The cost effectiveness (installation costs, operation, maintenance and lifetime, and objectives to be reached).

The development of boreholes and observation networks is an iterative process, which starts with some boreholes being drilled to identify the general schema and nature of the hydrogeological units (e.g. preferential and non-preferential pathways) in given regions, areas or sites. In many cases a certain amount of information or a certain number of working hypotheses (general concepts or models) will already be available and may serve as a basis for deciding the location and depth of the observation and sampling programmes. On the basis of the results obtained in these initial investigations, further reconnaissance programmes using boreholes and observation networks can be developed.

6.4. SITE STUDIES

The main goals of the site studies are to investigate and identify: the baseline (unperturbed) hydrogeological state of the site (host rock and surrounding formations), the potential flow and mass transport pathways through the repository, the geochemical interactions between the groundwater and the repository components, and the near field interactions by which hydrogeological changes may occur. The output of these investigations is of use in those assessments dealing with the performance of the repository structure and its near field and in the design of the repository.

These investigations require a detailed study of the physical flow system and detailed geochemical analyses at a scale which is determined, among other things, by the scale of heterogeneities of the important relevant features and the expected extent of the changes in the near field. The main characteristics and parameters to be assessed in the host rock and the surrounding formations in site studies are:

- Transmissivity and its scale dependence
- Effective porosity
- Precise location of water productive levels
- Pressure heads
- Direction of flow
- Transport mechanisms
- Hydrochemical and isotopic content of interstitial water and rocks
- Analysis of rock structure and stratigraphy
- Identification of structural discontinuities and their analysis
- Thermomechanical properties.

Investigations of the hydrogeological system in the underground part of the site are performed by surface based investigations or from underground facilities. Among the surface based investigations a distinction can be made between destructive techniques (such as drilling) or non-destructive, penetrative techniques (such as geophysical techniques). Several countries have built underground facilities specifically for the investigation of the hydrogeological systems of potential disposal host rocks. Underground research facilities are dealt with in the present report in Section 6.4.

When underground research facilities are planned for conducting hydrogeological investigations, it is important to identify the baseline hydrogeological conditions at the site of the underground research facility prior to any work being undertaken.

Some parameters that are not sensitive to changes over time can be determined during the drilling of the borehole, i.e. lithological characteristics (porosity, stratum thickness, etc.). Other parameters are variable over time and require long term observation in the boreholes (e.g. piezometric head), or may require longer equilibration time (solute content, temperature, etc.).

In cases where spatial variability and time related changes for some parameters are expected, a network of observation points is established (e.g. a borehole network). On a site scale, the hydrogeological observation network needs to be developed with the same considerations given to its design and optimization as are made for such a network on the area scale (Section 6.3). However, when such a network needs to be developed on a potential disposal site, considerations about the potential perturbations or interference caused by these boreholes are taken into account as well.

6.5. UNDERGROUND FACILITIES

Underground research facilities have either been purpose-built or have been developed in existing mines which have been specifically adapted. They have been operated for methodological purposes, such as developing testing or characterization techniques, model validation or the characterization of potential disposal sites. In the latter case, the investigations are intended to improve the understanding and knowledge of the hydrogeological system at the site and to provide sufficient confidence in that understanding to permit the preparation of a licence application to build (and operate) the repository.

The test programme to be run in an underground laboratory should be defined according to the concept of the final repository, the techniques to be used for its implementation, the waste types and packages, and the site characterization and performance assessment requirements.

The underground research facility makes it possible to characterize the host formations, which is difficult to do from the surface, and allows visual observation of larger volumes of rock.

The extensiveness of the underground facilities and ease of access, once built, allow sampling of the rock and the pore fluids or measurement programmes to be conducted at multiple locations and over long time periods. In the case of hydrogeological investigations this is particularly important, since good information is required about the spatial variability and the variability over time of many of these parameters.

Within the context of the development of an underground laboratory, the following should be considered:

- — Design and optimization of the laboratory layout and test programme, including the choice of the parameters to be determined, the location, the frequency of the experiments, observations, sampling and their duration;
- — Scale of the experiments, observations and samples;
- — Measuring or sampling devices (methods, design, calibration and installation, data transmission, etc.);
- — Interference in time and space (between the tests and other operations in the facility);
- — Data management (acquisition, storage, communication, documentation).

In situ investigations in underground laboratories allow very detailed examinations to be made (on a very small scale and in three dimensions) and assessing, to some extent, the scale effects on some parameters and processes. For instance, permeability can be determined on the centimetre scale as well as on the hectometre scale. Some hydraulic parameters can be determined by direct measurement or from undisturbed samples of the rock matrix and the interstitial fluids from the underground laboratory.

In addition to its function related to investigation of the hydrogeological systems, the underground laboratory may also be a starting point for the development of the final repository.

6.5.1. Crystalline rocks

An underground laboratory in crystalline rock can provide in situ confirmation of the flow and transport characteristics of the water conducting features identified in the hydrogeological investigations carried out at the surface and in boreholes. In common with the other types of investigation, they have an ‘effective scale’ on which they provide information. In this way, they can be useful in examining borehole based conclusions on a larger scale.

Even the construction of the laboratory can provide information to advance the understanding of the site. This involves predicting the rock mass conditions to be encountered by the excavation and the response of the rock mass and groundwater flow system to the excavation. During excavation, the actual conditions are monitored and compared with the predictions.

The information obtained is used to revise the conceptual and mathematical models of the site. The improved understanding can reduce the uncertainty in models associated with limitations on knowledge of the site. It can also narrow the ranges of parameter values used in the models, where the range is based on more limited knowledge of the heterogeneity of the natural system. As with the earlier investigations carried out from the surface, the investigations in the underground laboratory are an iterative process in which information from excavation and testing is evaluated before the next step is undertaken in the design and development of specific experimental activities.

The observations made and the tests conducted during excavation of the access to the laboratory and its test areas represent the first opportunity to obtain abundant in situ data on the mechanical response of the rock and its geomechanical properties. These data are needed for engineering design of the repository.

The main advantage of underground facilities to the hydrogeological characterization of fractured crystalline rocks is the improved exposure, in the most relevant location, of the fracture system. Since all crystalline rock conceptual models have at least some element of probabilistic description, certainty is directly related to the size of the measurement data set.

In addition to knowledge about the structural framework, underground facilities allow complex borehole based experiments to be performed, usually linked to extremely well characterized fractures or groups of fractures. It is this ability to examine, in detail, flow and transport in individual fractures and small networks of fractures which significantly enhances understanding and hence reduces uncertainty.

Underground openings, by their very nature, induce local changes. Apart from the more obvious mechanical effects, there are also changes related to the air–water interface around the drifts, the potential dissolution of gas and changes in groundwater chemistry. While these may not have major effects on the long term performance of a crystalline rock disposal concept, they must be taken into account in the experimental design.

6.5.2. Salt formations

The underground research facility will be designed according to the type of evaporite rock considered or investigated (dome salt or bedded salt).

In particular, the hydrogeological conditions of the overlying formations may specifically be taken into account, considering the construction design of the access shaft (freezing technique).

Independently of the type of salt considered, the underground research facility should allow a better determination of the host rock heterogeneities and discontinuities, as well as the characteristics and distribution of fluid inclusions, brine pockets and seams with a specific mineralogy.

When the option is to develop, at a later stage, a final repository in proximity to an underground research facility, care should be taken to avoid disturbing the site and creating potential preferential water pathways. This may have consequences in the strategy to be followed for the investigations. For instance, since one of the main goals of the underground research facility concerns the acquisition of data on the main impervious layers surrounding the salt host rock (ensuring its isolation at the top and the bottom), the access to these surrounding formations should be made from the laboratory.

6.5.3. Argillaceous formations

Since argillaceous sedimentary environments represent a continuity, the shaft sinking process allows confirmation of predictions about the various characteristics of the sedimentary sequence encountered. The predictions could be based on observations from reconnaissance drilling at the site or in a network surrounding the laboratory site.

The hydrogeological parameters and conditions that have to be investigated in situ in underground laboratories in argillaceous formations are:

— Fracture distribution of the porous medium (at different scales);
— Permeability (for fluids and gases), its variability (in space and in time in case of the need for equilibration or for assessing the time dependence of the permeability with regard to an external force, e.g. temperature), and degree of anisotropy;
— Matrix porosity (connective, closed), its variability (in space and in time in case of the need for equilibration or for assessing the time dependence of the porosity with regard to an external force, e.g. oxidation and mineral deposition in the pores) and pore diameters (for assessing the transportation of larger molecules and colloids);
— Matrix tortuosity, dispersion (variability and anisotropy);
— Storage coefficient (e.g. with respect to the assessment of the hydraulic transfer between the host rock and mined or tunnelled structures);
— Detection and characterization of water conducting features with advective groundwater flow for indurated argillaceous formations.

Similarly, the hydrogeochemical conditions that have to be investigated in situ in underground laboratories in argillaceous formations are:

— Coefficient of matrix diffusion (apparent and element specific) and/or retardation factor (with respect to electrical charge and size);
— Physico-chemical nature of the pore fluids (Eh, pH, solute content and composition, colloids);
— Isotope hydrology (with respect to transit times, residence times and confirmation of other parameters or pathways).

Underground laboratories contribute to the validation of models by allowing specially designed tests and experiments. For clay formations, validation exercises having hydrogeological aspects may be undertaken in the following areas:

- — Migration of radionuclides in the argillaceous medium;
- — Migration of gases (dissolved in solution or by gas permeation);
- — Intra-formational flow (in the case of heterogeneities of significant variability);
- — Hydraulic transfer between the host rock and the open repository;
- — Residence time of isotopes;
- — Clay creep around tunnelled structures taking into account pore pressures;
- — Oxidation of clay;
- — Hydro-thermomechanical behaviour of the repository in the near field around disposed waste packages;
- — Source terms, taking into account infiltration, chemical equilibria, leaching and corrosion of waste packages.

For excavation in argillaceous formations, the use of freezing and boring techniques with impervious lining of the openings may be envisaged for the aquifers or pervious formations encountered. Conventional excavation techniques with pervious lining of the walls may be considered for the impervious strata. The method used will have a different impact on the local hydrogeology and the responses of the host rock.

6.5.4. Volcanic tuff formations

Depending on the degree to which bedrock is obscured by alluvial cover at the ground surface, underground excavations may provide an unparalled opportunity to observe the patterns of fracturing at a repository site. Visual observations of fractures, faults and fault zones, along with maps of these features, may suggest certain conceptual models of flow, or may at least allow some conceptual models to be ruled out. Overall patterns of fracturing and faulting also suggest the amount of spatial variability that may exist in the hydrological properties at a repository site. Underground excavations permit observation of the spatial distribution of seeps which are suggestive of patterns of groundwater movement. Temporal variability in the magnitude of inflow, or of the chemical composition of the water and the timing of these changes relative to rainfall events may indicate the degree to which the repository horizon is connected by fracture pathways to the ground surface, which may be important for the characterization of unsaturated repository sites.

Underground excavations may further serve as a platform for drilling horizontal or subhorizontal boreholes, which may be an effective way to investigate and test faults or other structural features not directly intercepted by drifts. The flexibility in orienting boreholes underground offers a greater potential to investigate directional effects in transmissive properties and to compensate for bias introduced by drilling only vertical boreholes from the ground surface.

Underground excavations enable an assessment to be made of the effectiveness of mapping and geophysical techniques to extrapolate known features to unexplored locations and of the ability of hydrological models calibrated on the basis of data from surface based boreholes to predict hydrological conditions ahead of drift excavation. These exercises provide a general sense of the uncertainty that should be associated with similar predictions elsewhere.

Experiments conducted in underground excavations can be used to explore the spatial and directional variability in hydrological properties and, because they allow data to be collected at various scales, permit the effects of spatial scale and methods of spatially scaling or averaging to be investigated. Experiments designed to offer a means of iteratively calibrating, predicting and verifying model results across a range of spatial scales or among hydrological and transport processes are particularly valuable in establishing the amounts and type of data required for confidence in predictions made elsewhere.

An improved understanding of the basic mechanisms governing water and tracer movement in unsaturated, fractured tuffs needs to be developed. Experiments conducted at intermediate scales in excavated rock blocks, or in rock volumes characterized by borehole access through bounding drifts, provide an opportunity to investigate basic processes under reasonably well characterized and controlled conditions. Although the representativeness of parameter values derived from such tests would need to be evaluated, an improved understanding of processes derived from such tests may be important in constraining conceptual models, or in suggesting interpretations for other data collected under less well controlled conditions. Experiments would ideally target conceptual uncertainties identified as important to site performance.

Underground investigations may include an assessment of the engineered barriers and their interactions with the host rock. For repositories located in the unsaturated zone, where the heat generated by radioactive decay of the waste may itself be engineered to keep the waste relatively dry, the effects of waste generated heat on the hydrology, chemistry and mechanical stability need to be evaluated. Experiments using heat sources that simulate the heat output from waste canisters can be used to investigate these effects, although questions remain as to whether the effects of certain processes, such as mineral precipitation or dissolution, can be fully characterized by experiments of even a few years duration.

If chemical barriers are important to waste isolation, underground excavations enable the spatial variation in chemical properties such as sorption to be characterized. Similarly, evidence for the existence of preferential pathways such as faults may be investigated from underground drifts.

7. SUMMARY

The fundamental concept for the isolation and containment of radioactive waste in a geological repository is a multibarrier one. In this approach, natural as well as engineered, human made barriers are used to prevent or retard migration of the radionuclides towards the biosphere. The hydrogeological system, as part of the natural system, is however to be considered as a medium that could potentially cause the failure of the human made barriers and convey radioactivity towards the biosphere through the natural barriers.

The performance of the hydrogeological system within a waste disposal concept needs to be known in the form of a prediction of how it will evolve in the future. This is achieved by developing an understanding of how the system, as currently observed, works. The starting point for this process of understanding is to define a range of conceptual models which, at first sight, might explain the currently observed system. Investigations are designed to reduce the range of possible conceptual models, and hence the range of predictions. Regions of low groundwater flow, which are appropriate for radioactive waste disposal, are very slow to change in response to geological evolution. Hence, possible conceptual models need to include geological processes and time-scales in order to understand and explain current observations. This is quite unlike aquifer investigations, where a knowledge of current hydrogeological boundary conditions (i.e. water table topography) usually explains hydrogeological measurements sufficiently well. In potential repository situations, the knowledge of the influence of past geological processes on the current hydrogeology is used to predict it into the distant future. Naturally, this involves a distribution of possible futures, together with their associated uncertainty.

Hydrogeological investigations address issues associated with a variety of spatial and temporal scales. For convenience, hydrogeological investigations have been discussed in terms of regional, area and site scales. Although these subdivisions are somewhat arbitrary, and no absolute criteria can be given concerning the identification of the limits of each scale, it is clear that the processes of concern, the detail of the investigation and the methods of investigation will change, depending on proximity to the repository. In general, physical experimentation and characterization assume greater importance in the immediate site area in an effort to understand better the interaction of the repository and engineered barriers with the host formation and identify specific pathways that could potentially conduct radionuclides from the host formation to the area flow system. On the other hand, geological and isotopic evidence are relied on more heavily at the area and regional scales in order to identify processes and flow paths that may become relevant to waste isolation over a longer time-scale. It is important to recognize that these statements are intended to reflect a shift in emphasis, rather than imply an abrupt discontinuity across spatial scales in the methods used or the processes of concern.

It has also become clear that the potential for change in the hydrogeological environment needs to be considered. Because repositories are sited in formations that are poorly connected to the biosphere, the host formations and their environments may not be in equilibrium with present boundary conditions and may still be affected by boundary conditions imposed at some time in the past. Palaeohydrological investigations are often necessary to understand better the current conditions existing at some sites and to develop confidence that long term processes are understood sufficiently well that predictions can be made into the distant future.

A range of investigation methods should be considered and a multidisciplinary approach adopted. Modifications to standard hydrological testing methods and interpretation techniques may be required in order to address low permeability, non-aquifer systems. Investigation methods include desk studies, surface investigations and geophysical surveys, the study of analogue systems and penetrative investigations such as surface borehole drilling and underground research facilities. Any investigation should be targeted at understanding a key issue identified by the conceptual hypotheses.

Some general recommendations are made on the basis of experience gained from hydrogeological investigation of the geological waste disposal sites currently in operation. Conceptualization of the site should be as wide as possible in the early stages, with the investigations being targeted to reduce conceptual uncertainty. Long time-scales need to be taken into account, as low permeability sites are, in general, likely to be in a transient state. The density of information should be designed to focus on the proposed site. As the scale of investigation focuses on the site, the significance of smaller scale heterogeneities increases. For this reason, a distinction should be made between parameters which average over volumes of rock to describe potential fields (e.g. chemistry, temperature), and those which describe localized flow and transport properties (e.g. transmissivity, porosity).

The major issue for crystalline rocks consists in identifying the most favourable zone or block of rock of relevant size and depth and having very limited groundwater flow. Owing to the type of water circulation in this type of rock, the characterization of the fracture system must be made at all scales (from regional structures to microfracture), in order to identify the major circulation features. A comprehensive knowledge of the history of the rock massif (emplacement, tectonic, weathering) is therefore required, together with in situ measurement of hydraulic parameters, hydrochemical sampling and slurry of fracture infillings.

The main hydrological issue concerning salt formations, bedded salt or salt domes consists in assessing whether the isolation from the effects of important dissolution processes will remain for a sufficient period of time. Hydrogeological investigations should therefore be particularly concerned with the formations surrounding and adjacent to the host rock (with particular attention to the cap rock in the case of salt domes).

Clay formations considered as potential host rocks for repositories generally benefit from a quite homogeneous structure and composition over a sufficient area and thickness. Two complementary approaches are therefore needed to characterize the host formation itself (where diffusion is of primary importance in transport processes), and more permeable surrounding formations (where convection is likely to be the major transport process). Attention should, however, be paid to possible channelling through fractures in compacted clays.

In spite of a higher matrix porosity, old, indurated, volcanic tuffs possess similar hydrological properties to crystalline rock and are therefore studied in the same manner. The main advantage of the non-indurated, volcanic tuff formations envisaged for use in disposal lies in the thickness of the unsaturated zone. The main hydrogeological issue is therefore to demonstrate that the water table will not rise to the level of the repository during the required period of time. In this way, studies of the evolution of the water balance associated with geochemical studies are carried out. The processes of infiltration and percolation of water through the unsaturated zone are also carefully studied. With reference just to the investigation methods, it can be stated that appropriate methods are available for the hydrogeological investigation of sites for the geological disposal of radioactive waste. In general terms, their relation with, and role in, the siting, design and licensing of repositories are established.

Although the specific approaches to the hydrogeological investigation of sites may differ somewhat for different potential host media, there are many issues in common and many of the available methods for hydrogeological investigation would be used at any site. However, the differences in the potential host media and the differences between sites in the same medium mean that such aspects as the combination of methods used, the distribution of boreholes and the depth of investigations can vary substantially.

Improvements in methods are being made and will continue to be made, particularly with regard to the determination of the properties controlling the transport of radionuclides through geological formations and in hydrogeological and hydrogeochemical modelling.

In the hydrogeological investigations, it is necessary to include methods that can provide hydrogeological information about the rock between boreholes, such as long time duration pumping tests, tracer tests, long time monitoring in isolated intervals in multiple boreholes and geophysical surveys.

It is necessary to collect representative information by monitoring over a sufficiently long time duration. The duration depends on the site conditions, test conditions and the accuracy required.

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