Background Report
to RD&D-Programme 98

Detailed programme for research and development 1999–2004

September 1998

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Abbreviations

BIOMOVS	Biosphere Model Validation Study
BIOMASS	Biosphere Modelling and Assessment
BWR	Boiling Water Reactor
CLAB	Central Interim Storage Facility for Spent Nuclear Fuel
EIA	Environmental Impact Assessment
EIS	Environmental Impact Statement
EQUIP	Evidence from Quaternary Infills for Palaeohydrogeology
FEBEX	Full-scale Engineering Barriers Experiment in Crystalline Host Rock
GPS	Global Positioning System
HRL	Hard Rock Laboratory
ILW	Intermediate-level waste
LILW	Low and intermediate-level waste
LLW	Low-level waste
HLW	High-level waste
HRL	Hard Rock Laboratory
IAEA	International Atomic Energy Agency
KASAM	Statens råd för kärnavfallsfrågor (Swedish National Council for Nuclear Waste)
KBS	Kärnbränslesäkerhet = Nuclear Fuel Safety
KTH	Kungliga Tekniska Högskolan (Royal Institute of Technology)
MLH	Medium Long Holes
MSEK	Millions of Swedish kronor
NEA	Nuclear Energy Agency
NPP	Nuclear Power Plant
OECD	Organization for Economic Cooperation and Development
PAGEPA	PAlaeohydrogeology and GEoforecasting for Performance Assessment
PWR	Pressurized Water Reactor
P&T	Partitioning and Transmutation
RD&D	Research, Development and Demonstration
REX	Redox Experiment on detailed scale
RPV	Reactor Pressure Vessel
RVS	Rock Visualization System
SAFE	Safety Assessment of Final Repository for Radioactive Operational Waste
SEK	Swedish kronor
SFR	Final repository for radioactive operational waste
SGU	Geological Survey of Sweden
SKB	Svensk Kärnbränslehantering AB (Swedish Nuclear Fuel and Waste Management Co)
SKI	Statens kärnkraftinspektion (Swedish Nuclear Power Inspectorate)
SKN	Statens kärnbränslenämnd (National Board for Spent Nuclear Fuel)
SSI	Statens strålskyddsinstitut (National Radiation Protection Institute)
SFR	Final Repository for Radioactive Operational Waste
TRUE	Tracer Retention Understanding Experiments
TBM	Tunnel Boring Machine
TDS	Total Dissolved Solids
VDH	Very Deep Holes
VLH	Very Long Holes
VSP	Vertical Seismic Profiling
ZEDEX	Zone of Excavation Disturbance Experiment

Contents

1 Introduction

This report is a background to RD&D-Programme 98 /1-1/. The report gives an account of most of the research and development being conducted by SKB. The current state of knowledge is described, along with the goals and programmes that govern the continued work. The period of immediate concern comprises the next three years, 1999–2001. Particulars for the three years following that are for natural reasons less detailed and mainly indicate a direction.

Chapters 2 and 3 give an account of the development of the safety assessment, and the methods and models used to assess long-term safety. Thereupon follow a number of chapters (Chapters 4 through 17) that give an account of the R&D whose primary purpose is to support the safety assessment. That is not their sole purpose, however. There is also a description of some technical development of the deep repository and its components (see e.g. Chapters 6 and 14), as well as review of alternative methods such as partitioning and transmutation (Chapter 13). Methods for investigation and evaluation of sites for the deep repository are also being further examined and developed, with sights set on the commencement of a site investigation by no earlier than 2001 (see e.g. Chapters 7, 8, 9, 11 and 14).

A large part of SKB's research, development and demonstration is conducted in the form of projects. The majority of the projects have international participation. The Äspö HRL (Hard Rock Laboratory) is an excellent example of this. A considerable portion of SKB's project-oriented R&D is concentrated to the Äspö HRL. An important task for the Äspö HRL is to test and demonstrate parts of the disposal system on a full scale.

Finally, there is a chapter on scientific information (Chapter 18). We want to communicate our scientific findings to the public and to local politicians and community leaders to obtain acceptance for a deep repository.

It is the purpose of the safety assessment to develop and administer the methods and models for calculations employed by the safety assessment (Chapters 2 and 3). The topic-specific programmes (Chapters 4 through 11) serve to develop a better understanding of the processes dealt with in the safety assessment, to develop and review alternative models and to compile background data for the safety assessment. The barriers that protect man and the environment from the radionuclides in the waste are the point of departure for the topical classification of the programmes.

Waste

Nuclear power plants generate electricity and at the same time give rise to radioactive waste in the form of operational waste and spent nuclear fuel (SNF). Radioactive waste also arises when the nuclear power plant is decommissioned and dismantled (decommissioning waste). But most radionuclides which are produced by nuclear fission never leave the fuel, and a large portion of the radioactivity in SNF decays during interim storage, first at the power plants and then in CLAB.

Nuclear fuel is a ceramic material composed of poorly soluble uranium dioxide, and almost all of the radionuclides are bound inside the fuel matrix. SNF is a good waste form, even in comparison with other alternatives. It is therefore unnecessary to convert SNF to another solid waste form, such as vitrified HLW (high-level waste), unless this is simultaneously done to extract some of the contents. In reprocessing, the remaining fissionable material is extracted from SNF, but at the same time HLW is obtained in the form of a solution that needs to be solidified again, for example by vitrification.

Various laboratory experiments are conducted to investigate the properties of the spent fuel as waste in a deep repository and what happens if it comes into contact with the groundwater (Chapter 4). The results of these experiments – for example in the form of descriptions, measurement data and calculations models – are used as a basis for the assessment of long-term safety (Chapter 3). It is essential to examine in the safety assessment what would happen in the unlikely event that a canister is unable to keep the waste isolated from the groundwater.

The LILW (low- and intermediate-level waste) that arises during operation of the NPPs (nuclear power plants) goes to SFR (Final repository for radioactive operational waste) in Forsmark. SFR is an operational facility where radioactive waste from research, medicine, industry etc. is also disposed of. SFR is not dealt with in this report, but the results of SKB's R&D are also used to evaluate long-term safety in SFR.

One type of LILW that is dealt with in this report is long-lived LILW (Chapter 12). This waste consists primarily of reactor internals that are replaced in conjunction with maintenance or decommissioning, as well as some waste from research. The research waste is collected, treated and stored temporarily in Studsvik.

Canister and buffer

The canister of copper and cast iron is an essential barrier in the deep repository for spent nuclear fuel. Development of the canister and studies of its materials have been conducted within the framework of the encapsulation project /1-2/. Research and testing of the canister will be developed at the Canister Laboratory /1-1/. Studies of canister materials are, however, dealt with in this report (Chapter 5).

A buffer of bentonite will surround the canister and fill the space between the canister and the rock in the deposition hole. The purpose of the bentonite is to protect the canister against mechanical and chemical stresses. At the same time as it should have low hydraulic conductivity, it should also have some permeability in case e.g. gas should form in the canister. The heat that is evolved should be dissipated so that the temperature doesn't get too high. Too high temperature can, for example, jeopardize the stability of the buffer. Besides protecting the canister, the buffer is also the third barrier against the escape of radionuclides, after the canister and the SNF (the waste). If the canister should be damaged and water should enter and leach radionuclides out of the fuel assemblies, the buffer will retard the outward transport of the radionuclides. This is a vital function and many radionuclides decay completely or are greatly reduced before they manage to penetrate the buffer.

Rock as barrier

Certain vital properties of the bedrock are utilized to ensure the performance and long-term radiological safety of the deep repository:

- mechanical stability for a long time to come,
- a chemically stable environment with a groundwater that does not contribute to corrosion of the canister material or alteration of the buffer material and which gives low solubility and high retardation of the substances in the waste,
- as slow and unchanged a groundwater flux as possible, which limits the transport of radionuclides and substances that can adversely affect the waste products and the backfill.

There are clearly couplings between these properties. Besides choosing a host rock that possesses the above vital geoscientific properties, it is essential to minimize the risk of future intrusion by:

- avoiding rock volumes, or nearness to rock volumes, with a potential interest for mining of metals or minerals, energy storage or energy extraction,
- locating the repository on such a site and at such a depth that the risk of intrusion by drilling (wells, prospecting, exploitation) is very little.

The geological aspects are primarily associated with the performance and safety of the repository, but are also of importance for its construction. There is a connection between the configuration of the repository, its safety and its positioning in the rock. However, this connection does not have to be such that construction-related difficulties always entail long-term safety risks. For example, clay-filled zones can present rock engineering problems, but are not an obvious problem for future radiological safety. Figure 1-1 shows schematically how geoscientific information and data are managed according to scientific discipline and which models are devised with a view towards long-term safety, performance and construction.

Importance of the biosphere

The biosphere is the part of the earth where most organisms, animals, plants and people live. The biosphere consists of the ecosystems that are present in bodies of water, agricultural areas, forests and cities and the near-surface soil layers and groundwater reservoirs. It is not until they reach the biosphere that leaking radionuclides are of any importance, and it is there the effects, i.e. the dose of radioactivity, are measured or calculated. Much radiological safety legislation is therefore based on doses to humans in the biosphere, and the calculated doses, or the risk to which the doses give rise, are used as a standard of comparison between different disposal alternatives or sites. The natural ecosystems must also be protected, which requires a description of the effects on other organisms than man.

Accordingly, the most important thing is to prevent radionuclides from reaching the biosphere, but the biosphere can also have barrier properties such that harmful substances are either isolated in inaccessible parts of the biosphere or diluted to such low concentrations that the consequences for people and ecosystems are limited. In the siting process it is therefore important to choose sites where these conditions are met for a reasonable length of time in the future. However, the greatest effects of a deep repository on the biosphere are not caused by radioactivity, but arise in connection with the construction and operation of the repository. Areas that are particularly sensitive, for example nature reserves and other valuable biotopes, are therefore avoided.

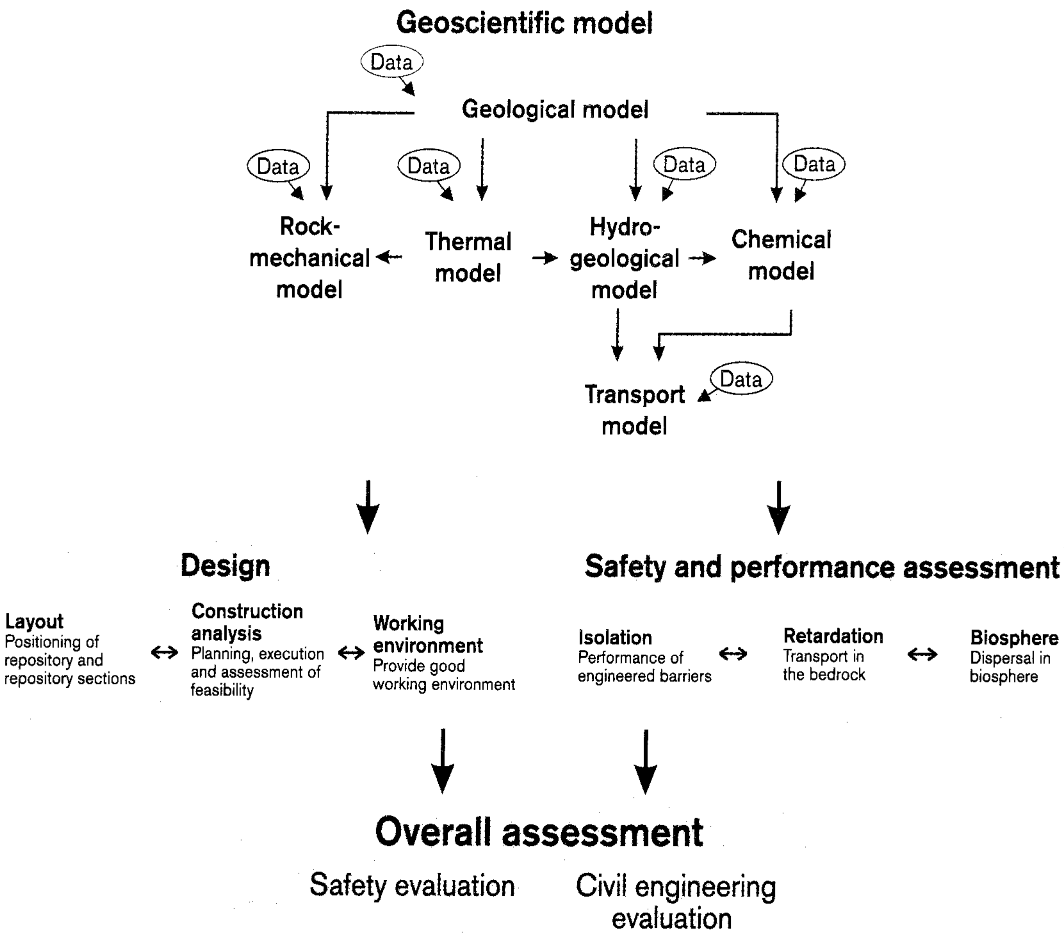


Figure 1-1. Schematic description, arranged according to scientific discipline, of how bedrock data and information are managed and modelled with a view towards safety, performance and construction.

2 Methods for safety assessment

The ongoing safety assessment, SR 97, will be completed in the beginning of the coming three-year period. Development of methods and models will then be based in part on the experience gained from SR 97. A first natural step in the ensuing work will therefore be to carry out evaluations of the lessons learned from SR 97 within various sub-areas of the safety assessment. Models for different subsystems will then be utilized for evaluations during the site investigations.

In addition, an assessment will be made of the alternative disposal concept based on emplacement in deep holes. The scope of this assessment will be considerably smaller than that of SR 97. This may be a suitable opportunity for testing a modified or new methodology for coming safety assessments.

2.1 Introduction

Here follows first an explanation of some important concepts and steps in a safety assessment, as a background to the presentations of the programmes for different sub-areas.

By "disposal system" is meant in the following: the deep repository with its fuel-filled canisters, surrounded by buffer clay in deposition holes, the backfilled tunnels and the bedrock around the repository. Upwards, the disposal system is bounded by the boundary between the geosphere and the biosphere. A more distinct system boundary can be established in a sharper discussion. Different courses of events within the disposal system are studied in detail.

Immediately after the repository has been built, the disposal system with all its components is in an initial state. This state can be described by a number of state variables, such as the geometric dimensions of the canister, deposition hole and buffer, the temperature in different parts of the repository, the radionuclide content of the fuel, the concentrations of sulphide and potassium in the groundwater, rock stresses, etc. The state variables characterize the repository thermally, hydrologically, mechanically and chemically. The physical structure of the repository is also characterized by these variables.

With time the state of the repository is changed by a number of processes such as radioactive decay, heat transport in the buffer, groundwater movements, corrosion of the copper canister, etc.

State variables and processes influence each other in a complex network. The copper corrosion process is affected by two state variables: the concentration of copper corrodants in the boundary layer between buffer and canister, and the temperature. The concentration of copper corrodants is in turn determined by the transport process of diffusion in the buffer, whereby corrodants are transported from the groundwater through the buffer to the canister surface. Copper corrosion in turn leads to a change in the geometry (thickness) of the canister, another state variable. Thus, the state variables are changed with time by a number of parallel and coupled processes.

Via the processes, the repository undergoes an evolution in time in this manner. This evolution is also affected by the interaction of the repository with the surrounding environment. This interaction may be continuous in time, e.g. the influence of the

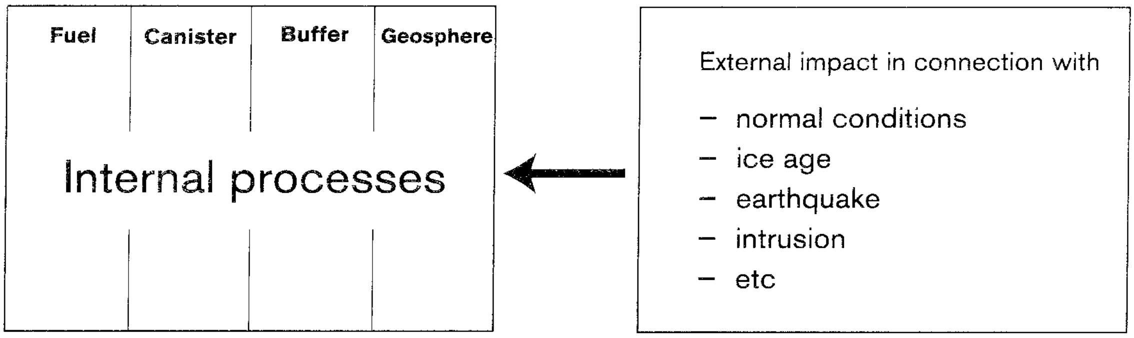


Figure 2-1. The repository has an initial appearance or state. Its evolution is then determined by internal processes and external impact.

climate system, or it may take the form of sudden events, such as human intrusion. The description of these different forms of interaction with the environment may require thorough analyses of surrounding systems. See also Figure 2-1.

The purpose of the safety assessment is to describe the evolution of the repository and to determine the safety-related consequences of this evolution. The consequences must at any moment be reflected in the state variables, e.g. the integrity of the copper canister, concentrations of radionuclides in the groundwater, or flow of radionuclides from geosphere to biosphere.

A structured compilation of state variables and processes is required to describe the evolution of the repository. A vital part of the methodology for a safety assessment is therefore to prepare a system description. The description must be able to serve as a basis for both the execution and the reporting of the safety assessment. State of knowledge and development programme for the system description are presented in section 2.2.

2.1.1 Uncertainties

In a safety assessment, it is necessary to handle information that is surrounded by uncertainties. Some uncertainties are qualitative, as expressed in the questions:

- Are all important processes identified?
- Do we understand the mechanisms and principles behind the different processes?
- Is the structure of the system description correct and the choice of state variables adequate?
- How well do we understand the processes and the interaction with the environment qualitatively?

Other uncertainties are quantitative:

- How does the process proceed? Even if the mechanism is well understood, data necessary for the quantitative description may be associated with uncertainties. One aspect of this is the natural variability that distinguishes certain data in a safety assessment.
- How well can we identify the initial state?
- How well can we quantify the interaction with the environment?

Let us for a moment, for the sake of discussion, assume that we knew everything about the initial state, were able to identify all active processes, understood the processes qualitatively and knew all data to quantify them, and assume that the repository's interaction with the environment today and in the future were known. Then we could build a faithful mathematical model of the repository and predict its evolution in detail. We could provide a single reliable description of the repository's future evolutionary pathway.

This is, of course, not possible. Instead we must somehow deal with all the uncertainties that will always surround the information on which a safety assessment is based. A key approach to dealing with this uncertainty is to study a number of alternative evolutionary pathways which together can provide reasonable coverage of what might happen to the repository in the future. This is what we mean when we talk about analyzing different scenarios in a safety assessment.

2.1.2 Scenarios, variants

First we formulate what we might call a "likely" or "normal" initial state: The repository is assumed to be built completely according to specifications, all copper canisters are completely intact, etc. Let us further assume that the interaction with the repository's environment is roughly like it is today, which means, among other things, that the present-day climate is assumed to remain the same. Let us now, with these premises (this initial state and this interaction), study the repository's evolution and see what possible consequences in the form of e.g. releases of radioactivity this could lead to. In studying this evolution, we include in one way or another all relevant processes identified in the system description. This is then our base scenario in the assessment.

Other premises as regards initial state and interaction give other evolutionary pathways for the repository and presumably other consequences. As an alternative initial state, we can, for example, choose a situation where a given portion of the canisters have a defective copper shell (which has not been detected by quality inspection following fabrication) but otherwise use the same premises as above. This would give an alternative evolutionary pathway for the repository, probably with other consequences than the first one. This evolutionary pathway can be called the canister defect scenario.

Other circumstances to be explored would be different alternatives as regards the influence of or interaction with the repository's environment, such as climate change, earthquake and human intrusion. Each of these premises gives unique evolutionary pathways and consequences.

The choice of scenarios, or rather the choice of a set of different premises for scenarios, is a vital part of a systematically executed safety assessment. The chosen scenarios should together provide reasonable coverage of conceivable evolutionary pathways for the repository. The technique of assessing several different scenarios is thereby one way to handle uncertainties in the knowledge concerning initial state and external influence/ interaction. The method for choice of scenarios is discussed further in section 2.3.

Within the framework for a scenario there is often room for a number of variants. Variants can also be used to assess alternative initial states, for example to shed light on how different extents of a fracture zone of uncertain location in the bedrock would affect the safety of the repository. The borderline between what is a separate scenario what is just a variant of another scenario is fluid and really a matter of definition. Uncertainties in the understanding of different processes can also be studied by means of variants of one and the same scenario. Different models for how water is transported in the bedrock can, for example, be used in two otherwise identical variants. Uncertainties in data for different processes can also be studied by means of variants.

2.1.3 Four steps

In simplified terms, the execution of a safety assessment can be said to consist of the following four steps:

- System description
- Choice of scenarios
- Analysis of chosen scenarios
- Evaluation of results and reporting

With this general introduction as a background, programmes and goals are presented below for the first two steps in the methodology: The method for system description and the method for choice of scenarios. The remaining two steps cannot be discussed in general method terms in the same way. They must instead be exemplified in the practical execution of an assessment, which will be done in SR 97.

2.2 System description

As noted above, the system description is a structured presentation of the disposal system's state variables, which among other things express the repository's physical structure, and of the processes which change the repository over time.

Previously this information has been structured in interaction matrices /2-1, 2-2/. Today there are matrices that describe near field, far field and buffer. Since then, the system description has been developed to a format that is better suited to the execution and reporting of the safety assessment. This is roughly how the system description for SR 97 will be done:

1. The repository is divided into four system parts: fuel (including canister cavity), canister, buffer/backfill and geosphere.

2. For each system part (e.g. the buffer), a list is made of all active processes. The list is based on the processes that have previously been judged to be vital in the work with the interaction matrices. To lend further structure to the description, the processes are divided into the categories thermal (e.g. heat conduction in the buffer), hydrological (e.g. water transport in the buffer), mechanical (e.g. swelling in the buffer) and chemical (e.g. ion exchange processes in the buffer).

3. Within each system part, all processes are then studied for the purpose of finding a suitable set of state variables for that particular system part. Important state variables in e.g. the buffer are its geometric dimensions, temperature, smectite content, water content, pore water pressure and pore water composition.

Each process is documented in a structured manner which includes, among other things, a general description of the process, an account of model studies and experimental studies, a discussion of uncertainties, and information on how the process can be dealt with in the safety assessment. An initial version of such process documentation will be presented with SR 97.

Each process can be schematically illustrated in a standard manner. All processes within a system part can then be compiled in a THMC (Thermal, Hydrological, Mechanical, Chemical) diagram, which is based on the list of THMC processes (step 2 above) and state variables (step 3). The interaction between different system parts is also expressed in the diagram. Here as well, two adjacent system parts mainly influence each other thermally, hydrologically, mechanically and chemically.

The four THMC diagrams for fuel, canister, buffer/backfill and geosphere and their documentation thereby comprise the system description for a safety assessment. In the analysis of the different scenarios, it should be possible to base the description of the repository's evolution on the same structure.

2.2.1 Goal and programme

Goal: To develop a database with process descriptions that can be used directly in coming safety assessments.

The use of a system description in the form of THMC diagrams and process descriptions in SR 97 will be evaluated.

Then a well-documented database will be developed with processes, state variables and couplings based on the THMC description. The database should contain documentation on all essential processes at approximately the same level as in the special background report with process descriptions that is compiled for SR 97. It must be able to be updated regularly and reused in large parts in coming safety assessments.

The database can take the form of an expanded and augmented version of SKB's database of features, events and processes of importance for the safety of the repository. SKB's database will also be linked to the OECD/NEA's recently completed international database. In this way, comparisons with similar databases produced within other countries' waste programmes can be facilitated. The utilization of other databases can be a means of checking the completeness of the system description.

THMC diagrams with associated documentation constitute one of several possible formats for a system description. Based on the evaluation of the application within SR 97, the need for further development will be assessed and specified. The system description in the planned safety assessment of deep holes may be carried out with a completely or partially new methodology. Object-oriented analysis /2-3, 2-4/ can be an alternative or a complement to present-day methodology.

2.3 Method for choice and formulation of scenarios

How should the scenarios be chosen to provide a reasonable coverage of evolutionary pathways for the repository? The following procedure is currently employed: Conceivable initial states and possible forms of external interaction/influence are systematically examined. As in the system description, the interaction/influence is divided into thermal, hydrological, mechanical and chemical. The consequences for performance and safety are estimated by describing how the disposal system evolves in the different cases.

Conceivable initial states are examined by studying all state variables in the system description. External influence/interaction is dealt with by identifying surrounding systems or phenomena with which the disposal system interacts. This is done from the perspective of the system design and the system description and with the support of FEP lists.

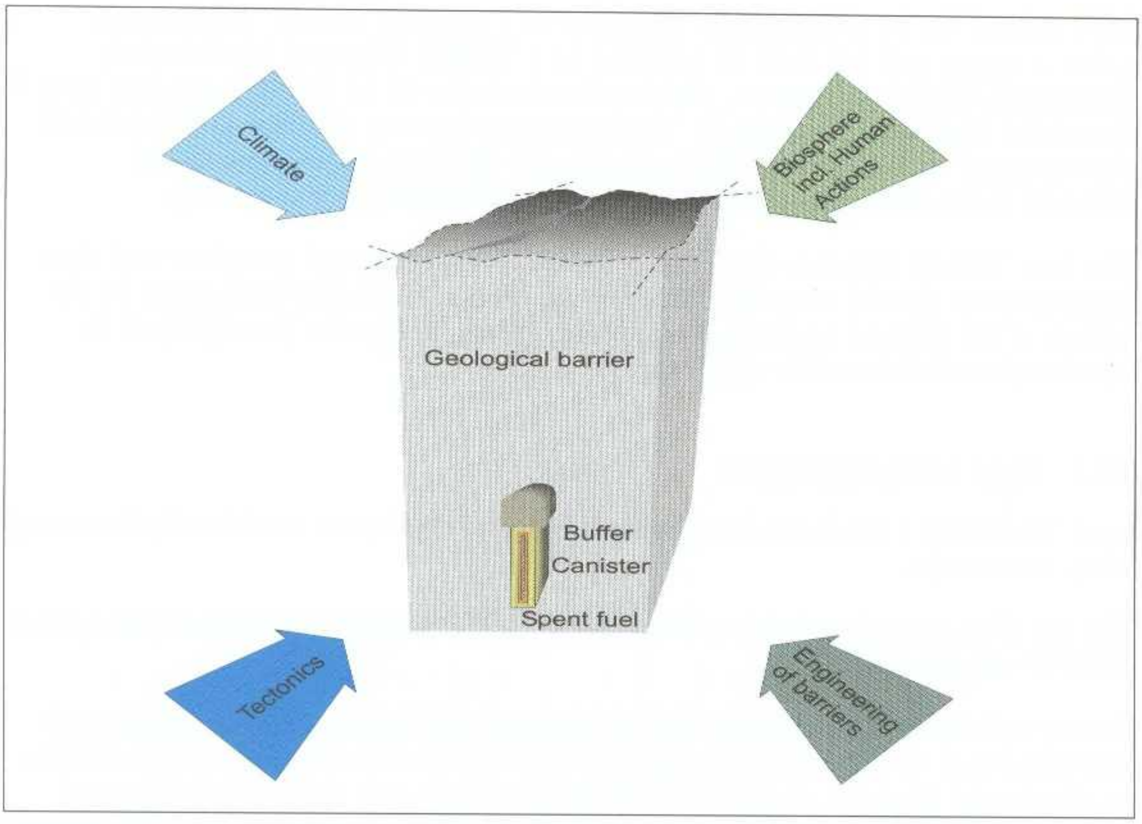


Figure 2-2. *Four categories of systems or phenomena with potential importance for the safety of the disposal system can be identified.*

The identified systems and the phenomena have been divided into four categories, see Figure 2-2. One or more scenarios can be formulated within each category.

The surrounding systems and phenomena shown in Figure 2-2 are examined in SR 97. For each category, conceivable interaction is dealt with in terms of THMC. Directly involved system parts are identified. Thermal, hydrological, mechanical and chemical couplings and their importance for the system parts are described. A preliminary assessment of the importance and occurrence of the coupling is made. If the coupling is judged to be of importance for the safety of the repository and/or the probability of it's occurring is deemed to be high, a scenario based on it is formulated.

One category of scenarios concerns the engineering of barriers. Here it is analyzed how different conditions and possible accidents in the engineering of the barriers can affect the initial state of the repository. Affected state variables and processes are thoroughly documented in THMC diagrams and/or interaction matrices. Information for conceivable variations is often given in the system premises for the safety assessment, and the consequences of the variations are explored within the base and canister defect scenarios, see Figure 2-3.

A separate analysis of surrounding systems and phenomena is required for the other categories. One example is climate. The earth's climate system and how and why it changes are described separately. Climate change affects conditions on the surface of the repository, which in turn affect the deep repository. The conditions on the surface which affect the deep repository are described, divided into thermal, hydrological, mechanical

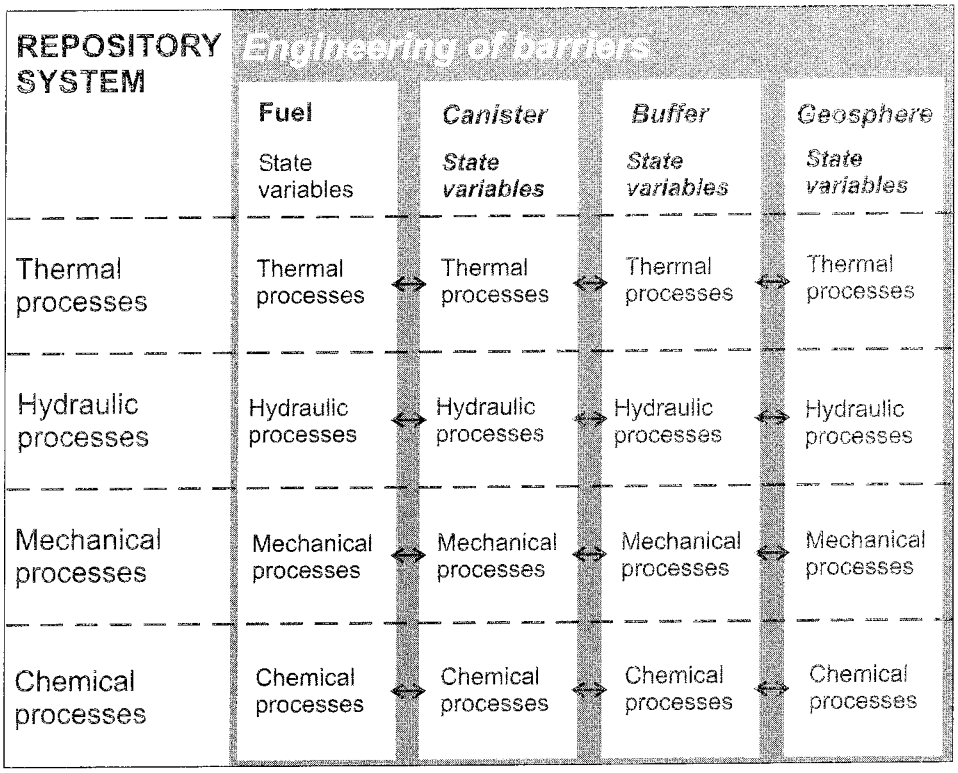


Figure 2-3. *Systems or phenomena that belong to the category "engineering of barriers" are often included as premises for the safety assessment and are described in the system description. Variations and their consequences are investigated in the base and canister defect scenarios.*

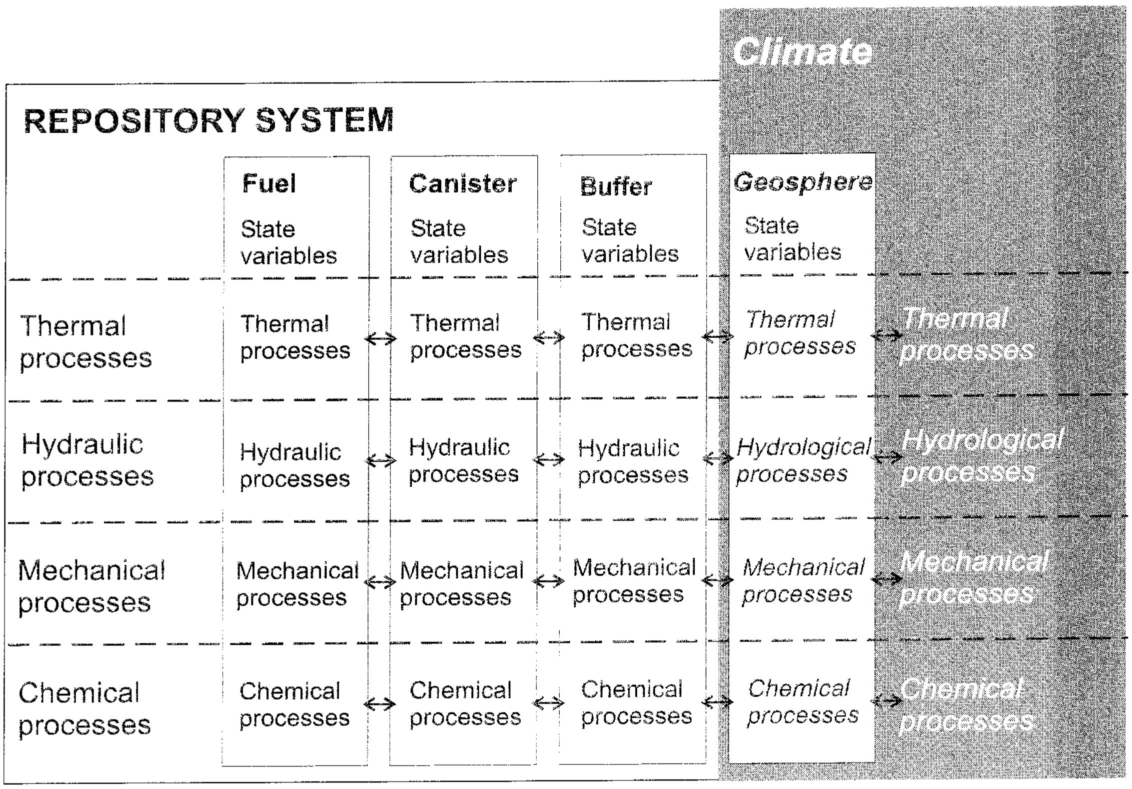


Figure 2-4. *Conditions on the surface caused by changes in the climate and their impact on the disposal system are described in terms of THMC.*

and chemical, see Figure 2-4. The same procedure applies to other couplings that can be said to constitute boundary conditions or external events.

2.3.1 Goal and programme

Goal: To develop and describe a method for scenario selection based on the system description. The method shall include systematics for:

- Survey of realistic future evolutionary pathways, situations and conceivable critical situations or extreme cases.
- Handling of expert opinions.
- Formulation and explanation of scenarios.
- Traceability to the purpose of the safety assessment.

The programme contains the following measures:

- Description, documentation and evaluation of the method for choice of scenarios which has been applied within SR 97.
- Augmentation of the process and FEP database based on THMC diagrams and interaction matrices with additional processes that are associated with surrounding systems and phenomena.
- Formulation of a strategy for handling scenarios based on human actions.
- Further development of formulation of climate scenarios based on evaluation of the application in SR 97.

A methodology for formulation and analysis of tectonics scenarios is described in Chapter 7.

2.4 Handling of uncertainties

Handling of uncertainties is an integral part of the work with a safety assessment and can therefore not be described as a separate activity. In the method description for the safety assessment, it is nevertheless valuable to systematically examine different types of uncertainties and the method for handling them.

2.4.1 Goal and programme

Goal: To find a practically feasible method for handling uncertainties.

As was mentioned in the beginning of the chapter, the information underlying a safety assessment is always associated with uncertainties of various kinds.

An important part of a safety assessment consists of handling these uncertainties in a methodical fashion, showing what different types of uncertainties mean for the results of the assessment, etc.

SR 95 /2-5/ contains a systematic survey of different types of uncertainties and how they enter into the different steps of the safety assessment. The ambition in SR 97 is to go one step further in the practical handling of uncertainties in an assessment. Here follows a short description of how different types of uncertainties will be handled in SR 97.

Qualitative uncertainties

Process identification: The identification and ranking of processes from FEP databases, via interaction matrices to THMC diagrams will be described and documented in SR 97.

Process understanding: A discussion of understanding and conceptual uncertainties will be held in the documentation for the system description that comprises a part of the reporting of SR 97.

System description and state variables: An important property of the new process-oriented description in the form of THMC diagrams is that it should be general and freely allow the addition of processes and state variables as needed. State variables can be freely added as new processes require new variables to fit into the description. Ultimately, the question of whether the choice of variables is adequate is determined by how well all component processes and their interrelationships are understood.

Uncertainties in the understanding of the interaction with the repository's surrounding environment: This question relates directly to the choice of scenarios, see section 2.3.

Quantitative uncertainties

Numerical uncertainties in input data to transport calculations: For all processes that directly influence the release and transport of radionuclides, numerical uncertainties in input data are dealt with in a standard manner according to a set template. The result of this handling of numerical uncertainties will be presented in a special background report to SR 97. After the picture of input data with associated uncertainties has been clarified, a number of variants of calculation cases will be formulated to illustrate the importance of different uncertainties.

Numerical uncertainties in the initial state: The initial state will be discussed qualitatively and quantitatively in the documentation for the system description for SR 97. Many aspects of the initial state enter directly into the transport calculations, for example the incidence of damage to the canister's copper shell or the radionuclide inventory. Such uncertainties are handled in the formulation of different calculation variants as described above. Other uncertainties, e.g. the situation with regard to rock stresses around the repository, are treated in special discussions.

Numerical uncertainties in the interaction with the surrounding environment: These are handled from case to case in the individual analyses of the surrounding systems.

Programme

The further development that is required will be dependent on the outcome of the SR 97 review.

The application of the method for handling uncertainties provides an opportunity to identify dominant uncertainty areas. Possible measures to reduce uncertainties are discussed in connection with the different research fields.

2.5 Where can the processes identified in the safety assessment be found in the research programme?

According to section 2.2, a number of processes that can eventually lead to changes in the repository are identified in safety assessments. For each process, a description is given of state of knowledge, remaining uncertainties and how the process will be handled in an integrated safety assessment.

Starting with the upcoming safety assessment SR 97, the ambition is to be able to use the evaluations in the safety assessment actively to prioritize work in the research programme. It can be a question of identifying aspects of different processes where further research is warranted in order to better be able to evaluate long-term safety, or deciding that further research on a process is not warranted.

As a first step towards this goal, we show in Table 2-1 where the different processes that are dealt with in the safety assessment are addressed in the research programme. The table includes those processes that have been identified in SR 97 for fuel, canister, buffer/backfill and geosphere. Note that the final process categorization in SR 97 may differ from the table in some respects.

For many processes, current knowledge has been deemed sufficient, and they are therefore not to be found in the research programme. This means firstly that knowledge of the process is adequate for performing a safety assessment which somehow includes the

Table 2-1. The table shows the thermal, hydrological, mechanical and chemical processes that will be dealt with in SR 97. Nuclear-physical processes are yet another category for the canister. The final selection of processes in SR 97 may differ in some respects from the categorization in the table. The table shows for each process the section in the background report to RD&D-Programme 98 in which the process is addressed, or states that current knowledge of the process has been deemed sufficient.

Process *Only relevant if the copper canister is damaged	Section where goal and programme are described
FUEL/CAVITY IN CANISTER	
Nuclear-physical processes	
Radioactive decay	3.2 (Sufficient knowledge)
Induced fission (criticality)*	Sufficient knowledge
Thermal processes	
Heat generation/attenuation	3.2
Heat transport	Sufficient knowledge
Hydraulic processes	
Water and gas transport in the canister's cavity, boiling/condensation*	3.5

Process *Only relevant if the copper canister is damaged	Section where goal and programme are described
Mechanical processes	
Thermal expansion/cladding failure	Sufficient knowledge
Chemical processes	
Radiolysis of water in canister cavity	Sufficient knowledge
Radiolysis of residual gas in canister cavity	Sufficient knowledge
Corrosion of fuel's metal parts*	Sufficient knowledge
Dissolution/alteration of fuel	4.6 (3.3)
Water dissolution of gap inventory*	Sufficient knowledge
Speciation of corrosion products from cast iron insert*	3.4
Speciation of radionuclides, colloid formation*	4.6, 10.8 (3.6)
Helium production	3.2 (Sufficient knowledge)
Radionuclide transport	
Advection*	Sufficient knowledge
Diffusion*	Sufficient knowledge (3.6)
Sorption in canister*	Sufficient knowledge (3.6)
Colloid transport in canister*	Sufficient knowledge
Radionuclide transport with gas*	Sufficient knowledge
CAST IRON INSERT/GAP/COPPER CANISTER	
Thermal processes	
Heat generation/radiation attenuation	Sufficient knowledge
Heat transport	Sufficient knowledge (5.3)
Mechanical processes	
Deformation of cast iron insert	5.3
Deformation of copper canister by external pressure	5.3
Thermal expansion/contraction	5.3
Deformation by internal corrosion products*	5.2
Chemical processes	
Corrosion of cast iron insert*	5.2
Galvanic corrosion*	Sufficient knowledge
Stress corrosion of cast iron insert	
Radiation-induced processes in cast iron insert	Sufficient knowledge
Corrosion of copper canister	5.1
Stress corrosion of copper canister	5.1
Radiation-induced processes in copper canister	Sufficient knowledge
Radionuclide transport* – see radionuclide transport under fuel/cavity in canister	
BUFFER/BACKFILL	
Thermal processes	
Heat transport	Sufficient knowledge (14.4.5)
Heat generation/attenuation	Sufficient knowledge
Hydraulic processes	
Water transport in unsaturated conditions	6.4.1
Water transport in saturated conditions	6.4.1
Gas transport	6.6.2, 6.4.3

Process *Only relevant if the copper canister is damaged	Section where goal and programme are described
Mechanical processes	
Swelling	6.3 (14.4.5)
Erosion	Sufficient knowledge
Mechanical interaction buffer/backfill	6.3 (14.4.5)
Mechanical interaction buffer/canister	5.3
Mechanical interaction buffer/near-field rock	6.6.2 (14.4.5)
Mechanical interaction backfill/near-field rock	6.3
Mechanical interaction backfill/plugs	14.4.5
Thermal expansion	Sufficient knowledge
Chemical processes	
Ion exchange processes; surface-chemical processes	6.4.2
Chemical smectite degradation	6.6.2 (14.4.5)
Dissolution/precipitation of impurities	(6.2.5, 14.4.5)
Colloid formation	10.8
Radiation-induced smectite degradation	Sufficient knowledge
Radiolysis of pore water	Sufficient knowledge
Microbial processes	10.8
Advection	Sufficient knowledge
Diffusion	Sufficient knowledge (6.6.1, 6.4.2)
Gas dissolution	Sufficient knowledge
Interaction between plug concrete and backfill	6.5
Radionuclide transport	
Diffusion*	Sufficient knowledge (4.2, 6.4.2, 6.6.1, 10.2)
Sorption*	Sufficient knowledge (6.6.1, 6.4.2)
Advection*	Sufficient knowledge
Colloid transport*	10.8
Speciation*	See fuel/cavity
Decay*	Sufficient knowledge
GEOSPHERE	
Thermal processes	
Heat transport	Sufficient knowledge
Hydrological processes	
Groundwater movements	3.7, 8.3
Gas transport	8.3
Mechanical processes	
Fracture formation	7.6
Reactivation	7.6
Creep deformations	7.6
Thermally caused deformations	7.6
Chemical processes	
Advection, mixing	9.6 (9.3.1)
Diffusion	9.6 (9.3.2)
Dissolution/precipitation in rock matrix	9.6 (9.4)
Dissolution/precipitation of fracture-filling minerals	9.6 (9.4.5)
Microbial processes	9.6, 10.8 (9.4.3)
Colloid formation	9.6 (9.4.4)
Gas formation/gas dissolution	9.6 (9.3.3)
Freezing-out of salt	Sufficient knowledge

Process *Only relevant if the copper canister is damaged	Section where goal and programme are described
Radionuclide transport	
Advection and dispersion*	Sufficient knowledge
Sorption*	10.8 (10.1, 10.2)
Molecular diffusion and matrix diffusion*	3.7.1, 10.8 (10.2)
Colloid transport*	(10.3)
Speciation*	(10.4)
Transport in gas phase*	10.8 (10.3)
Decay*	Sufficient knowledge

3 Models for safety assessment

Certain computer models are being developed especially for use in the safety assessment. The goal of the work with these models and their associated databases is that they should be kept up-to-date in terms of understanding of the modelled processes and advances in the computer field. Some of the models should be designed so that they can be coupled in calculation chains.

More specific goals during the period are specified under the individual headings below.

3.1 Handling of coupled models

For some time now SKB has had access to a program package called PROPER intended for probabilistic calculations of radionuclide transport. In recent years a modern menu-based user interface called MONITOR 2000 has been developed and works satisfactorily today.

3.1.1 Goal and programme

Program maintenance and regular updating of MONITOR 2000 and PROPER will take place during the period. PROPER is now being used in a multi-computer environment. This has made new demands on PROPER's source code. It has also opened new opportunities for reducing the calendar time when several calculation cases have to be run with PROPER, since MONITOR 2000 can allocate the computing work among several computers for parallel processing.

MONITOR 2000 will be evaluated after SR 97. The use of MONITOR 2000 will gradually increase at a practically feasible pace. Development of user-friendly routines for simplifying large computing tasks, maintenance and adaptation to new PROPER submodels will be carried out in MONITOR 2000. The entire PROPER package will be revised to reduce today's execution times.

3.2 Models for radionuclide inventory and decay heat

Radionuclide inventories and decay heat for the spent fuel are computed with the codes ORIGEN-2, CASMO and SCALE. There are four types of uncertainties in the computations: reaction cross-sections, yields, decay constants and kerma conversion factors for neutron dose calculations. Despite the uncertainties, the models determine the inventory with a maximum uncertainty of 12 percent for fission products and 20 percent for actinides.

The calculation programs and underlying data thus provide a good basis for determining the source term for dose and temperature calculations.

3.2.1 Goal and programme

SKB must have continued access to modern calculation programs for radionuclide inventories and decay heat.

No own development of calculation programs for inventories will be conducted. The internal documentation of the reliability, verification and validation of the programs will be strengthened.

3.3 Models for fuel dissolution/alteration

3.3.1 General about fuel dissolution models

The greater part of the radionuclides in spent nuclear fuel lie embedded in the uranium dioxide matrix and cannot be released until the matrix has been dissolved or transformed structurally. A safety assessment must therefore include a calculation model that describes dissolution/alteration of the uranium dioxide in the fuel.

Three possible approaches for such a model are:

- to regard the fuel's solubility as being limited by the uranium dioxide and calculate the dissolution rate as a product of the water flux and the solubility;
- to assume that U(IV) in the fuel is oxidized to U(VI) by radiolytically produced oxidants. The rate is dependent on the reaction rate between oxidants and fuel and the production of oxidants;
- to assume that the fuel matrix does not have any barrier function at all and that radionuclides are released from individual solubility-limited phases.

The model that best represents reality or that is known with certainty to exaggerate the consequences is used in a safety assessment. Uncertainties in both understanding and available data can also make it interesting to demonstrate differences in results from different models.

3.3.2 Solubility-limited model

In a solubility-limited model, it is assumed that radiolytically produced oxidants are no longer of any importance for the stability of the fuel. The presence of iron (II and 0) in the canister, together with the relatively low dose rates, could make this possible. Fuel leaching tests under anoxic conditions also show that it is possible that no appreciable oxidation occurs. The solubility of uranium dioxide in fuel is close to 10^{-7} M. The water flux in a damaged disposal canister can be estimated at 0.01–1 l/y, depending on the size of the perforation in the canister shell. With these data and 10,000 moles of uranium in a canister, a solubility-limited model gives a fuel dissolution rate of the order of one hundred thousandth to one ten thousandth of the fuel in a million years.

3.3.3 Model with radiolytic oxidation

The possibility cannot be ruled out that radiolytic oxidation will be of importance for the dissolution of the fuel matrix. In for example SR 97, a model is therefore used that describes dissolution as a function of oxidant production and oxidant reaction in order to calculate matrix dissolution.

Radiolysis splits water into equal parts of oxidizing and reducing species. One of the reducing species, H_2, is much less reactive than the oxidizing species, which can lead to a net oxidation of the fuel.

The idea of a model that describes a radiolytic oxidation was first presented in SKB 91 /3-1/. There it was assumed that the oxidation rate, as well as the release of radionuclides, was proportional to the α-dose rate in the fuel and the proportionality constant was derived from the release rate for strontium-90 obtained from fuel leaching tests under oxidizing conditions. Similar models have also been used in TVO-92 and SITE-94.

Premises

A new and more sophisticated radiolysis oxidation model has been developed for SR 97. The model is based on calculated production of radiolytically produced species in water and reaction between these species and the uranium dioxide. The premises of the model are:

- The radiolytic reactions are assumed to take place in a 100 mm thick water film around the fuel pellets. This is based on the size of the fuel-clad gap, which is 100 mm on fabrication. The cladding is assumed to be defective so that water can leak in, but due to its high resistance to general corrosion, it is assumed that it will otherwise physically enclose the fuel for a very long period of time. The thin water film prevents concentration gradients from forming for the radiolytically produced species, since diffusion across 100 mm is very fast and constant concentrations can therefore be assumed across the film. If it is instead assumed that the fuel pellets have free access to water, i.e. that the water film is much thicker than 100 mm, concentration gradients and transport within the film must be taken into consideration. There is no model that can do this, but calculations with increasing film thickness indicate that the final fuel dissolution rate is independent of the thickness of the layer.
- Both α- and β-radiolysis are taken into account. β-radiolysis tends to produce radicals, while α-radiolysis produces molecular species.
- The reactions between H_2O_2 and O_2 and uranium dioxide are assumed to be first order.
- The reaction rate between the molecular oxidants H_2O_2 and O_2 and the uranium dioxide is taken from experimentally measured values (with the assumption of a first-order reaction).
- Generated H_2 does not leak out, but will remain in the system. This can be justified by the fact that the partial pressure of hydrogen in the canister from corrosion of the steel insert will be higher than that from radiolysis.
- Approximately forty reactions are included in the calculations, including two reactions with uranium dioxide.

Calculation results

Simulations with the model show that the system reaches a kind of pseudo-steady-state after a period of one month to one year. Then the concentrations of H_2, H_2O_2 and O_2 reach more or less constant values and the oxidation rate of uranium dioxide assumes a low value. This value decreases slowly with time but can, for the purposes of the safety assessment, be regarded as constant. With reference values for all parameters in the model, the calculated value corresponds to a situation where a fraction of 10^{-8} of the fuel

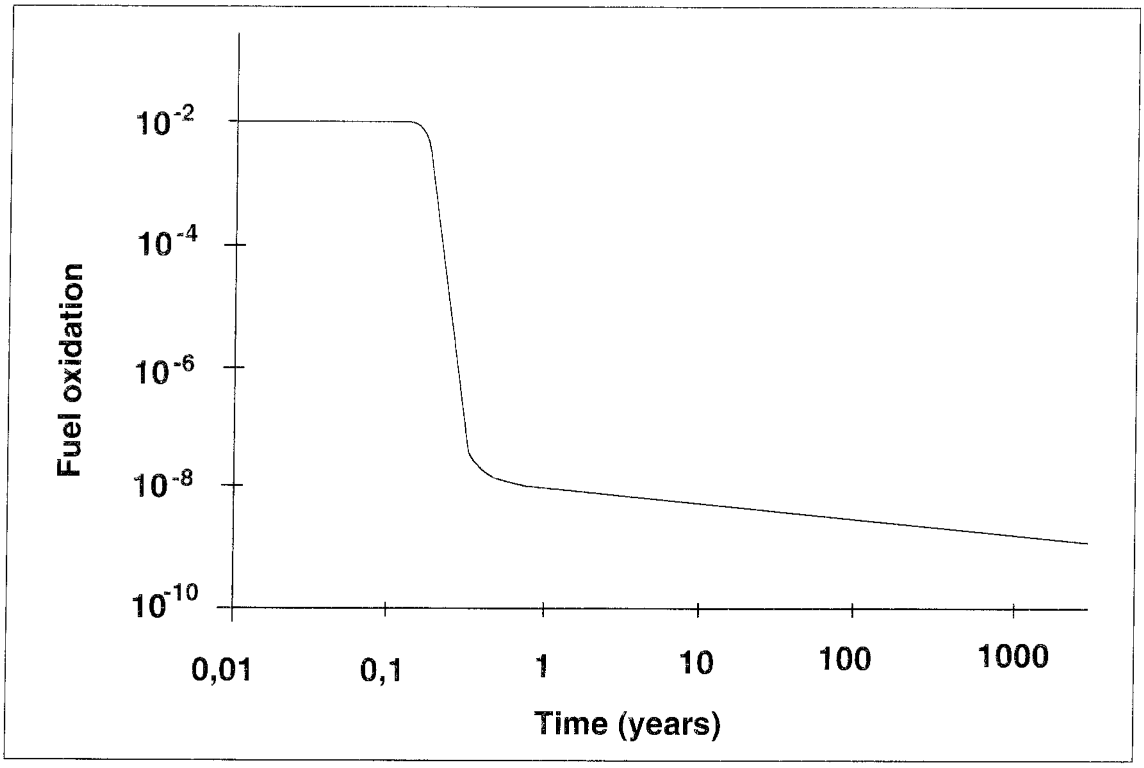


Figure 3-1. *Oxidation rate (expressed as hydrogen production) as a function of time.*

dissolves every year (Figure 3-1). The steady-state situation is caused by the fact that when the concentration of H_2 in solution reaches a certain value (about 10^{-3}), reactions between H_2 and radicals start to become important:

$OH + H_2 \rightarrow H_2O + H.$

Atomic hydrogen is highly reactive and reacts in turn with H_2O_2 and O_2.

3.3.4 Model with immediate dissolution

A model where all fuel is immediately dissolved is unreasonably pessimistic, but can be used as a conservative case which overestimates the consequences of fuel dissolution in the safety assessment.

Comparisons

A model based on the solubility of uranium gives a rate of dissolution/alteration of between approximately 10^{-11} and 10^{-13} (fraction of inventory per year assuming that the water flux in the canister is between 0.01 and 1 l/y), the oxidation model for SR 97 gives a rate of 10^{-8} per year, while the model with immediate dissolution has an infinite dissolution rate. Even though the differences are great, the consequence for safety is limited for two reasons:

The nuclides that dominate the release from the repository are not completely matrix-bound, but occur in segregated phases that are released even if the matrix is stable.

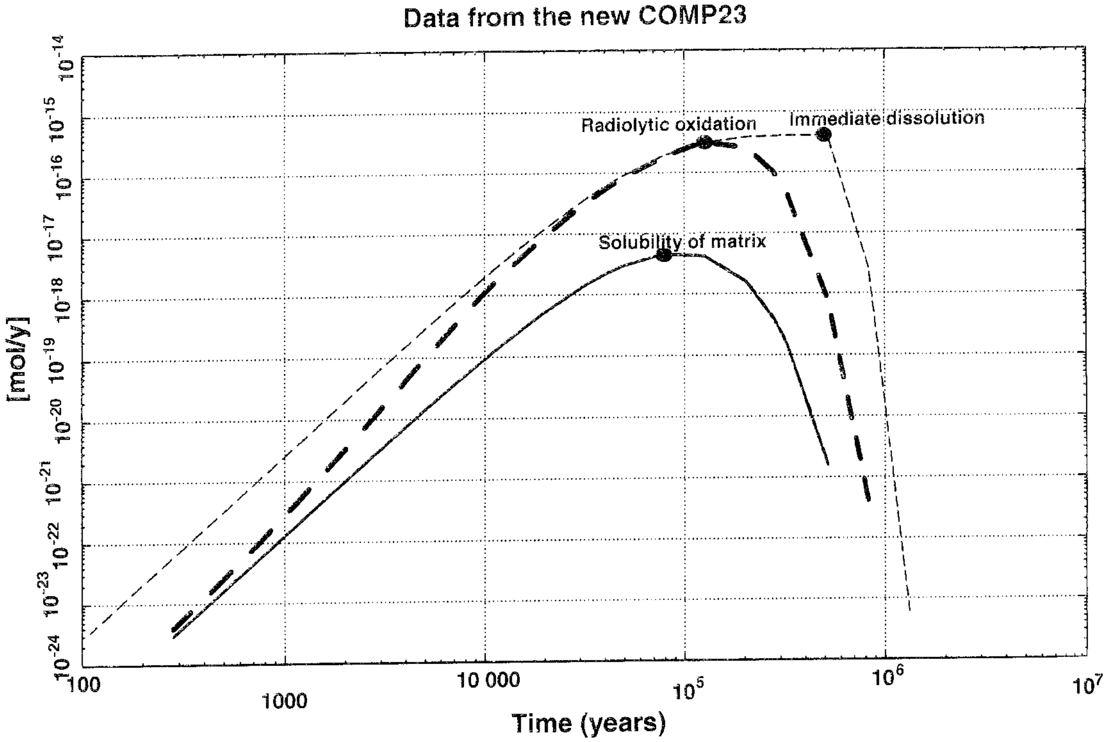


Figure 3-2. Release of Pu-239 from the near field with different fuel alteration models.

Many completely matrix-bound nuclides, such as plutonium, have very low individual solubilities and are released very slowly, even if the matrix dissolves rapidly. An example of the latter effect is that Pu-239, with an inventory of 20 moles per canister and a solubility of 10^{-9} M, is released at a rate of 10^{-10} to 10^{-12} per year due to its individual solubility. As a result, the difference in release is not dramatic even when different matrix alteration models are used (see Figure 3-2).

Nuclides with low concentrations in the fuel, such as Am-241, are however affected considerably by different matrix alteration rates, since a low alteration rate means that it takes a very long time for the nuclide to reach its saturation concentration in the canister. In the case of Am-241, a alteration rate of 10^{-8} entails that it will never reach its saturation concentration.

3.3.5 Goal and programme

Models for fuel dissolution are being developed within the fuel programme. The goal for the safety assessment is to devise tools for *quantifying* the release of radionuclides from the fuel based on the best data available.

The calculation model that has been developed for SR 97 will be tested and analyzed.

To strengthen the basis for future safety assessments, an alternative model will be developed, tested and compared with those used today. This model as well will be based on radiolytic oxidation of the fuel, but will also take into account other components in the near field such as canister, buffer impurities, etc.

3.4 Chemical modelling in the near field

A realistic description of the chemical environment in the near field is important for calculations of radionuclide solubilities and transport, but also for determining the stability and longevity of the engineered barriers. The chemical environment is determined by numerous factors:

- The natural groundwater composition on the site.
- The influence of repository construction, in particular oxygen from the pre-closure period.
- Engineering and reinforcement materials and forgotten materials.
- Bentonite and copper canister.
- In a scenario with defective canisters, also the iron insert and the spent fuel.

In the natural groundwater composition it is above all pH, ionic strength and carbonate concentration that are of importance. pH influences all chemical processes to a varying extent. Ionic strength is of importance for the swelling pressure in the buffer and in the tunnel backfill. Karnland /3-2/ shows that even highly compacted bentonite loses its swelling capacity at salinities in excess of 10 percent, i.e. 100 g/l. The salinities measured in Swedish groundwaters are not that high, however. Ionic strength and above all calcium concentration are of importance for the ion exchange processes and the dissolution of impurities in the buffer.

Deep groundwaters normally do not contain oxygen, but air that is left in the deposition tunnels after closure of the repository can affect the redox conditions around the repository at an early stage. There is also speculation concerning the possibility that oxygenated water could penetrate down during the deglaciation period following an ice age, see the chapter on groundwater chemistry.

Concrete and reinforcing material used for rock support and in plugs will have an influence on the pH of the water in the near field. It is, however, possible to choose concrete of such quality and in such quantity that this effect is minimized.

The bentonite buffer is the component that has the greatest effect on the chemistry of the near field. The Na-montmorillonite in the buffer has a surface with two kinds of active positions: surface positions and edge positions. Ion exchange reactions occur at the surface positions, while the edge positions have other acid/base characteristics /3-3/. The surface of the clay mineral is of great importance for the pH buffering in the near field.

The impurities in the bentonite are stable in the environment where the clay was originally mined. In the repository, however, it will be exposed to a water which differs in certain respects from that on the site of origin, in terms of both composition and temperature. Most of the impurities in the bentonite are nevertheless stable in normal Swedish groundwaters, but there are some important dissolution processes:

- Calcite is stable in groundwater. In bentonite, however, the ion exchange process will compete for the free calcium ions (the equilibrium reaction $2XNa + Ca^{2+} \leftrightarrow X_2Ca + 2Na^+$ competes with $Ca^{2+} + HCO^-_3 \leftrightarrow calcite + H^+$). The carbonate concentrations in the groundwaters that come into contact with the bentonite are sufficiently low for the ion exchange process to dominate and calcite will be dissolved. At the same time, this entails a consumption of hydrogen ions and an raising of the pH. The water flux in the buffer is very low and the reactions are near equilibrium. Calculations show that it can take a million years to consume all calcite with Gideå groundwater, while only 10% of the calcite is consumed in the same length of time with Äspö water.

- Pyrite is also stable in groundwater. Penetrating oxygen-containing water can oxidize the pyrite, however. Pyrite oxidation generates protons and can thereby lower the pH, but this is buffered by the aforementioned dissolution of calcite. There is enough pyrite in the buffer to guarantee that all initial oxygen left on closure of the repository will be consumed. The quantity is also sufficient to prevent any penetrating oxygenated water from coming into contact with the canister for hundreds of thousands of years.

- Calcium sulphates (gypsum and anhydrite) and calcite have lower solubility at high temperatures than at low ones. At an early stage, when the canister temperature is high, it is possible that they will be dissolved in the colder portion of the buffer and precipitate on the canister surface.

- The largest fraction of the impurities in the bentonite consists of quartz and feldspars. These are stable in the repository environment, but their solubilities increase with increasing temperature. In the deposition holes where a temperature gradient exists, the higher temperature at the canister, where the saturation of the pore water with dissolved silicon gives the highest Si concentration, gives rise to transport of this element towards the colder rock, so that enrichment and silicon precipitation in the outer portions of the bentonite can be considerable.

The copper canister is thermodynamically stable in the repository environment and will not have any impact on the chemistry of the near field.

In the event of a defective copper canister, water may come into contact with the iron insert and the fuel, which will cause the iron to start to corrode and water molecules may be split by radiolysis. Both of these processes can have a substantial effect on the chemical composition of the water.

3.4.1 Goal and programme

The goal is to be able to carry out an integrated modelling of the chemical processes in the near field.

Today models are available for describing the chemical processes in the near field individually (equilibrium models, dissolution kinetics, ion exchange models, corrosion, etc.). These processes are, however, coupled in many cases. During the coming period, studies will be conducted to shed light on how the chemistry of the near field may evolve if all processes are taken into consideration, but also on how the disposal system reacts to external and internal disturbances.

3.5 Modelling of evolution of damaged canister

The performance of a canister with a penetrating defect (perforation) has recently been studied rather thoroughly. An important result is that even a damaged canister has potential to prevent radionuclide transport for very long periods of time. A study to assess just how long a time has been carried out and the results reported /3-4/. A simple model is presented in the report for the evolution of the canister after an initial penetration in the canister's copper shell. The model is used to predict:

- the ingress of water into the canister (as a function of the size and shape of the defect, the conductivity of the buffer, the corrosion rate and the pressure inside the canister),
- the build-up of corrosion products inside the canister (as a function of available water in the canister, the corrosion rate and the properties of the corrosion products),
- the effect of the corrosion products on the structural integrity of the canister.

A number of variants for the location of the perforation in the copper shell have also been studied. The study shows that it may take over two hundred thousand years before the canister becomes filled with water even if it had an initial penetrating defect.

3.5.1 Goal and programme

The goal is to be able to describe the evolution of a damaged canister taking into account all important processes.

A damaged canister can very well offer a very effective barrier to radionuclide transport, but its evolution may be complicated to describe, since it depends on many disparate processes. The two most important processes are the entry of water into the canister and the consumption of such water due to corrosion. These processes are in turn dependent on numerous other processes such as gas pressure inside the canister, surface area available for corrosion, properties of the corrosion products, size and growth of the perforation, etc.

These processes will be studied in detail during the coming three-year period; their relative importance and coupling will be explored. Some form of validation experiment may also be deemed advisable to perform. The work will be carried out in cooperation with the canister and buffer programmes.

3.6 Models for radionuclide transport etc. in the near field

The near-field model NUCTRAN calculates radionuclide transport in complex geometries /3-5/. The model can also handle transient processes. The different parts of the near field – such as the hole in the canister wall, the canister's inner volume, the buffer, the tunnel backfill, fractures in the deposition hole, etc. – are described by a number of compartments, see Figure 3-3. The method resembles the discretization that is done in a finite-difference or integrated finite-difference model for three-dimensional problems, but a compartment model uses much fewer cells or compartments. So as not to lose accuracy in the calculations due to the coarse discretization, analytical solutions are used to handle transport phenomena in sensitive areas. Examples of sensitive areas are the hole in the canister wall and the mouth of the fracture towards the deposition hole.

NUCTRAN can also model the influence of filler material, damages in the Zircaloy tubes and a growing hole in the canister. On the other hand, there is no function for calculating canister penetration (corrosion or other mechanisms), so the penetration time must be

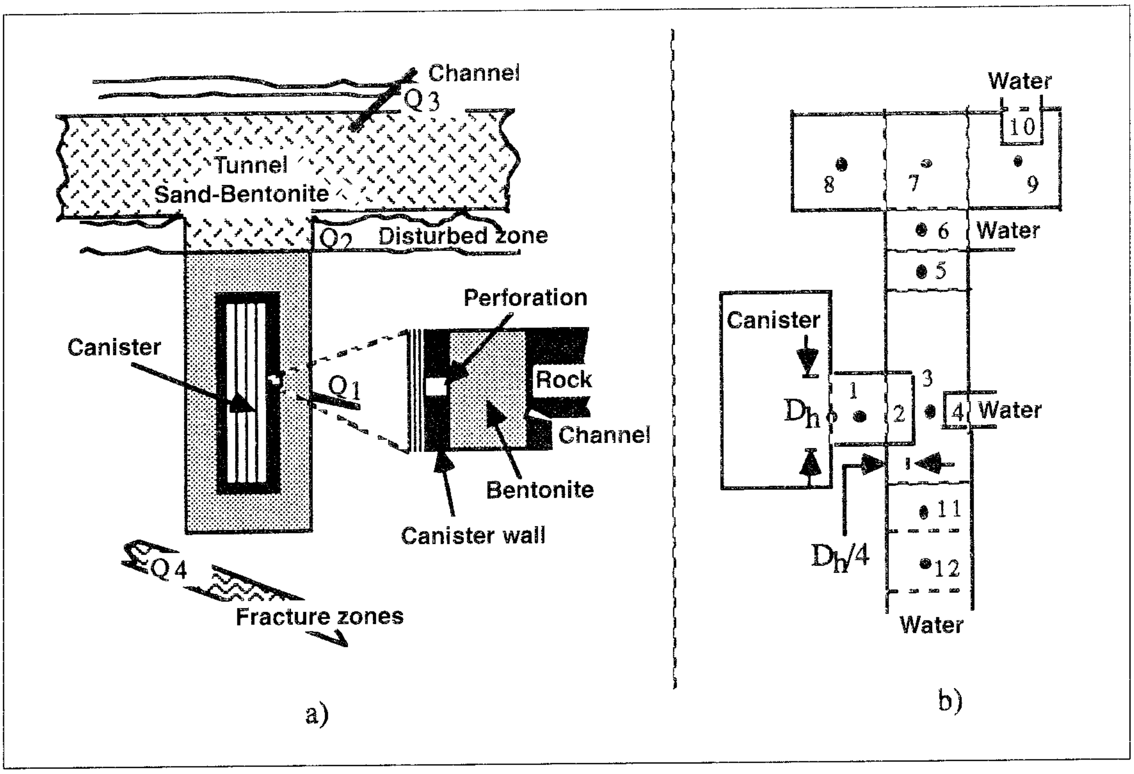


Figure 3-3. Geometry of the near field and its description in NUCTRAN.

specified. Nor is today's version of NUCTRAN capable of calculating solubilities split between different isotopes of the same element.

In the model variant COMP23, NUCTRAN has been modified so that the model can be used together with the administration program PROPER in a model chain for radionuclide transport. COMP23 and NUCTRAN are otherwise identical.

NUCTRAN also offers several options for modelling dissolution/alteration of the uranium dioxide matrix (see section on fuel dissolution). The greater part of the fission products and virtually all actinides are embedded in the matrix and cannot be released until the matrix has been dissolved. The options are:

- dissolution with uranium dioxide solubility,
- dissolution proportional to α–dose rate,
- constant dissolution rate,
- immediate dissolution.

NUCTRAN has been verified against other transport models with good results.

During the past three-year period a special version of NUCTRAN has been developed for performing calculations for radionuclide transport for SFL 3-5, see further section 12.3.

3.6.1 Goal and programme

The objective is to develop and maintain NUCTRAN/COMP23 as principal tools for calculation of radionuclide transport in the near field.

One of the most important parts of the development programme for NUCTRAN/COMP23 is to combine the variants that exist today into a single final version. This work will be commenced when the ongoing safety assessments are finished. Further verification studies will be carried out. Above all, the handling of complex geometries needs to be verified. Handling of split element solubilities was planned to be introduced into the model in FUD 95. This has not been done and has lower priority, but the possibility will be explored.

3.7 Models for groundwater flow and radionuclide transport in the far field

At the present time, SKB has access to a set of different models for groundwater flow and radionuclide transport in the bedrock. The different models consist firstly of different conceptualizations of the rock mass and its water-bearing structures, and secondly of different numerical models within the same conceptualization.

A more comprehensive description of the various groundwater flow and radionuclide transport models is provided in SR 95 /3-6/. The discussion here therefore centres mainly on new applications or model improvements that have taken place within the current RD&D period or since the SR 95 safety assessment.

The continuum models NAMMU or PHOENICS are usually used for groundwater flow. Both NAMMU, which was developed by AEA Technology in the UK, and PHOENICS have recently been used in SKB's applications for modelling of groundwater flow where density effects have been included /3-7, 3-8/. Modelling with density effects neglected has also been done /3-9/.

HYDRASTAR has mainly been used so far for groundwater flow on a local scale. HYDRASTAR is a stochastic continuum model developed by SKB over a period many years. A number of improvements and additions have been made in the mode during the current RD&D period:

- A new version, in which the simulated conductivity fields can be calibrated against measured pressure values, has been implemented /3-10/ and used in a modelling study of a pumping test at the Äspö HRL /3-11/.
- Visualization of the results from HYDRASTAR, for example conductivity fields and fracture zones, has been improved by the use of the graphic package AVS.
- A new geostatic model for the spatial variability in hydraulic conductivity has been implemented /3-12/.

The model for radionuclide transport in the far field is FARF31, a one-dimensional transport code that includes advective and dispersive transport, matrix diffusion with equilibrium sorption in the matrix, and chain decay. FARF31 has not been developed during the current RD&D period. Instead, work has been done to ascertain how FARF31 could be modified to permit spatial variability in controlling parameters such as flow-wetted surface area and matrix porosity.

Besides stochastic continuum, SKB has continued to develop and use other conceptualizations as well for modelling of flow and transport on a local scale. CHAN3D has already been utilized previously for simulation of pumping and tracer tests at the Äspö HRL /3-13/ and has now also been used for a safety assessment study with coupled near- and far-field description /3-14/. Furthermore, the discrete fracture network model FracMan has been utilized in initial safety assessment studies /3-15/. The study shows how transport pathways can be calculated by means of a search algorithm and how parameters for radionuclide transport codes can be calculated for these transport pathways. A coupled near- and far-field description can be achieved in this concept as well.

Finally, work has also been started to describe radionuclide transport in PHOENICS by means of PHOENICS/PARTRACK. The models CHAN3D, FracMan and PHOENICS now have their own transport routines developed to a greater or lesser extent and can thus in principle all be used to replace the HYDRASTAR/FARF31 package.

3.7.1 Goals and programme

The general goals of model development in the far field are:

- to have access to relevant calculation tools for performance of safety assessment,
- to keep the models updated and keep track of advances in knowledge within the area,
- to ensure that the models are also applicable for site evaluation in the siting work.

A specific goal in the safety assessment is that SKB should, after the coming 3-year period, also have full access to alternative models (for example discrete models) for flow and transport in the geosphere.

The general direction indicated in RD&D 95 as regards development of far-field models within the safety assessment is still valid. The safety assessment study SR 97 will be completed and reviewed during the current RD&D period. Depending on the outcome of this assessment and review, a considerable measure of flexibility in future modelling strategy must be permitted at the present time.

The development and use of HYDRASTAR will continue as an important component in far-field modelling. The need for alternative geostatic models for hydraulic conductivity, such as non-parametric or fractal models, will be investigated and possibly implemented. To make HYDRASTAR more general and universally suited for site-specific simulation, there may also be a need to be able to include hydraulic anisotropy and more types of boundary conditions that the model permits today. However, the question that is deemed to be one of the most important for the future is the development of methods for scaling-up /3-16/. HYDRASTAR contains an algorithm for scaling-up of values from the measurement scale to the discretization scale in the model and for calculation of corresponding regularized geostatic models. Furthermore, empirical scaling relationships between the measurement scale and the discretization scale have been determined and used. Questions surrounding scaling-up have been discussed intensively among researchers for some time now. It may be necessary to review the routines for scaling-up in HYDRASTAR. A question related to scaling-up is how groundwater modelling on different scales (regional/local) should be coupled correctly. This question is also expected to be explored with respect to the coupling of NAMMU and PHOENICS with HYDRASTAR. Finally, an evaluation should be made of possible concepts for conditioning the conductivity fields in HYDRASTAR to different types of geophysical data.

FARF31 will continue to be the most important model for simulation of radionuclide transport. As mentioned above, the possibilities of including spatial variability of transport parameters along the streamtubes have been explored. This work will be continued; in addition, the use of effective parameters will be developed. The objective is to indirectly include the effects of heterogeneity by the use of effective parameters in the existing version of FARF31. The primary advantage of this approach compared with an explicit description of the heterogeneity in the model is a computational gain. To ascertain the simplified conditions under which the use of effective parameters works, the version with an explicit description of heterogeneity should also be developed into a finished tool.

In parallel with the development of FARF31, the possibility of performing complete calculations of radionuclide transport in discrete fracture network models is being developed (FracMan). In a discrete fracture network model, where the flow geometry is described explicitly, matrix diffusion can be modelled with a higher degree of realism. A number of different procedures are possible for handling transport in FracMan. It is either possible to calculate effective transport parameters for certain dominant transport pathways and then use them in FARF31, or it is possible to record the transport properties along corresponding pathways and then use them in the modified version of FARF31, which takes heterogeneity into account explicitly. A third alternative, which is in some respects the most appealing, is to solve the transport problem directly in the fracture network. Then it is possible to describe more complex transport phenomena such as matrix diffusion in stagnant parts of the fractures. The possibilities of obtaining access to or developing this type of transport model will be explored.

A concept of central importance for the results of the safety assessment is the flow-wetted surface area /3-16/, i.e. the surface area available for matrix diffusion and sorption in radionuclide transport. This parameter cannot be calculated in HYDRASTAR, but must be estimated in another way for use in FARF31. In FracMan, the flow-wetted surface area can be calculated directly based on the geometry of the fracture plane under given assumptions, which are described above. However, certain general questions remain to be solved concerning how the flow-wetted surface area is to be estimated /calculated in individual fracture planes. To answer these questions, a generic development effort may possibly be pursued. Among other things, model studies of transport in individual fractures can be carried out for the purpose of studying the connection between hydraulic parameters and parameters that govern matrix diffusion.

Development of the flow and transport model CHAN3D will continue. During the current period, work will be pursued to explore how the model can be "validated" against field data, and which type of field measurements are needed for this. The dispersion concept in the model will also be further developed. Furthermore, CHAN3D will presumably be used for more complete safety assessment studies with coupled near- and far-fields.

To be able to exemplify which parameters have the greatest influence on the transport of radionuclides in the geosphere, it may be an advantage to make use of simplified models as a complement to the more complex models described above. Existing analytical solutions for relevant transport processes can serve a purpose here. A project aimed at defining key parameters, and further developing and implementing existing analytical models has been begun and will be carried further. The results may be of interest for both safety assessments and/or site evaluation. Thus, the work may have clear links to the ongoing projects that deal with how site investigations should be conducted and siting factors defined. These latter projects are, however, considerably broader in their objectives and also deal with, for example, construction-related and chemical and mechanical stability aspects. For a thorough discussion of these projects, see /3-17, 3-18/.

3.8 Models for radionuclide migration in the biosphere

In order to be able to assess the radiological consequences of possible releases of radioactive substances from a final repository, it must be possible to describe transport in the biosphere, from groundwater recipient to man and other organisms. The overriding goal of SKB's studies of the behaviour of radionuclides in the biosphere is to be able to carry out credible consequence calculations in the safety assessments. The description of the biosphere must fulfil three different purposes:

- events and processes must be described in a realistic manner, with an explanation of why certain processes are important and a detailed explanation of why other processes have been excluded,
- it must serve as a yardstick for comparing different facilities, technical solutions or repository sites,
- it must show that regulatory requirements on safety and limit values have been met.

For modelling that aims to show that dose limits are not exceeded it may be acceptable to greatly overestimate the consequences. But a thorough knowledge of the biosphere is required to justify the simplifications that are made in dose estimates in connection with optimization. Since the processes that occur in the biosphere are clear to a large group of experts from other disciplines as well as non-specialists, clear logical simplifications are required that nevertheless describe the biosphere in a scientifically intuitive manner.

The greatest uncertainty in dose calculations exists today in the biosphere models. Most of the uncertainties are due to inadequate conceptual descriptions of ecological processes, in contrast to the usually better described physical and chemical processes that occur in the biosphere. Another part of the uncertainty lies in the availability and quality of data.

The overriding goal of the biosphere programme is to reduce the uncertainties and calculate the most important processes in the biosphere from a radiological viewpoint using up-to-date scientific methods.

3.8.1 Understanding and conceptual models

SKB's modellings of radionuclide migration in the biosphere have been carried out with BIOPATH. BIOPATH has been utilized for KBS-3, SFR and SKB 91 and has been progressively refined as a result of efforts by, among others, SKB, as summarized in a review in /3-19/. The model concept used in BIOPATH has by and large been adopted in most models that handle radionuclide transport in the biosphere /3-20, 3-21, 3-22, 3-23/.

The lack of alternative models and conceptualizations makes a careful validation of the data difficult /3-24/ and the need to shed light on the consequences for surrounding fauna and flora in a safety assessment requires further development of the models, see Chapter 11. These models are based on the radionuclide flow in the entire ecosystem and not just in specific pathways that are critical to man (e.g. well or cow's milk).

Site-specific conditions are modelled in the safety assessment SR 97, which means that the structure of the BIOPATH model has been adapted to local conditions. It has been assumed in the safety assessment that nuclides from the deep repository can be transported directly to the recipients in an annual quantity that is given by the transport calculations for the near- and far-field. Since these transport calculations are based on streamtubes that discharge 20–40 m below the ground surface, it has been possible to couple these discharge points to the overlying biosphere, which can vary in character. For the modelling, this has meant that the biosphere has been divided into different classes which have been treated by means of a modular system /3-25, 3-26/.

Models have been developed to calculate the flux and exposure from releases of radionuclides to lakes, streams, coastal areas, swamplands and agricultural areas /3-27/. Furthermore, calculations have been carried out for direct use of contaminated groundwater (well). These models have then been used to calculate human exposure in the three site-specific areas for SR 97 /3-27/.

The higher detail resolution requires a better body of data and more accurate description of processes, which also focuses attention on deficiencies in data and models. The model is based on available map information /3-27/. Furthermore, a comprehensive literature survey was made of site-specific data on the biosphere /3-28/, hydrology and loose deposits /3-29/. An evaluation of what type of site-specific data are needed and an appraisal of what is gained by various improvements in measurement methods and calculations in comparison with the uncertainties that exist in the models are needed for future site investigations.

In addition, deficiencies in the description of transport from the far zone to the biosphere and the lack of a forest model were identified, which are more fully described in the review of the general biosphere programme (Chapter 11) and in the process report /3-30/.

3.8.2 Goal fulfilment in RD&D 95

The following interim goals, which have been fully or partially fulfilled, were set in the biosphere programme in RD&D:

- Quantification of the uncertainties that stem from the fact that the biosphere is constantly changing – results reported in /3-28, 3-31, 3-32, 3-33/ but work will continue in coming programmes.
- Compilation of site-specific evaluations of the potential and limitations of the candidate sites for changes in the biosphere – results reported in /3-27, 3-28, 3-29, 3-34/ but requires further studies.
- Improved body of data on which the transport models rest – results reported in /3-28, 3-29, 3-35, 3-36/.
- Validation of models by studies of analogous transport processes – results reported in /3-37, 3-38, 3-39/ and will always be important when new models are developed.

3.8.3 Goal and programme for future work

The overriding goal of the biosphere studies is to quantify the migration of radionuclides and other substances from the deep repository to the human environment, as well as the consequences of this migration. More concrete goals are to:

- evaluate which parameters can be described with generic data versus site-specific data,
- maintain and modernize modelling tools for the biosphere,

- integrate the biosphere models in the calculation chain,
- investigate alternative safety indicators.

The biosphere programme for the safety assessment aims at integrating the knowledge obtained in the general biosphere programme (see Chapter 11). This integration entails realistic simplifications that can be used within the entire model chain for radionuclide transport and analysis of uncertainties in comparison with other uncertainties in the calculation chain. In the long term, this entails fairly extensive re-evaluation of the conceptual description in the biosphere models based on the systems ecology approach described in the biosphere programme. The conceptual description, and later the numerical model, are based on an in-depth description of the processes in the biosphere /3-30/.

Alternative indicators for the impact on the biosphere or the performance of the repository will be tested in parallel /3-40/.

The underlying data will also be improved by the efforts being made to quantify and model transport processes such as particle resuspension and the review of circulation in the coastal area. The studies in the boundary layer between sediment and water, which has a powerful influence on the radionuclide flow, have led to a decision to re-evaluate the transport rates between geosphere and biosphere. Furthermore, a forest module will be developed for the calculation chain, since the forest is the dominant ecosystem at most considered sites.

The premises for the biosphere are controlled to a great extent by the climate and the distribution between land and water. Water flux, groundwater recharge and surface runoff are some of the most important physical factors influencing the dose. Postglacial land uplift and climate change alter the biosphere but also affect the performance of the repository. The results of research on these long-term changes in the biosphere programme will be integrated in the safety assessment either as time-dependent functions directly in the biosphere models or as special scenarios.

The modelling tools BIOPATH and PRISM require continuous maintenance and development as new insights are gained into processes. Furthermore, a sensitivity analysis is being performed to test whether the new processes influence the end result appreciably or whether the uncertainty in the parameters influences the result. It is important to test the sensitivity of the models to the variation in site-specific parameters. The result is a detailed plan regarding which variables must be determined in site-specific investigations and which can be taken or calculated from existing sources.

The choice of radiological acceptance criteria is of great importance for how biosphere analyses are to be done. The Swedish authorities are expected to issue regulations during 1998. This work and work within international groups such as the IAEA (BIOMASS) and the ICRP will be followed.

3.9 Quality assurance, computer models and calculations

Which computer models and input data are used in a given calculation are documented in MONITOR 2000. Version management is used for the whole computer program PROPER and all its submodels. The option of repeating older calculations is hereby provided, which improves traceability. However, completely identical results cannot always be recreated due to the fact that computers are continuously being replaced at the same time as compilers and other software will always be updated to newer versions. Older compilers cannot be guaranteed to work with newer computers. This means that it is not always possible to obtain an exact executable copy of an older computer program. However, this only affects the calculation results in the form of minor rounding-off errors.

The recently developed graphics program HYDRAVIS permits both input data to and results of hydrology calculations to be presented in a clear manner, which offers good opportunities for checking input data and the reasonableness of calculation results.

3.9.1 Goal and programme

Existing routines will be evaluated after SR 97. Experience from development work and production calculations will be continuously fed back, among other things in the form of new test cases for PROPER. Means of graphic presentation of calculations cases and results will be further developed. It should, for example, be possible to present the geometric structure used in the near-field model COMP23 graphically.

Control of traceability and quality in the safety assessments will follow SKB's quality and management manuals, which have been developed within the encapsulation and deep repository projects.

Questions of specific interest for safety assessments are:

- Verification of models used in the safety assessments by devising a number of test cases for individual submodels as well as for the entire calculation chain in PROPER. The test cases must be able to be used to test that new versions can reproduce older results.
- Version management of computer models and input data.
- Developing systems for filing of the executable PROPER files that are used in safety assessments.
- Documentation and traceability of executed calculations.

4 Spent fuel

Geological disposal of spent nuclear fuel in corrosion-resistant canisters is the main alternative for management of high-level waste in Canada, Finland, Spain, Sweden and the USA, and is also being considered in Germany and France, at least for certain types of fuel. In Sweden, research and development aimed at direct disposal was begun back in the 1970s. Studies of the durability of spent fuel in groundwater were begun in 1977, and the present-day research programme was adopted in 1982. The results of SKB's fuel leaching programme in Studsvik's Hot Cell Laboratory have led to a good understanding of how spent fuel corrodes in water. An overview of results and data obtained in SKB's programmes up to 1992 is given by Rosyth and Werme /4-1/, while more recent actinide data from fuel leaching experiments are dealt with by Werme and Spahiu /4-2/. This Chapter briefly provides a brief account of the investigations that have been performed to study the influence of the most important factors on leaching of spent nuclear fuel.

4.1 Corrosion of spent nuclear fuel – analysis methods

Most of the present-day data from corrosion and dissolution of spent fuel comes from sequential corrosion tests performed with fuel/cladding segments suspended in groundwater in a coil of platinum wire. The temperature has been the same as the ambient temperature. The leachates have been analyzed directly by means of mass spectrometry without either separation or isotope dilution. The analyses have been performed using an instrument with an inductively coupled plasma source (ICP-MS, Inductively Coupled Plasma – Mass Spectrometry), permitting multi-element analyses. This instrument has been in use since 1992. The isotope composition of the fuel has been calculated based on data on enrichment, burnup and decay /4-3/. After these preparations, a large number of samples (about 200) from the experimental fuel corrosion programme have been analyzed with ICP-MS. Several of these samples were archive solutions from previous samplings. The results of the ICP-MS measurements for uranium, plutonium, strontium, caesium and technetium made on these samples have been compared with equivalent results from the previously used analysis methods /4-4/. Satisfactory agreement between the methods was obtained for the three fission products (see Fig. 4-1), but for uranium and plutonium CIP-MS gave 10–20% higher values than the conventional analysis methods. This comparison programme has also shown that a plutonium loss from solution by precipitation and/or sorption had occurred in the archive solutions during storage.

As previously, considerable pains have been taken to improve the analysis methods, which are needed to determine the very low concentrations of actinides and fission products. Efforts have also been made to improve the quality of the analysis data. The main goal of the fuel programme is to propose and validate models for fuel corrosion. These models cannot be better than the quality of the input data.

An example of work to improve analysis methods for leachates is the ICP-MS analyses of actinides. They can be improved considerably by developing procedures for isobar separation. Without such separation, both ^{241}Am and ^{241}Pu, for example, contribute to the same peak in the mass spectrum, and it is therefore difficult, not to say impossible, to analyze americium without separation. An alternative is separation by means of ion chromatography. An ion chromatography column from Dionex has been installed in Studsvik

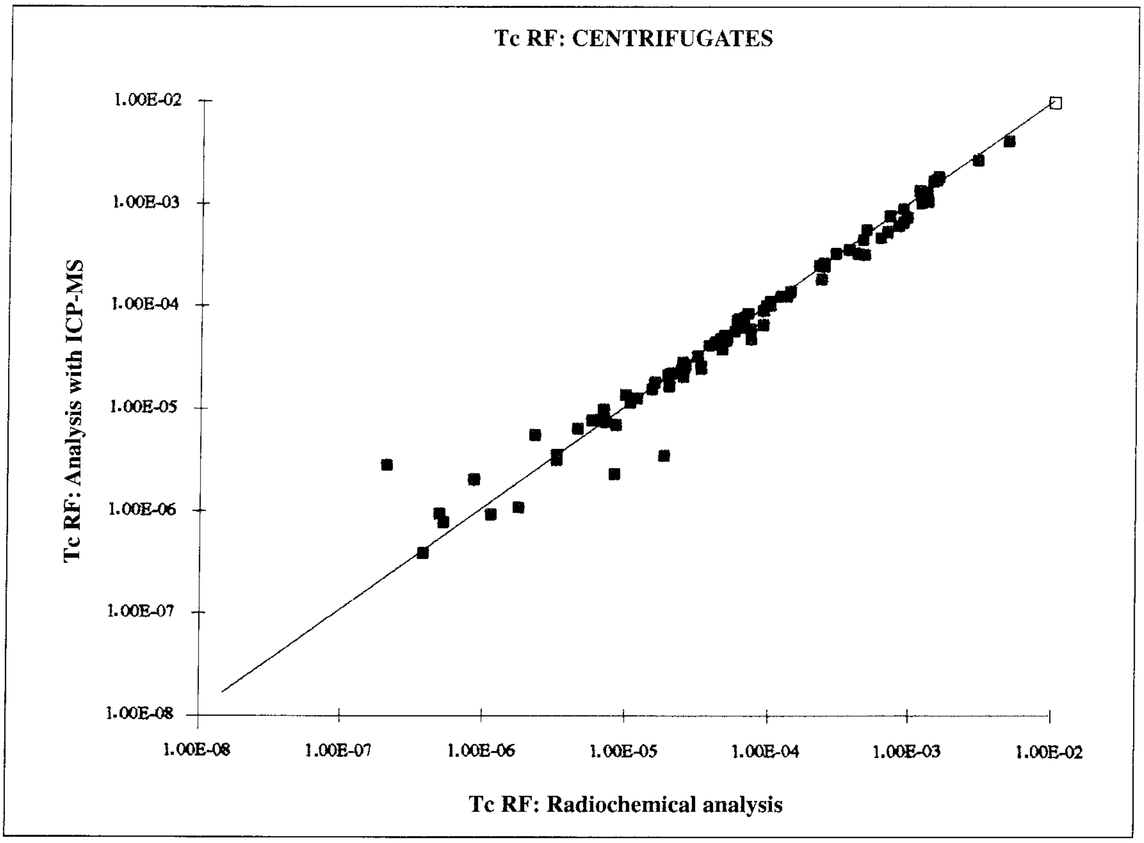


Figure 4-1. *Comparison of quantity of released technetium in the centrifugates determined by radiochemical analysis and ICP-MS.*

during the period, and experiments have been conducted involving separation of actinides and fission products with different valencies. The plan is to use this equipment in the future both to concentrate the solutions from flow leaching experiments and to separate the ordinary samples, mainly with regard to actinides.

Trivalent lanthanides are also of importance for safety, and with the ICP-MS method we can measure low concentrations of these nuclides. It has, however, been found that the solubilities and speciation of these nuclides under the conditions expected in a deep repository are not available. Therefore, thermodynamic data for the aqueous species of the rare-earth metals have been compiled and the most important ligands for granitic groundwaters have been selected and validated /4-5/. It turns out that during the first phase of fuel dissolution, the concentrations of rare-earth metals are determined by the dissolution of the UO_2(s) matrix. Later, solid phases of phosphates, hydroxy-carbonates and carbonates may limit their solubilities.

To better understand and be able to model the fuel dissolution process, it is valuable to know how important parameters, such as pH and redox potential (E_h) in the leachate, vary during the process. During the preceding period, in-situ measurements of pH and Eh during leaching in a hot cell have been started at the fuel laboratory in Studsvik. The method uses a computerized system for potentiometric measurements. Experiments inside and outside the hot cell have now been under way for more than two years. The stability of the measurement system for long periods in the presence of the strong radiation field in the hot cell has been tested; pH values stable to within 0.05 pH units/year have been measured in buffered systems. Measurements are being made in distilled water under oxidizing conditions to follow the changes in pH and redox potential during the leaching process.

In comments on SKB's previous research programmes, SKI has proposed studies of fuel leaching in the presence of corrosion products from the canister /4-6/. We have therefore performed blank experiments with unirradiated $UO_2(s)$ to test leaching in the presence of various reductants from the near field, such as magnetite and metallic iron, before carrying out experiments with irradiated fuel in the hot cell. It was found that there were not any data in the literature on the kinetics of the reduction on magnetite surfaces of e.g. uranyl ions in carbonate solutions. Thermodynamically, magnetite should reduce U(VI) to U(IV), but in the experiments (with unirradiated uranium) in Studsvik we could not see any effects on the concentrations of uranium in solution despite the presence of magnetite. The kinetics of the reduction of U(VI) on magnetite surfaces in different media are now being studied separately (at the Barcelona Polytechnic University in Spain).

4.2 Matrix dissolution

In recent years, the samples from SKB's fuel corrosion programme have been analyzed by means of ICP-MS shortly after the conclusion of the corrosion tests. Analyses of archive samples from previous experiments have also been performed. Together with previous results, this has made it possible to compile a much larger analysis database, which has then been used in a new evaluation /4-7/.

Some of these new analysis data come from experiments with fuel specimens (from two reference rods, a BWR and a PWR) that have been corrosion-tested for over ten years. The majority of the data come from 16 fuel/cladding specimens from a short BWR rod that had a burnup in the range 27.0 to 48.8 MWd/kg U. Detailed investigation and characterization of three other specimens from the rod showed that the samples with high burnup in this series had a fuel structure that should theoretically favour increased corrosion. These samples had been exposed to more than five years of corrosion during nine water contact periods. The corrodants used were a simulated bicarbonate groundwater and a deionized water. Both oxidizing and nominally anoxic (oxygen-free) conditions were included in the test matrix.

Much of the emphasis in the evaluation has therefore been placed on the possible effects of linear power density and burnup on corrosion. However, investigations of the variation of the release rates of selected fission products with water contact time, and their total release during five years of corrosion, showed that the corrosion rates during the first weeks were lower for samples with high burnup than for samples with slightly lower burnup (see Fig. 4-2). Later, the corrosion rates converged for all samples. This has been interpreted as the result of burnup-related differences in the fuel's microstructure, especially differences in the interlinked network of porosity and grain boundaries, rather than differences in the periphery of the fuel pellets.

A database with all fuel leaching data from SKB's fuel programme has been compiled during the period. The database code ACCESS has been used, and the different conditions and parameters to be stored in the database have been evaluated. The structure of the database is established and most of the results that have been obtained in SKB's fuel leaching programme have been stored. Storage of all data, compilation of a manual with experimental procedures and description of the database are still under way. Efforts to make the database more user-friendly will also continue.

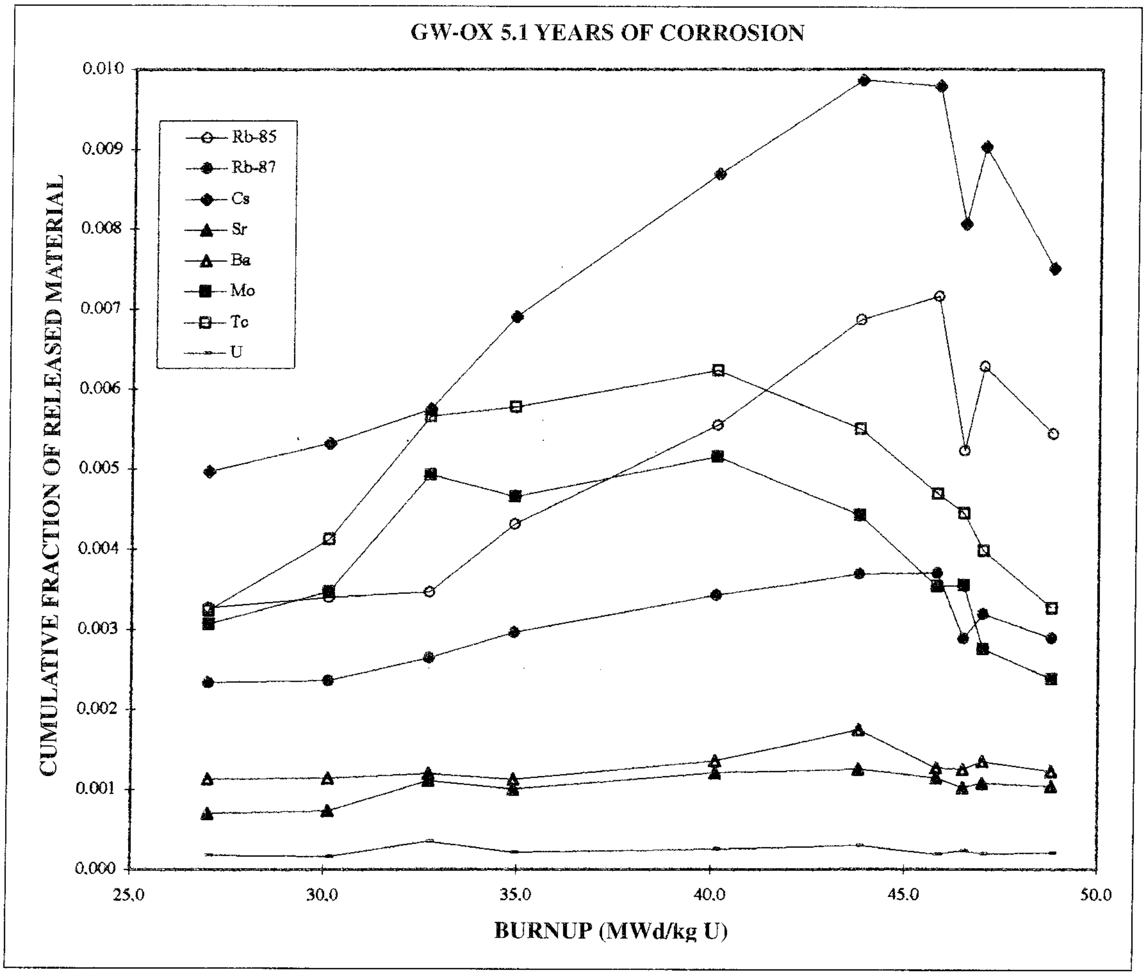


Figure 4-2. Series 11 corrosion tests: Cumulative fraction of released material in the centrifugates from 10 GW-OX corrosion tests (9 contact periods: Total corrosion time 5.09 years).

The results of fuel corrosion tests carried out under oxidizing conditions suggest that the release of ^{99}Tc to solution takes place by dissolution of metallic particles containing Mo, Tc, Ru, Rh and Pd. The size and composition of these metallic particles is dependent on burnup and temperature in the fuel during irradiation. Samples from reference fuel have been dissolved in concentrated nitric acid and a heavy residue consisting mainly of these metallic particles has been separated /4-8/. Investigations of small samples of dissolution residues in a scanning electron microscope (SEM) and by means of electron probe microanalysis (EPMA) have been used – together with the results of analyses of the filtrates and ORIGEN calculations of the inventories of Mo, Tc, Ru, Rh and Pd in the fuel – to determine their composition. In dissolution tests in simulated groundwater with two samples from these residues, concentrations of Mo and Tc of the same order of magnitude as in corrosion tests with spent fuel were measured.

The fuel area that is accessible to corrosion attack by groundwater is an essential parameter in determination of absolute corrosion rates. This is particularly true in the processing of data from flow leaching experiments recently begun in Studsvik. Previously, the specific area of the fuel has been determine by means of the BET method for two of the reference fuels used in SKB's experimental programme /4-9/. In measurements with Kr sorption, reproducible values of the area were obtained in the range 70–120 cm^2/g. For the flow leaching experiments, several PWR fuel fragments have been ground and screened, after which the area of two fractions (0.125–0.25 mm and 0.25–0.5 mm) has been determined by the Kr-BET method. The fuel samples that will be used in the fuel leaching experiments are stored in an Ar atmosphere.

An experiment combining fuel corrosion and radionuclide diffusion in bentonite clay started in 1985. Several segments of a fuel rod were placed in diffusion cells, surrounded by compacted bentonite. The diffusion cells were then placed in cylinders containing synthetic groundwater with a low salinity, which had been equilibrated with bentonite. A total of ten cells were started. Metallic iron, metallic copper or the Fe(II) mineral vivianite (iron(II) phosphate) has been added to the clay in some of the cells. The experiments were performed with contact times of 101, 197, 386 and 2213 days. The experimental set-up and some results have been reported in previous publications /4-10–4-13/.

Thanks to the development of an analysis method for different actinides from one and the same clay sample /4-14, 4-15/, it has been possible to carry out the first real analyses of actinides in bentonite clay that has been in contact with spent nuclear fuel. Due to overlapping spectral lines in both alpha and mass spectrometry, the actinides must be separated prior to analysis. The concentrations of the different actinides in the bentonite clay are very low, which has made the development of the analysis method a prerequisite for being able to analyze other actinides than americium and curium. Actinides in detectable concentrations can be found in the bentonite clay only a millimetre or so from the surface of the spent fuel. The analyses have been concluded and the results concerning actinide transport in bentonite clay were presented at the conference Migration 97 /4-16/.

The results for leaching of uranium from the fuel and uranium transport through the compacted bentonite were based on measurements of the uranium isotope ^{236}U, since the background concentrations of the natural uranium isotopes ^{238}U and ^{235}U were considerably higher (around 8 ppm) than the quantity of uranium released from the fuel. The apparent diffusivity of uranium was determined to be $1.8 \cdot 10^{-13}$ m²/s. With the addition of metallic Fe to the bentonite clay, the diffusivity decreased by two orders of magnitude to $3.2 \cdot 10^{-15}$ m²/s, which could be interpreted as a reduction of U(VI) to U(IV). From data obtained after a contact time of 386 days, the diffusivity of neptunium (^{237}Np) was determined to be $1.3 \cdot 10^{-14}$ m²/s. The transport measured in the six-year cells was much slower, however, ($\sim 10^{-17}$ m²/s).

Data for leaching and diffusion of plutonium are shown in Figure 4-3. The diffusivity of plutonium after a diffusion time of 6 years was $2\text{-}8 \cdot 10^{-17}$ m²/s. This is at least an order of magnitude lower than previously reported diffusivities ($<3 \cdot 10^{-16}$ m²/s /4-11, 4-17/).

Figure 4-4 shows data for the diffusion of americium after a diffusion time of 6 years. The value of $D_a = 3\text{-}6 \cdot 10^{-16}$ m²/s agrees well with literature data /4-18/.

All in all, it can be said that values of apparent diffusivities for actinides that have previously been reported in the literature (see compilation in /4-19/) are generally higher, with the exception of uranium. The results show that the fraction of actinides found in the bentonite clay after a contact time of 6 years comprises only 10^{-5}–10^{-8} of the amount in the fuel. The results also show that the released fraction is largely the same for uranium, neptunium, plutonium and americium, indicating congruent dissolution.

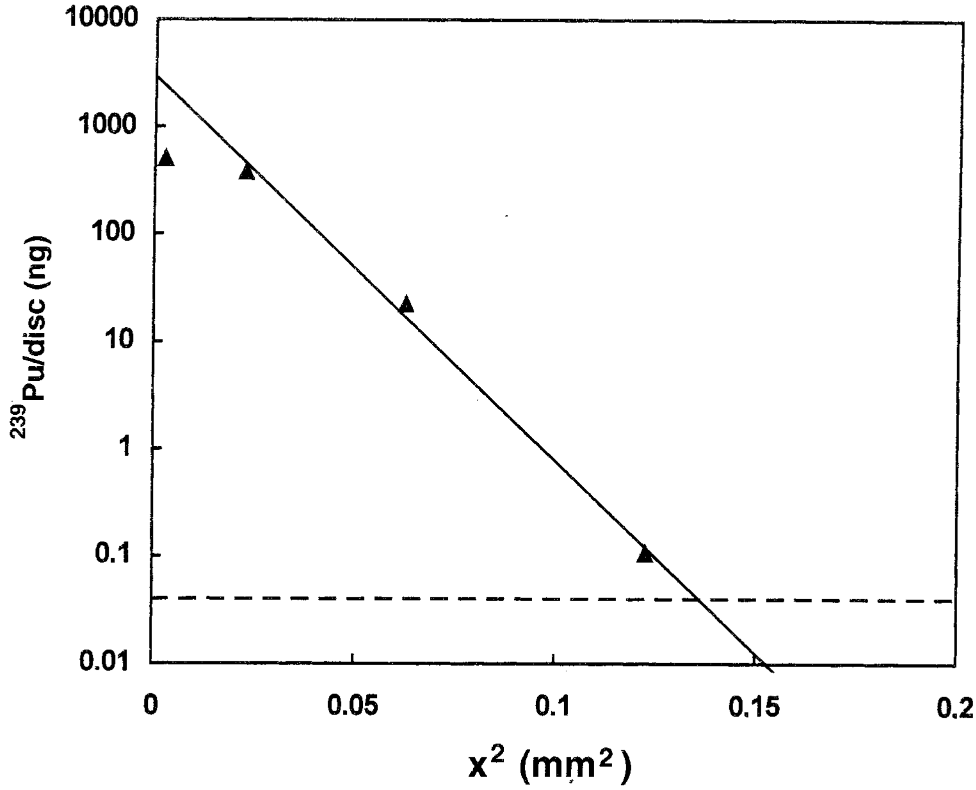


Figure 4-3. *Concentration profile for plutonium after a diffusion time of 6 years. The curve corresponds to a D_a of $2 \cdot 10^{-17}$ m^2/s. The dashed line shows the detection limit.*

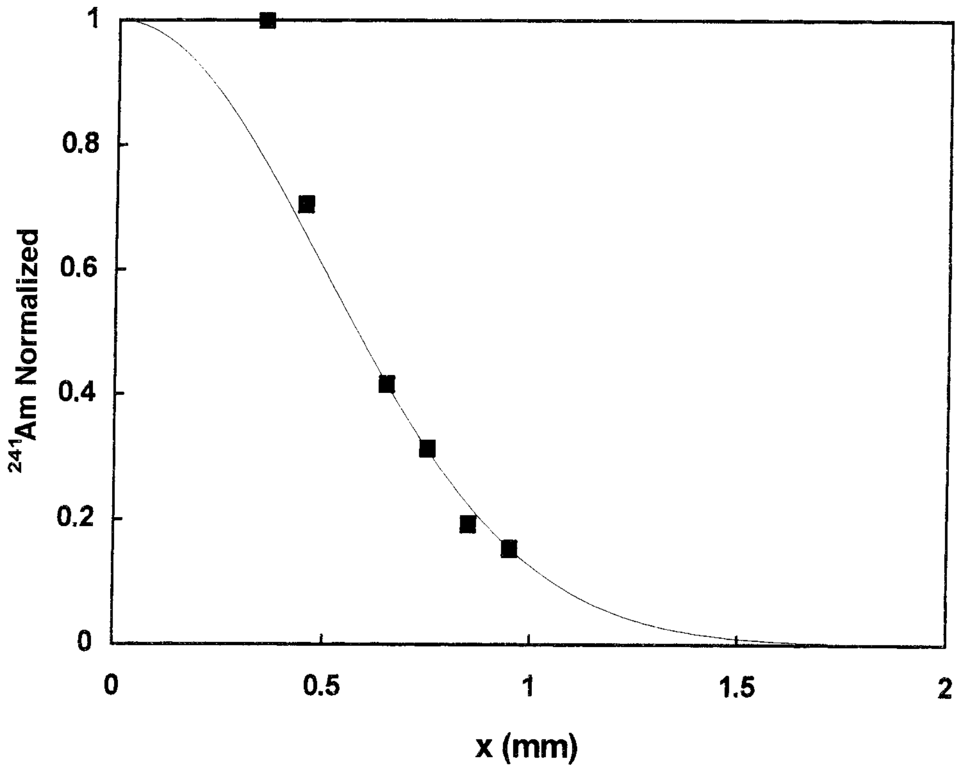


Figure 4-4. *Concentration profile for americium after a diffusion time of 6 years. The curve corresponds to a D_a of $5 \cdot 10^{-16}$ m^2/s.*

4.3 Radiolysis

Radiolysis is a very important process for fuel dissolution, since it can disturb the reducing conditions in deep groundwaters by producing oxidants. Radiolysis of water produces equivalent quantities of oxidants and reductants. The consumption of oxidants by reaction with the fuel surface results in a surplus of reductants, mainly hydrogen. A mass balance study of radiolytic oxidants, reductants and dissolved uranium has been done in a closed system which from the beginning contained fragments of spent fuel and anoxic (oxygen-free) distilled water /4-20/. In these experiments, the hydrogen concentration rose constantly, while the oxygen concentration remained very low. Mass balance calculations of oxidants, reductants and dissolved uranium indicate a clear deficit of oxidants in the system. Long-term radiolysis tests have shown the same result: the oxygen concentration rises for one week to a maximum value, after which it decreases with time. The hydrogen concentration rises constantly for more than eight months, while the oxygen concentration remains low /4-21/.

When, in new experiments with initially anoxic solutions, millimolar concentrations of carbonate were also added, the concentrations of radiolytically produced H_2 and O_2 increased continuously. A preliminary analysis of experimental data indicates mass balance between oxidants and reductants, when H_2, O_2, H_2O_2 and dissolved uranium are included in the calculations. It is possible that a more realistic model for radiolytic oxidation of spent fuel can be developed by including these data in the kinetic model that is currently being developed.

In another study, the thickness of the water layer in which gamma radiolysis affects the corrosion of UO_2 fuel has been determined. It was found that the thickness of the water layer was equivalent to the diffusion length of the radicals formed /4-22/.

4.4 Models for fuel dissolution

Efforts to develop a model for fuel dissolution under oxidizing conditions have continued throughout the period. The model that is being developed is a kinetic model instead of an equilibrium model. This is necessary since the spent fuel constitutes a dynamic redox system. Oxidants and reductants are constantly being formed by radiolysis at the fuel/water interface. The main processes that occur in the system are:

- Production of oxidants by radiolysis of water. A great deal of work has been devoted to calculating the production rate of radiolytic oxidants in order to reproduce experimental observations of the evolution of oxidants in the fuel/water system.

- Oxidation of UO_2 in surface coordination positions with simultaneous reduction of oxidants in the system. Extensive literature searches and data processing runs have been done to estimate the most probable oxidation rates for the fuel matrix. This is complicated by the fact that it is usually the combined oxidation and dissolution rate that is reported in most experiments.

- Dissolution of the oxidized positions accompanied by release of uranium to the solution. The species that are formed by uranyl in the solution are dependent on the water chemistry of the system.

- The possibility of formation of secondary U(VI) phases and their influence on the alteration of the $UO_2(s)$ matrix has also been taken into account. This was done by first making calculations without taking into account the formation of secondary uranium phases, and then by taking into account their formation assuming equilibrium between solid phase and solution. As a third possibility, the kinetics of the dissolution-precipitation of the secondary uranium phases while solubility equilibrium is being reached was also taken into account.

All of these processes have then been incorporated in a kinetic model by developing mass balance equations for each component: oxidant, uranium, oxidized and non-oxidized positions on the fuel surface. The calculation model is called RDC (Reducing Capacity).

Finally, the model has been tested and calibrated against data from leaching experiments with unirradiated uranium dioxide, against data from spent fuel and even against experimental data from the evolution of oxidants in the fuel/water system. In all of these cases, it has been possible to provide an acceptable explanation of experimental data for the evolution of the uranium concentrations in these systems /4-23/.

The evolution of the plutonium concentrations in fuel leaching experiments with time has also been described recently with the RDC model /4-24/. In most experiments with fuel leaching under oxidizing conditions, the plutonium concentration increases during the first weeks to more than ten times the solubility of the solubility-limiting phase and then falls slowly down to this value ($2 \cdot 10^{-9}$ M) after a few months. This behaviour has been modelled with the premise that the dissolution rate of plutonium is expressed as a fraction of the dissolution rate of the $UO_2(s)$ matrix, which is proportional to the fraction of plutonium in the spent fuel. Plutonium is dissolved mostly as Pu(IV) hydroxide, which is a compound known for its strong tendency to form colloidal particles. This explains the initially elevated plutonium concentrations. The following coagulation of these colloidal particles to form amorphous plutonium hydroxide explains why the plutonium concentrations change with time. Another result of the modelling of the fuel dissolution data is that it has been possible to estimate the solubility product of amorphous plutonium hydroxide to be of the same order of magnitude as the literature value, which increases the reliability of the model. This further development of the model has been presented /4-24/ and the work will now focus on determining important kinetic parameters and further refining the model.

4.5 Natural analogues

From experiments and modelling studies of uranium minerals as natural analogues for spent fuel, a standard model for dissolution of uraninites has been developed. This model has shown that the original redox state for the UO_{2+x} phase dominates the redox situation in the water and thereby also the solubility of the uranium oxide phase /4-25/. The long-term stability of the spent nuclear fuel is heavily dependent on the paths taken by the oxidative alteration of the uranium matrix.

Thermodynamic studies of secondary alteration products have given a value for the solubility product of becquerelite /4-26/ which indicates that becquerelite has a larger stability range than previously determined. More recent mineralogical data on these intermediate U(VI) phases show that they can incorporate trace elements in their structures. This could have an inhibitory effect on the release of radionuclides by radiolytic alteration of the fuel matrix, especially in view of the previously mentioned greater stability of becquerelite. The experiments and the modelling studies of uranium minerals as natural analogues for spent fuel could be used to make estimates of the corrosion of spent nuclear fuel. A doctoral thesis on this subject has also been presented /4-27/.

The stability of the U(VI) silicate phases soddyite and uranophane has also been determined experimentally. These phases may be the end products of the oxidative alteration of nuclear fuel. To avoid the experimental uncertainties found with natural samples, synthetic phases produced in accordance with accepted procedures are used. This has led to a determination of the stability of soddyite /4-28/. Determining the solubility of uranophane was more problematical. Even with synthetic phases and with solution compositions that would guarantee the thermodynamic stability of the solid phase, it was difficult to get reproducible results.

4.6 Goals and programme

The overriding goals of the fuel investigations are to:

- Understand the processes that control the release of the different nuclides from the fuel.
- Continue to improve existing release models for use in future safety assessments.
- Develop a realistic fuel leaching model prior to application for permits for detailed characterization and construction of a deep repository.

4.6.1 Solubility limitations and dissolution kinetics

The ongoing experiments with PWR and BWR fuel will continue with a limited number of samples during the period. These experiments have now been going on for 10 (PWR) and 15 (BWR) years. However, corroded fuel will continue to be studied during the period to identify any solid phases (corrosion products) that have formed during leaching.

The influence of radiolysis products from fuel on the redox conditions in anoxic systems has been studied continuously with the aid of redox electrodes in leach vessels with spent fuel. The results to date show that the measurement systems are stable under the conditions in a hot cell. Redox electrode measurements aimed at further elucidating the importance of radiolysis for fuel dissolution under reducing conditions will continue also in the presence of redox-sensitive components from the near field, mainly iron and iron corrosion products.

Flow reactors have been utilized in studies of the kinetics associated with the dissolution of sparingly soluble solids. This technique has been tried out at Studsvik during the period. The experimental set-up has been tested with uranium(IV) oxide in order to optimize flow and other experimental parameters. It will be used for the fuel studies aimed at determining the dissolution rates of fuel under aerobic and anaerobic conditions.

4.6.2 Radiolysis

Deep groundwaters are anoxic. Under these conditions, uranium dioxide is stable and a simpler model for solubility-limited dissolution of UO_2 can be employed. The fuel dissolution rate will be very low due to the low water flux in the vicinity of the canister in the deep repository. The anoxic, reducing conditions may be affected and changed by the radiation from the fuel, which could possibly create local oxidizing conditions near the fuel surface due to radiolysis. If this happens, a model for oxidative dissolution of UO_2 may have to be used. The choice of model is dependent on the magnitude of the effects of radiolysis on fuel oxidation.

The work that has been conducted by the Division of Nuclear Chemistry at KTH (the Royal Institute of Technology) will continue with high priority during the period, focusing on two types of experiments. Firstly, specific short-duration experiments will be conducted for the purpose of determining the influence of carbonate on the production of radiolysis products. These experiments will be supplemented by fundamental experiments with pulse radiolysis to determine rate constants for the radiolysis reactions that are still inadequately understood. Secondly, long-duration experiments (1.5 to 2 years) will be conducted to investigate the effects of radiolysis in closed systems. The conditions in the final repository resemble a closed system more closely than the system that it has so far been possible to study at Studsvik, where it has not been possible to completely prevent limited escape of radiolysis products.

One of the most important oxidants produced by radiolysis is hydrogen peroxide. Kinetic studies of oxidation of the uranium dioxide matrix by hydrogen peroxide will therefore be started. In the safety assessment scenarios, it is generally assumed that the copper canister remains intact for hundreds of years. After this time, only alpha radiolysis is of importance. To simulate corrosion and dissolution of very old fuel, alpha-doped uranium dioxide (i.e. uranium dioxide to which an alpha-emitting isotope such as ^{238}Pu has been added) has been synthesized in cooperation with ITU in Karlsruhe. This material will be used for radiolysis studies.

4.6.3 Redox conditions in the near field and redox kinetics

Redox conditions are of very great importance for fuel dissolution. Processes and reactions that affect, and are affected by, these conditions must therefore be characterized. Tetravalent actinides often have a substantially lower solubility than pentavalent or hexavalent actinides. The influence of potential reductants such as iron and iron corrosion products, such as magnetite, on fuel dissolution will begin to be investigated during the period.

Since uranium dioxide can be precipitated when dissolved uranyl species come into contact with steel, studies of the kinetics of redox reactions between different oxidized actinide species and uranium oxide will be initiated during the period. Another potential reductant is hydrogen, which is formed in large quantities in a damaged canister both by radiolysis but above all by corrosion of the iron in the canisters. At ambient temperature, hydrogen can only reduce in the presence of a suitable catalyst, but there are reports in the literature /4-29, 4-30/ that suggest that the surface of $UO_2(s)$ could activate hydrogen. The influence of high hydrogen pressures on fuel dissolution will begin to be investigated during the period.

4.6.4 Solubility investigations of tetravalent actinides

Fundamental chemical data on several actinides are lacking or are incomplete. This is particularly true of the solubility of actinides with the oxidation number IV in oxide form at neutral to basic pH. This deficiency in fundamental data was also pointed out by SKI in the evaluation of SKB's research programme RD&D 95 /4-6/. A long-range research programme is therefore being started during the period to investigate the solubility of tetravalent actinide oxides from undersaturation. At the same time, oxidation number speciation and characterization of solid phases is being carried out. For interpretation of solubility data, a special emphasis will be placed on investigation of kinetics for:

- dissolution,
- redox reactions and disproportionation of different oxidation numbers,
- change in solid phase (crystalline-to-amorphous transformation due to strong self-irradiation).

The execution of this programme entails production and characterization of the relevant solid phase, plus development of experimental technique for oxidation number speciation and characterization of solid phase. Since actinide(IV) oxides are expected to have very low solubility at neutral pHs, methods for analysis of extremely low actinide concentrations must be developed.

4.6.5 Models for fuel dissolution

The work of developing models for fuel dissolution will continue. The modelling strategy will be to integrate the mechanisms and the rate of formation of radiolytic oxidants with effects of oxidizing layers and with the kinetics of their consumption.

During the period, the work will focus on a more long-term evolution towards a realistic model for fuel dissolution under reducing conditions under the influence of radiolysis. Since new analysis methods have yielded reliable data, even for nuclides that have not previously been able to be analyzed, the work will be expanded to encompass many more nuclides.

4.6.6 Model validation via natural analogues

Since the Oklo reactor became active, a number of different events have occurred in the reactor zones and in the nearby areas. To determine the extent to which the information obtained from the Oklo project can be applied to and used for validation of fuel dissolution and transport models, it is essential that the time scale for these more recent events be established and that the impact they might have had on the present-day situation be determined. This will be done within the framework of the Oklo project.

4.7 Competence maintenance

4.7.1 Studsvik HCL

The Studsvik Hot Cell Laboratory (HCL) is a unique research centre of central importance to SKB's fuel programme, not only because it is the only place in Sweden where fuel experiments can be performed, but also because of the large number of experimental techniques, analytical methods and measurement procedures that have been used and developed – in many cases in the course of the current research programme. Some of them were developed to meet a need in the programme and are therefore unique, even in an international perspective. The Studsvik HCL is also a research resource for the research team at KTH who are carrying out the radiolysis investigations and for the research team at CTH (Chalmers University of Technology) who are studying fuel leaching in the presence of bentonite as well as doing actinide chemistry work. It is in the interest of the programme to maintain and constantly develop the scientific competence that exists at this research centre in Studsvik.

4.7.2 Nuclear chemistry

Owing to the nature of the irradiated nuclear fuel, departments of nuclear chemistry are of the greatest importance to the programme. They are the only Swedish institutions that can directly contribute data to the programme (at other places only analogues of spent fuel and its components can be studied). The two departments of nuclear chemistry in Sweden each cover important parts of the fuel programme.

5 Canister material

The ability of the canister to isolate the waste is important for long-term safety, and there are a number of requirements which the canister must meet /1-1/. The design premises for the canister for spent fuel are presented in a separate report /1-2/. Sealing and nondestructive testing of the canister will be developed at the Canister Laboratory /1-1/. Ongoing knowledge development and further testing of models for corrosion of materials in the canister will continue, for example in the form of the tests in the Äspö HRL (Hard Rock Laboratory) (see section 14.4.5).

5.1 Corrosion testing, copper

The thermodynamic database for copper is being revised. This work will be finished in 1998. Discussions have been initiated regarding possible experimental augmentation of data, especially high-temperature data, if the literature survey should show that this may be necessary.

Pitting of copper is being investigated in a pilot study being carried out during 1998. Additional experimental studies will be commenced in the autumn of 1998 and continue in an initial phase during 1999. The work of validating the pitting model will begin in 1999.

Bacteria-induced corrosion of copper could possibly be of importance for canister life. Ongoing studies of, among other things, the survival of bacteria in bentonite are expected to be finished by 1 June 1999. The results of this work will determine whether and in what form the work will continue.

Stress corrosion cracking (SCC) has been identified as an important field of further study. Experimental investigations of the rate of crack growth during stress corrosion are being pursued at the Department of Materials Science and Engineering at KTH. This work will continue during most of the period and may be supplemented by other experimental investigations.

A literature study of possible *corrosion of canisters prior to emplacement* was carried out in 1997. The study will be supplemented by experimental investigations of both corrosion in a realistic atmosphere in the Äspö HRL and samples exposed to compacted bentonite after several months of atmospheric exposure. These experiments will be carried out at the Äspö HRL.

A programme for *corrosion testing in a realistic environment* will be carried out at the Äspö HRL during the coming three-year period. The investigations will include exposures in water-saturated oxygen-free bentonite and reducing deep water as well as stress corrosion testing.

5.2 Corrosion testing, cast iron

In the event water enters the canister, the cast iron insert will corrode, causing hydrogen to form. This leads to the formation of corrosion products (magnetite) in the gap between the copper and the cast iron accompanied by a build-up of pressure inside the copper canister, owing to the lower density of the magnetite. This could eventually aggravate a small defect in the copper canister. However, analyses of the course and consequences of corrosion are based on a number of assumptions which are usually not supported by experimental evidence. It is therefore important to try to study the corrosion in a gap between iron and copper and, if possible, obtain a measure of the forces that can be exerted by the swelling corrosion products.

An initial phase includes designing equipment for corrosion testing, and if the experiments give the desired results the programme will be supplemented with analyses of corrosion products and experimental determination of the mechanical properties of the corrosion products.

5.3 Material testing

Creep testing of weld metal is being carried out at the Institute of Metals Research. This work will continue with long-term tests. Testing of material from fabrication and welding of full-scale canisters at the Canister Laboratory will be carried out continuously during the coming three-year period.

Theoretical analysis of phosphorus alloying of sulphur-containing copper is being conducted at Fysikum at Uppsala University. The results of an initial phase were reported in May 1998, and the work will continue with a second phase in 1999. The work will be supplemented by experimental studies.

The distribution of phosphorus and sulphur in oxygen-free copper is also being studied at the Department of Physics at the Chalmers University of Technology. This work has had the character of small targeted efforts, mainly utilizing the analytical equipment available at CTH. Additional efforts of the same scope as before are planned for 1999 as well.

Strength and temperature calculations have been carried out for the canister. The calculations have shown that there is a need for experimental validation in full-scale experiments. This will be carried out in an initial phase on a full scale in the laboratory, for example the prototype repository in the Äspö HRL. Additional calculations may also be needed to simulate the gradual application of load as the swelling pressure slowly builds up in the bentonite.

5.4 Nondestructive testing

A programme for development of hardware and software for ultrasonic testing of welds in copper is under way at Teknikum at Uppsala University. The main strategy is development of systems for phased array testing and software for noise reduction. The programme will continue during 1999 on the same scope as during 1998. Work to verify the equipment for nondestructive testing will be defined in consultation with the Canister Laboratory.

6 Buffer and backfill

Smectite-rich clay, which exists in very large quantities all over the world in the form of bentonite, was proposed as a buffer between the canister and the rock already in the KBS-1 concept defined in the 1970s. Determining the properties of bentonite has therefore been a central task all along.

The problem with evaluating the performance of the buffer and the backfill is that they are constantly changing. This makes it urgent to identify processes that lead to alteration and dissolution of the smectite minerals and to explore secondary processes in the form of precipitation of cementing substance.

6.1 Functional requirements

6.1.1 Requirements on buffer functions

The choice of buffer material is based on the following requirements:

1. Hydraulic conductivity should be so low that transport of corrodants and radionuclides takes place solely by diffusion.

2. Gas permeability must be sufficient in the event large quantities of gas should form in the canister, and the passage of gas must not create lasting permeable channels or cavities in the buffer.

3. Swelling pressure must be sufficiently high to provide good contact with surrounding rock and with the canister, but not higher than what the canister and host rock can withstand.

4. Deformability must be great enough so that rock movements can be absorbed without the canisters being damaged, but not so great that the position of the canisters is altered.

5. Colloidal particles must be filtered by the buffer.

6. Thermal properties (thermal conductivity) must not lead to unacceptable physical and chemical changes in the buffer.

6.1.2 Buffer properties that provide desired function

Based on the above requirements, a number of required buffer properties can be preliminarily identified:

Hydraulic conductivity

The main purpose of the buffer is to guarantee that diffusion is the dominant transport mechanism around the canisters. With an MX-80 buffer with a density of 2000 kg/m^3, the buffer's transport capacity for diffusion is at least 10,000 times higher than its transport capacity for advection.

Ion diffusion properties

Bentonite has very favourable properties when it comes to restricting the escape of radionuclides from a defective canister. However, its effectiveness in this respect is heavily dependent on the properties of the individual nuclide (diffusivity, sorption coefficient and half-life) and the geometry of the near field (canister defect, transport pathways in the rock). As a result, no specific requirements can be made on the buffer with regard to ion diffusion properties.

Gas conductivity

The buffer must not have properties that might jeopardize the function of the other barriers. This means that hydrogen formed by corrosion of the iron insert in a defective canister must be able to escape without creating unacceptable pressures. The experiments conducted under SKB's auspices show that bentonite opens up at a pressure equal to the swelling pressure.

Swelling properties

Swelling capacity is required of the buffer to fill the space between canister and rock and to seal openings caused by thermal and tectonic effects. The required expansion capacity of the buffer is estimated to correspond to a minimum swelling pressure of about 1 MPa, which presupposes a density of at least 1900 kg/m^3 for MX-80 in the water-saturated state.

Deformation properties

The most important deformations of the buffer are upward expansion by displacement of the tunnel backfill and shear caused by displacements in the rock. The upward expansion can cause lifting of the tunnel floor, resulting in fracture widening and sharply increased hydraulic conductivity /6-1/.

Displacements in the rock can occur in the form of tectonically or thermally induced shear of fractures that intersect the deposition holes. Horizontal fractures situated at the mid-height of the canister comprise the most critical case. Practical tests with MX-80 clay with a density of up to about 2050 kg/m^3 and application of a semi-empirical rheological model have shown that predicted rock movements do not bring about buffer deformations that give rise to canister damages /6-1/.

Microbial properties

Bacterial growth has been found to occur in MX-80 buffer with a density of up to 1700 kg/m^3 at water saturation, while 1900 kg/m^3 does not permit survival or reproduction of bacteria of the kind studied in SKB's research work /6-2/. This means that the latter density can be regarded as the minimum suitable density.

Thermal properties

The ability of the buffer to transfer heat from canisters to rock is primarily important in that low thermal conductivity will result in high buffer temperature. This leads to more rapid dissolution of the smectite content and a vapour pressure that can lead to expulsion of water vapour from the buffer through overlying tunnel backfill. To minimize the negative effects of excessively high temperature and temperature gradient, the maximum buffer temperature has been set at 100°C according to the basic concept.

Choice of buffer density

During the past RD&D period, SKB has drawn the conclusion, based on the above considerations, that buffer consisting of MX-80 should, after water saturation, have a density of 1900–2100 kg/m^3.

6.1.3 Requirements on backfill functions

The deposition tunnels constitute conductive pathways in the rock which greatly increase the water flux through the repository if they are not backfilled with material that has a hydraulic conductivity comparable to that of the rock. One principle is therefore to use a fill with very low permeability where the rock is intact and more permeable material where the tunnels are intersected by fracture zones. At these points, permeable sections can also be enclosed and provided with drainage during the filling work to keep the water pressure down and avoid piping and erosion.

Another principle is not to have specific requirements on the impermeability of the backfill, but instead limit axial flow in the tunnels by installing watertight plugs in strategic positions. In both cases, the excavation-disturbed zone around the tunnels must be taken into consideration. To prevent water flux, plugs can be built in suitable positions and recessed into the rock to eliminate flow around the plugs.

Even with plugs, which can be built both where the rock is fracture-poor and at fracture zones, it is vital to use expanding backfill in nearby tunnel sections in order to provide active support to the roof and walls of the tunnels. This prevents the gradual loosening-up of the rock which otherwise leads to an increase of the load on the plugs. The following general requirements can be regarded as reasonable for the backfill:

- Deformability (compressibility) must not so great that excessive upward expansion of the buffer in the deposition holes takes place.

- The backfill should not have significant chemical effects on the buffer.

- Where the backfill is supposed to restrict groundwater flow, specific requirements on hydraulic conductivity and swelling pressure will be formulated.

In order to prevent chemical effects on the buffer, the backfill should have an insignificant content of potassium-bearing, carbonate-rich and sulphur-bearing minerals. This means it should have a low content of potassium, which regulates the transformation of smectite to illite /6-3/, and of calcium, which leads to poorer swellability of the clay and enrichment of e.g. gypsum at the canister surfaces. Sulphur minerals can also give rise to free sulphur, which contributes to gypsum formation and which increases corrosion of the canister's copper shells. Backfill with smectite and quartz as main components is particularly suitable.

6.1.4 Requirements on the near-field rock for constructability

The most important requirements concern discontinuities, i.e. in practice fractures of great extent, which are water-bearing (conductive) and can undergo shear. They are subject to the following restrictions:

- Discontinuities that intersect deposition holes determine the stability of the rock and the feasible means of applying buffer and backfill. Water influx must be limited to permit application of the buffer. However, a remaining option is to achieve sufficient sealing in the application phase by grouting.
- Highly conductive discontinuities which intersect deposition tunnels can cause such great water influx that clay-rich tunnel backfills cannot be applied without special measures, such as grouting.

6.2 Knowledge gained during the past RD&D period

6.2.1 Fundamental knowledge

Natural bentonites have considerably lower hydraulic conductivity and gas permeability than a fabricated buffer of the same density /6-4/. This is because the microstructural homogeneity of natural clays is far better, due to, among other things, creep to stable particle positions over a long period of time. The artificial buffer material consists of bentonite grains that have been compressed so that a channel-like pore system remains. On wetting, this system is filled completely or partially with clay gel formed by particles released from the grains. The channel system comprises a more permeable portion of the buffer than the swollen grains, which retain much of their original high density /6-3/. Water and gas therefore pass through the buffer with greater ease than in natural clays.

It is probable that the homogeneity of the artificial buffer will also increase over a long period of time due to cumulative movements on a molecular scale. this can be illustrated by the use of a microstructural model (GMM), which has been developed during the period so that it is possible to describe quantitatively the changes in grain arrangement that take place from compression of the buffer blocks to the fully water-saturated, ripened stage /6-5/.

Numerous processes and parameters act in conjunction in the buffer, for example simultaneous influence of temperature, hydrology and mechanics (THM). Our understanding of such functions has increased considerably in part as a result of international collaboration /6-6/. The same applies to chemical changes, such as illitization via uptake of potassium in the buffer from the surrounding rock and backfill. Another chemical process which significantly concerns the influence of pH is the one which takes place when concrete is in contact with smectitic clay contained in the backfill. This question has been explored experimentally in hydrothermal tests, and theoretical geochemical models are being developed in international cooperation.

The work of identifying and characterizing buffer and backfill materials has been gathered in SKB's series of working reports under the name "Bentonite and Backfill Handbook", which is regularly updated /6-3/. This work has primarily focused on determining important physical and chemical properties of smectitic materials that are available commercially in very large quantities internationally. Furthermore, it has been considered urgent to develop and adapt laboratory methods and field tests for the purpose of standardizing testing procedures for buffer and backfill materials. To understand the influence of important parameters such as density and pore water chemistry on the function of these materials, conceptual and theoretical models have been developed in parallel with this work. They are coupled to microstructural processes and make it possible to predict changes in properties of practical importance as a consequence of e.g. density changes, ion exchange processes and gas passage.

6.2.2 Technology development

Extensive testing and development of technology for fabrication of practical forms of buffer and backfill has taken place. It is now possible to produce highly compacted (100 MPa) buffer blocks a cubic metre in size by means of isostatic and uniaxial pressing, and they can be given the shape of cylinders or rings for rational handling /6-7/. The strength of such blocks, which is determined by structural defects on a micro- and macro-scale, is being tested in ongoing work.

For rational emplacement and compaction of backfill, trials have been conducted at Äspö using materials with different clay contents and ballast types. This has led to abandonment of the technique involving horizontal deposition and compaction to just over half the tunnel height and injection of the uppermost part. The reason is that inflow of water causes practical difficulties, such as loosening-up. A technique involving application and compaction on a slope from floor to roof is now deemed to be the most advantageous, but problems caused by water ingress can still occur and different methods for dealing with such problems as erosion are being tried, for example enclosure of drainage layers /6-8/.

Methods for freeing canisters from the buffer have been investigated and several procedures appear to be feasible, including disintegration of the buffer. This method, which is suitable owing to the microstructure and surface chemistry of the buffer, has been tested experimentally on a laboratory scale and appears to permit relatively quick freeing of the canister. It involves spraying a calcium or sodium chloride solution on the buffer, which thereby disintegrates and is pumped away in a closed system where the clay material is extracted and the salt solution is recirculated /6-9/.

6.2.3 Interaction with surrounding environment

The interaction between buffer, near-field rock, canisters, backfill and concrete plugs has been investigated and development of conceptual and theoretical models for wetting of the buffer and the backfill is under way. The results of the Buffer Mass Test (BMT) in the Stripa project /6-10/, which show that the rock structure and the initial state of the buffer strongly influence the rate of water uptake in the buffer, will be analyzed in detail to determine the cause-and-effect relationship.

The effects on canisters of displacements along discontinuities which intersect deposition holes is determined in part by the deformation properties of the buffer. Experimental and theoretical evidence exists for assuming that decimetre-sized shear movements occurring during the course of a few tenths of a second do not cause canister rupture /6-1/.

When it comes to the backfill, experience from ongoing tunnel filling trials at Äspö shows that water seepage can cause problems with piping and erosion in clayey material during application. The crucial question, which has been partially explored, is what clay content and density the backfill should have in order to give sufficient support to the roof and walls of the tunnel. This is related to what limits are set on the water flux in the rock immediately surrounding the tunnels and how tight plugs should be made with a view towards durability.

The influence of saline groundwater on the bentonite's swelling pressure has been further investigated. Verifying laboratory tests have been performed /3-2/. Different models for calculation of swelling pressure in bentonite were tried out. It was found that only the thermodynamic model handled the effect of moderately saline groundwater with decent accuracy. At high salinities, all models underestimated the swelling pressure in comparison with results measured in the laboratory, but the introduction of 1) an internal osmotic term and 2) equilibrium calculations where the bentonite's charge-compensated cations were taken into account (Donnan exclusion) gave good agreement between thermodynamically calculated swelling pressures and measured values for all salinities. The "new" thermodynamic model provides support for a somewhat changed and less conservative view of the properties of the buffer at high salinities. The buffer is expected to develop swelling pressure at all conceivable salinities (included saturated saline solution) and only marginal differences are expected between sodium- and calcium-rich groundwater. The bentonite in the backfill, however, is expected to be more sensitive to high salinities as a consequence of the relatively low bentonite density. This must be taken into consideration in the choice of backfill and the requirements that can be made on its function.

6.2.4 Function in deep repository

In the deep repository, the stress situation in and deformability of the bedrock will affect the buffer and the backfill both during the construction phase and in a long time perspective. The stability of the deposition holes is a question that has in part been clarified and is of great importance for the choice of hole positions. The build-up of piezometric pressure during the construction phase will influence the risk of erosion and piping and the wetting rate of the buffer and the backfill. The chemical composition of the groundwater will influence the water saturation process, particularly in backfill with low clay content, in a manner which is under investigation.

The most important process is the temperature increase of the buffer and the near-field rock. The basic concept presupposes incompletely saturated buffer, and that can lead to water flux in vapour form accompanied by salt enrichment and vapour influence on the clay content. Such effects can be minimized by the use of buffer blocks with a high degree of water saturation, for which technology is now available /6-11/.

6.2.5 Choice and availability of buffer material

SKB's reference material, MX-80 Volclay, has a smectite content of at least about 70%, but this varies, among other things because the material is taken from relatively thin but extensive bentonite layers with varying conditions of formation /6-3/. One of the reasons this clay was chosen as a reference is that the dominant adsorbed ion species is Na, which gives better expandability than when Ca and Mg occupy the ion exchange positions, as is the case for most European bentonites. These are converted to Na form on an industrial scale by soda treatment, which leads to some enrichment of calcite or dolomite.

Since the conductivity requirements are also met by clays with a lower smectite content and these clays more easily satisfy the condition for highest swelling pressure, a few clay materials with a content of expandable minerals of around 50% may qualify. Such clays with Na as the dominant adsorbed cation are found in Denmark and Northern Germany /6-3/. There they comprise very thick and homogeneous clay sediments; up to 100 m layer thickness has been measured. When it comes to accessory minerals of importance for buffer and canister life, for example minerals containing potassium and sulphur, they are comparable to MX-80. Such materials will be investigated during the coming RD&D period.

6.3 Calculation models

Within the framework of an EU project, model development has taken place in three areas that are of particular importance in explaining and predicting processes of a physical/chemical nature. One of the areas concerns the microstructure of buffer and backfill starting from the compaction stage and on through the period when water saturation and homogenization take place. Different densities and electrolyte contents have been assumed to shed light on changes in pore size distribution and fraction of mobile and bound water. The model, which now exists in 3D form, provides a basis for explanation and quantitative calculation of hydraulic processes and diffusive ion transport as well as gas passage. The model is being further developed to also cover rheological functions such as shearing and swelling.

Coupling of thermo-hydro-mechanical functions is taking place in another EU project. This work is a continuation of the investigations begun in the previous RD&D programme in the form of a THM model based on the numerical code ABAQUS. The model has been further refined and has begun during the period to be applied to practical cases, such as PNC's buffer tests in the underground laboratory in Kamaishi in Japan /6-6/. See also the FEBEX experiments (section 14.4.5).

Utilization of highly compacted bentonite in O-rings to seal concrete plugs in tunnels is planned in field tests at Äspö, and such plugs may also be used as temporary closures in a final repository. The placement and design of plugs of this type has been investigated by the use of numerical models of the coupled hydraulic function of rock mass, disturbed zone and bentonite-sealed concrete plug /6-12/. The data obtained in this way will be used as a basis for designing recesses in the rock and determining the geometry and location of plugs in rock of varying structural composition.

6.4 Transport processes

6.4.1 Hydraulic processes

The microstructural modelling has provided a greater understanding of the mechanisms for water flow, ion migration and gas transport in buffer and backfill. As far as flow is concerned, the models show that the water is only mobile in a small part of a cross-section through buffer with the density in the water-saturated state that is being considered, i.e. 1900–2100 kg/m^3. The hydraulic gradient has a great influence on hydraulic conductivity, and Darcy's law has limited validity /6-5/. At the very low gradients that prevail in a final repository in the steady state there is in fact no flow at all through the buffer. The scale dependency of hydraulic conductivity, a matter of special importance for the hydraulic performance of the tunnel backfill, can be described with the aid of simple statistical expressions if the conductivity of the individual elements is known /6-5/.

A process of great importance in connection with water saturation of the buffer, and one that has been given mathematical form in the THM model, is flow at incomplete water saturation. This question, which will be treated by means of the microstructural models developed, can only be treated empirically today.

Another process of a similar nature and importance is transport of water in vapour form. It is modelled as a diffusion process with the temperature gradient and the vapour pressure gradient as driving forces /6-5/.

6.4.2 Ion diffusion

The processes associated with diffusive transport through the buffer have been investigated in connection with the EU project that concerns microstructural modelling. Partial answers have hereby been found to fundamental questions such as surface and pore diffusion, and the various mechanisms associated with cation and anion migration have been clarified to some extent /6-13/. One difficulty that has not yet been overcome is that chemical process such as complexation during ion transport cannot be modelled.

The usual mathematical expressions for diffusive transport are applicable to anion diffusion, since sorption can be disregarded. One important lesson that has been learned is that the filter function must be taken into account in a relevant manner in the use of diffusion cells in the laboratory /6-5/. For evaluation of the diffusion coefficient for cations such as caesium and strontium, the filter function must also be taken into account, and it is also necessary to perform separate batch tests to determine the capacity factor (retardation factor), which is a function of the sorption coefficient Kd, the density and the porosity of the buffer.

6.4.3 Gas flow

A question that has been treated in particularly great depth, both theoretically and experimentally, is the transport of gas, mainly hydrogen, through the buffer. A large number of experiments have shown that the bentonite will not allow gas to pass through until the pressure inside the canister exceeds the sum of the swelling pressure and the piezometric pressure /6-14, 6-15, 6-16, 6-17/. When the pressure reaches this value, a transport pathway is formed through the bentonite and gas is released. The pressure will drop and, if gas production is low enough, the transport pathway will be closed. This takes place at a so-called "shut-in" pressure, which is dependent on the swelling pressure. At pressures lower than the shut-in pressure, gas is only transported by diffusion (see Figure 6-1). If, on the other hand, gas production is sufficient to maintain a higher pressure, the gas transport pathway will be kept open.

The "GAMBIT Club" is a joint cooperation project between SKB, ANDRA, NAGRA, PNC and POSIVA. The purpose of the project is to develop a calculation model that is capable of quantifying gas transport through bentonite. Phase I of the project started in 1996 and has just been concluded. The emphasis during phase I has been on developing an understanding of the mechanisms and the controlling processes for gas transport in highly compacted bentonite and on implementing and testing a preliminary calculation model. The model is based on the most probable interpretation of available experimental data for gas transport in bentonite, i.e. that gas penetration in the clay takes place by induced microfracture formation in the clay and that the permeability of the transport pathways formed is dependent on the effective stress (or the equivalent, when the boundary condition constant stress is used, of the gas pressure). The probability of initial

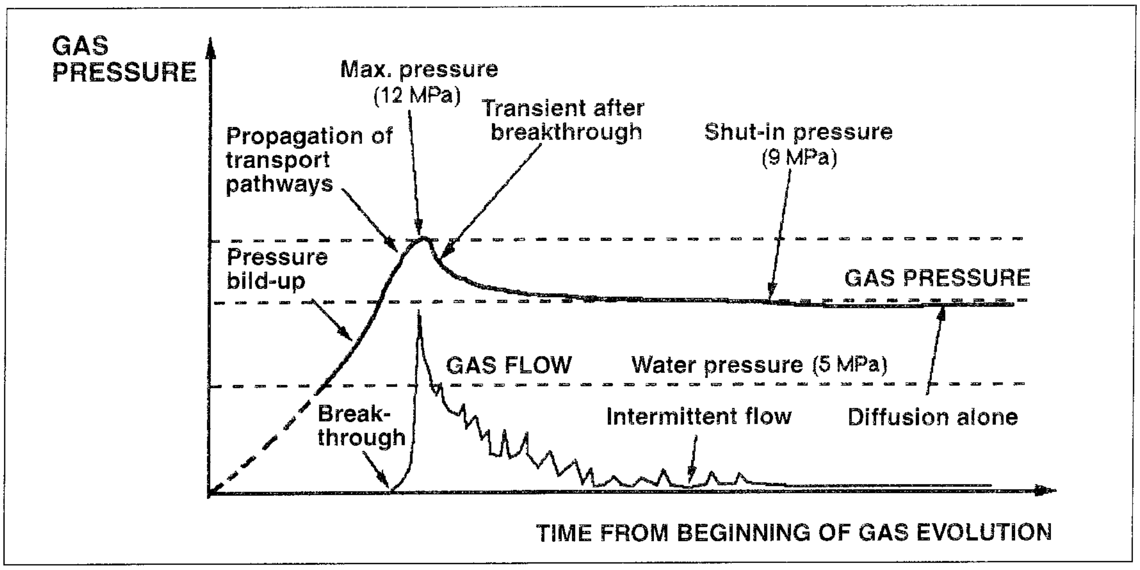


Figure 6-1. Course of gas transport through bentonite.

transport pathways for gas in highly compacted bentonite was judged to be very small. This makes it necessary for the gas to break the interlamellar water films by micro-fracturing, and the new model therefore contains two steps: one step for propagation of the gas transport pathways, and one step for continuous gas flow. The second step occurs after the gas has broken through on the downstream side. The theory of elastic fracture mechanics has been used to develop a model for the fracture propagation through the clay which is included in the first step. In the second step, a gas flow is established through the clay. The propagation of the transport pathways is dependent on the gas pressure, and in the model the pressure-dependent propagation is so designed that it recreates the behaviour of the gas in the experiments.

6.5 Concrete

The use of cement-based materials is limited to the fabrication of concrete plugs in the deposition tunnels and the immobilization of long-lived low- and intermediate-level waste. Contact between the cement matrix in the concrete plug and the bentonite component in the backfill can lead to reactions between cement in the concrete and smectite in the backfill. For the SFR silo, which is surrounded by bentonite, a simple degradation model was developed which entailed dissolution of the cement's $Ca(OH)_2$ component and diffusive transport of the reaction products /6-18/.

The equivalent effect on the smectite content of the backfill has not been investigated. Continued joint international work is being conducted in the field with the preliminary conclusion after 16 months of hydrothermal experiments that some transformation of smectite to illite and chlorite has taken place as a consequence of potassium release from the cement, that some quartz growth has taken place and that calcium silicate hydrate has been formed in the smectite /6-19/. The resulting, most important change is that the swellability of the backfill, already weak from the start, decreases as a consequence of illitization and cementation. Continued work is also aimed at determining how cement grouting of the rock around the deposition holes and temporary concrete reinforcements around the top end of the holes affects the buffer.

6.6 Goal and programme

The work is aimed at producing results that are needed for the safety assessments to be submitted in support of permit applications, for prediction and planning of the field tests in the Äspö HRL, and for the design of the deep repository that begins when data from site investigations becomes available. The target specification for buffer and backfill will be detailed during the aforementioned 3-year period.

6.6.1 Questions that have essentially been explored

New knowledge and experience are used for progressive upgrading of the KBS-3 concept as regards geometry and composition of buffer and backfill.

Among the questions that can be considered to have been explored are temperature evolution and the impact of heat on the pore water pressure in the buffer. The question of whether significant erosion and removal of buffer that has penetrated into fractures in surrounding rock can take place has been adequately explored. As far as transport processes are concerned, the appraisal is that water flow through the buffer is negligible at an expanding mineral content of at least 50% and a density in the water-saturated state of at least 1900 kg/m^3, which enables buffer materials of a less exclusive kind than MX-80 to be chosen. The capacity of diffusive transport is sufficiently well known for relevant safety assessments to be carried out.

As far as choice of buffer material is concerned, extensive tests have been conducted of various kinds of commercially available smectitic clay materials and the results compiled in database form. Further work of this nature is continuing. A large number of materials have also been investigated for backfilling of tunnels and shafts, and the results also reported in database form. The composition of the backfill depends on the functional criteria and on how the backfill is to be applied and compacted. These questions are being investigated in ongoing Äspö projects.

6.6.2 Remaining questions

Long-term chemical stability is the most important question. The previously used illitization model is still regarded as a useful tool. When applied to the KBS-3 concept, it gives the result that less than 10% of the smectite content is transformed to illite in a time scale of hundreds of thousands of years. The crucial question is the choice of parameter values, and attempts have been made to derive e.g. the activation energy from natural analogues. Even though the mechanisms of smectite transformation are sufficiently well-known to justify the use of that model, this does not rule out the possibility that other processes may be of greater importance and lead to more rapid change. It is, for example, possible that brammallite (sodium illite) can be formed by drying-out and permanent collapse of montmorillonite stacks and that cementation can take place by precipitation of silicon released from the lattice in the part of the buffer with the highest temperature. Such processes may be the cause of the loss or strong reduction of the swelling capacity of smectite that has been found in experiments involving steam treatment at high temperature (the "Couture effect"), /6-20/. SKB's current assessment is, however, that cementation and permanent contraction of the smectite particles may be a greater problem than illitization. Natural bentonites that have undergone cementation by precipitation of silicon and aluminium compounds due to the effects of heat exhibit, for example, low swelling pressures due to cementation effects /6-21/. These effects will therefore continue to be focused on during the coming RD&D period. Verifying experiments will be performed in the Äspö HRL.

When it comes to understanding of gas transport, great progress has been made during the past period. Some questions remain, however: it is still not quite clear how boundary conditions influence gas transport, nor do we have a finished model that can extrapolate results from gas transport experiments to the conditions that exist in a repository. These questions will be deal with during the coming period.

It may be difficult to achieve the block density that is required for the ripened buffer in the deposition holes to have sufficient density. This can be accomplished by filling the gap between the block and the wall of the hole with pellets of highly compacted clay powder, but seepage from the rock must then be low enough so that piping and erosion do not occur. These questions are dealt with for the purpose of finding a general solution and trying possible procedures in planned field tests in the Äspö HRL.

The process involved in swelling of the buffer and subsequent consolidation under the influence of the inner mass of high density can be described conceptually, but accompanying microstructural changes, which can lead to considerable anisotropic water permeability, cannot be modelled. The question, which may be of crucial importance for the wetting rate of the buffer in the deposition holes, is intended to be investigated.

Instantaneous displacements of more than a millimetre or so along flat discontinuities that intersect deposition holes are not probable, but cumulative shear deformations of a few hundredths of a millimetre could occur in a long time perspective /6-1/. This could entail exposure of fuel assemblies and steel canister components to groundwater and thereby accelerated dissolution of the fuel as well as gas evolution and expulsion of contaminated water to a near-field rock that has become porous due to tectonics. The question, which is related to the question of how shear movements in the earth's crust are associated with stress states and structural composition, calls for deeper study.

The main purpose of the backfill is to support the surrounding rock. The question of what other requirements should be made on the backfill, choice of backfill material and backfilling technique is currently the subject of investigation.

7 Structural geology and the mechanical stability of the rock

A KBS-3-like repository presupposes a crystalline host rock. This section deals with geological and bedrock-structural conditions, as well as the rock's mechanical properties and geodynamic and mechanical processes. Stability questions may be associated with natural or induced movements, depending on the configuration of the repository.

A relatively detailed background and summary of SKB's activities with regard to geodynamic and mechanical processes up to and including 1995 was given in RD&D 95 /7-1/. The background description of these processes given in the following is in part an abridged version taken from RD&D 95. The emphasis lies on what has happened at SKB during the past three years. The reader is otherwise referred to SKB's Annual Reports /7-2, 7-3, 7-4/ and SKB's TR series of technical reports.

7.1 Geological and bedrock-structural conditions

The bedrock in Sweden can be divided into three major units: The crystalline basement, the Caledonide mountain range and the sedimentary bedrock regions outside the mountain range. Most of Sweden's crystalline basement was formed by means of foldings, alterations and magma intrusions occurring between 2,500 million and 500 million years ago. What we see today of the exposed surface of the crystalline basement lay at great depths when it was formed. Erosion has reduced the thickness of the crystalline basement by 10–30 km.

The Swedish waste management programme has focused on magmatic and highly metamorphic rock types as host rock for a repository. The rock types are often gneissified with a granitic composition.

Basic rock types, particularly gabbro, have been proposed as an alternative, since they are able to offer better sorption properties and conditions for self-healing of fractures. However, the occurrence of large and homogeneous rock volumes with bodies of basic rock types is strictly limited. From a rock engineering point of view, experience from basic rock types does not differ essentially from experience from more acid bedrock. In terms of hydraulic properties, available results show that basic rock types are generally slightly less hydraulically conductive than granites and gneisses. The range of variation within a rock volume is considerable, however. The relatively low thermal conductivity of basic rock types necessitates utilizing large repository volumes in order to keep temperatures from becoming too high in the near-field. Another negative factor is that gabbro is often of interest for extraction of metals (e.g. nickel). In summary, manifest difficulties are encountered in trying to find large homogeneous rock volumes with basic rock types for a deep repository, and a comparison that takes into account hydrogeology, geochemistry and rock engineering does not reveal any obvious advantages for gabbro in relation to granitic rock types /7-5/.

The Swedish crystalline basement is intersected by certain very old super-regional zones of deformation. The Southwest Scandinavian Gneiss Province is bounded on the east by a zone that extends from Skåne to Värmland, known as the Protogine Zone. Within the Southwest Scandinavian Gneiss Province, the Mylonite Zone stretches from the Norwegian border in Värmland southward via Värmlandsnäs to Varberg. The Mylonite Zone is a sign of severe deformations in the bedrock about 1,000 million years ago. East of the zone the rock types are mainly gneisses of magmatic origin, while west of the zone surface rock types are most common. The Tornquist Zone is a very elongated zone within the Eurasian plate. The zone constitutes a boundary between the Baltic Shield and an extensive depressed area in the western part of continental Europe. In Skåne, the Tornquist Zone takes the form of crystalline basement horsts and intervening deep depressions with sedimentary rock.

Structural-geological interpretations have traditionally only served as a basis for qualitative descriptions of the bedrock and its tectonic history. The nuclear waste sector, with quantifying mechanical and hydrological calculations on different size and time scales, makes extraordinarily exacting demands on the use of characterization methods that can be followed clearly through the entire siting and site investigation programme. It is SKB's experience as far as geological characterization is concerned that methods for mapping and describing geological structures are relatively well-developed. However, a further refinement of existing interpretation methods is required for characterization of discontinuities (lineaments, zones and fractures) /7-6/.

The aforementioned discontinuities are examples of brittle deformation. Large parts of the bedrock have also been deformed plastically. This occurred early in geological history when today's erosion surface lay at a depth of many kilometres and the bedrock behaved like a viscous mass. Plastic deformation was particularly widespread in certain persistent zones, called regional shear zones. Today, these zones can be distinguished as foliated or gneissified parts of the bedrock. Such zones have been identified in feasibility studies, for example of Östhammar Municipality. Here they enclose bodies with relatively unaffected bedrock, so-called tectonic lenses. There is today no clear understanding of how regional shear zones and tectonic lenses affect safety in a deep repository. Higher hydraulic conductivity, increased heterogeneity and increased risk of future rock movements may possibly be negative factors. For precautionary reasons, areas affected by plastic shear zones have therefore been dismissed in the feasibility studies.

7.2 Mechanical properties of the crystalline basement

The Swedish crystalline basement is characterized by its constituent rock types and by its discontinuities, mainly fractures and fracture zones. The intact portions of the rock (the rock blocks), the discontinuities and any groundwater occurring in them constitute the rock mass. When the rock mass is loaded, it is deformed due to deformation of the individual rock blocks and due to displacement, compression or widening of the discontinuities. In addition to the strength and deformation properties of the rock, the frequency, orientation and mechanical properties of the discontinuities must therefore be taken into account /7-7/.

As a rule, the stability of the rock is affected by a number of concurrent processes or mechanisms. When the stresses in the rock change, the discontinuities will be affected, whereby their properties and the properties of the rock mass as a whole are changed. Temperature-induced mechanical processes play an essential role as far as the rock is concerned. Furthermore, the coupling between mechanical and hydraulic conditions can also be significant. The thermo-mechanical coupling is relatively well-explored, while so-called constitutive relationships between mechanical and hydraulic properties in fractures comprises a growing field of study /7-8/.

Stability problems in rock stem from both shearing along existing fracture planes and compressive or tensile failure in the intact rock. The shearing problem dominates in Swedish bedrock.

Failure and strength properties are determined by compressive, tensile and shear strength. The tensile strength of crystalline rock is about 10 percent of the compressive strength. The strength of a rock material is normally described by a failure criterion, e.g. Mohr-Coloumb's or Hoek-Brown's.

The strength theories for the intact crystalline are relatively well-developed and tested on a laboratory scale. Mechanical characteristics of major discontinuities such as fracture zones are, on the other hand, relatively unknown. A compilation of existing information has been carried out /7-9/ based on observations from limited parts of zones or from large-scale load changes, mainly in the mining industry.

The stability of the rock mass is determined primarily by the geometric arrangement of existing discontinuities and their mechanical properties. The mechanical properties of the discontinuities are normally described by means of idealized stress-strain relationships for normal deformations and shear deformations. Small shear deformations are primarily elastic, while larger shear deformations (sliding) indicate that the shear strength has been exceeded. The discontinuities affect stability and stress distribution, partly because they cannot transmit tensile stresses, and partly because they cannot fully transmit fracture-parallel forces at low normal stresses. If the mechanical equilibrium of the rock mass is disturbed due to local or regional stress changes, some of the deformations required to re-establish equilibrium take place along certain oriented and loaded discontinuities. The mechanical equilibrium of the rock mass can also be disturbed by the fact that the effective normal stress and thereby the shear strength in the fractures is reduced by pore pressure increases.

7.3 Geodynamic and mechanical processes

Discontinuities in rock range in size from hundreds of kilometres to fractions of a millimetre. The patterns of the discontinuities appear on everything from a millimetre scale to a kilometre scale and are characterized by brittle shear failures and/or tensile failures. Owing to the tectonic processes with varying stress situations that have acted on the Baltic Shield over hundreds of millions of years, it is not likely that extensive fracturing or propagation will occur within the next 100,000 years /7-10, 7-11, 7-12/. It is, however, much more likely that deformations in the bedrock will occur as reactivation of already existing fractures and fracture zones, and that strength will depend on the properties of the fractures in the rock mass. Fractures and fracture zones will "cancel out" the displacements due to altered primary stresses and induced loads. Stability in a deep repository is affected by both geological processes and induced movements due to the geological configuration of the repository /7-7/.

SKB's activities deal with the following disciplines and processes when it comes to overall geodynamics:

Tectonics is a collective term for the deformation of the earth's crust and the structural forms arising as a result. The term covers deformation and structural forms from a millimetre to a kilometre scale. SKB is compiling knowledge of the different tectonic regimes to which the Baltic Shield has been exposed during the past 1,200 million years with a focus on different dominant stress fields associated with them.

Glaciations, which are very likely to occur in the northern hemisphere within the next hundred thousand years or so, raise questions concerning mechanical stability, groundwater hydraulics and groundwater chemistry. SKB has had a numerical glaciation model of Scandinavia developed. The model is time-dependent and includes thermo-mechanical coupling. The glaciation model is driven by changes in the air temperature and the state of the ice mass on a predetermined topography. With the model it is possible to describe boundary conditions for thermo-hydro-mechanical calculations in a general manner (see also Chapter 16).

Land uplift following the most recent glaciation is a conspicuous geological process in Sweden, especially along the coast of Västerbotten in northern Sweden where the land is rising relative to the Bothnian Sea at a rate of about 9 mm per year. At the beginning of the melting phase of the Weichsel Glacial Stage (about 18,000 years ago), the surface of the world ocean was about 120 m lower than today and the surface of the ocean started to rise (eustatic rise). The warmer climate brought large flows of meltwater to the oceans. As the continental ice sheets gradually melted, the pressure of the ice on the earth's crust decreased and a process of land uplift began (postglacial isostatic rebound). Viewed in an overall perspective, postglacial land uplift has been and is a relatively continuous process in space and time. Deeper knowledge regarding the process of land uplift can be expected to be gained via data from the recently established GPS (Global Positioning System) network. Around 20 permanent measurement stations were recently put into operation in Sweden.

Neotectonic and postglacial movements have been thoroughly studied. By "neotectonic movements" is usually meant displacements that have taken or are taking place during the current tectonic regime, i.e. during the time when the Atlantic Ocean has existed. Movements after the most recent deglaciation are called postglacial. It is essential to ascertain whether such movements can lead to new fracturing or seriously alter the hydrogeological or chemical conditions for a deep repository. Postglacial faults in the northern part of the Baltic Shield have been known and have been the subject of investigations for about 20 years. At present the postglacial faults are considered for the most part to be reactivations of older dominant zones, but the occurrence of new fractures on a limited scope cannot be ruled out. The causes of the postglacial movements are probably a combination of relatively rapid changes in the vertical loads (associated with deglaciation) and horizontal compression from the Mid-Atlantic Ridge related to continental drift. Landslides and violently disturbed soil strata (seismites) are clear indications of brief instability.

Seismicity can be said to be a sign of active tectonics on a geological time scale. More than 95% of all earthquakes take place at the boundaries of the continental plates. Approximately a million earthquakes with a magnitude of more than 2 on the Richter scale take place annually in the world. Of these, about 10 quakes occur in Sweden. In other words, our country is a seismically inactive area. The biggest earthquakes in Sweden reach a maximum magnitude of about 5. The Swedish earthquakes are mainly concentrated in two areas. One area extends from Lake Vänern down to the west coast. The other area follows the coast along the Gulf of Bothnia towards Tornedalen and northern Lapland. The majority of the Swedish quakes take place deep down in the bedrock. The epicentre of the quake normally lies about 10–20 km below the ground surface. The mechanisms that control the quakes within the continental plates, for instance within the Baltic Shield, are relatively poorly understood. In Sweden, the discussion concerns whether the earthquakes are controlled by the processes of plate tectonics, the ongoing process of land uplift, or a combination of the two mechanisms. As far as the effects of earthquakes on underground facilities are concerned, the mechanical stresses on such facilities are in general less than for facilities on the surface of the ground. Many observations, above all from mines, exist to support this contention. In summary, Sweden is located in a seismically relatively unaffected region. There are no signs today that this will change on a 100,000-year time scale, except for the changes in stress conditions that might be caused by a future ice age.

Induced loads are rock stresses that arise as a consequence of the disturbance caused by the very existence of a deep repository or its construction. The creation of cavities in the rock mass causes stress redistribution and stress concentrations. The short-term stress picture around the repository depends on, besides the properties of the rock mass (initial stresses, fracturing and strength), the extraction method (careful or conventional drilling and blasting) and the geometric shape ("rectangular" or "circular" tunnel cross-section). The rock excavation work (drilling, blasting) causes some fracturing of the rock near the tunnels. A high-strength and fracture-poor rock increases the risk of rock burst. Heat generation in the stored waste gives rise to an elevated temperature in the vicinity of the deep repository reaching up to about 80°C locally, which then slowly declines. Locally around the deposition tunnels, the thermal load causes increased tangential stresses.

The chances that stability problems will arise are thus greatest in the near-field, where stress levels and stress anisotropy can be considerable. Some principal types of R&D problems related to movements in existing fractures can be distinguished:

- Rock blocks are loosened from cavity walls due to absent or insufficient friction.
- Shear movements are triggered along fractures intersecting deposition holes.
- Large stress concentrations with a risk of failure in intact rock arise next to cavity walls as a result of shear movements along tangentially oriented discontinuities.
- Channels form, widen or close in the immediate vicinity of the deposition holes or tunnels as a consequence of shear movements in systems with unfavourably oriented fracture intersections.

7.4 Activities in relation to goals in RD&D-Programme 95

A number of projects relating to the stability of the bedrock and planned for the period 1996–2001 were described in RD&D-Programme 95. A brief situation report follows:

Geological and bedrock-structural conditions

- Determination of the extent and thickness of former sediment layers on the sub-Cambrian peneplain with the aid of fission tracer dating. – Several reports have now been compiled /7-13, 7-14/. The reports provide a basis for discussing former vertical load situations and their consequences on the Baltic Shield during the Phanerozoic in relation to ice loads during the Quaternary period. It is highly probable that Devonian sediments with a thickness of 2–4 km covered most of the Baltic shield for hundreds of millions of years following the formation of the Baltic Shield. These sediments are now eroded away.
- Refine methods for identification of subhorizontal structures in the bedrock. – Field activities have been carried out regionally in the environs of Äspö. Methods of interpreting seismic reflection surveys have been improved /7-15/.

- Refine quantitative criteria for classification of discontinuities in the bedrock. – Determination of the criteria that will be employed to determine exclusion distances to repository sections and canister positions has been started within the framework of SKB's project on siting factors /7-6/ but method development and interpretation activities will continue during the coming three-year period.

Mechanical properties of the crystalline basement

- Gain a better understanding of the *representativity of rock stress measurements* by compiling available measurement data. – A joint project with the foundation Svensk Bergteknisk Forskning, SveBeFo, has been conducted with exemplifying data from the Äspö HRL /7-16, 7-17/. Among other things, the results say that differences in vertical stress can only partially be explained by depth dependence. A comparison between the overcoring method and the hydraulic fracturing method shows that the stress measurement is scale-dependent with relatively greater variability for overcoring data.

- Perform and interpret *rock stress measurements at depths* down to 1500 m in the KLX 02 borehole at Laxemar in the municipality of Oskarshamn. – By modification of available equipment for hydraulic fracturing, it has been possible to measure rock stresses down to 1400 m. Conclusions from the project "Project Deep Drilling KLX 02, Laxemar" are reported in Chapter 17 /7-18/.

- Determine *normal stiffness in the field for fractures*. - Field work has been carried out with the modified equipment for rock stress measurements. The method was tested in the deep hole in Laxemar with successful results /7-18/.

- Contribute towards *rock-mechanical theory development* when it comes to *creep movements* of tunnel walls and assessments of *effective stresses* in fractured rock. – Several projects have been carried out for the purpose of theory development /7-19, 7-20/. The effective stress concept was introduced by Terzaghi in 1936 and has been very useful for understanding geotechnical materials, especially different types of water-saturated soils. Continuation of this development work is deemed to be worthwhile when it comes to creep processes and their understanding.

Geodynamic and mechanical processes

- Gain a better understanding of the fracturing of the crystalline bedrock in a historical tectonic perspective by means of e.g. field studies of maximum displacements for discontinuities (fractures and fracture zones) on different scales. – Within the framework of a study of the effects of earthquakes on a deep repository, existing databases have been presented concerning relationships between earthquake magnitudes, length and width of structures and displacements. Good reason exists to continue the work with mapping field studies /7-21/.

- Explore the potential for hydraulic fracturing and/or propagation of existing fractures and fracture zones in conjunction with a glacial cycle. – The glaciation model developed by SKB offers a means to evaluate these effects. Certain analytically oriented studies have been initiated in cooperation with the Dept. of Geotechnical Engineering at the Chalmers University of Technology in Gothenburg. Under the assumption of highly simplified boundary conditions, calculations show that at very high water pressures, jacking might be possible to relatively great depths (about 200–300 m). This process could explain the stratified fine sediments that have been encountered in rock fractures. These activities will continue.

- Study aseismic movements and ongoing land uplift with the aid of recently installed permanent stations in the Swedish GPS network. – Several studies of this subject have been published. One report deals with the Swedish GPS network /7-22/. Other reports deal with isostasy and eustasy /7-23, 7-24, 7-25/. A basis now exists for good prediction of land uplift for the next ten thousand years.

- Gain a better understanding of the causes of the earthquakes that occur in the Baltic Shield. – Above studies as well as compilations of brittle tectonic history /7-10, 7-11, 7-12/ deal with this question, which requires further R&D. During the past few years, SKB has shown an interest in the results of the international Europrobe/Eurobridge project in order to obtain a better picture of regional differences within the Baltic Shield when it comes to the appearance and properties of the lithosphere.

- Compile experience of the earthquakes that have occurred at the Kamaishi Research Mine in Japan and generalize the effects, if any, on an underground facility. – The work has continued within the framework of a bilateral agreement between SKB and PNC, Japan. SKB has compiled simple situation reports. Now that PNC's activities in Kamaishi are being discontinued, an official report on the results of the earthquake project is expected.

- Further refine methods for dating of previous fracture zone movements. – SKB has not conducted any activities during the past three-year period, but intends to initiate projects in this field once again as a follow-up of the previously published studies /7-26/.

- Investigate the possible effect of a deep repository on the strength of the rock in a regional perspective. – The question is whether the deep repository is to be viewed as a horizontal plane of weakness acting in concert with or independently of regional fracture zones. The study, which requires some rock mechanics model development, has not been initiated.

7.5 Goals and programme

The R&D activities are aimed at quantifying and exploring the consequences of long-term tectonic impact, including earthquakes and glacial cycles. Prioritized goals during the period 1999–2004 are thereby to:

- compile available knowledge on what the tectonic and seismic consequences may be of a deep repository in the Swedish bedrock,

- compile a method for mapping and interpretation of structural-geological elements, lineaments, zones and fractures. The method will be used for characterization of the geological prospects for construction and operation of a deep repository.

Some prioritized R&D activities for the period 1999–2004 focusing on structural geology and mechanical stability are summarized below.

7.5.1 Geological and bedrock-structural conditions

SKB will *devise a standard and defined interpretation methodology for discontinuities* in the bedrock and further refine this characterization with regard to hydraulics and mechanics for *classification of discontinuities* in the bedrock. This is included as part of the basis for judging exclusion distances to repository sections and canister positions. The work should be viewed as a continuation of the methods employed in SKB's siting projects, the Äspö HRL and the Stripa Project. It is essential that different types of uncertainty factors be elucidated in connection with this characterization and classification.

Database on displacements for discontinuities (fractures and fracture zones) on different scales. By means of field studies that determine maximum observable displacements in relation to the length of the discontinuities, it should be possible to gain a better understanding of the fracturing of the crystalline bedrock in a historical tectonic perspective.

Continue *mapping of the extent and thickness of former sediment layers* on the sub-Cambrian peneplain with the aid of fission track dating. The study will provide additional data as a basis for discussing former vertical load situations and their consequences on the Baltic Shield during the Phanerozoic in relation to ice loads during the Quaternary period.

7.5.2 Mechanical properties of the crystalline basement

Importance of regional plastic shear zones. Plastic shear zones have drawn attention recently. SKB intends to study their importance for a deep repository. For example, their hydraulic conductivity will be studied by utilizing SGU's (Geological Survey of Sweden) well data base. Further, studies will be initiated concerning the question of whether repeated rock movements are or have been more common in these zones that elsewhere (reactivation). This can be done by studying the correlation between the zones and present-day earthquakes and by utilizing the sub-Cambrian peneplain as a reference surface.

Understanding of *fracture propagation.* The conceptual uncertainties involved in understanding fracturing in the form of spalling are deemed to be relatively small. There is, for example, a wealth of experience from the mining industry. Our understanding of fracture propagation from existing fractures in a larger rock volume is, on the other hand, highly limited. The processes have mainly been studied for single fractures in two dimensions and not for interconnected fracture systems in two dimensions. SKB intends to continue the studies that have been initiated.

Representativity of rock stresses. Analyses of the reactivation of discontinuities are, like analyses of the intact rock, influenced by the primary rock stress situation and the structure of the rock. Rock stress measurements are performed as a basis for the design work and structural models must be devised on different scales. The conceptual uncertainties with regard to stresses and structures are assumed to increase with increasing scale. There are reasons to continue efforts to understand the representativity of rock stresses.

Contribute towards *development of rock mechanics theory* when it comes to *creep movements* of tunnel walls and deposition holes. The conceptual uncertainties with regard to creep processes in fractured rock are great in relation to other mechanical processes. There are no general expressions for time-dependent deformation under a triaxial state of stress. Data uncertainty is deemed to be great for both the empirically based and the simplified rheological models when applied to the canister hole scale and repository scale. Up to now it has not been possible to take into account volume dependence and the fact that block movements are determined by how discontinuities are deformed over time and how movements that cause separation of blocks affect the stress situation in the remaining rock.

7.5.3 Geodynamic and mechanical processes

Compilation project on large-scale mechanical stability. SKB has been studying exogenetic and endogenetic processes in the Baltic Shield for about twenty years in a series of projects. An integrated project dealing with brittle tectonic evolution with respect to orogeneses, continental displacement, seismicity, glaciations, land uplift, etc., is planned during the next three years. The compilation should be viewed as an important source of information for the site investigations and should supply the boundary conditions for the mechanical assessments in the site-specific safety assessments.

Effective stress effects in conjunction with a glacial cycle. The picture of water pressure distribution in conjunction with a glacial cycle is still hypothetical, and research is being conducted to clarify, among other things, the influence of glacial streams and permafrost. By taking into account changes in water pressure during a glacial cycle, the risks of jacking and shearing can be assessed more accurately.

Gain *a better understanding of the causes of earthquakes* that occur in the Baltic Shield. A number of studies are now available that shed light on the effects of earthquakes on a deep repository, but knowledge is limited regarding the causes of present-day seismic activity in the Baltic Shield, as low as it is. Super-regional studies of the lithosphere can shed light on the question from a new perspective.

Investigate the cause and depth of crystalline rock caves. At many places in the country there are large accumulations of boulders known as bedrock caves whose mode of formation has not been clarified. One explanation is that they are the result of a seismic event /7-27/. There are other explanations as well. SKB has begun a project to clarify how the boulder accumulations were formed and to ascertain the depth of one of these formations, the Boda Caves at Iggesund.

7.6 Rock-mechanical models

A number of mechanical questions are touched upon during feasibility studies, site investigations and detailed characterization for the deep repository. The construction-related aspects are integrated to a high degree with mechanical questions, which in turn have a bearing on the performance and long-term radiological safety of the repository. In the safety assessment, which assesses the long-term radiological consequences, different scenarios are considered, assuming an initial state where the canisters have been deposited and the deposition tunnels backfilled.

Evaluation of stability in the near-field and a suitable configuration of deposition drifts and deposition holes has a bearing on performance in both the short and long term. Special attention must be devoted to the excavation-disturbed zone (EDZ). A large number of analyses have been made to determine how large deformations of deposition holes are required to cause damage to the canister, but continued modelling work is being pursued. The results of this work can, together with the mechanical analyses, be used to develop criteria for acceptance of deposition tunnels and drifts, and provide guidance for suitable orientation and layout of the same (e.g. assessment of reinforcement need and risk of rock spalling problems, assessment of the generation of a disturbed zone). The evaluation should preferably be based on quantitative calculations. The modelling tools used are equivalent to those used on a larger scale, but in order for the modelling to be meaningful, discontinuities need to be described with a higher degree of detail.

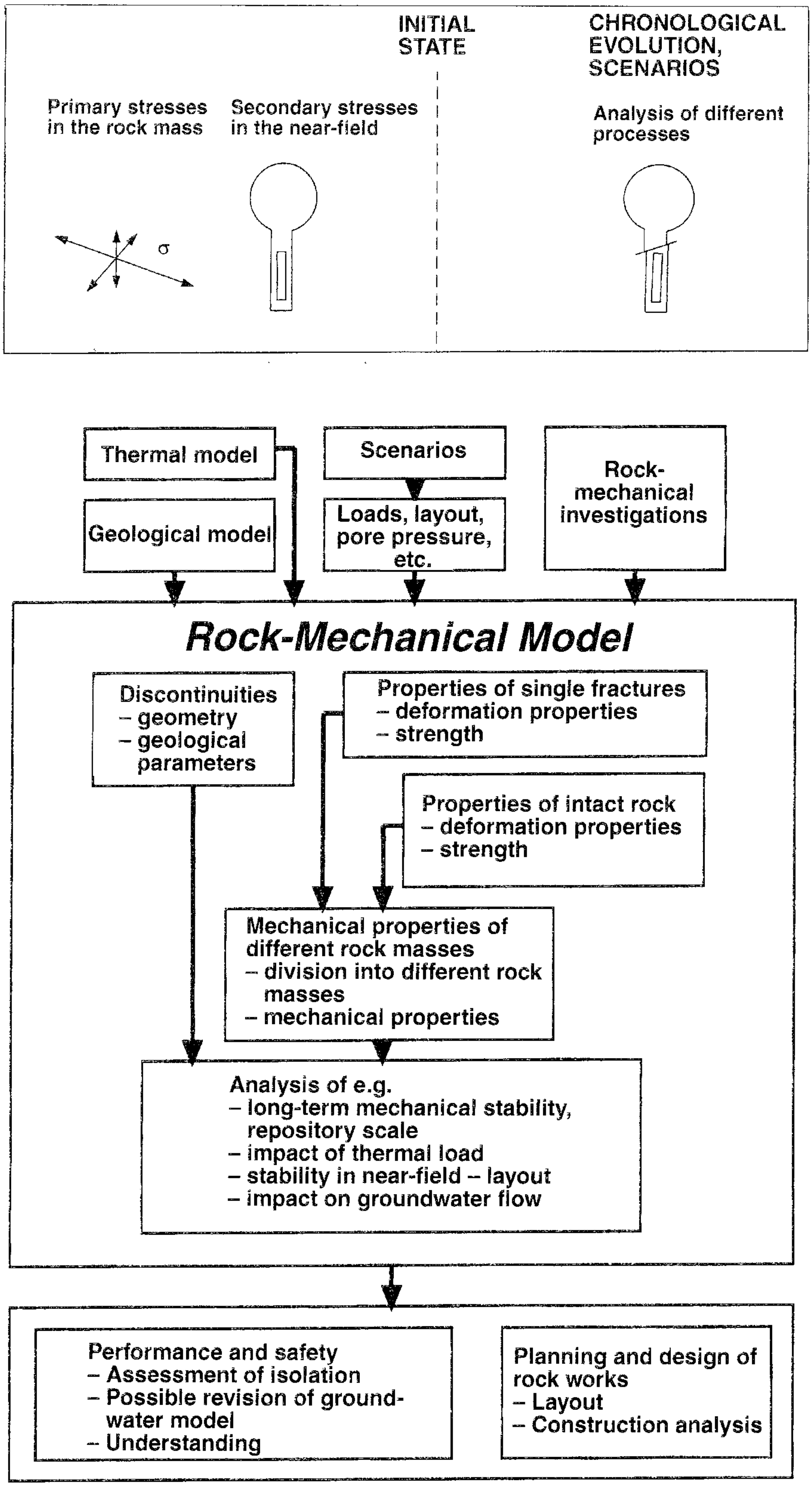


Figure 7-1. *Top: Assessment of the long-term safety of the repository requires relevant descriptions of the initial state and the chronological evolution. Bottom: The rock-mechanical questions with analyses in their context of requirements on input data and purpose /7-28/.*

The repository-scale analysis does not necessary have to be performed with quantitative models. Identification of large-scale deformation zones and determination of the general stress situation may be sufficient. The line of reasoning can in this case be based on more qualitative and/or generic analyses of the large-scale influence of heat, ice loads etc. The large-scale analysis must, however, be able to give boundary conditions to a rock-mechanical analysis on a near-field scale. And quantitative analysis must be done in order to ensure that the thermal expansion does not cause problems, for example tensile stresses that go down to excessively great depths. The quantitative analysis can be done with calculation programs where stresses and deformations are calculated for given external loads. In some models the rock is described as being composed of discrete blocks bounded by discontinuities. Different deformation and strength models can then be assigned to the discontinuities and the rock mass in the blocks. There are other modelling techniques explicitly for fractures as well. The rock can also be described in its entirety as a continuum where material models and material parameters are chosen with respect to the frequency, orientation and mechanical properties of the discontinuities.

A rock-mechanical model with its contents and various purposes can be schematically described as shown in Figure 7-1. The following processes are included in analyses of questions regarding mechanical stability in the geosphere that have a bearing on the performance and long-term safety of the repository in a safety assessment:

- Fracturing. New fractures in intact rock and propagation of existing fractures.
- Reactivation. Movements in existing discontinuities.
- Creep deformations. Continuous time-dependent deformations.
- Thermally-induced deformations. All deformations of the above type that are especially related to the evolution of temperature in the repository.

In a long-term perspective, the scope of the processes may be large or small. To make safety-related assessments, it is necessary to understand and be able to describe the initial state, and to be able to estimate the scope and consequences of the different processes for different scenarios (Figure 7-1, top). Rock-mechanical models are devised and analyzed for this purpose (Figure 7-1, bottom) /7-29/.

As a rule, the stability of the rock is affected by a number of concurrent processes or mechanisms. When the stresses in the rock change, the discontinuities will be affected, whereby their properties and the properties of the rock mass as a whole are changed. Mechanical processes generated by temperature play an essential role as far as the rock itself is concerned. The coupling between mechanical and hydraulic conditions can be important as well (see Figure 7-2) /7-30, 7-31, 7-32/. Some important coupled processes are:

- Change of effective stresses (normal stresses) and thereby changed shear strength of discontinuities due to temperature change (T-M) or due to change in water pressure (H-M).

- Change of aperture or fracture mineral content and thereby changed conductivity properties in discontinuities due to instantaneous or time-dependent shear deformation (M-H).

- When deposition holes are drilled, discontinuities can be deformed or propagate as a consequence of rotation or other changes in the local stress field. This can lead to changed hydraulic conductivity in the near-field (M-H).

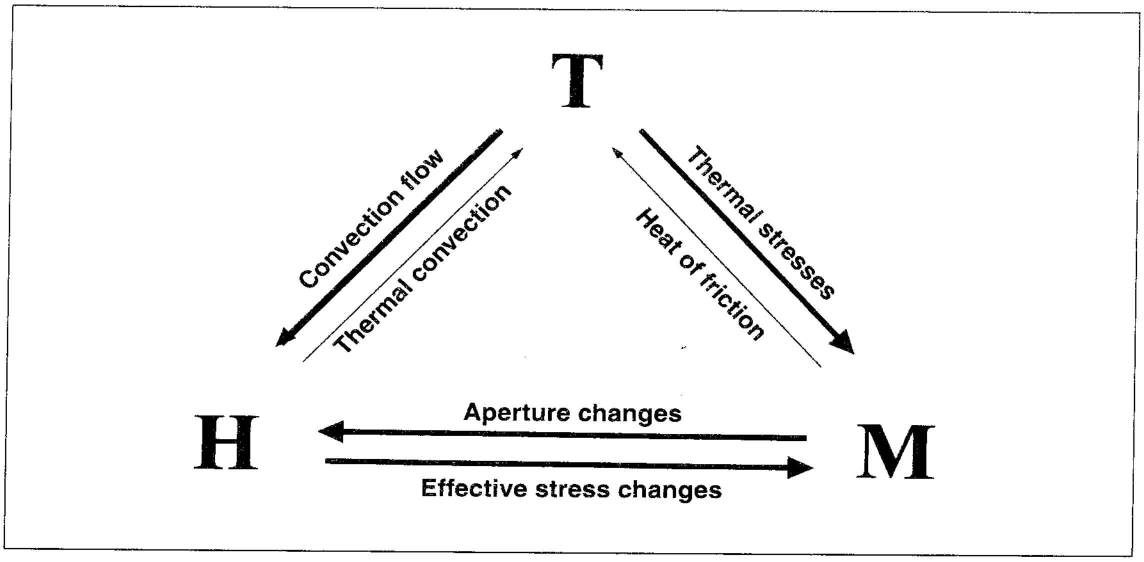


Figure 7-2. Thermo-Hydro-Mechanically coupled processes in schematic form. After Stephansson et al., 1996 /7-33/.

Coupled thermo-hydro-mechanical models have been developed and verified in the DECOVALEX Project (international cooperative project for the DEvelopment of COupled models and their VAlidation against EXperiments in nuclear waste isolation). One of the conclusions from the first stage of the project is that the temperature field around a repository can very well be described in pure thermal conductivity terms without reference to hydro-mechanical coupling. Stress and displacement conditions are often consistent between different modelling concepts, while the hydraulic results have shown appreciable differences. The general validity of the results is also very sensitive to the choice of boundary conditions, according to whether the calculation cases are two- or three-dimensional /7-31/.

8 Water flow in rock

The ability of the rock to limit the transport of various substances is dependent on groundwater flows and flow paths. These are in turn determined by the hydraulic conductivity and inhomogeneity of the rock, the topography and water balance in the area, etc. If water transport takes place without the influence of retention mechanisms, it is regarded as non-reactive. Non-reactive transport process includes advection (convection), kinematic dispersion and molecular diffusion. The total retarding effect on nuclide transport is determined by diffusion into intact rock (matrix diffusion) and by the bedrock's sorption properties. These are in turn determined by the groundwater chemistry, the mineralogical composition of the rock, microfractures in the rock, the character of the fracture pattern and the availability of sorption surfaces.

The following description is in large part a summary of the results that have been presented in SKB's Annual Reports in the past few years, as well as in other individual SKB reports. However, additional activities that may be required to achieve adequate knowledge of certain processes and related problems are also discussed. Many of the questions brought up here are also dealt with, and overlap, some projects in the Äspö HRL.

8.1 Groundwater flow and advection

The previous programme identified the need to create a database on kinematic porosity and dispersion in fractured rock, to investigate how absolute pressure and hydraulic gradients can be linked to groundwater recharge and discharge areas, to process well data to determine if this type of data is usable and can be used to see differences between different areas, and finally to investigate mixing processes between saline and fresh groundwater in relation to land uplift.

Regarding kinematic porosity and dispersion, these two parameters are of great importance to know for predicting the transport of non-reactive substances in the bedrock; in the case of sorbing substances, a number of other parameters may have greater importance for the final transport process. Work within this area has been pursued within the Äspö HRL in the so-called Fracture Classification and Characterization Project and the Tracer Retention Understanding Experiments (TRUE, see Chapter 14). Both of these projects furnish relevant information on the properties of the rock for estimation of fracture porosity. It can further be mentioned that a literature survey has been carried out to compile data from tracer tests carried out on a number of different sites /8-1/; this survey also gives indications of relevant transport properties.

A project has been conducted to study large-scale groundwater movements resulting from topographically controlled gradients. One purpose has been to ascertain recharge and discharge areas for a repository situated at a depth of about 500 m. In an initial phase, an analytical solution to the problem was derived. The analysis shows that the travel time from repository to biosphere can be expressed as a function of, among other things, gradient and ratio between length scales for topography and hydraulic gradient /8-2/. In a second phase, this methodology was applied to three different sites in a regional perspective /8-3/. The results gave very long travel times compared with earlier numerical modelling; one explanation may be that the regional flow is not manifested at a repository depth of about 500 m, where local conditions instead govern the flow.

In a related project it has been investigated whether the well archive of the Geological Survey of Sweden (SGU) can be used to characterize the hydraulic properties of the crystalline bedrock on a regional scale /8-4/. This was done by comparing SGU data with borehole data from two sites where SKB had previously performed analyses. The results revealed that data from the well archive are usable, even though depth dependence is difficult to evaluate due to the preference for drilling to greater depths in low-permeable rock.

Research concerning mixing processes between saline and fresh groundwater in relation to land uplift and the evolutionary stages of the Baltic Sea has been conducted during the current programme period. The results are described in Chapter 16 as a part of the Palaeohydrogeological programme.

8.2 Characterization of fractures with regard to flow, advection and retention

An earlier project aimed at studying fracture apertures and morphology by means of image processing analysis has been concluded /8-5/. The flow through fractures in a biaxial cell was also analyzed as a complement to this study. The experimental results were used to verify numerical and analytical flow and transport models /8-6/. The analytical and numerical results overestimated the aperture by approximately a factor of two compared to the measured aperture.

A continuation project has also been initiated for the purpose of developing this type of image analysis technique for images generated by means of a TV logger (BIPS). Being able to measure and characterize the hydraulic and retarding properties of fractures in-situ in this manner would be valuable in site characterization. More about this project is discussed under "Goals and programme" below.

Finally, it can also be mentioned that the image analysis methodology as developed in /8-5/ has also been put to use within TRUE (section 14.4.4).

8.3 Goals and programme

The purpose of the work is to gain a better generic understanding of both groundwater flow and transport processes such as advection and retention mechanisms. This generic knowledge is applicable both in safety assessment models (Chapter 3) and for site characterization and the site selection process. The work is conducted with strong links to equivalent relevant activities at the Äspö HRL and can be seen in part as an integrating function between this research and the needs of the safety assessment. The most important specific goals for the coming period are:

- to address scaling-up questions, and
- to investigate what factors control local flow patterns.

The goals are discussed in detail below.

An important question to address during the coming period is scaling(-up) of parameters in modelling of groundwater flow and transport. This primarily concerns parameters such as hydraulic conductivity, but may also concern more transport-oriented parameters.

The scaling-up problem has been identified in completed and ongoing studies within SKB /8-7/. The question is how measurements performed on a given scale can be scaled up to the discretization scale used in a numerical model. This question is of particular relevance for continuum modelling. Related questions include which scale is really investigated in field tests (support scale), and how boundary conditions are transferred from models with a larger domain and discretization to smaller but more detailed models. Scaling-up of conductivity and transfer of boundary conditions are also discussed under Models for Safety Assessment (Chapter 3).

SKB plans to carry out both field tests at the Äspö HRL and generic modelling studies to address scaling questions. A specific question to investigate is whether the scale problem for continuum models can be eliminated in part by a coupled use of discrete fracture network and continuum models.

A question of continued great importance for the future is that of the groundwater's recharge and discharge areas. In the conducted study /8-3/ it was found that regional flow does not appear to affect the flow conditions for a planned repository to an appreciable degree; the local conditions appear to control the flow situation instead. The question to investigate is thus what local factors/properties have a controlling influence on the flow pattern. One such factor is the influence of watercourses, lakes and local topography. A correct understanding of these near-surface hydrological processes is also required for a better description of the coupling between geosphere and biosphere.

A compilation and accumulation of knowledge regarding two-phase flow and gas transport will be carried out. Within the safety assessment, these questions enter into several of the geosphere's different sub-analyses. A thorough review of which sub-areas should be prioritized for future research is required before further work is initiated.

The project concerning fracture analysis with the aid of a downhole TV logger (BIPS) will continue. The BIPS technique is believed to be capable of furnishing information mainly on the hydraulic, but also perhaps the retarding, properties of the more conductive fractures.

9 Groundwater chemistry

The importance of the groundwater chemistry for the deep repository and its coupling to the minerals and hydraulic properties of the rock are dealt with in this chapter. An overall objective is to make sure that the chemical environment in the repository is favourable. For this purpose we do the following:

- Clarify chemical conditions and processes that affect the repository's barrier performance initially (during operation) and in the future (after closure).
- Support and refine the geohydrological groundwater flow models, especially with respect to past and future conditions.

9.1 Chemical composition of the groundwater in Sweden

SKB has investigated hydrogeochemical conditions at great depth in the bedrock at different places in the country. Groundwater sampling and analysis were carried out in connection with the study site investigations in the early 1980s at Stripa, at Finnsjön and on Äspö. A compilation of all these results is provided in Tables 9-1 and 9-2, divided into sites with fresh water and sites with saline groundwater.

Table 9-1. Concentration interval for 95% and 99% of all observations of the most important chemical factors for the barrier performance of the fuel, the canister, the clay and the rock on *sites with fresh groundwater.* There are a total of 491 observations from sites with fresh groundwater. They originate from an average of five deep borehole sections in 2–5 boreholes in the study sites Taavinunnanen, Kamlunge, Gideå, Svartboberget, Fjällveden and Klipperås. Concentrations given in mg/l.

Component	95% of all observations	Median value	99% of all observations
pH	6.2 – 9.2	8.1	6.1 – 9.3
Cl	0.6 – 440	5.8	0.5 – 470
SO_4	0.1 – 230	3.0	0.1 – 480
HCO_3	9 – 270	120	7 – 300
Ca	3 – 110	16	2 – 190
K	0.5 – 5	1.8	0.1 – 6.2
Fe (dissolved)	0.007 – 20	0.88	0.004 – 28
HS	0.01 – 1.1	0.01	0.01 – 1.2
TOC	1.2 – 40	4.4	0.5 – 67

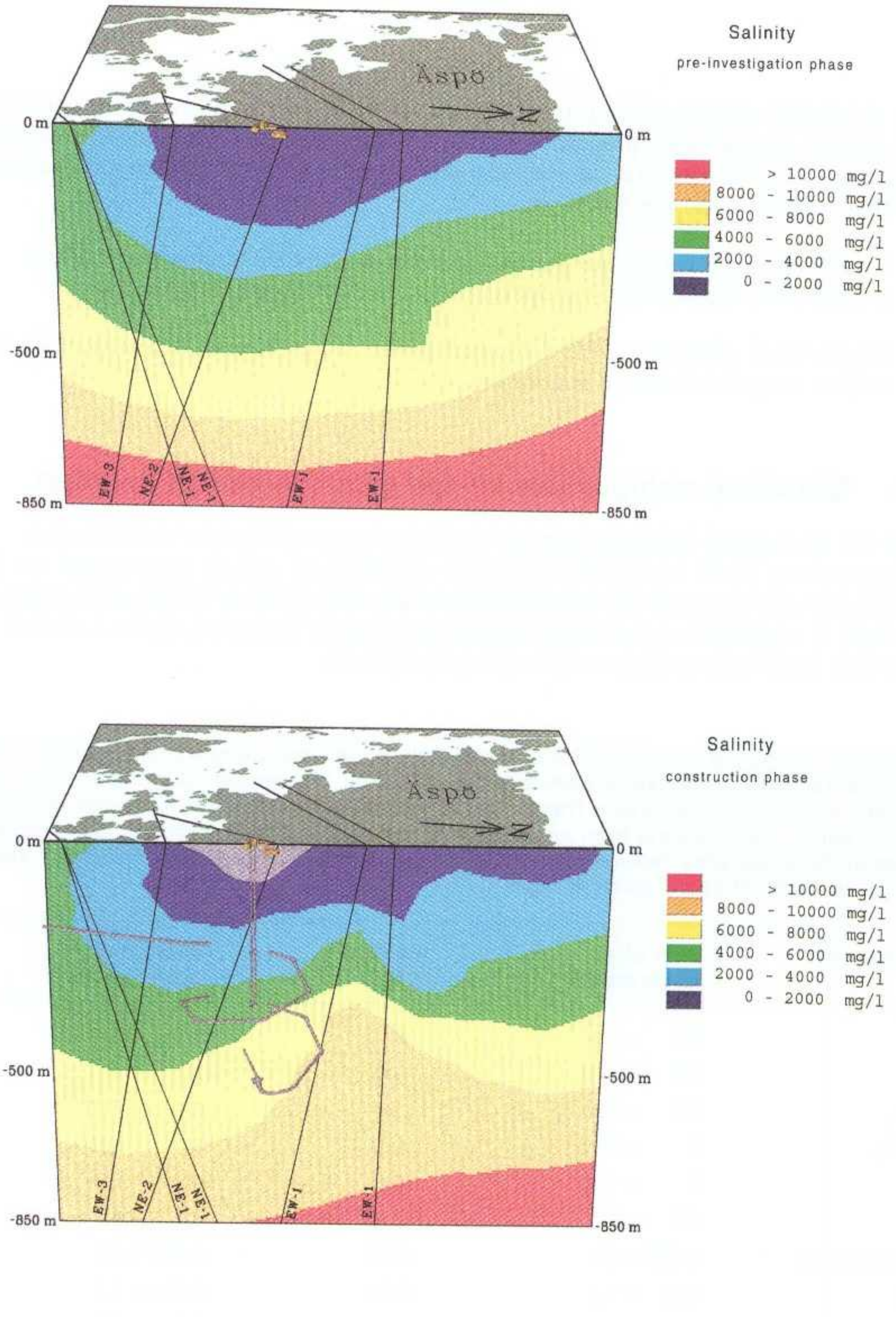


Figure 9-1. *Salinity distribution in the bedrock around Äspö based on observations in boreholes before and after the tunnel construction phase. The Kriging method has been used to interpolate between the observation points.*

Table 9-2. Concentration interval for 95% and 99% of all observations of the most important chemical factors for the barrier performance of the fuel, the canister, the clay and the rock on *sites with saline groundwater*. The table contains a total of 395 observations from the Simpevarp area, mainly Äspö, but Laxemar and Ävrö are also represented. Chloride concentrations above 12,000 mg/l derive from the 1,700 m deep hole KLX 02 at Laxemar. Concentrations given in mg/l.

Component	95% of all observations	Median value	99% of all observations
pH	6.3 – 8.4	7.9	6.0 – 8.5
Cl	9.6 – 30000	4200	5.7 – 47000
SO_4	21 – 930	280	17 – 1100
HCO_3	7 – 320	61	6 – 450
Ca	15 – 13000	1100	10 – 20000
K	1.3 – 30	6.8	1 – 33
Fe (dissolved)	0.02 – 3.2	0.34	0.003 – 4.4
HS	0.01 – 2.6	0.41	0.01 – 5.0
TOC	0.5 – 24	5.9	0.1 – 29

9.2 Groundwater types and their origin on Äspö

The investigations and evaluations that have been conducted intermittently throughout the Äspö project since the start in 1987 have yielded more detailed knowledge concerning groundwater types and their origin. The large quantity of data of high quality has made it possible to create a finely shaded picture of the origin and evolution of the groundwater /9-1, 9-2/. Two workshops in the series Äspö International Geochemistry Workshops /9-1, 9-3/ have contributed very significantly to bringing our knowledge to its current level. Even though the models only describe conditions around Äspö, the knowledge concerning the origin and evolution of the water types can be directly applied to any other conceivable site evaluation.

Both fresh and saline water occurs in the bedrock around Äspö. The fresh water is located in the upper 100 metres below the surface, after which the salinity increases with depth, see Figure 9-1. The nearly linear increase in salinity with depth could be interpreted as indicating that fresh water on the surface is gradually replaced by saline water at depth. But it is not that simple. If oxygen-18 data are considered as a function of chloride concentration, they are found to follow different trends, despite the fact that both substances are non-reactive and are not affected by reactions between groundwater and mineral, see Figure 9-2. This shows that waters of different origins have been mixed and occur in different proportions at different places in the rock. Saline waters may derive from today's Baltic Sea water, old relic Baltic Sea water from the Littorina stage about 7,000 years ago and saline water that originates from the rock /9-1, 9-2, 9-4/. Fresh water can also have varying origin. One fraction derives from the melting of the most recent continental ice sheet about 13,000 years ago, while another fraction derives from rainwater that has infiltrated into the ground since Äspö rose above the surface of the sea about 3,000 years ago.

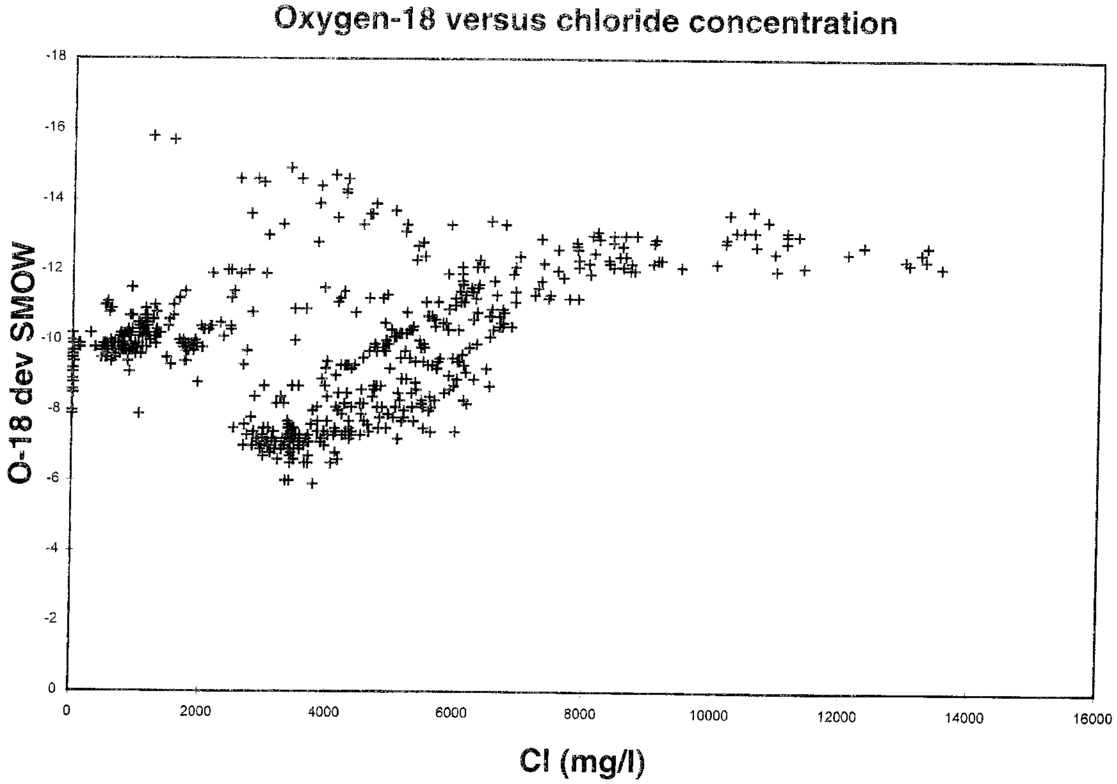
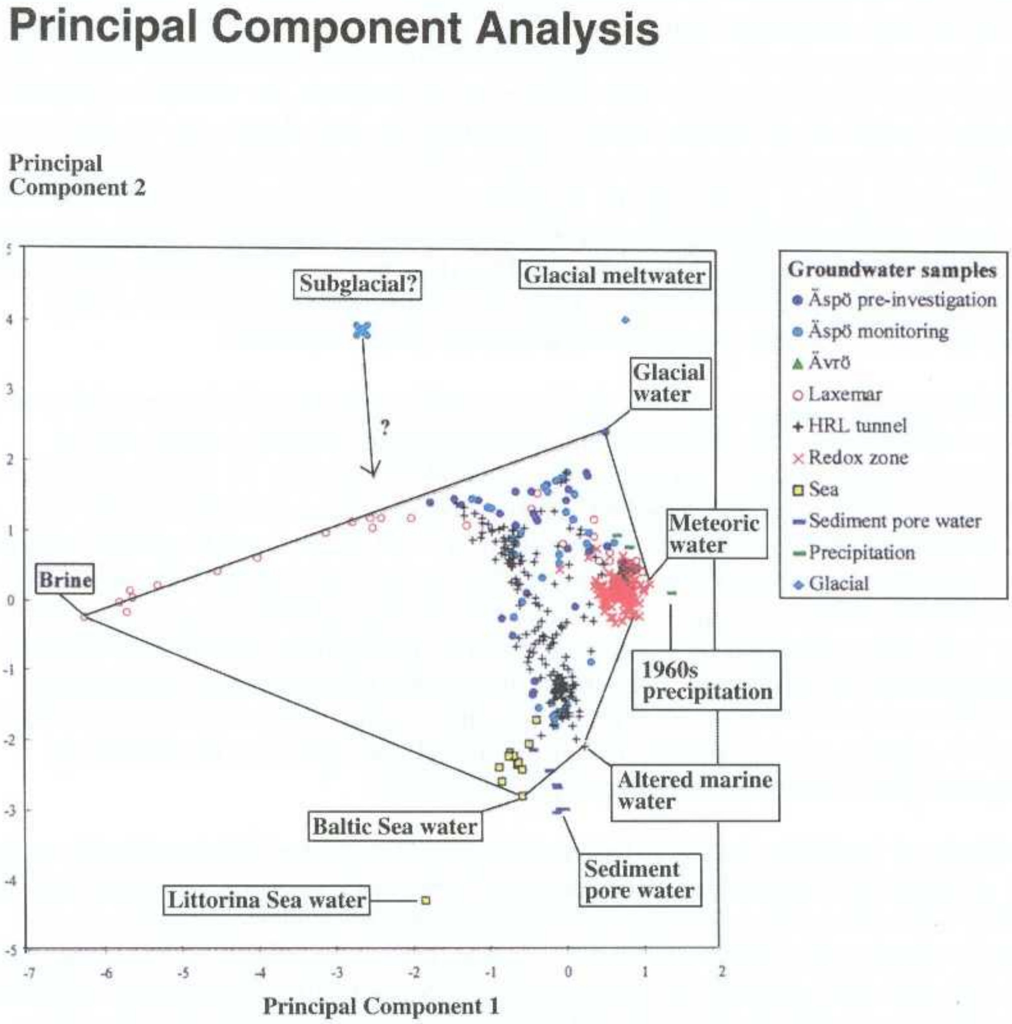


Figure 9-2. *Oxygen-18 as a function of chloride concentration.*

It is possible to continue to include more and more of the chemical constituents in this analysis and thereby increase the information content. If, for example, the tritium concentration is included, a higher resolution is obtained and a better opportunity to trace correlations and origins. Tritium shows conclusively whether water that has infiltrated during modern time is present and that such water has been transported to the place it was encountered during the past 40 years. This water lies nearest the surface in the rock.

However, it quickly becomes impossible to keep track of the relationships between the different parameters by means of visual observation. A statistical multivariate method is therefore used to correlate the variables to each other. By means of principal component analysis, it is possible to compress the information from all parameters into a few principal components. With the aid of the first and second principal component, 72% of the variability in the ten most important chemical parameters can be described /9-1/. Further, by plotting the two principal components against each other, it is possible to identify extreme points that lie at the outer limits and constitute end-members in the groundwater system.

In the next stage the most important end-members have been identified with respect to the origin of the water, and the other points can be regarded as a mixture of water from the identified end-members (see section on model development). The chemistry of groundwater from Äspö and the deep borehole KLX02 at Laxemar, which is located about 3 km west of Äspö, can thus be described as a mixture of 5 reference waters, all of which are found in the bedrock and all of whose origins can be derived /9-1, 9-2, 9-4/. These are called: glacial water, (meteoric) fresh water, sediment water, Baltic Sea water and brine, see Figure 9-3. Of these reference waters, Baltic Sea water and meteoric water



$$\text{Component 1} = -0.25\,[Na] - 0.08\,[K] - 0.23\,[Ca] - 0.05\,[Mg] + 0.11\,[HCO_3] - 0.24\,[Cl] - 0.23\,[SO_4] + 0.08\,[^3H] - 0.03\,[^2H] + 0.01\,[^{18}O]$$

$$\text{Component 2} = -0.04\,[Na] - 0.23\,[K] + 0.05\,[Ca] - 0.24\,[Mg] - 0.16\,[HCO_3] + 0.02\,[Cl + 0.02\,[SO_4] - 0.10\,[^3H] - 0.27\,[^2H] - 0.29\,[^{18}O]$$

Figure 9-3. *M3 chart, see section 9.7, of all hydrochemistry observations from the Äspö area. The distance from any given point to a reference point is inversely proportional to the fraction of reference water in the given point.*

are well defined, since they can be determined by sampling and analysis. Glacial water, sediment water and brine are, on the other hand, characters that have been derived, i.e. that have not been able to be determined via sampling and analysis.

Even though the classification and distribution of the different water types is simple and straightforward, there are uncertainties in the results. Contributing to this is the fact that it is difficult to determine how large a portion of the observed mixture is actually caused by disturbances caused by the investigations. Drilling causes the greatest disturbances. In all drilling, the drilling water is therefore marked with a dye tracer that makes it possible to correct for the disturbance caused by drilling. There is, on the other hand, no way to correct for the short-circuit with accompanying mixing which the borehole causes when it penetrates water-bearing sections with different pressure levels. An example of difficult-to-interpret conditions is the fact that we find tritium at great depth, e.g. on Äspö down to a depth of 400 m and at Laxemar even deeper. If these tritium concentrations were relevant, and not just an artefact of the boreholes and measurements, it would mean that water that has infiltrated during the past 40 years has been transported down to levels of 400 m at Äspö and even deeper at Laxemar. This does not agree with other observations and interpretations, which show that water at this depth otherwise consists of large portions of old relic Baltic Sea water, old brine and glacial meltwater.

RD&D-Programme 92 gave a thorough account of how the chemical composition of the water, in combination with different stable and radiogenic isotopes, can be used to determine the groundwater's residence time. RD&D-Programme 95 further identified a number of recently tested and hypothetical isotope methods as being potentially very useful. However, after having tested these methods /9-1/, there is at the present time no reason to single out any particular isotope method as the one that gives the most information. Rather, different isotopes are suitable for identifying different processes. The best picture is therefore provided by a combination of a large number of different methods. Chronological series of selected high-quality data from different points facilitate the interpretation and reduce the uncertainties (possible explanations of measurement data). Figure 9-4 contains a comparison between the model that existed at the end of the investigation phase and the model that applies now /9-2/.

Hydrochemical modelling is always based on measured data. An initial qualitative examination of these data leads to an understanding of which processes are active and why the chemistry looks like it does. Calculations are then performed for the purpose of confirming or rejecting the initial assumptions. Gradually, the description is broadened and made more and more detailed. In this way, Model 96 is a further development of Model 90. Model 96 is the model of the groundwater chemistry on Äspö that was devised in 1996 based on data from surface boreholes and tunnel boreholes. Model 90 is the equivalent model, based on data from surface boreholes, devised in 1990. Both of these models contain 3 important components: 1) conceptual models based on what it is thought to look like down in the rock, 2) interpolations of measurement data, and 3) results of mathematical calculations (e.g. M3, see further under the section "Model development). The illustrations in Figure 9-4 are a combination of these.

Model 96 is based on all the knowledge that has been obtained from investigations and evaluations performed during the tunnel construction phase. It is thereby more elaborate and detailed than Model 90. Figure 9-4 must therefore be regarded as an attempt to illustrate differences and similarities in the models rather than to compare the models. In brief, the following improvements can be noted from Model 90 to Model 96:

- Mixing of waters of different origin and composition is the process that has influenced the water chemistry the most. Figure 9-3 shows that certain water types have been mixed with each other, while others have not been mixed. This is attributable to the hydrological conditions that previously prevailed. For example, there is a clear mixing line between brine and glacial water, between glacial water and meteoric water, and between Baltic Sea water and glacial water. On the other hand there are no points along the mixing line between Baltic Sea water and brine. All of these mixtures can be attributed to currently and previously prevailing groundwater flow conditions.

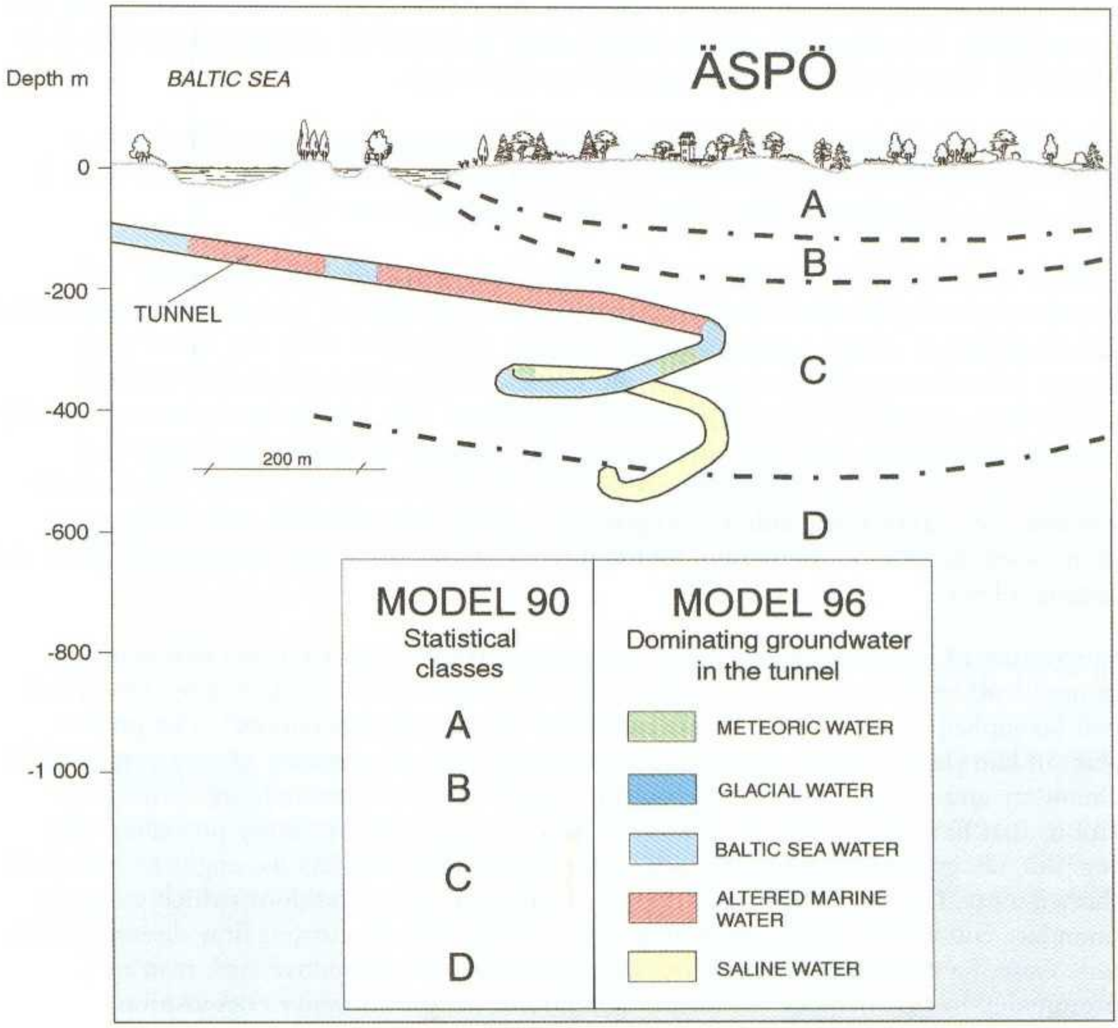


Figure 9-4. *A comparison between the models of the groundwater chemistry on Äspö after the pre-investigation phase and after the construction phase.*

- Discrepancies in the concentrations of individual substances between measured values and values calculated based on the mixing proportions are quantitative measures of products of chemical reactions. For example, the scope of ion exchange reactions and effects of bacterial degradation processes can be calculated in this manner /9-1, 9-5/.

In a careful comparison of Model 90 and Model 96 in Figure 9-4, it must also be taken into account that the water inflow to the tunnel has affected the hydrochemistry and resulted in a slightly different distribution for the different water types. Figure 9-1 shows a comparison between the salinity distribution before and after tunnel construction. What can particularly be noted is an upconing of brine as a result of the drawdown in the tunnel.

Model 96 thus shows how the resolution in the description and knowledge of groundwater conditions has been increased. For a simplest possible comparison, it can be said that class A in Model 90 corresponds to meteoric water in Model 96. This is the only direct equivalence in both models. Glacial water, which is an important component in Model 96, has no direct counterpart in Model 90, even though a fraction of cold (glacial) water could be discerned in oxygen-18 isotope data /9-6/. The division between (old and recent) Baltic Sea water and altered marine water in Model 96 corresponds to class C in Model 90. Class D corresponds in general to saline water.

The biggest difference is nevertheless that Model 90 describes a class affiliation in a depth interval, while Model 96 indicates the proportions of the different water types in each point, exemplified in Figure 9-4 by the dominating water type.

RD&D 95 presented a plan for standardizing methods and tools for modelling and visualization of hydrochemical data. Figure 9-1 is an example of a combined interpolation and visualization using a program called VOXEL ANALYST. With the aid of these images it has been possible to present and discuss results among a broader circle of people than just those who performed the modellings. The interpolated pictures naturally contain uncertainties, but they nevertheless offer a means for informing people in a simple way how the water chemistry is spatially distributed. These efforts will continue towards the goal of being able to integrate the software for VOXEL with RVS, a program developed for 3D modelling that is directly connected to the database SICADA, see section 14.4.3.

Integration of hydrological, chemical and isotope data is a research area that was mentioned in RD&D 95 where new software (the M3 code) has been developed, tested and will be applied in the future, see further under "Goals and programme". The present state of knowledge can be summarized as showing that the extensive mixing suggested by chemistry and isotope data is only partially supported by the groundwater flow simulations that have been carried out /9-7/. There are traces of previously prevailing flow regimes, i.e. groundwater types which, according to flow simulations, ought to have been flushed away. One probable reason for this is that pressure conditions (which comprise boundary conditions in flow modellings) have varied and the current flow directions have only existed a short time. Another reason is that the low-conductive rock matrix presumably has a "memory" of former conditions, i.e. groundwater composition.

The mathematical and statistical methods that have been used in the evaluation of Äspö data have been tested to ascertain their ability to describe the hydrochemical conditions on a hypothetical candidate site, even before any investigation has been conducted. The work has been carried out on the basis of all the data that has been collected from the early KBS-3 investigations, including the Finnsjö Project and the Äspö Project /9-8/. Each of the sites in turn has been excluded from the database, which has then been used to describe the hydrochemistry on the excluded site. This has been done for all investigated sites: Äspö, Finnsjön, Gideå, Fjällveden, Klipperås, Kamlunge, SFR, Stripa, Svartboberget, Lansjärv, Taavinunnanen, et al. The predicted values are then compared with the measured values. Two essential results of this work are that:

- the scatter in the predicted values for each site is greater than the variability in the measured data on any of the sites,
- the surface water chemistry, which has also been included from SGU's well archive, cannot be used to describe the depth conditions.

The conclusion is therefore that the statistical processing does not in fact provide a better picture of the chemical conditions on a site. Since this processing has embraced all of SKB's groundwater chemistry data, it must also be kept in mind that quality has varied widely. The representativity of the water samples taken earlier ('70s and '80s) was low, 15%, compared with those taken on Äspö ('90s), 60%.

Other methods will be tested in future to find suitable methods for predicting the groundwater chemistry, see section 9.6.

9.3 Important physical processes

9.3.1 Mixing

The groundwater moves in the rock's fracture system to even out prevailing pressure differences, rapidly in lithological units with high hydraulic conductivity and slowly in less conductive units. In this way the flow will be concentrated to individual flow paths with good conductivity. These paths in turn intersect, converge and diverge constantly. In this way, the water that moves in the flow paths will be mixed. Under static conditions with constant driving forces, the difference in chemistry between the waters that are mixed will be small. On the other hand, large differences will exist in cases when the flow field changes direction and water of a completely different type enters the flow paths. It is in these situations that the effect of mixing is greatest. The location and magnitude of groundwater recharge and discharge, and the magnitude of the hydraulic potential (i.e. pressure differential), are the factors that determine the mixing conditions. An example of contrasts in this respect is the large pressure differential that can occur between different parts under a glacier in comparison with the complete equilibrium that prevails below sea level.

After the most recent ice age, the different stages of the Baltic Sea have influenced the mixing of the groundwater to varying degrees depending on where the sites are located in relation to the coastline. The conditions that have prevailed on different occasions can also be derived from this. As the continental ice sheet retreated, glacial water penetrated down into the bedrock and mixed with the water that was already there. It is impossible to set a limit on how deep the glacial water reached, but there is a level around 100–300 m deep where a large fraction of water that has infiltrated under cold climatic conditions is generally found. Glacial water at greater depths may originate from some earlier glaciation. On sites that have been sea-covered at some time since the ice age, fractions of old marine water are generally seen. In some cases, however, the fraction of marine water is relatively small and saline water at depth instead derives from a brine, a very saline water that has been in the rock for millions of years. By definition, a water is a brine when its total salinity exceeds 100 g/l, i.e. 10%, regardless of origin.

The water chemistry shows that areas that have been covered by sea have also been infiltrated by marine water. The driving force for this infiltration is the higher density of saline water, which has penetrated down into the rock to the depth where the salinity of the water is equally high. Land uplift has since raised previously sea-covered sites above the surface of the sea, exposing them to recharge and discharge that is controlled by precipitation and the level of the groundwater table.

The time constant for these different mixing phenomena is still unknown. Ongoing research is aimed at ascertaining how stable the mixing conditions are and how they will change with time, see programme for next six-year period.

9.3.2 Diffusion

If the groundwater moves very slowly, diffusion will control the transport of solutes. One can then speak of stagnant conditions, i.e. the groundwater is stationary. The definition of *stagnant water* is thus that it occurs when solutes are transported faster by diffusion than by water flow (advection). How stagnant the water is depends on the time scale on which it is regarded. In this context, *immobile* designates that no great changes have taken place during a glaciation cycle or over even longer time spans. These conditions can exist in two different contexts: At great depth where regional large-scale conditions dominate over the local pressure gradients, and in impervious rock units where local pressure gradients are not able to transport the water. A precondition for this is that the product of the pressure gradient and the hydraulic conductivity is lower than the diffusivity in water of the dissolved salts, i.e. diffusion dominates over advection when the diffusivity is greater than the Darcy flow. This is often the case in rock units outside water-conducting structures /9-9/.

Brines occur and are encountered everywhere holes are drilled in rock to great depths. The depth at which they are encountered varies sharply, however, from a few hundred metres to several kilometres. This shows how deep the superficial circulation cells have reached some time after the brine was formed, which may be millions of years in the past. The absence of brine therefore does not necessarily indicate that recent circulations of surface water have occurred, but it does show that water exchange has occurred at this depth some time after the rock types were formed. The occurrence of brines is a clear indicator that stagnant conditions prevail.

Brines can be formed in several different ways. A distinction is made between those that have been formed in the rock, *autochthonous*, and those that have been formed outside the rock and then been transported down into the rock, *allochthonous*, e.g. dissolution of evaporites /9-10/. Different possible origins of these brines have been discussed by Lamén /9-11/. It cannot be determined whether one origin is more likely than the other. Both probably occur. What is certain is that a brine at great depth in crystalline rock is always very old and can thereby be regarded as stagnant. The conditions we see today will remain unchanged during the geologically short span of time required for safe isolation of nuclear waste.

9.3.3 Gas generation

The groundwater contains a varying quantity of gas. Usually nitrogen dominates at a concentration of 80%, followed by methane, helium, argon and carbon dioxide at very low concentrations. In rare cases, high concentrations of hydrogen and methane can also occur. The total quantity of dissolved gas usually lies in the range 1–5 volume-percent (at NTP) and is generally higher at depth. Naturally occurring gas levels mean that the gas leaves solution and forms a separate gas phase at a depth of between 13 and 50 m, in the event the water is transported upwards.

The origin of the gas is still unclear. There are several possible explanations:

- air-saturated infiltrated surface water,
- result of microbial activity,
- gas transported up from the interior of the earth.

Since the composition of this gas, with the exception of oxygen, is often the same as the gas mixture in air, it might reasonably be assumed that much of it derives from air-saturated water that has infiltrated the bedrock. However, the concentration of dissolved gas is almost always higher than the concentration that can go into solution under atmospheric pressure.

Considerably higher gas concentrations have been encountered in the Finnish site investigations at Olkiluoto, up to 2 litres of dissolved gas (NTP) per litre of water. In these cases, methane dominates.

9.4 Important processes in groundwater-mineral interaction

The water-mineral processes that influence the composition of the groundwater are:

- Equilibrium with minerals on fractures and in the rock matrix
- Surface reactions: ion exchange and sorption.
- Bacterially mediated reactions.
- Dissolution and precipitation of minerals.

At the present time our knowledge of which reactions dominate is such that we can regard equilibrium between substances dissolved in water and aluminium silicates in the rock and the fracture coatings as insignificant. At prevailing (low) groundwater temperatures, only a few dissolution and precipitation reactions achieve equilibrium, namely those that involve calcite, gypsum, fluorite, pyrite and certain iron mineral phases. These in turn affect the concentrations of other substances by means of co-precipitation and sorption.

Ion exchange and sorption have proved to be of great importance in saline groundwater /9-12/. The reason for this is that the capacity of the exchange is often proportional to the concentration in the water, i.e. clay minerals that have been loaded with calcium during a freshwater-dominated phase have the capacity to exchange all sodium in even a marine water when it infiltrates the bedrock. Then other cations, which in freshwater situations have a strong tendency to adhere, will be bound much more weakly under saltwater conditions. The new knowledge comes from investigations in water-conducting fractures that have been performed in the Äspö tunnel, which have shown that the quantity of clay minerals in the fractures is much greater than previously suspected. New, gentler drilling technology makes it possible to obtain drill cores in which the clay minerals remain in the fractures. The clay minerals have high ion exchange capacity.

The rock contains water and residual products that could not be accommodated in the crystal lattice when the rocks were formed, e.g. chloride, sodium and calcium. This water contains large quantities of dissolved salts, mainly the aforementioned sodium, calcium and chloride. If the salinity of the water exceeds 10%, i.e. 100 g/l, it is called a brine /9-10/. Stagnant conditions generally prevail in such water owing to its high density, and in time the water reaches an even higher density due to the fact that more salt is leached out of the rock matrix. The water thereby becomes even less mobile.

An increasing degree of chemical equilibrium in non-saline groundwater is an indication that the water is stagnant. In this case as well, one can assume that the currently prevailing conditions are constant and from there analyze how changes in the hydrological conditions affect the situation.

9.4.1 pH evolution

The pH of the groundwater is usually in the range 6.5–9.5. Variations occur between different sites, while the variation within one and the same site is much less. Only rarely is the pH higher than 9, and then in deep saline water. The opposite, pH values under 7, occur in conjunction with extensive microbial activity in superficial groundwater and sometimes in very deep (below 1,000 m) saline groundwaters.

The factor of greatest importance for the pH in the infiltrating groundwater is reactions between carbon dioxide dissolved in the water and calcite mineral in the rock's fracture system. The carbonate system is in a state of equilibrium and the carbonate ions give the water its pH-buffering effect /9-13/. The total carbonate concentration is often in the range 100–300 mg/l and seldom exceeds 600 mg/l. Extremely high carbonate concentrations can occur as a result of biological activity. Concentrations of 1,000 mg/l have been recorded on occasion. The biological processes have then also buffered the pH to 7.

At greater depths the carbonate concentration normally decreases and salinity increases. In non-saline deep waters as well, the carbonate content declines as an indirect effect of increasing pH. The high pH is considered to be a result of feldspar weathering, which releases calcium which, by precipitation of calcite, lowers the carbonate content. Saline groundwaters that have been isolated for a long time generally have a lower pH than non-saline stagnant waters. The reason may be that hydrogen ions located in the mineral layers can be replaced by cations in the water so that the pH never gets as high /9-14/.

The pH-buffering capacity of the groundwater resides in the carbonate system. This capacity is, however, small in relation to the buffering capacity of the minerals. The quantity of calcite deposited on the fracture surfaces is of greater importance for buffering against e.g. acidification than the carbonates in the aqueous phase. There is just as much capacity in feldspars, which can also buffer against acidification.

9.4.2 Redox evolution

Redox conditions in the rock and the groundwater are of central importance for deep disposal of nuclear waste. Oxidizing conditions increase corrosion of the copper canister, and certain radionuclides will be transported both faster and in higher concentrations in an oxidizing than in a reducing environment in the event of canister leakage. Based on data from SKB's site investigations, the groundwater is reducing at repository depth (500 m) under prevailing conditions. The oxygen present in the surface water is consumed either by microbially catalyzed processes or by oxidation of principally Fe(II) or sulphide minerals. These processes take place either in the soil cover or near the surface of the bedrock. The depth in the rock to which oxidized groundwater can reach thus depends on the composition and thickness of the soil layers (e.g. organic matter content, fine- or coarse-grained, etc.) and on fracture mineralizations, and last but not least on the hydraulic driving force (i.e. the velocity and direction of the groundwater flow). In connection with the construction of a deep repository, the hydraulic driving force will be altered so that the flow in towards the tunnels increases. This will probably mean that more surface water (possibly oxygenated) will reach the rock's fracture system. The large-scale redox experiment that was carried out during the tunnel construction phase in the Äspö HRL simulated these conditions and clarified the importance of bacteria, which proved to be able to adapt quickly to changed conditions /9-15/.

It has been speculated that the increase in hydraulic driving force, together with the decline in organic production that is expected to occur as a consequence of a glaciation, will greatly increase the transport of oxygenated water downward in the rock. Calculations are currently being performed of how far such oxygenated water might reach. Preliminary results show that the outcome is highly dependent on what groundwater flow is assumed in the calculations. To further elucidate the effects of earlier glaciations, it is therefore of interest to:

- determine the prevailing depth of the transition zone between oxidizing and reducing conditions in the rock or soil strata,
- determine the maximum depth to which oxygenated water has affected the rock or fracture minerals during e.g. earlier glaciations,
- determine the reduction capacity in the rock's fractures that can be used up by an increased inflow of oxygen-containing water.

The redox evolution in the repository after closure will be dependent on how the repository is built, how water enters the facility and which (residual) materials are left when the facility is closed.

Under undisturbed conditions, which prevail before the repository is built and which are expected to be reinstated some time after closure, it can be assumed that the environment is reducing and that the Eh of the groundwater, which is determined by iron and sulphide minerals in the rock, lies at a level such that uranium (and technetium, neptunium and plutonium) occur in reduced low-soluble form. The Eh will then be coupled to the pH and vary within the range –100 to –400 mV for pH values in the range 7–9.

The redox buffering capacity will lie in the accessible iron and sulphide minerals in the fractures. Numerous experiments have been conducted both to explore the reaction kinetics /9-16/ and the reaction capacity /9-17/ of iron-bearing minerals. Laboratory experiments are also being conducted within the framework of the ongoing REX experiment (see section 14.3.3), both with and without the presence of bacteria.

9.4.3 Microbial processes

The groundwater chemistry is affected by chemical reactions and by microbes. In recent years the importance of microbes has come under greater scrutiny and been investigated more thoroughly than before (see also section 10.5). The most important single lesson learned is that bacteria rapidly consume dissolved oxygen in infiltrated groundwater. It is thereby clear that as long as the repository is open, no dissolved oxygen will be transported down to repository level with the groundwater /9-15/. Another important lesson is that bacterial sulphate reduction can produce sulphide in concentrations in excess of those that normally occur in groundwater /9-5/.

During the construction and operation phase, the inflow of groundwater to the facility will affect the redox conditions. However, the increasing water flux in the rock above the repository is not expected to appreciably affect the water's redox properties, since an increased flow of superficial oxygenated water will be balanced by the microbes so that all available organic matter is consumed anyway. Stoichiometrically, 4 mg/l of organic matter of the composition CH2O is enough to reduce 10 mg/l of dissolved oxygen. If the concentration of organic matter is higher, reduction of trivalent iron and sulphate will take over when the oxygen has been consumed /9-18/.

In the repository, oxygen is present in the air that comes into contact with minerals on the wall, and in the water that constantly enters the facility as long as it is kept open. Since all water flows towards the facility, there is no reason for this oxygen to enter the rock, so the only oxygen that remains on closure is that present in the tunnels and in the microfractures in a limited zone around the tunnels. How it will react is dependent on several factors. Generally, the following processes can be seen:

- The concentrations of organic matter in the inflowing water may be low, but if any organic matter remains after closure, bacterially induced oxygen consumption will almost certainly take place.
- When all oxygen has been consumed, the microbial processes will continue and convert iron(III) minerals to bivalent iron and sulphate to sulphide. The scope of these reactions is dependent upon the availability of the different components.
- An important factor to take into account concerns the quantity of organic matter in the form of bacteria mats on tunnel walls and in drainage ditches that remain at closure. This material constitutes a substrate for continued bacterial activity after closure as well.

9.4.4 Colloid formation

Colloids occur in superficial water but are rare in deep groundwaters. They consist of different kinds of small particles that do not sediment. Colloids can form in conjunction with precipitation reactions, for example when two different types of water mix and oversaturation occurs. Another source of colloids is weathering of minerals. Since the natural concentrations of colloidal material in deep groundwaters are so low /9-19/, the conclusion can be drawn that normal processes in the form of mixing and precipitation or chemical weathering do not generate concentrations of colloids that could be of importance to the safety of the deep repository (see also section 10.3). One type of disturbance that gives rise to extensive colloid formation in deep groundwater is admixture of atmospheric oxygen. After closure, it is therefore conceivable that the water might contain elevated concentrations of colloidal material during a transition period.

9.4.5 Dissolution and precipitation of fracture minerals

Reactions between water and minerals give rise to alteration of primary to secondary mineral phases. This is called chemical weathering, and the secondary mineral phases consist of, among other things, different kinds of clay minerals. Units of crushed rock in which both mechanical and chemical degradation has occurred at different times since the rock was formed contain a large quantity of different secondary fracture-filling minerals. A careful mapping will reveal the sequence in which these minerals have been formed /9-20/. It is, however, normally difficult to determine when and under what conditions this has occurred. By far most fracture-filling minerals have formed under hydrothermal conditions in the distant past.

On isolated fracture surfaces there are also precipitated minerals that have been formed by the mixing of waters of different compositions. Such precipitations are calcite, gypsum, siderite, pyrite, fluorite and certain iron oxides. The existence of these mineral phases permits conclusions to be drawn on the water chemistry that existed at the time of their formation. The opposite phenomenon – dissolution of fracture-filling minerals – can, on the other hand, neither be identified nor quantified. For example, rapid transport of a water rich in carbon dioxide can dissolve calcite in a flow path relatively quickly and, when this water mixes with another water, precipitate calcite on the fracture surfaces. A comparison with the conditions in a similar fracture at greater depth, where calcite still occurs, can provide some valuable information on the dissolution rate and thereby the groundwater flux /9-21/.

Calcite mineral is a particularly useful indicator for influx of recently formed groundwater. In areas where carbon-dioxide-rich groundwater has infiltrated the bedrock, it can be seen that calcite dissolution has occurred down to a depth of about 100 m. The fraction of calcites in fracture-filling minerals in the water-conducting fractures can be estimated to be in the order of 5–40%. From this, it can be concluded that calcite mineral is an active and effective buffer against infiltrating acidic groundwater. Different analyses have also been carried out for the purpose of describing how acidification will affect the groundwater chemistry at repository level /9-22/. The conclusions are that the capacity of the minerals in the rock is sufficient to buffer against any conceivable acidification scenario.

SKB is participating in the EU project EQUIP, whose goal is to test new instruments and methods for detailed mineral analyses and to use the results to ascertain previously prevailing groundwater chemistry and flow conditions, see further under section 16.1.

9.5 Geohydrochemical sampling and analysis

SKB's programme and equipment for sampling and analysis of groundwater have undergone extensive development between the time of the study site investigations and the construction of the Äspö HRL. Following the completion of pre-investigations and prior to the construction phase in the Äspö project, sampling and analysis classes were established to facilitate and guide the sampling that was carried out in the tunnel. These classes will also be utilized in coming site investigations (see table below).

Class 1: Simple sampling for check of temporal stability.

- Electrical conductivity, pH, uranine*

Class 2: Simple sampling for type classification.

- Electrical conductivity, pH, Cl, HCO_3, uranine*

Options: ^2H, ^3H, ^{18}O

- Frozen sample archived

Class 3: Simple sampling for determination of principal components (no redox).

- Electrical conductivity, pH, Cl, HCO_3, SO_4, Br, uranine*, cations (except Fe, Mn)** and SO_4 analyzed as sulphur with ICP-AES

Options: ^2H, ^3H, ^{18}O

- Frozen sample archived

Class 4: Extensive sampling for complete hydrochemical characterization.

- Electrical conductivity, pH, Cl, HCO_3, SO_4, Br, Fe (total, bivalent), uranine*, DOC, cations** and SO_4 as sulphate with ICP-AES, ^2H, ^3H, ^{18}O
- Frozen sample archived both acidified and unpreserved

Options: HS, NH_4

Class 5: Extensive sampling for complete hydrochemical characterization, including special analyses.

- Electrical conductivity, pH, Cl, HCO_3, SO_4, Br, F, Fe (total, bivalent), uranine*, DOC, cations** and SO_4 as sulphur, HS, NH_4, ^2H, ^3H, ^{18}O
- Frozen sample archived both acidified and unpreserved

(to be contd.)

(contd.)

Options: NO_2 (or NO_2+NO_3), PO_4, I and TOC

- ^{14}C age (Percent Modern Carbon), ^{13}C per mill PDB (Peedee Belemnite, standard)
- U and Th (element analysis and/or isotopes)
- Other trace metals (INAA and/or ICP-MS)
- The isotopes ^{226}Ra, ^{228}Ra and ^{222}Rn

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*) Determined only when Uranine has been used as marker for drilling water.
**) Cations: Na, K, Ca, Mg, Si, Fe, Mn, Li and Sr.

9.6 Goals and programme

Activities during the upcoming six-year period 1999–2004 will focus on a better integration of the geohydrological conditions in hydrogeochemical analyses and evaluations. The goals are to:

- determine what chemical changes in the natural environment the repository may cause in the near field during construction and prior to closure,
- assess possible changes in the chemical conditions in a repository area over the life of the repository,
- underpin the models for water flow and transport in the rock by deducing previously prevailing flow conditions.

Activities aimed at improving knowledge of barrier functions are more important than the demonstration aspect. The barrier functions that influence and are influenced by hydrochemistry are isolation (crucial importance), retention (great importance) and dilution (some importance). Understanding, predictability and investigation technique will be accorded greater weight than competence maintenance and the value of expert opinions.

Specific investigation activities include the following:

- Testing and refinement of new and existing equipment for water sampling in boreholes drilled from the ground surface and underground facilities, underground even in low-conductive rock ($K<10^{-10}$ m/s).
- Investigations of the composition and occurrence of fracture-filling minerals, focused on previously prevailing hydrochemical conditions, on redox conditions, on ion exchange capacity and on nuclide migration modelling.
- Laboratory and field experiments for the purpose of clarifying the kinetics of the calcite system and its response to pH changes.
- Sampling, analysis and data compilation to see where and how often deep groundwater, including deep-lying saline water, is transported up to the ground surface.
- Collect chronological series of isotope data for precipitation and chemistry data from observation boreholes.

Minimizing disturbances to the groundwater chemistry in order to secure usable data continues to be an important aspect of the planning of programmes for site investigations. It is necessary to devote sufficient time in order to obtain high quality in the groundwater samples and to know which factors can adversely affect the chances of obtaining samples of high quality. Chemistry samplings carried out with SKB's chemistry equipment in, for example, the Palmottu Project are furnishing additional knowledge and lessons concerning which conditions are important. A narrower focusing of the core mapping work on those minerals that can be used to interpret previously prevailing conditions is planned to be included in the programme.

The specific major modelling efforts are, in order of priority:

- Within the framework of the "Äspö Task Force for Modelling of Groundwater Flow and Transport of Solutes", to carry out a combined hydro and chemistry modelling of the groundwater situation around Äspö during and after the tunnel construction phase, see programme for the Äspö HRL.

- To carry out the evaluation of previously prevailing hydrochemical conditions within the framework of the ongoing EQUIP project (EU), see programme for the Äspö HRL.

- To make use of the Äspö Task Force and EQUIP modellings to describe possible scenarios for the evolution of the water chemistry on Äspö in a time perspective of 100, 1,000, 10,000 and 100,000 years ahead.

- To couple geochemical, hydrochemical, isotope-chemical and geohydrological descriptions to a predictive model and test its ability to describe the conditions on an unknown site.

- To clarify the importance of calcite and kinetics when it comes to sealing and opening up water-conducting fractures in conjunction with changes in hydrochemical conditions, for example during the period the deep repository is open.

The work will be pursued within the framework of existing and new sub-programmes or projects.

Modelling of possible hydrochemical changes over the life of the repository is an ongoing cooperation project with Posiva within the framework of their participation in the Äspö HRL. This also includes sampling and analyzing groundwater from low-conductive rock and deep-lying saline water. The central question in the project concerns the temporal and spatial stability of the very saline groundwaters that have been encountered at a depth of about 1,000 m at Laxemar and at Olkiluoto, one of Posiva's candidate sites. An important question is: Can the water at any time in the future be transported up to a repository level at a depth of about 500 m? According to plan, Posiva will select a repository site in 2000 and Olkiluoto is one of the candidate sites.

A sub-programme aiming at hydrochemical site evaluation will be carried out in different steps. To start with, the most recent data from the deep borehole KLX02 will be evaluated together with earlier data from the same borehole and conditions on Äspö. The most important questions in this evaluation are:

- Are data representative and reliable?
- Is there a regional flow in the deep groundwater?

- What changes with time cause the drawdown from the Äspö tunnel?

In the next step, the chemical situation in the entire area will be evaluated and related to conditions in the vicinity, i.e. what is known about Kråkemåla and Klipperås.

A new programme will include identification of the most important processes for the hydrochemistry based on all (M3) modellings carried out. We intend to couple the hydrological descriptions to the hydrogeochemical ones and to develop the M3 code so that it can be used for predictions of the conditions on a site. This requires a program routine that permits direct modelling, in contrast to the inverse modelling for which the program is currently used. At the same time we want to obtain a better picture of the uncertainties in the M3 concept and be able to determine how great the variations are in the assumed type waters, for example the oxygen-18 concentration in glacial meltwater and in ordinary meteoric water.

An ongoing doctoral project is investigating the kinetics of the calcite system. The work, which was begun in 1997, is expected to be completed in 2000. As a conclusion, a field experiment will probably be conducted on Äspö, where the water chemistry (especially pH) will be varied so that the response in the calcite system can be studied.

The international cooperation in the hydrochemistry field that has been initiated via the series of Äspö Geochemistry Workshops will continue in the already ongoing Task #5 modelling and in the EQUIP project. Furthermore, we will participate in projects under the auspices of the IAEA and the OECD/NEA to a greater extent than before.

9.7 Hydrochemical modelling tools

9.7.1 Concept

Modelling of groundwater chemistry is often based on equilibrium models and the assumption that the minerals in the rock determine the water composition, either by assuming a steady-state system where complete equilibrium exists throughout the system, or by simulating a transport where the water is progressively equilibrated with different minerals. The former is called equilibrium modelling and the latter reaction path modelling. A number of reliable equilibrium and reaction path codes exist today which are specially developed for calculations in water-mineral systems. The most common equilibrium codes are EQ 3, EQUIL, WATEQ, PHREEQE, etc. Among the most common reaction path codes are EQ 6, PHREEQEF and NETPATH. These codes all have their own thermodynamic database.

In evaluation of Äspö data, both equilibrium and reaction path modellings were initially carried out /9-6/. It turned out, however, that the water chemistry could largely be described as the result of mixtures containing more than two water types. It was thereby also necessary to calculate the mixing proportions with several components simultaneously.

9.7.2 Method

Performing hydrochemical evaluations is usually complex work carried out by specialists. The results of this work are often presented in the form of subjective qualitative models and process descriptions. To facilitate this evaluation and enable it to be carried out in an objective and quantitative manner, a mathematical method has been developed. It is based on multivariate analysis followed by mixing calculations. The resultant computer programme and the idea are called M3 (Multivariate Mixing and Mass balance calculations) and can be used to trace the origin of the groundwater, calculate mixing proportions and carry out mass balance calculations even in cases where the groundwater data are otherwise difficult to interpret. The groundwater composition, which has traditionally been used to describe reactions that occur in the bedrock, can now also be used with increased accuracy to trace the effects of modern or ancient groundwater flows on the groundwater chemistry.

The M3 model is a groundwater response model, which means that the changes in the groundwater chemistry are investigated in relation to an ideal mixing model devised for the area in question. The complexity in measured data determines the configuration of the mixing model. The discrepancies from or similarities with the ideal mixing model are assumed to be caused by mixing or reactions. Assumptions concerning the composition of fracture minerals or uncertainties in thermodynamic constants do not affect the modelling, since it is only based on the measured groundwater composition.

M3 uses an approach that is opposite to that of many other standard groundwater models. In M3, the mixing processes are evaluated and calculated first, where the changes in the groundwater chemistry that cannot be described by mixing are explained by reactions. M3 consists of three steps: the first step is an ordinary principal component analysis, followed by mixing and finally mass balance calculations. The measured groundwater composition can be described in terms of mixing proportions as percentages of different water types and/or as additions or losses in mg/l of element concentrations that are associated with reactions in the rock.

As many variables as possible are included in the calculations. All principal components – sodium, potassium, calcium, magnesium, chloride, sulphate, carbonate and the isotopes oxygen-18, deuterium and tritium – are included as variables in a principal component analysis where the information from all variables is combined to the least possible number of linear combinations. The first principal component describes the variability in the input data. The second principal component describes the remainder which the first principal component could not describe, etc. In the Äspö case, the first two principal components are used, which together describe 72% of the variability.

The analysis of the calculated principal components is done by marking in an XY plot the value pair for each observation. In this plot, the extreme points (i.e. reference waters and end-members) are identified. Calculations of mixing proportions are then carried out in all observation points. With these mixing proportions, a chemical composition is then calculated which is compared with the measured one, substance by substance. Differences are regarded as being the result of chemical reactions.

The M3 code has been developed as an application of MATLAB and is comparable to other existing codes as regards use.

9.7.3 Continued development

The M3 concept will be applied to data from different sites – e.g. SFR, Oklo, Palmottu etc. – to identify the essential processes and test the ability of the programme to describe the groundwater chemistry on an unknown site.

The M3 code has been developed and applied to data from Äspö. The programme needs to be compared with similar codes such as NETPATH. The testing will be carried out with both real and synthetic data. In the case with synthetic data, the calculations are performed so that in one case only mixing occurs, in another only reactions and in a third both mixing and reactions. The results of the tests will determine what additional development steps are needed.

VOXEL ANALYST is a commercial program that is utilized for hydrochemical modelling and visualization. It is based on MICROSTATION, i.e. the same program as the RVS system is based on. This program will be used for a continued integration of geochemical data. SKB's GIS database, which contains all of SKB's geological and geophysical maps, is being expanded with a hydrochemical part where the results of different modellings will be stored in the form of images and 3D objects. Hydrochemical data from SICADA visualized in cross-sections, areas and volumes will be stored as 3D objects which can be used directly in the RVS system. This provides good traceability to the data on which the different visualizations are based. This database is also planned to contain a standard for the work units, coordinates, background values, interpolation methods and colour tables that are used for modelling and visualization of hydrochemical data. This simplifies communication between different programs and makes it possible to compare results from different modellings.

10 Chemistry

Chemical processes are important for the deep repository's barriers. The safety assessment needs to know what chemical reactions take place in the repository's near field and out in the rock. It is particularly important to determine how radioactive elements can be released, transported and retarded. These processes have been identified, and the ongoing work is aimed at furnishing the safety assessment with different types of vital data, such as sorption and diffusion constants for radionuclides in rock and bentonite. Chemical investigations are not limited to the Chemistry programme, but are also included in related programmes such as Fuel, Buffer, Bedrock, etc. A trend is to initiate general studies in the Chemistry programme and then, if it proves necessary, proceed to more applied investigations in related programmes. It is also common that competence is developed within the Chemistry programme and subsequently put to use in related programmes.

The results obtained within the Chemistry programme are presented in reports, publications and theses. A good information source in this respect is SKB's Annual Reports, in which all important results obtained during the year are summarized and referenced. The annual reports provide more details than this account, which has been deliberately kept brief so as not to be burdensome for those who wish to obtain an overview of what has happened since the last RD&D programme. The annual reports are written in English to ensure wide dissemination.

10.1 Radionuclide chemistry

In the previous programme, the chemistry of plutonium was identified as a prioritized area. The database for plutonium, which is used to calculate solubility, needs to be improved and steps have now been taken. At the same time, this is a good example of a task which has gradually been shifted from the Chemistry to the Fuel programme, since the results are primarily needed to describe the leaching of spent fuel.

Solvent extraction is a technique that is used to study the complexes which radionuclides form in solution. The size of the complex constants can be measured and the advantage of this technique is that it works at low concentrations, which are typical for radionuclides dissolved in the groundwater (trace concentrations, i.e. $<10^{-7}$ mol/l). Solvent extraction has been evaluated and compared with the results yielded by other methods /10-1/.

Some chemical reactions do not take place spontaneously, even if they are thermodynamically possible. This is particularly true of some redox reactions. An exchange of electrons must be able to take place in all redox reactions, but is sometimes prevented. It is thus necessary to make sure that the reaction actually proceeds as expected, at least if it is of importance to safety. An example of this is reduction of dissolved technetium and neptunium ions by divalent iron in a repository /10-2/. The experiment shows that sorption of the reactants on a mineral surface is an important step in the reaction path /10-3/. Only then can the redox reaction take place. The reduction causes a drastic decrease in the solubility of both technetium and neptunium. Their solubility can decline by as much as six orders of magnitude, which is in principle the difference between "soluble" and "insoluble". New experiments are being conducted to show that uranium dioxide, which is a constituent of the fuel, also acts as a reducing agent.

10.2 Sorption and diffusion

The mechanisms for sorption of radionuclides – such as cobalt, thorium, neptunium and uranium – on mineral oxides have been thoroughly investigated /10-4, 10-5, 10-6/. The conclusion is that the hydrolysis of the metal ions controls the sorption and determines its strength. This is in fact not surprising. Early Kd measurements (by Bert Allard and co-workers) with actinides showed a strong correlation with hydrolysis, but now the mechanism for this has been substantiated. Complexing agents can reduce the importance of the hydrolysis, which means that e.g. carbonate ions can influence the process in the groundwater. The surface complexation model is used to describe the sorption. The sorption of Co, Th, Np and U is not affected by ionic strength (salinity), which shows that they form so-called inner sphere complexes. Typical exceptions are Cs and Sr, which are sensitive to ionic strength and instead form outer sphere complexes. The surface complexation model is valuable as a method for demonstrating our understanding of the sorption mechanisms and it can also be used to trace uncertainties, but it is not practically feasible to substitute surface complex constants for Kd values in the safety assessment, at least not yet.

Matrix diffusion, i.e. diffusion of radionuclides into the interconnected system of water-filled microfractures in the rock, is the most important retention mechanism in the rock. In fact, sorption of radionuclides on the mineral surfaces in the microfractures is much more important for the calculated retention than sorption on the surfaces in the open fractures where the groundwater is transported. It is therefore the properties of the rock near the water-conducting fractures that are significant. Important properties for retention of radionuclides are diffusivity De, porosity e (diffusion porosity) and sorption in the rock matrix, Kd. Other important properties in this context are "flow-wetted surface" and "penetration depth" for diffusion. Over the years a fairly large quantity of information has been accumulated on matrix diffusion and associated phenomena. Available data should provide a very good basis for safety assessment calculations, but it is not always so easy to obtain sufficient information on individual experiments, which is necessary in order to be able to use the results. Literature data on matrix diffusion has, however, been compiled as a first step in creating a new database for future safety assessments. The literature survey includes not only experiments, but also results of studies of natural analogues /10-7/. The literature survey has served as a basis for the choice of constants for SR 97 (see below).

Diffusion of caesium, strontium and iodide in compacted bentonite has been measured /10-8/. This has been done previously, but we decided to repeat the measurements with greater care, since they are so important for the safety assessment. It was found that the diffusion of I^- is hindered by the negatively charged clay mineral particles, a phenomenon known as anion exclusion. Diffusion of Cs^+ and Sr^{2+}, on the other hand, is enhanced, since they are mobile in the concentrated layer of cations on the negatively charged surfaces, see Figure 10-1. The latter phenomenon is called surface diffusion and also occurs in conjunction with matrix diffusion, i.e. when radionuclides diffuse into the microfractures in the rock.

Finally, the constants that are needed to calculate sorption and diffusion of radionuclides in granitic rock and bentonite clay have been compiled and reported for use in the safety assessment SR 97 /10-9, 10-10, 10-11/.

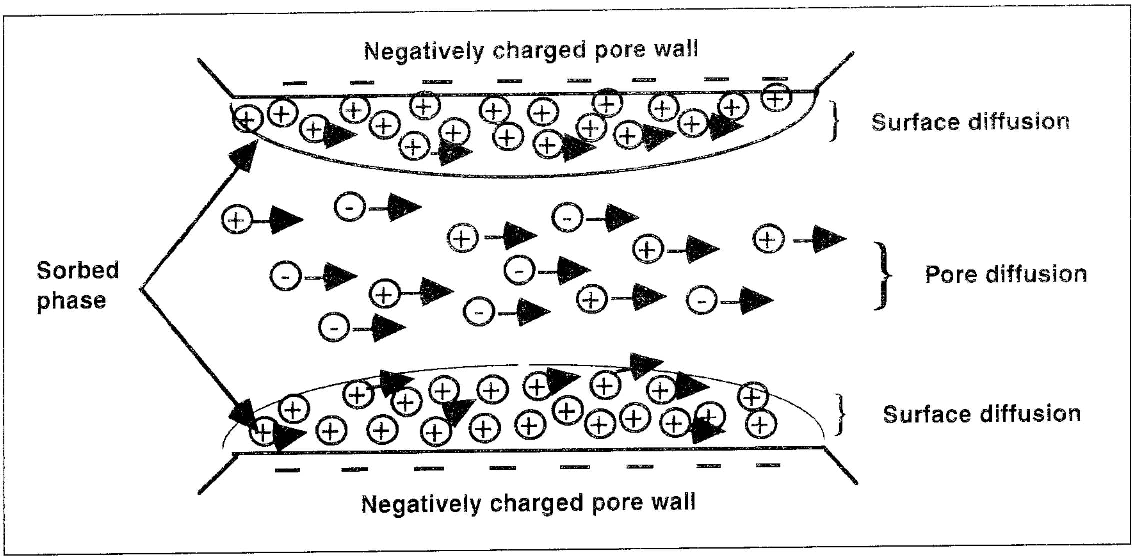

Figure 10-1. *Schematic illustration of ion diffusion in a pore space between negatively charged mineral surfaces. The anions are limited to a small pore volume due to electrostatic repulsion, while the cations are concentrated in the sorbed but mobile phase. (Illustration according to Neretnieks and Ohlsson, Chemical Engineering, KTH).*

10.3 Colloids

The concentration of natural colloids in deep groundwaters is very limited. Careful analyses give colloid concentrations of around 0.05 mg/l /10-12/. That is very low – low enough, in fact, to be of no importance. Besides the natural colloids, however, it must be considered whether materials in the repository can in any way contribute by giving rise to their own colloids. For example, bentonite can in principle release colloids in the form of clay particles. This has also been discussed, and an important prerequisite for the continued stability of the bentonite gel is that the concentration of cations in the groundwater, particularly divalent cations, doesn't become too low /10-12/. Deep groundwater is mineral-rich, so this condition is amply fulfilled (conc. Ca^{2+} >0.1 mmol/l).

A disturbance that really gives rise to colloids in reducing groundwater is ingress of atmospheric oxygen. Elevated concentrations of colloids in the repository can thus arise after closure, at least until all oxygen has been consumed.

Another type of colloidal transport that has been discussed is that gas bubbles from e.g. iron corrosion could carry contaminated clay particles from the repository. In order to ascertain the importance of such a scenario, a calculation of radionuclide transport with gas and particles was carried out. The result showed that the releases were insignificant, even with very conservative assumptions regarding "bubble transport" /10-13/.

10.4 Organic substances

Analyzing low-molecular organic components that are present in the groundwater besides humic and fulvic acids has proved to be difficult. On the other hand, there is nothing to indicate that such substances are of importance except possibly as a source of nutrients for bacteria. As far as complexation is concerned, humic and fulvic acids are still of interest. It is essential that the levels of humic substances always be low in a repository.

Organic substances can also be introduced from the outside during construction and operation of the repository. In a repository for high-level waste, this will be limited as far as possible, but in the case of low- and intermediate-level waste it must be expected that this waste will contain quite a lot of organic matter. This is dealt with in greater depth in Chapter 12, "Other long-lived waste".

10.5 Microbes

The most important areas for microbe studies in relation to the long-term safety of the final repository were reviewed in connection with the preceding RD&D report /10-14/. With the guidance of the conclusions in the report, the investigations have continued and the new results have been compiled in technical reports or published in scientific journals. Microbe studies has been a prioritized area. The investigations have been connected with the Äspö HRL and the URL in Canada /10-15/, as well as with the analogue studies in Oklo, Gabon /10-16/ and in Maqarin, Jordan. Many of the microbial investigations that were first carried out at Stripa and then at Äspö have been fully reported /10-17/. Laboratory experiments have also been performed, for example to see whether sulphate-reducing bacteria can survive in a bentonite buffer /10-18/. A new summarizing report has been published for the period 1995 to 1997 /10-19/. This report explains and analyzes the results achieved during the period. The scientific basis consists of 11 separate articles published in scientific journals, which are appended to the report. Following are examples of the conclusions that are drawn:

- There are microorganisms that live at great depths in granitic rock.
- Microorganisms that use hydrogen as an energy source and carbon dioxide as a nutrient source (carbon) have been encountered in deep granitic groundwaters.
- The most important gases in the groundwater are helium, nitrogen, methane and carbon dioxide. All can be produced or consumed by bacteria, except helium.
- Achieved results clearly show that oxygen is consumed by bacteria in a closed repository.
- Sulphide can be produced by bacteria under repository conditions by reduction of sulphate.
- The bentonite buffer that surrounds the copper canisters constitutes a hostile environment for microbes due to the combination of radiation, heat and low availability of water (i.e. low chemical activity of pore water in highly compacted bentonite).
- Microorganisms can recombine the products that are formed by radiolysis of water.
- Transport of radionuclides by bacteria is theoretically possible, but the concentrations of bacteria in deep groundwaters are too low for this to be of any significance.
- Microorganisms that can produce complexing agents need to be further investigated.
- It appears as if the hyperalkaline groundwater in Maqarin, and thereby also pore water in concrete, is too extreme an environment for bacteria. While bacteria have been found in the water at Maqarin, they are not active and not alkalophilic, i.e. they are not native there.

The most essential points are those that concern sulphate-reducing bacteria and their survival in the repository. Since this is significant for the copper canister, special attention has been given to this subject, and it is included in the studies being conducted within the Encapsulation project.

10.6 Validation experiments

Concrete is used to stabilize and package LILW (low- and intermediate-level waste). It is also used to build repositories for such waste (e.g. SFR). Concrete is in general a very useful material for underground construction, for example for paving of floors, shot-creting of walls and roofs, grouting of rock fractures, various kinds of structures, etc. A future repository for spent fuel does not make any absolute demands on the use of concrete, but it can be advantageous to have that option. That is why we are investigating what it means to have concrete in all types of repositories. Portland-type cement contains alkali hydroxides and portlandite, which give the pore water in the concrete a high pH. To determine how this affects the rock and the groundwater in a repository, laboratory experiments are being conducted where simulated cement pore water is allowed to run through columns filled with crushed minerals. The objective is to validate the models that are used to predict alkaline weathering and other changes. The experiments are being performed by BGS (British Geological Survey) in the UK with the support of Nagra, Nirex and SKB. The work has been proceeding since 1993. The results of a first phase have been reported, but the work is not yet finished.

Further validation experiments that are under way but have not yet been reported are: 1) radionuclide migration in overcored rock fractures; 2) simulation of near-field transport from buffer to rock, and; 3) transport of colloids in a clay buffer.

10.7 Hazardous substances

SKB's research for the safety assessment is essentially focused on the radiological toxicity of the waste. A small portion of the substances included in the waste can, however, be classified as chemically toxic hazardous waste. This is particularly true of some metals such as lead, cadmium and beryllium. Hazardous substances are being inventoried and the safety of a repository with regard to these substances is being tested. A deep repository also provides protection against non-radioactive substances; see, for example, the Swedish Environmental Protection Agency's report on final disposal of mercury /10-20/. Long-lived LILW contains substantial quantities of hazardous metals, which is taken into account in the assessment of long-term safety (Chapter 12).

10.8 Goals and programme

The chemistry programme has the following goals for the next three years (and longer):

- Determine (redox) reactions for the most important radionuclides in the repository.
- Improve data on sorption and diffusion in rock and backfill.
- Investigate the importance of colloids and microbes for the long-term safety of the repository.
- Start new and finish old validation experiments.

Experiments are being conducted aimed at investigating how uranium(IV) in the repository affects other actinides. We hope that it will be possible to draw conclusions from this in a few years. Furthermore, some time is being devoted to studying complexes of radionuclides with phosphates and sulphates for the purpose of improving our knowledge in this area.

Colloids in the groundwater, like humic substances, are hardly regarded as a problem anymore. This does not mean that they can be completely disregarded either. On a future site, we fully anticipate having to perform analyses of such components to ensure that conditions are as expected in this respect. Colloids in the near field, for example from the materials present there, are important and not quite as thoroughly studied as natural colloids. Experiments are being performed to provide further support for the conclusion that bentonite clay acts as a filter for such particles.

Microbes in deep groundwaters will be further investigated. We are mainly interested in the microbial processes to the extent they have a bearing on a deep repository. The Äspö HRL will also continue to play an important role, and in-situ tests with microbes are planned. If possible, we will select a spot deep down in the Äspö HRL and reserve it for these tests.

A method is being developed for easier and faster measurements of matrix diffusion. We foresee the need to conduct such measurements on samples from a future repository site. The advanced models for surface sorption of radionuclides on minerals will be further tested. The primary goal is not to find a substitute for sorption coefficients (Kd values), but to understand the mechanisms of sorption.

The laboratory experiments with concrete pore water and rock minerals that are being conducted by BGS (British Geological Survey) will, according to plan, soon be concluded and the results reported. A conceivable follow-up to this is in-situ tests. Plans are being made for such tests and discussions are being held with Nagra on international co-operation in the underground laboratory in Grimsel. Other organizations have also expressed an interest. Supplementary tests could be carried out at Äspö.

10.9 Competence development

Many of the investigations for the chemistry programme are being conducted by researchers at universities and institutes of technology. Nuclear chemistry, natural waters and microbiology are prioritized areas. These subjects are still of interest to basic research, as evidenced by the fact that such work is often included in various kinds of academic theses. We believe this ensures high quality in the investigations and enables us to maintain a high level of competence for both ongoing and future investigations. In a longer perspective, more production-oriented research is needed, for example to carry out a large number of analyses in conjunction with a site investigation.

11 Biosphere

In order to be able to assess the radiological consequences of possible releases of radioactive materials from a final repository, it is necessary to describe transport from the rock to man and to other organisms. The overriding goal of SKB's studies of the behaviour of radionuclides in the biosphere is to be able to carry out credible consequence calculations in the safety assessments. The biosphere studies must:

- describe events and processes in a realistic manner, with an explanation of why certain processes are important and a detailed explanation of why other processes have been excluded,
- serve as a yardstick for comparing different facilities, technical solutions or repository sites,
- show that regulatory requirements on safety and limit values have been met.

For modelling that aims to show that dose limits are not exceeded it may be acceptable to greatly overestimate the consequences. But in connection with the construction of a deep repository, these overestimates of the effects can lead to unnecessary measures or misallocation of priorities. Furthermore, a thorough knowledge of the biosphere is required to justify the simplifications that are made in dose estimates in connection with optimization. Since the processes that occur in the biosphere are clear to a large group of experts from other disciplines as well as non-specialists, clear logical simplifications are required that nevertheless describe the biosphere in a scientifically intuitive manner.

The biosphere is characterized by wide variation and is perceived as being complex and unpredictable. The greatest uncertainty in dose calculations in today's models is dependent on the biosphere. The largest part of the uncertainty is due to inadequate conceptual descriptions of ecological processes, in contrast to the usually better described physical and chemical processes in the biosphere. Another part of the uncertainty is caused by a lack, and poor quality, of data. Previously, generic data have been used almost exclusively. The reason for this has been the great changes that occur in the biosphere within relatively short periods of time. For periods after the beginning of the next Scandinavian ice age this is correct. But over the next 1,000 years, site-specific databases and specific assessments can provide a basis for a relatively meaningful forecast. The point of departure for the dose calculations is current conditions, which must then be described sufficiently well in order to be able to make realistic calculations.

The overriding goal of the biosphere programme is to be able to reduce the uncertainties and describe the most important processes in the biosphere from a radiological viewpoint with an up-to-date scientific knowledge base.

11.1 Understanding and conceptual models

SKB's modellings of radionuclide migration in the biosphere have been carried out with BIOPATH, a calculation program developed by Studsvik EcoSafe and included in the international BIOMOVS work. BIOPATH has been utilized for KBS-3, SFR and SKB 91 and has been progressively refined as a result of efforts by, among others, SKB, as summarized in a review by Edlund, 1998 /11-1/. The model studies were distinguished at the beginning (in the 1970s) by their holistic approach, which was then new in the environmental field. The models were based on releases around nuclear power plants, and later adapted to a hypothetical deep repository. But it was still assumed that the release takes place directly into the recipient as an annual unit release. This hypothesis was justified by the fact that it was considered to be a conservative assumption to disregard the transport and the processes between the geosphere and a surface recipient. This model concept has largely been adopted in most models that deal with radionuclide transport in the biosphere /11-2–11-5/. These simplifications may be warranted for the safety assessment, but for an understanding and justification of the simplifications they are insufficient. In some cases they may furthermore underestimate the doses /11-6/. Moreover, a thorough validation of the data is difficult when alternative models and conceptualizations are lacking /11-7/. The viewpoint that it is important to shed light on the consequences for surrounding fauna and flora in a safety assessment is gaining increasing ascendancy /11-8/. This requires models that are based on the radionuclide flow in the entire ecosystem and not just in specific pathways that are critical to man (e.g. well or cow's milk).

In the past few years, there has been a development of biosphere models for toxic contaminants (e.g. /11-9, 11-10/) based on the principles of systems ecology. These models have usually tackled problems associated with accumulation and effects on the environment, in contrast to radioecological models, which have mainly aimed at predicting doses to man. These models have also been aimed at describing and using generic processes, where the radioecological models often use composite model parameters. In order to be able to describe the biosphere with credibility, it is important that the conceptual models that are used conform to general scientific paradigms within ecology, ecotoxicology and environmental protection besides radioecology. For this reason, experience and developments within these fields will be monitored so that new model concepts can be incorporated in the radioecological models in the coming research programme.

11.2 Model development

The current safety assessment has been related to site-specific conditions, which means that the structure of the BIOPATH model has been adapted to local conditions. It has been assumed in the safety assessment that nuclides from the deep repository can be transported directly to the recipients in an annual quantity that has been calculated from the transport calculations for the far field. Since these transport calculations are based on streamtubes that discharge about 20–40 m below the ground surface, it has been possible to couple these discharge points to the overlying biosphere, which can vary in character. For the modelling, this has meant that the biosphere has been divided into different classes in a modular system /11-6, 11-11/.

Models have been developed to calculate the flux and exposure from releases of radionuclides to lakes, streams, coastal areas, swamplands and agricultural areas /11-6/. Furthermore, calculations have been carried out for direct use of contaminated groundwater (well). Human exposure has then been calculated for the three site-specific areas in SR 97 /11-12/.

The higher resolution in different modules requires a better body of data and a more accurate description of processes. This focuses attention on deficiencies in data and models, for example shortcomings in the description of transport from the far field to the biosphere and the lack of a forest model, which is described below and in the process report /11-13/. The model for SR97 was based on available map information /11-12/. A comparison was then made with a literature survey of available site-specific data on the biosphere in these areas /11-14/, hydrology and loose deposits /11-15/. An evaluation of what type of site-specific data are needed and an appraisal of what is gained by various improvements in measurement methods and calculations in comparison with the uncertainties that exist in the models are needed for future site investigations. Furthermore, a careful plan must be drawn up so that undisturbed site-specific data can be secured before other invasive activities hinder their interpretation.

11.3 Transport processes

Transport processes determine what ecosystems and organisms will be exposed to radionuclides and how great the dilution will be. Large parts of this are dealt with in present-day models under the premise that the radionuclides are dissolved in water. A revision has been made of the residence time of the water around Äspö /11-16/ with the aid of new models for near-coast water flux. An attempt has been made to model the near-surface hydrology /11-15/, but further refinement is needed to be able to describe what parts of the biosphere can be exposed to radionuclide leakage. A large portion of radionuclides in the environment will, however, be bound to particles, humic complexes and organisms. The transport of radionuclides in the biosphere is therefore dependent to a great extent on particle transport, which has not been explored to any great extent in previous studies. Additional examples of important transport processes are described in the process report /11-13/. The scale and relative importance of these processes will be evaluated in the coming research programme.

11.4 Forest ecosystem

The forest is the dominant recipient for most hypothetical sitings /11-14/. The forest has been at the focus of several projects which have studied the fallout from Chernobyl, see review in /11-17/. Most studies have seen the short-term consequences of the radionuclide transport, and the source has been atmospheric fallout. But so far, few calculations have been made of dispersal and accumulation of nuclides from a deep repository in this ecosystem. The most important long-term processes are probably accumulation of nuclides in the soil profile and biological leaching processes that transfer nuclides to biota. The lysimeter tests performed in BIOMOVS II /11-18/ suggest that biological processes in the ground are the most important transport mechanism from the groundwater to the top ground layers. These processes will be evaluated in the coming research programme and a model for the forest ecosystem will be developed.

11.5 Sediments

The sediments in seas, rivers and lakes constitute potentially important areas that influence the transport of radionuclides to biota. In many potential discharge areas, the radionuclides will pass through a sediment stratum. The permeability and adsorption of the sediment influence the patterns of distribution and dilution /11-19, 11-20, 11-21/. A marked change in redox conditions, salinity and biological activity occurs in the boundary layer between sediment and water /11-22, 11-23/, which can greatly affect the radionuclide flux. These processes have not been taken into account in the calculations of radionuclide transport from the geosphere to the biosphere. The radionuclide flux will be restricted to begin with, but accumulation of radionuclides can go on for thousands of years before they are liberated by resuspension caused by land uplift, which can result in doses that are thousands of times higher. It is therefore important to evaluate the stability and retention capacity of the sediment strata.

11.6 Long-term variations in climate, land uplift and salinity

The premises for the biosphere are controlled to a great extent by the climate and the distribution between land and water. These factors are also important boundary conditions for the transport models in the geosphere. Postglacial land uplift influences which biotope is dominant in an area. Water flux, groundwater recharge and surface runoff are some of the most important physical factors influencing the dose. These factors are highly variable and stochastic, but their range of variation can be studied with models of present-day conditions and a reconstruction of conditions since the most recent ice age.

Påsse /11-24/ has described how the shoreline has been displaced since the ice age and made a forecast for the next 10,000 years, assuming a constant sea level. During the next 100 years, the sea level may rise about 0.4 m due to the greenhouse effect /11-25/. But in the longer term, a future glaciation will once again bind water in glaciers, causing a lowering of the sea level by about 100 m /11-26, 11-27/. This affects discharge areas at the coast, which in turn has repercussions on the environment around the deep repository. This also affects the salinity of the Baltic Sea and the composition of the biosphere. Salinity influences which ecosystems will dominate in the Baltic Sea and what properties the radionuclides have. A compilation has been made of knowledge concerning the salinity of the Baltic Sea since the last ice age, but the future salinity is difficult to predict /11-28/. Salinity is determined by how easily saltwater can enter the Baltic Sea and by total runoff in the Baltic Sea basin /11-29/. Lowering of the sea level reduces the inflow or completely isolates the Baltic Sea from the North Sea, resulting in a lowering of salinity. When a glaciation commences, water will be bound in the ice, reducing the runoff to the Baltic Sea. This means that dilution of the saltwater decreases, so that the Baltic Sea becomes more saline. Stigebrandt /11-29/ has shown that salinity would be greatly increased (by about 0.4 percentage points) by a 30% reduction of the freshwater influx. Only when the oceanographic model is coupled to a runoff model and to land uplift can a better description be obtained of probable future conditions in the Baltic Sea.

The climate also affects groundwater recharge and water flux in lakes and watercourses, which are important factors for flows at repository level but also for what kind of biosphere can be expected. An estimation of conceivable variations in groundwater recharge in the Äspö area has been made by SMHI /11-30/. These results can then be coupled to the climatic evolution that has taken place during the Holocene (see literature review /11-31/) to reconstruct the groundwater picture and predict its possible future evolution (e.g. /11-32, 11-33/).

11.7 International work

The international project BIOMOVSII was concluded in 1996 and produced several reports where SKB participated actively in the work. The primary objectives of the project were to test the accuracy of the predictions made by biosphere models for certain selected scenarios and nuclides, to explain differences in model predictions based on differences in model structure and input data, and to recommend future studies for improvements /11-3–11-5, 11-18, 11-34, 11-35/. The reports showed the importance of uncertainties, model evaluation and correct conceptual models. This was illustrated by comparisons between models and experimental data /11-18/. It was found that the greatest shortcoming is the lack of a correct process description. The processes that are not normally handled are biological and ecological processes (root transport, bioturbation), whereas physical and chemical processes (e.g. adsorption) are in many cases better described. SKB is participating and monitoring the work, which is now continuing with BIOMASS under the auspices of the IAEA.

The work within BIOMOVS and BIOMASS has been successful in reaching a consensus in many issues and practical problems, but the forum for the discussions is nevertheless a small group with few contacts with outside knowledge concerning other environmental threats. To vitalize the work, modern knowledge within systems ecology and ecotoxicology must be applied to radionuclide transfer in the biosphere. It is therefore important to disseminate the findings of these programmes to others, but also to bring this competence into BIOMASS.

11.8 Goal fulfilment in RD&D 95

The following interim goals, which have been fully or partially fulfilled, were set in the biosphere programme in RD&D 95:

Quantification of the uncertainties that stem from the fact that the biosphere is constantly changing has been done in several reports /11-14, 11-21, 11-36, 11-37/ but will continue in coming programmes.

A site-specific evaluation of the potential and limitations of the candidate sites for changes in the biosphere has been initiated /11-12, 11-14, 11-15, 11-38/ but requires further studies.

An improved body of data has been compiled for transport models /11-18, 11-19, 11-39/.

Models have been validated by studies of analogous transport processes /11-18, 11-19, 11-39/, and this will always be important when new models are developed.

11.9 Goal and programme for future work

The overriding goal of the biosphere studies is to quantify the migration of radionuclides and other substances from the deep waste repository to the human environment, as well as the consequences of this migration. The main purpose of this knowledge is to serve as a basis for safety assessments of future repositories.

- Develop methodology to handle risk assessment for biota, for example how doses to animals and plants are described and evaluated.
- Describe processes in the interface between biosphere and geosphere.
- Evaluate the role of the structure and function of the ecosystems for transfer of elements from the geosphere and distribution in biota.
- Analyze the importance of transport in biota, particles and water in the biosphere.

- Identify important differences in the analysis of a slightly different climate.
- Identify effects of land uplift on the mobilization of elements that have been stored in sediments and how salinity and chemical conditions in the groundwater are affected.
- Evaluate which parameters can be described with generic data versus site-specific data.
- Maintain and modernize modelling tools for the biosphere.
- Develop and maintain competence within biosphere modelling.
- Participate in the international work with biosphere models.
- Monitor research being conducted within radiation protection and radiation effects.
- Analyze and evaluate alternative safety indicators.

11.9.1 Process-oriented conceptual models

A natural continuation of the work presented in the process description /11-13/ is to use process-oriented models. A systems ecology approach takes into account processes and compartments in the ecosystems and can thereby reduce the large spread in transfer constants to avoid overly conservative assumptions in the safety assessment. Since the methodology is based on mass balances, even the simplest model includes the entire radionuclide flow. A more detailed model can shed light on quantitatively important or critical processes. The result is a general model which is flexible enough to be able to answer new questions. The purpose is to be able to judge where substances will accumulate and what ecosystem types and organisms are most sensitive, as well as what the consequences of this are for man. This is a long-term effort and has great significance as a general tool.

Most of the studies in the biosphere programme (e.g. the forest ecosystem, transport, and sediments) will be based on these principles. Specifically within this topic, a framework will be constructed by means of:

- A more in-depth process description.
- A review of existing ecosystem models of radionuclides; alternatively, the enrichment and distribution of analogous substances.
- A simulation of how the complexity and productivity of different relevant types of ecosystems impact on where and how much different substances accumulate in biota.
- Inventory of which databases can be used outside of radioecology.
- Alternative indicators for the impact on the biosphere or on repository performance.

11.9.2 Transport processes

Transport processes determine which ecosystems and organisms will be exposed to radionuclides and how large the dilution is. The greater part of radionuclides in the environment will be bound to particles, humic complexes and organisms. The transport of radionuclides in the biosphere is therefore dependent to a great extent on particle transport. This means that a dilution in water, for example, is an underestimate of the doses that can be obtained. Projects are aimed at evaluating the relationship between particle transport and water transport in aquatic systems and transport of particles and organisms in the terrestrial environment.

- Literature and model studies of particle transport versus water transport.
- Review of circulation in coastal areas with new near-coast oceanographic models.
- Near-surface hydrological models to quantify horizontal transport and discharge areas in the biosphere.
- The importance of migrations of organisms for the dilution of radionuclide content in food.
- Experimental work regarding transport, accumulation and uptake mechanisms through the ecological food chain in aquatic environments.
- Resuspension of sediments (see sediments).
- Transport of food products and its importance for dilution of radionuclides.
- Determine minimum possible transport need for a self-sufficient population.

11.9.3 Forest ecosystem

The forest is the dominant recipient for most hypothetical sitings, but so far few calculations have been made of dispersal and accumulation of nuclides from a deep repository in this ecosystem. The work will be based on literature studies and models. It will chart important mechanisms and processes in the forest ecosystem. This knowledge will then be translated into relevant models that describe and calculate doses for outflows to the forest. Important issues that have been identified so far are:

- Accumulation processes in the soil profile.
- Root transport.
- Enrichment and weathering processes in soils caused by mycelium formation.
- Colloid transport.
- Effects of long-term forestry practices, e.g. felling site burning, ground damages.
- Groundwater fluctuations.
- Discharge areas (see transport processes).

11.9.4 Sediments

A marked change in redox conditions, salinity and biological activity occurs in the boundary layer between sediment and water, which can greatly affect the radionuclide flow. These processes have not been taken into account in the calculations of radionuclide transport from the geosphere to the biosphere. In the short term, these processes will probably reduce the outflow and result in lower doses, but in the long term large quantities of radionuclides may accumulate and subsequently be liberated by land uplift, resuspension or the like, giving rise to high doses. Furthermore, the organisms that live in sediments are exposed to high concentrations, which can be passed on in the food chains to e.g. fish. The work will be based on literature and model studies, but may also require supplementary field work and experimental work.

- Discharge areas will be charted and described.
- Processes that influence dispersal and transport in loose soil strata will be studied.
- Redistribution processes in connection with land uplift.
- Biological uptake mechanisms.
- Chemical and physical processes in the boundary layer.
- Feedbacks to the geosphere and geochemistry.

11.9.5 Long-term variations in climate, land uplift and salinity

The premises for the biosphere are controlled to a great extent by the climate and the distribution between land and water. Water flux, groundwater recharge and surface runoff are some of the most important physical factors influencing the dose. Postglacial land uplift influences which biotope is dominant in an area. Salinity influences which ecosystems will dominate in the Baltic Sea and what properties the radionuclides have. These factors are also important boundary conditions for the transport models in the geosphere. The project area intends to shed light on various conditions in Sweden up to the next ice age. The point of departure will be a reconstruction of events since the most recent ice age and processes occurring in other climate zones. The work will be based on literature studies and modelling. Some important topics are:

- Groundwater recharge and its sensitivity to climate change.
- Past and future runoff.
- Salinity changes in the Baltic Sea due to land uplift and climate change.
- The importance of permafrost and the tundra for radionuclide transport in the biosphere.

11.9.6 Model development

The modelling tools BIOPATH and PRISM require continuous maintenance and development, whereby new insights regarding processes are incorporated. Furthermore, a sensitivity analysis will be performed to test whether the new processes appreciably affect the end result or whether the uncertainty in the parameters affects the result. It is important to test the sensitivity of the models to the variation in site-specific parameters. The result is a detailed plan of which variables have to be determined in site-specific investigations and which can be obtained or calculated from existing sources.

- Sensitivity analysis of existing models.
- Evaluation of measurement accuracy of parameters.
- Model development and maintenance.

11.9.7 International work

Standards, methodology and legislation that are important to comply with and actively propose improvements in are discussed in the international work within such organizations as the IAEA, EU and NKS. Similarly, new findings within radiation biology, environmental protection and systems ecology research that are of importance to the biosphere work are presented. The following activities are considered to be important:

- Active participation in BIOMASS.
- Follow the work within the EU, NKS.
- Follow and present work at important meetings on radiation biology, environment protection and systems ecology.
- Follow the work at SKI and SSI and monitor legislation.
- Present the biosphere work to the public, researchers and students.

11.10 Competence development

The systems ecology perspective that is being introduced requires that knowledge from radioecology be integrated with systems ecology principles based on natural mechanisms. This will be done by enhancing competence at Studsvik with systems ecologists and/or other consultants, but also by introducing radioecological topics to ecologists at universities and institutes of technology to ensure long-term competence development and active research in the future.

A competence build-up is taking place by means of an experimental programme at the University of Kalmar's Marine Biology Laboratory dealing with uptake mechanisms and transport of radionuclides through the food chain in aquatic environments.

12 Other long-lived waste

LILW (low- and intermediate-level waste) is transported to the final repository SFR in Forsmark. Most of this waste comes from the operation of the nuclear power plants, which treat and package the waste prior to shipping it to SFR. A small portion comes from research, industry and medicine, and this waste is packaged and stored in Studsvik, which itself produces similar waste. Studsvik has its own rock cavern for interim storage.

However, some of the waste in Studsvik has too high a content of long-lived radionuclides to be accepted at SFR. This is mainly waste from research, and such waste is currently set aside. Some used reactor internals from the nuclear power reactors, including core components, also have too high a long-lived radionuclide content to be shipped to SFR. They are currently being stored at CLAB (or at the nuclear power plants). A separate section will therefore be built – probably adjacent to the deep repository for spent fuel – for disposal of all long-lived LILW. This section could also receive the short-lived operational waste from the operation of CLAB and the encapsulation plant that arises after SFR has been closed and sealed. Operational waste and decommissioning waste would comprise about half of the volume of the total inventory.

The separate section of SFL intended for other long-lived waste than spent fuel will consist of three different chambers called SFL 3, SFL 4 and SFL 5. Long-lived waste from Studsvik will be disposed of in SFL 3, along with "SFR waste" that arises after SFR has closed. Decommissioning waste from CLAB and the encapsulation plant will be sent to SFL 4, along with sundry leftover equipment in the form of transport casks/containers and the like. SFL 5 will receive the power reactor internals.

A prestudy was made of the performance of the barriers in SFL 3–5 and the results were reported in 1995 /12-1/. The point of departure was the conceptual design presented in SKB's Plan Report from 1993, plus a new inventory and characterization of the waste. The quantity of radionuclides in the waste had been estimated, along with some other components of importance such as metals, organic material, concrete, etc. In the prestudy we tried using the scenario method, which was then relatively new. Some research work was initiated, and foreign organizations with experience in this field were contacted for an exchange of information and cooperation, e.g. Nirex, Nagra and ANDRA.

The goal, which was enunciated in the preceding RD&D programme with regard to long-lived LILW, was to *prepare future safety assessments*, but this has been broadened during the period to *carrying out a preliminary safety assessment*. The work is being conducted in project form. An initial step in the execution of the task has been to improve the estimate of the composition of the waste and come up with a new design for the facility.

12.1 LILW to SFL

The waste sent to SFL 3 will come from Studsvik, CLAB and the encapsulation plant. LILW from Studsvik is mainly packaged in 200-litre steel drums or in concrete moulds. Precipitations are conditioned with cement directly in the drums. Drums with ashes, trash and scrap have a smaller inner drum and a fill of concrete between the drums. Other LILW from Studsvik is packaged in smaller 85-litre steel drums, which are in turn placed in ready-made concrete moulds 1.2 m on a side with room for 5 drums. Smaller quantities of waste can be packaged in another manner. The waste from Studsvik contains some organic material, and there are even some toxic metals such as lead, cadmium and beryllium.

The operational waste from CLAB is currently packaged in concrete moulds 1.2 m on a side. Ion exchange resins are conditioned with cement and solid waste is embedded in cement. We have assumed that future operational waste from encapsulation will be treated in the same way.

The total volume of packaged waste in steel drums or concrete moulds in SFL 3 is estimated to be about 6,000 m^3, of which 2,000 m^3 comes from Studsvik and 4,000 m^3 from CLAB and the encapsulation plant. The dominant radionuclide in the waste during the first 700 years is ^{63}Ni, after which ^{59}Ni dominates. We have chosen 2040 as year zero, since that is the year closure of the facility is expected to take place. The calculated activity content of different waste types is based on experience from measurements and the use of correlation factors (for unmeasured nuclides).

The waste to SFL 4 will be low-level and consist of decommissioning waste from CLAB and the encapsulation plant, transport casks/containers and storage canisters for spent fuel from CLAB. Emplacement in SFL 4 will thus take place at a late stage. The decommissioning waste from CLAB consists of contaminated metallic parts from cooling and purification systems in the facility, plus residues of chiselled-off contaminated concrete. The storage canisters for spent fuel from CLAB will either be decontaminated and released for unrestricted use or emplaced in SFL 4. For the time being we have assumed the latter. The decommissioning waste from the encapsulation plant will be of the same type as from CLAB, but the quantities will be smaller. All decommissioning waste is packaged in steel cases 2.4 m on a side.

The total volume of waste to SFL 4 is estimated at 10,000 m^3. Most of it consists of steel and concrete. We expect to be able to avoid organic material. The activity content of SFL 4 will be relatively low and dominated by ^{60}Co during the first 20 years.

The waste sent to SFL 5 will consist almost entirely of metallic parts that have been in the reactors for a long time and are therefore neutron-activated and surface-contaminated (from primary reactor water). On decommissioning of the nuclear power plants, large quantities of low-level decommissioning waste will be shipped to SFR for final disposal, while reactor internals and core components will be interim-stored in CLAB for at least 30–40 years before disposal in SFL 5. This also applies to components with a high specific activity that have been replaced during reactor operation. Future decommissioning waste from the research reactor at Studsvik will also be accommodated. According to current plans, the waste to be sent to SFL 5 will be packaged in 4.8-m-long and 1.2-m-wide concrete moulds with an inner steel cartridge. The package will be backfilled with cement mortar.

The total volume of waste to SFL 5 is estimated at around 10,000 m^3. The waste consists of stainless steel and some other metals but does not contain any organic material. It contains some toxic metals such as lead (lead channels) and beryllium (Studsvik waste). The activity content of SFL 5 is higher than that of SFL 3 and 4. At the time of final disposal, the activity content will be dominated by ^{63}Ni, ^{60}Co and ^{3}H (from BWR control rods). In a longer perspective, ^{63}Ni will dominate during the first 700 years, and then ^{59}Ni.

12.2 Repository design and layout

Based on the quantity of waste and the types of waste packages that have been proposed, a new layout has been devised for SFL 3–5 /12-2/. This repository is proposed to be an annex to the deep repository for spent fuel, SFL 2. The idea is to place SFL 3–5 at a depth of between 300 and 400 m at a distance of at least 1 km from SFL 2. The two repository chambers SFL 3 and 5 consist of two identical rock vaults, and SFL 4 is simply the tunnels that lie around SFL 3 and 5, see Figure 12-1. Much of the experience gained from SFR has been utilized. The design of SFL 3 and 5 is based on the rock vault for LILW in SFR, see Figure 12-2.

SFL 3 consists of a rock vault with a loading-in section for waste at one end and a loading-in section for concrete at the other end. The two connecting tunnels are so long that tunnel plugs can be cast after completed deposition. The enclosure is divided into three separate sections, which are in turn divided by partitions into 7 different pits. The waste packages are placed in the pits and backfilled stepwise with porous concrete. When one pit is full, it is covered with a lid (concrete slab) and a concrete overpack. After completed deposition, the rock vault is backfilled with crushed rock and concrete plugs are cast.

When deposition in SFL 3 and 5 is concluded, the transport tunnels outside, i.e. SFL 4, can be used for deposition. SFL 4 is separated from other chambers by concrete plugs. Altogether, about 700 m of tunnel is needed to accommodate all decommissioning waste and other waste. The waste packages are placed on the tunnel's concrete roadbed, which is in turn laid on compacted gravel. After completed deposition, the tunnels are backfilled with crushed rock.

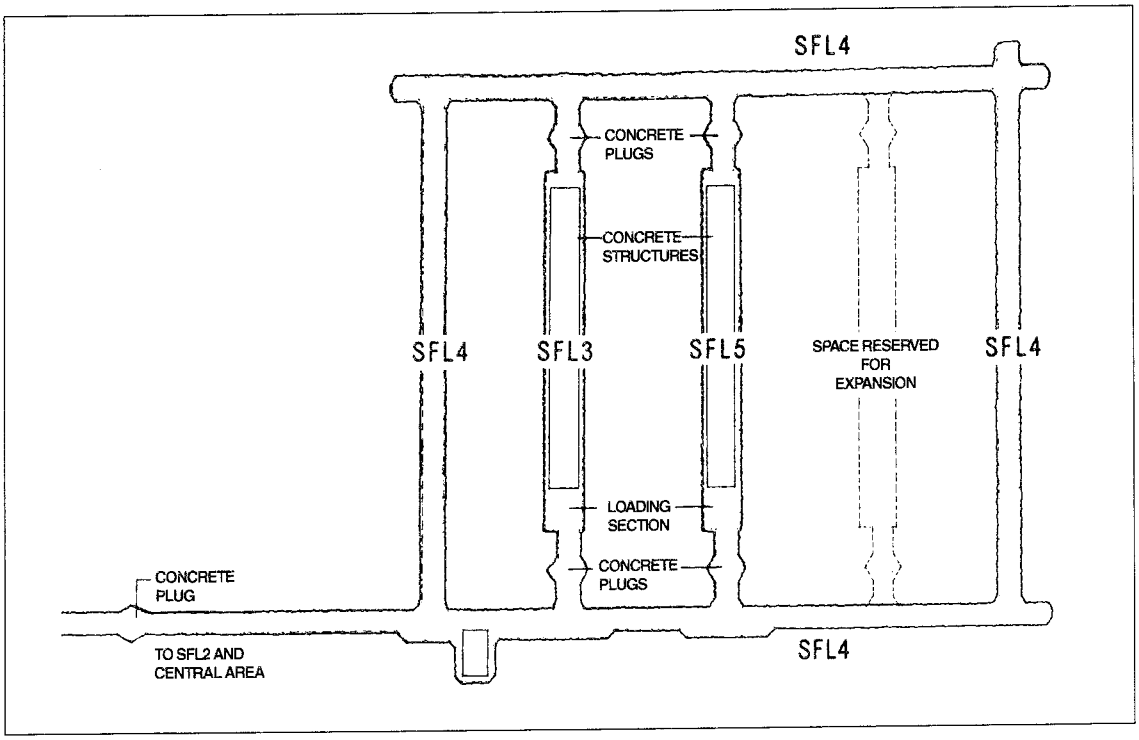

Figure 12-1. Schematic plan of SFL 3–5.

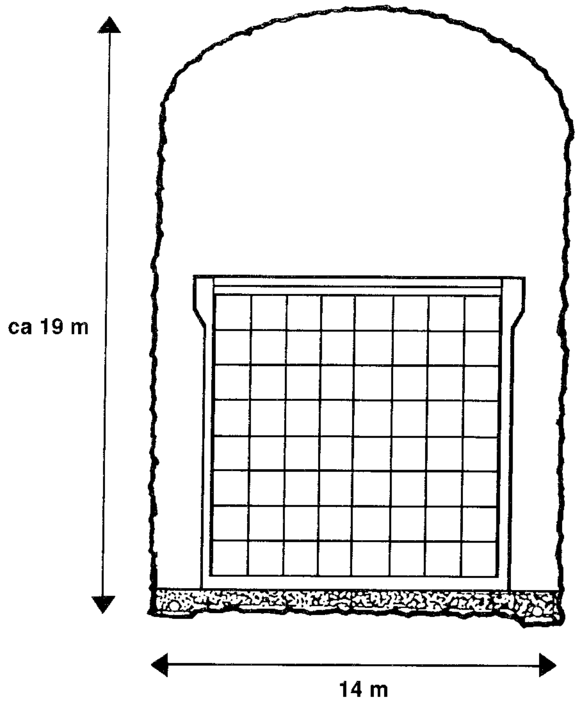

Figure 12-2. *Schematic cross-section of SFL 3 and SFL 5. The concrete structure containing the waste packages rests on a bed of gravel. The empty spaces between the rock and the concrete structure are backfilled with crushed rock at closure.*

SFL 5 is more or less identical to SFL 3. This is possible due to the fact that operational waste and core components are packaged in the same standard module. The concrete moulds are stacked in the pits and backfilled with porous concrete.

Because SFL 3 and 5 are identical, the waste can, if necessary, be distributed between them. It is also possible to extend SFL 3 and 5, or build another rock vault parallel to the other two, see Figure 12-1. Approximately 700 m of a total available tunnel length of about 900 m has been utilized for SFL 4.

12.3 Performance and safety

The engineered barriers in SFL 3–5 consist of waste packages, backfill of porous concrete, concrete structures, backfill of crushed rock and concrete plugs. The stability of the concrete and its influence on the chemical environment are of importance for the properties of the barriers. The concrete that is usually used for this purpose is Degerhamn Standard Portland cement. It is sulphate-resistant due to its low aluminium content. The readily soluble alkali hydroxides in fresh cement cause a high pH. If the alkali hydroxides are leached out, the pH declines slightly and is stabilized by portlandite instead (pH 12.5). It will take a very long time to leach out all portlandite from the repository, and it is essentially this that will determine the chemistry in the near field, even in the very long term. Chemical retention of radionuclides due to low solubility, high sorption and slow diffusion are essential properties of the barriers in the repository.

The groundwater can influence the chemistry in the near field and contribute to transport of radionuclides. Even if the repository is located at great depth and the site is selected with care, some water flow in the rock fractures around the repository must be expected. But flow in the concrete structures and the waste is avoided by diverting the water through the backfill of crushed rock (hydraulic cage). It is a simple and effective arrangement. Johan Holmén has examined the hydraulic conditions in SFL 3–5 and presented this in a doctoral thesis at Uppsala University /12-3/.

Since the water flow in the concrete structure and the waste is very low, diffusion plays a greater role. The computer code NUCTRAN has been developed to calculate the transport of radionuclides from a damaged canister in SFL 2 /12-4/. Slightly simplified, it can be said that NUCTRAN works like a three-dimensional calculation model with finite differences, but fewer cells are needed, which shortens the computation times. This method can also be applied to the near field for SFL 3–5. It has been tested by using both NUCTRAN and TRUMP and then comparing the results. The computer code TRUMP uses the traditional method of finite differences for calculations like these. The comparison showed that NUCTRAN can be used to advantage to calculate the release of radionuclides from SFL 3–5 /12-5/.

System and process descriptions are used as a method for analyzing the long-term safety of the repository. The work builds further on the scenario description formulated in conjunction with the prestudy /12-1/. Examples of important processes in SFL 3–5 are water flow, gas transport, metal corrosion, chemical degradation of organic material, cement dissolution, ettringite formation, and everything that has to do with the release and transport of radionuclides.

12.4 Laboratory investigations

Laboratory investigations are being conducted to gather the necessary data and devise models for assessing long-term safety. The work is primarily aimed at the chemistry of the radionuclides in the repository (solubility, sorption, diffusion, etc.), the influence of organic substances and the evolution of the concrete. Prior to the preliminary safety assessment of SFL 3–5, basic chemical data will be compiled on the concrete, water composition (in the repository), sorption, diffusion and solubility of radionuclides, plus the influence of organic material. Experiments are being conducted and some have been reported. The intention is that the experimental programme should continue after the safety assessment has been completed.

Composition and properties of cement have been described in a technical report /12-6/. Even though modern cement of the Portland type has not existed for very long, there is reason to be more optimistic than in previous safety assessments as far as the long-term properties of the concrete are concerned. There is a tendency for old concrete to get better with time, provided that it is kept in nearly stagnant groundwater, such as in a repository.

Leaching tests have been carried out with crushed concrete and simulated groundwater /12-7/. Both normal and saline groundwater was simulated. The evolution of pH and dissolved ions was analyzed. The minerals were examined to see what secondary phases were formed. The results were evaluated. Similar studies have been performed in e.g. the UK and Switzerland. A general conclusion is that the concrete controls the chemistry in the near field as long as the waste is of any safety-related importance, at least if the groundwater flow is low.

Most measurement values that are needed to calculate sorption, diffusion and solubility have been taken from the literature, but additional measurements have been made where information has been lacking or scarce. An example is the influence of cellulose degradation products. In concrete pore water, cellulose is broken down to isosaccharinic acid, which is a strong complexing agent. It affects e.g. the solubility of plutonium. Further experiments have been conducted to measure how diffusion and sorption of different radionuclides in cement are affected by isosaccharinic acid /12-8/. The experiments show that sorption of trivalent and tetravalent actinides is negatively affected, but a recovery takes place. Isosaccharinic acid is itself sorbed on cement, which is the probable explanation for why radionuclide sorption made some recovery. Sorption of nickel and caesium was not affected at all. The work is continuing and more results are on the way.

It has been claimed that a high pH from cement could reduce the rock's retention capacity. Weathering might clog the micropores in the rock and thereby obstruct matrix diffusion. Experiments performed in cooperation between Nuclear Chemistry at Chalmers and BGS (British Geological Survey) provide no support for such assumptions, but rather show that matrix diffusion is possible even after weathering products have precipitated /12-9/.

12.5 Goals and programme

The overriding goals of the activities are to:

- Inventory and characterize existing and foreseen waste.
- Refine the design of the repository.
- Prepare for and carry out safety assessments.

The work up to mid-1999 will be conducted in project form (Other Waste) and the goal of the project is to:

- Carry out a complete safety assessment of SFL 3–5 and publish the results.

When this has been done (by mid-1999), the activities will shrink in scope, become more research-oriented and be concentrated on the overriding goal of *preparing future safety assessments*. To carry out the preliminary safety assessment, the following activities are being pursued:

Waste characterization

- Specify quantities and volumes of existing and foreseen waste.
- Calculate the content of different radionuclides.
- Estimate the content of different materials.
- Discuss uncertainties.
- Compile the results in the report.

Basic chemical data

- Compile measurement values on diffusion, solubility and sorption of radionuclides.
- Determine the influence of organic substances (especially cellulose).
- Report the properties of groundwater and concrete in the repository.

Safety assessment

- Formulate scenario descriptions and perform scenario selection.
- Calculate radionuclide transport (for selected scenarios).
- Calculate dose (for selected scenarios).
- Give an account of long-term safety for SFL 3–5.

The ongoing activities are focused entirely on carrying out the preliminary safety assessment for SFL 3–5. Once that goal has been achieved, the scope of the activities within the programme Other Waste will diminish. The manpower resources that are then freed can be used to carry out performance assessments in other projects (e.g. SAFE, aimed at conducting a new safety assessment of SFR). Activities within the programme Other Waste are limited to research, with the goal of preparing future safety assessments. As a step in the new direction of the programme Other Waste, we are planning a cooperative programme with Studsvik Material so that we can make use of the alpha boxes available there. That would make it possible for us to conduct experiments with actinides and organic material under relevant repository conditions, i.e. with concrete pore water and high pHs.

12.6 Competence development

The long-term research that is being conducted to describe the chemistry of the radionuclides in a repository with concrete and various organic components entails an addition to the research activities being pursued on the topic Nuclear Chemistry. Results and expertise will also be able to be utilized for e.g. SFR. It is above all the Department of Nuclear Chemistry at the Chalmers University of Technology that has conducted the studies to date, but we have also drawn on the nuclear chemistry expertise at the University of Linköping (Prof. Bert Allard). Access to alpha boxes at Studsvik Material represents a further strengthening of the resources for nuclear chemistry work. Alpha boxes are an important resource for experimenting with actinides, and the only other place in Sweden where similar equipment is available is at Chalmers University of Technology.

13 Alternative methods

13.1 Partitioning and transmutation

13.1.1 Background

The purpose of transmutation is to reduce substantially the quantity of long-lived radionuclides that have to be disposed of.

The substances which make the greatest contribution to the long-lived radiotoxicity of the spent nuclear fuel are the so-called "transuranics" or transuranic elements, i.e. mainly plutonium but also neptunium, americium and curium. One tonne of spent nuclear fuel contains approximately 10 kg of plutonium and a total of about 1 kg of the three other transuranics. In time another 1 kg or more of plutonium is converted to americium and then to neptunium by decay of plutonium-241 (half-life approx. 14 years) and americium-241 (half-life approx. 430 years). Long-lived fission products and activation products such as technetium-99, iodine-129, caesium-135 and carbon-14 have much less radiotoxicity but are on the other hand more mobile in the geological environment that exists in the Swedish crystalline basement.

Transmutation entails transforming (transmuting) long-lived radionuclides to stable or short-lived nuclides by bombardment with neutrons in a nuclear reactor, i.e. the same nuclear reactions that take place in an ordinary nuclear reactor. The most effective reaction for transmuting transuranics is nuclear fission, other nuclear reactions lead to the formation of other long-lived radionuclides. The process also generates large quantities of energy that can be used to produce electricity, for example.

In order for the process to achieve its purpose, the long-lived nuclides to be transmuted must be separated (partitioned) from the remaining uranium, which comprises about 95% of the remaining fuel. Otherwise new long-lived radionuclides will be formed by nuclear reactions between uranium and neutrons, i.e. in the same way as the transuranics were themselves formed (neutron capture) in the ordinary reactors. If, on the other hand, it is considered desirable to make fuller use of the energy content in the uranium extracted from the earth's crust, the uranium can also be returned to the reactor and converted to plutonium to generate more energy. Reprocessing (and separation of different nuclides) is thus a prerequisite for transmutation (in both cases). We therefore speak of Partitioning and Transmutation (P&T) as a concept.

A goal that is sometimes stated for transmutation is to reduce the quantity of long-lived radionuclides by a factor of 100. If this succeeds, the radiotoxicity of the remaining high-level waste would, after about 500 years, lie at a level comparable to that of spent nuclear fuel after about 100,000 years. The remaining long-lived nuclides would still have to be disposed of in a deep repository. However, the design of this repository would be changed and the requirements on the engineered barriers would be reduced.

A first step, which is already applied in many countries, is to reprocess the spent nuclear fuel and re-use the plutonium and uranium in new nuclear fuel. This greatly reduces the quantity of plutonium in the waste to be disposed of. However, this can only be done on a limited scale in today's reactors (LWRs). Reprocessing and recycling of plutonium can be done two or three times before the composition of the plutonium is such that the reactor's safety and operating characteristics are adversely affected. Furthermore, repeated recycling leads to an increase in radiation protection problems during fuel fabrication.

The use of a combination of partitioning and transmutation to reduce the quantity of long-lived radionuclides in waste from nuclear energy production was proposed back in 1964 by Steinberg and co-workers /13-1/. The development of P&T up to the end of the 1980s has been described by Croff in a study published in 1990 /13-2/.

Some research funded by the National Council for Radioactive Waste (Prav) at the Department of Nuclear Chemistry at Chalmers University of Technology was conducted in Sweden in the 1970s and early 1980s. Interest in this research waned as interest in reprocessing and plutonium recycling cooled.

Interest in P&T was reawakened by technological developments during the 1980s and was manifested at an international conference in Saltsjöbaden in 1991 /13-3/ as well as by political decisions in several countries. In the 1990s, the development of accelerator technology led to an awakening of interest in exploring the possibility of using accelerator-driven systems for transmutation.

SKB's RD&D-Programme 1992 /13-4/ proposed that a deep repository for spent nuclear fuel should be built in stages. An initial stage would include a small quantity of spent fuel and be followed by a careful evaluation of the results of this stage and by parallel research and development on alternative methods in Sweden or abroad. As a basis for this future evaluation, SKB considered it urgent to support and, to some extent, initiate Swedish research on interesting alternative methods, particularly transmutation of long-lived radionuclides. The programme stated that it was of particular interest to study the degree of separation of long-lived nuclides, the technically feasible efficiency of transmutation, material problems and the reliability and safety of the processes.

SKB therefore initiated cooperation with the Department of Nuclear Chemistry at Chalmers University of Technology in Gothenburg and with the Centre for Safety Research and the Department of Neutron and Reactor Physics at the Royal Institute of Technology in Stockholm. This cooperation has been broadened slightly over the years.

During the 1990s, development in the field has been summarized in a number of technical reports from SKB /13-5, 13-6, 13-7, 13-8/. The situation up to the beginning of 1998 is summarized in a recently published report in Swedish /13-9/. See these reports for a more detailed review of various technical questions and Swedish studies. The reader is also referred to the series of SKB Annual Reports for the years 1993–1997 /13-10, 13-11, 13-12, 13-13, 13-14/.

13.1.2 State of knowledge

The feasibility of carrying out partitioning and transmutation as a step in the management of spent nuclear fuel (SNF) and high-level waste (HLW) can today be considered to be more or less scientifically proven. However, it is still too early to judge whether this type of waste treatment has cost or safety advantages in a short time perspective compared with present-day plans for management of SNF and HLW. Neutrons from thermal reactors, fast reactors and accelerator-driven subcritical reactors can be utilized for transmutation of long-lived radionuclides.

Thermal reactors and fast reactors have been built and operated with good experience for a long time, while accelerator-driven systems still only exist on the drawing board. Each of these neutron sources has its advantages and disadvantages for transmutation, and each is presumably best-suited for certain types of radionuclides. Upon comparison, it is generally agreed today that transmutation in reactor types with high-energy (fast) neutrons has advantages with regard to reduction of the total quantity of heavier transuranics, coupled with relatively efficient energy production. Reactors with low-energy (thermal) neutrons, on the other hand, have advantages if the sole aim is to reduce the quantity of certain radiotoxic nuclides and produce energy at a low cost.

A possible development in the future would be the use of systems with multiple reactor types. Scenarios along these lines have been described in French /13-15/ and Japanese studies. Thermal reactors and/or fast reactors are used for energy production and for burning of plutonium. The special properties of an accelerator-driven system are exploited to bring about an effective transmutation of neptunium, americium and possibly curium, as well as possibly other radionuclides with small reaction cross-sections. The accelerator-driven system is then a complement to more conventional nuclear reactors.

As already mentioned, all transmutation processes must be combined with an appropriate chemical separation process where untransmuted material is recovered from irradiated material with high efficiency. What is left is radioactive waste. When judging the efficiency of a combined P&T process, there is a strong link between the recovery rate of the partitioning process (reprocessing), the efficiency of the transmutation process (burnup, conversion rate of long-lived radionuclides) and the losses of untransmuted material to different waste streams. Both aqueous liquid-liquid extraction and different pyrochemical separation methods have been proposed for the partitioning process.

Extensive knowledge exists regarding aqueous liquid-liquid extraction, based on more than 40 years of experience of industrial-scale operation. As a result, both the advantages and problems associated with this technique are well understood. On the other hand, pyrochemical separation methods for treatment of radioactive substances are still considered to be in the laboratory stage and require considerable further development of both methods and new types of equipment. As a result, we still lack good knowledge of the advantages and disadvantages of these methods in the treatment of radioactive materials on an industrial scale. It is still too early to try to compare aqueous chemistry with pyrochemistry on an equivalent knowledge basis.

Interest in pyrochemistry is currently greatest in the USA and Russia, while the big nations in the EU and Japan continue to focus most of their development efforts on improvement and further development of aqueous methods. If P&T is to be a realistic alternative to present-day fuel cycles, further large-scale and long-term R&D efforts in the area of separation technology are required.

It is quite clear today that P&T cannot eliminate the need of a final repository for high-level waste. In a short perspective, the radioactivity of the waste will in fact be even higher than in the spent fuel, owing to the fact that long-lived radionuclides are largely transformed to much more short-lived ones. The shorter half-life means, on the other hand, that the radiotoxicity of the waste declines relatively rapidly. Despite the use of an efficient P&T method, the waste will contain smaller quantities of very long-lived radioactive substances.

Processing of the fuel is also a means of producing plutonium or other fissionable material in relatively pure form. Nevertheless, there are certain ways to design the fuel, spallation target or whole accelerator-drive systems to be more proliferation-resistant than is the case with ordinary reactors and fast reactors.

13.1.3 Swedish work

Activities at CTH

Development of selective high-efficiency separation processes began in 1974 at the Department of Nuclear Chemistry, Chalmers University of Technology (CTH) in Gothenburg, with financial support from the National Council for Radioactive Waste (Prav), and in the beginning also from AB Atomenergi.

The project led to pilot-scale trials at the beginning of the 1980s with the use of 16 litres of concentrated high-level waste solution from the old Norwegian-Swedish reprocessing plant in Kjeller, Norway. The function of both chemistry and apparatus was thereby verified. The process worked more or less as expected and yielded very good separation at an extremely high efficiency. For example, total efficiencies were measured of >99.8% for neptunium, >99.99% for plutonium and >99.83% for americium. After the liquid-liquid extraction-based separation process, purified HLW contained less than 1/100,000th of the original alpha activity. Most of the results have been published /13-9/.

The Department of Nuclear Chemistry at Chalmers University of Technology has been conducting an SKB-funded project in the field of P&T since 1991, and since May 1996 the Department is also participating in the EU programme Nuclear Fission Safety and in the project NEWPART (New Partitioning Techniques). Other organizations participating in the NEWPART project include CEA (France), the University of Reading (England), the European Transuranic Institute (EU), Forschungszentrum Karlsruhe (Germany), Forschungsanlage Jülich (Germany) and ENEA (Italy). The Department is also collaborating on a less formal basis with LANL (USA) and JAERI (Japan).

Activities at the Department include development of new aqueous separation processes. To reduce the quantity of waste from future advanced separation processes, the extraction reagent contains only carbon, hydrogen, oxygen and nitrogen (the CHON principle), which means that the reagent is completely burnable and does not contribute to the secondary waste. Three different types of reagents are being studied.

Activities at KTH

The research in the field of transmutation at the Royal Institute of Technology (KTH) in Stockholm is primarily concentrated on accelerator-driven systems (ADS). This research has developed considerably in recent years. At present, five researchers are working on the project, funded mainly by SKB. The research is primarily focused on:

Neutronics in accelerator-driven systems

Careful investigations of the transmutation behaviour of acceleration-driven systems as a function of the neutron spectrum are necessary. A thorough analysis has been made of simulations performed by Monte Carlo methods. The analysis shows that liquid lead as a coolant makes it possible to sustain constant transmutation rates for many isotopes, even with wide variations in concentration. Lead also makes it possible to reach the resonance cross-section range for long-lived fission products such as ^{99}Tc and ^{129}I.

Burnup calculations

A coupling between Monte Carlo code for simulation of neutronics at a fixed composition of the fuel and a burnup code has been developed as a part of a project aimed at creating a complete tool for calculations on accelerator-driven systems.

Spallation process

Understanding of accelerator-driven systems is incomplete without studies of the spallation process. Such studies are being carried out with the aid of the high-energy transport code FLUKA. Calculations of heat generation in, and optimization of, targets are among the most important results thus far.

Radiotoxicity

Studies of the radiotoxicity of materials formed in the spallation process and their contribution to the toxicity of the waste from an accelerator-driven system on a long timescale are being conducted with the aid of the calculation codes FLUKA and ORIGEN.

Reliability and safety for accelerators

A study is being conducted with the goal of creating a database with information on accelerator behaviour to permit probability-based safety assessments and reliability projections. The project has been initiated in cooperation with LANL (Los Alamos National Laboratory) in the USA.

International cooperation

International cooperation is mainly focused on projects being conducted jointly with the Los Alamos National Laboratory in the USA and IPPE (Institute of Physics and Power Engineering) in Obninsk, Russia. The KTH group has formulated, been assigned and carried out the certification process for an ISTC project – fabrication of a spallation target of liquid lead/bismuth – in Obninsk. (ISTC = International Science and Technology Center in Moscow, funded mainly by the USA and the EU.) The target is an indispensable part of the experimental activities that are needed to prepare a future demonstration plant for accelerator-driven systems. The goal is to carry out bombardment of the fabricated spallation target in LANL's linear accelerator within 2–3 years from now.

The group is also participating in studies of subcritical kinetics in the French MASURCA reactor at CEA/Cadarache, which is driven by an external neutron source.

Cooperation has been initiated with the EU's research centre in Ispra, Italy, to investigate the thermohydraulics of liquid metals with simulation tools.

The Section for Reactor and Neutron Physics at KTH is coordinating the EU project IABAT (Impact of Accelerator BAsed Technologies on nuclear fission safety).

Other activities in Sweden

A project is being conducted at the Svedberg Laboratory in Uppsala for measurement of cross-sections for neutrons in the high-energy range 20 to 100 MeV, which is of great interest to furnish data for calculations on accelerator-driven systems. The project is being funded in part by grants from SKB, the nuclear power plants and SSI.

13.1.4 Assessment of the future of partitioning and transmutation

Widespread international agreement exists among competent organizations and experts that even a successful development of partitioning and transmutation (P&T) will not eliminate the need for a deep repository /13-16, 13-17/. It may, on the other hand, alter the design premises for the deep repository and its barriers and greatly reduce the quantity of long-lived radionuclides that need to be deposited in the deep repository.

Development of P&T involves development of new nuclear technology and requires substantial resources and time. Large national programmes exist in France and Japan. According to a 1991 law, the French are aiming at an interim goal to be reached in 2006. The costs of the programme are reported to be US$ 600 million over 15 years /13-19/.

The Japanese have not stipulated any exact timetable for their programme. The costs lie in the order of tens of millions of dollars per year /13-19/.

In the USA, Los Alamos National Laboratory has proposed a five-year (to begin with) development programme aimed at accelerator-driven transmutation /13-18/ at a cost of US$ 115 million. The ambition is to then continue with a half-scale demonstration plant.

Within the EU, there are proposals to increase funding of the development of accelerator-driven systems based on ideas put forth by Carlo Rubbia at CERN /13-16/.

However, these programmes are just the beginning of the development work before the necessary verifying large-scale tests can be performed. Successful development and application of P&T will also require an adaptation of the entire nuclear fuel cycle with respect to recovered uranium. Extensive international cooperation will be needed to succeed in this undertaking. For Sweden's part, such cooperation can take place within the EU, for example.

The premises for an application of P&T differ from country to country. The countries that reprocess their fuel today – e.g. Belgium, France, Japan, Switzerland, the UK and Germany – have already taken the first necessary step of separating out residual uranium and plutonium. Other countries that have opted for direct disposal – e.g. Finland, Spain, Sweden and the USA – must abandon this line. Considering time and costs, Development and application of P&T is more likely in a scenario with continued use, renewal and possible expansion of nuclear energy than in the opposite case.

In the Swedish scenario with a legislated decision not to build new nuclear power plants, a future domestic application of P&T would require a reversal of this decision – it would be ill-considered to build a plant for P&T without making use of the energy generated in the transmutation process. A conceivable future alternative might also be to purchase P&T at foreign plants and then "merely" deal with the waste.

The costs of P&T are naturally impossible to calculate with any certainty before the principal design of the system has been determined. A scenario for the USA encompassing plants for accelerator-driven transmutation of 70,000 tonnes of spent nuclear fuel from the approximately 100 American LWRs /13-18/ has a reported estimated cost of about SEK 320 billion in investment and about SEK 10 billion per annum for 65 years of operation – for a total of nearly SEK 1,000 billion over a period of about 65 years. This does not include development costs. During this time, the quantity of transuranics would be reduced from about 600 tonnes to less than 1 tonne. At the same time, approximately 4,000 TWh of electricity (worth about SEK 0.25/kWh or a total of about SEK 1,000 billion) would be obtained. How the costs of deep disposal enter into this calculation is unclear.

An important question that requires further research is the trade-off between a further reduction of a relatively small, perhaps only hypothetical, risk far in the future on the one hand, and a considerable increase in the risk of exposure in the present or in the near future due to greatly increased handling of short-lived radionuclides on the other hand.

Application of P&T is in one respect something of an "all or nothing" enterprise if the motive is merely to "simplify" final disposal. It requires that all spent nuclear fuel undergo the treatment. If any fraction is exempted, disposing of this fraction will in principle require the same engineered barriers, development and licensing (and evoke the same concern and questions) as direct disposal of all spent fuel.

The development of new nuclear technology may also have the goal of more efficiently exploiting the energy content in the uranium extracted from the earth's crust. In this scenario, transmutation may be an interesting and important "by-product" that will significantly influence the future management of the spent nuclear fuel.

Development of P&T has attracted strong interest on the part of many people. Continued research can help to maintain a high level of competence in the field of nuclear technology during the time such technology comprises an important resource in society.

There is a widely-held scientific conviction that present-day types of fuel cycles, in combination with planned waste management and geological repositories, will offer adequate protection for humanity for all foreseeable future time. At the same time, however, there is considerable interest in exploring the possibility of whether a further reduction of the future potential hazard of the waste can be obtained by partitioning and transmutation, and at what cost this can be accomplished. The strength of a P&T process would be that it would also drastically reduce the hypothetical possible future consequences of unforeseen events. On the other hand, a broad commitment to the development of P&T processes will obscure the fact that the future risks of a well-executed deep repository are already deemed to be very small.

13.1.5 Programme for the period 1999–2004

Goals

The goals of SKB's R&D regarding partitioning and transmutation of long-lived radionuclides are:

- to review how this technology is being developed and how it may affect waste streams from nuclear installations and their nuclide content,
- to judge if, how and when this technology can be utilized to simplify, improve or develop a system for final disposal of nuclear fuel waste from the Swedish nuclear power plants.

Data are being gathered continuously in accordance with annual activity plans. Overall assessments are made before important decisions in the nuclear waste programme. Thus, according to the requirements on alternative methods reporting, an assessment of P&T methods is to be included in the supporting documentation for decisions on the siting of the encapsulation plant and the deep repository. An overall assessment will also be made in conjunction with the evaluation following the initial stage of deposition of encapsulated nuclear fuel in the deep repository.

Future direction of the work

SKB's main task is to manage and dispose of the nuclear fuel waste in a safe manner (Section 10 of the Nuclear Activities Act). We also have a responsibility to follow and participate in the development of various alternative methods for managing and disposing of spent nuclear fuel, and to evaluate how these methods can affect long-term disposal. This is fully compatible with the main line of building an initial stage of a deep repository for encapsulated spent fuel.

SKB notes that accelerator-driven systems is currently the alternative line of development for P&T that is attracting the greatest interest both in Sweden and in several other countries. The development of such systems is very costly and heavily dependent on international collaboration. SKB further notes that several fundamental technical questions need to be further cleared up by research before major projects can be defined regarding accelerator-driven systems. In view of the development situation, the resources needed and relevant energy policy decisions in Sweden, we do not deem it prudent for us to initiate major development projects.

SKB intends to continue conducting domestic research at universities and institutes of technology with roughly the current scope. The primary purpose of the research should be to help to clarify fundamental technical questions pertaining to partitioning and transmutation. Particular emphasis should be placed on questions relating to safety, materials, process design and the composition of the waste streams. In this way domestic competence is created and a knowledge bank is built up to enable SKB to assess the prospects and characteristics of systems for P&T. The work will continue to be pursued in close contact with international development work in the field.

SKB is also open to the possibility of participating at an appropriate time and in an appropriate fashion in any international projects – particularly EU projects – that may be launched.

13.2 Disposal in deep boreholes

13.2.1 Geoscientific premises

One of the alternatives for deep disposal being studied by SKB is emplacement of canisters in very deep (2,000–4,000 m) boreholes, known as the VDH (Very Deep Hole) concept. During the past three-year period, a study for the purpose of knowledge-building has been carried out of the geoscientific conditions at great depths (1,000–5,000 m) in crystalline bedrock /13-20/. In an introductory part of the study, available geoscientific data from relevant geological environments in different parts of the world are compiled. These data are based on investigations in deep boreholes and mines and on geophysical measurements from the ground surface. The presentation is broken down into the following topics: lithology, fracture mineralogy, fracturing, temperature, permeability, pore pressure, mechanical properties, state of stress, seismicity, fluid composition and bacteria. Based on these data, an integrated interpretation has then been carried out and a conceptual geoscientific model of general conditions down to a depth of 5 km proposed. In summary, the following conclusions are drawn concerning these geoscientific conditions:

- It is relatively easy to predict lithology in granitic bedrock down to about five kilometres.
- Fracture mineralogy can be an indicator of how an observed fracture was formed. If the mineral composition is in equilibrium with the surrounding rock, then the fracture probably formed under ductile conditions. Otherwise the fracture probably formed under brittle conditions. Brittle fractures are probably the most water-conducting.
- Surface- and borehole-geophysical data show that the frequency of open fractures declines significantly below about one kilometre.
- Despite a scarcity of data, the study shows that the average permeability is around three orders of magnitude lower at a depth of 5,000 m than at 1,000 m.
- In general, the pore pressure is close to the hydrostatic pressure. (The exception is the deep Kola borehole, where approximately 50% higher pressures have been measured in the depth interval 1,000–2,800 m).
- Mechanical properties in terms of fracture strength and deformation can be measured at the surface and are relevant at depth.
- Rock stress appears to increase linearly down to a depth of about five kilometres. The magnitude of the vertical stress generally lies between the magnitudes of the horizontal stresses, which reflects a tectonic regime characterized by strike-slip faulting.
- The groundwater down to a depth of at least about 500 m is a mixture of differing origins, but is dominated by fresh meteoric water. Exceptions are areas below former highest coastlines, which at shallower levels can exhibit remnants of fossil saline water. At great depths, below 1,000 m, brines (waters with very high salinities) are often encountered.
- The geothermal gradient in the Fennoscandian Shield is 15–20°C/km. (These temperature gradients have also been predicted with reference to the heat flow in the shield's lithosphere.)
- By international comparison, Sweden has a low earthquake activity. However, the possibility of earthquakes with magnitudes of 5 or 6 cannot be excluded. A few earthquakes with epicentres in the upper 5 kilometres have occurred during the 20th century.
- New investigations have shown that bacteria live at great depths in the bedrock, independent of the biosphere, and are capable of producing methane. This means that certain previous interpretations of the chemical evolution of the groundwater may have to be modified.

In general, the bedrock can be described by saying that the upper kilometre contains considerably more open fractures than the deeper portions. Water-filled or water-conducting fracture zones exist down to very great depths, however. In areas with a relatively flat topography, active groundwater circulation is mainly limited to the upper kilometre, while the water has a relatively high salinity below this level. The very saline, deep groundwater exists in a nearly stagnant environment. In areas with greater topographical differences, infiltrating fresh water can be driven down to deeper levels. These are the main features of the conceptual geoscientific model.

13.2.2 Goals and programme

SKB's goals for the coming six-year period, 1999–2004, are to:

- perform a system analysis of the alternative repository with deep holes,
- perform a safety and performance assessment for the VDH concept.

The drilling technology aspects of the VDH concept were examined in the aforementioned study, but the deposition technique must be developed and evaluated so that a radiologically safe procedure is achieved. A follow-up of the previously executed PASS study (Project Alternative Systems Study) /13-21/ is therefore planned. When the system analysis is finished, a relatively comprehensive performance and safety assessment will be performed. The study will be based on the databases and the conceptual model that have now been produced.

In the absence of deep boreholes, the proposed conceptual model can be tested and possibly improved with the aid of certain geoscientific measurements and studies. Such studies can be integrated with SKB's other programmes for development of investigation methods and coordinated with the activities being pursued for supportive geoscientific R&D.

14 Äspö Hard Rock Laboratory

14.1 Introduction

A proposal for the construction of an underground hard rock laboratory was put forth in R&D-Programme 86 /14-1/ and was very positively received by the reviewing bodies. In the autumn of 1986, SKB began field work for the siting of the underground laboratory in the Simpevarp area in the municipality of Oskarshamn. At the end of 1988, SKB made a decision in principle to site the laboratory on southern Äspö Island about 2 km north of the Oskarshamn nuclear power plant. After consideration and approval by the appropriate authorities, the civil engineering works began in the autumn of 1990. The surface and underground portions of the laboratory stood completed in 1995.

The work at the Äspö HRL is divided into three phases: the pre-investigation phase, the construction phase and the operating phase. During the **pre-investigation phase, 1986–1990,** siting of the Äspö HRL took place. The natural conditions in the bedrock were described and predictions were made with respect to the geohydrological and other conditions that would be observed during the construction phase /14-2/. Planning for the construction and operating phases was carried out.

During the **construction phase, 1990–1995**, extensive investigations, tests and experiments were carried out in parallel with the civil engineering activities. The tunnel was excavated to a depth of 450 m and construction of Äspö Research Village was completed. Äspö Research Village was put into use during the summer of 1995. The underground civil engineering works were completed in the summer of 1995.

The **operating phase began in 1995**. A preliminary programme for the investigations and experiments that would be carried out was presented in a background report to RD&D-Programme 92 /14-3/. In this programme, attention is focused on the investigations and tests that are planned to be carried out during the period 1999–2004.

The Äspö HRL has been designed to meet the fundamental needs of the planned research, development and demonstration activities. The underground portion takes the form of a tunnel from the Simpevarp Peninsula to the southern part of the island of Äspö. On Äspö, the main tunnel runs in two turns down to a depth of 450 m, see Figure 14-1. The total length of the tunnel is 3,600 m. The first part of the tunnel was excavated by drill & blast (D&B). The last 400 metres were excavated with a tunnel boring machine (TBM) with a diameter of 5 metres. The underground excavations are connected with the surface facility by a hoist shaft and two ventilation shafts. On the surface is Äspö Research Village with offices, storerooms and hoist and ventilation building, see Figure 14 -2.

As more and more research and demonstration projects have been scheduled, new experimental sites have been required underground. During the winter of 1996/1997, 200 metres of new research tunnels were added at the -420 m and -450 m levels. In January-February 1998, an additional 30 m of research tunnels were mined. The personnel force stationed at the mine has also gradually increased, and the office and stores portions were expanded during the winter of 1997/1998. Additions include a meeting and exhibition section plus storerooms and laboratories.

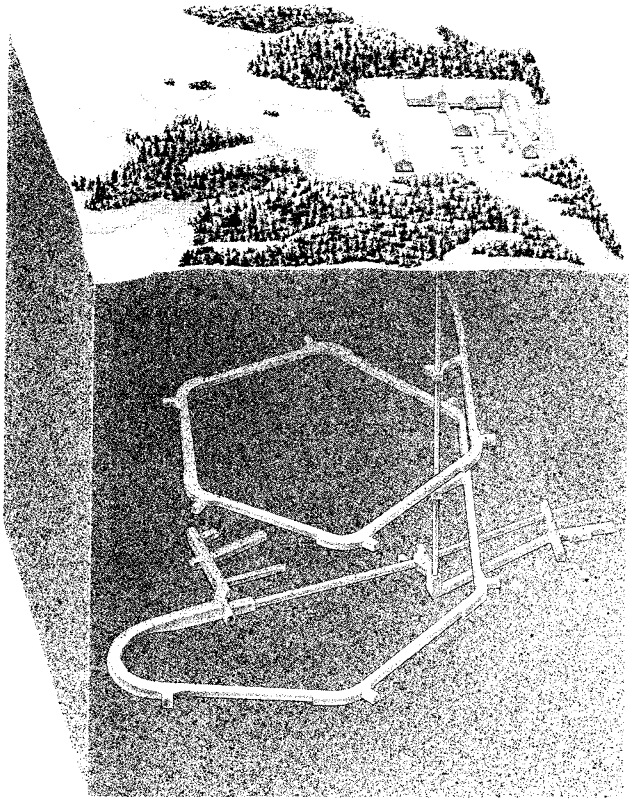

Figure 14-1. *The underground portion of the Äspö HRL reaches a depth of 460 m. The underground facility is connected with offices, workshops and storerooms on the surface by a hoist shaft and two ventilation shafts.*

Figure 14-2. *Bird's-eye view of Äspö Research Village.*

14.2 Goals

One of the fundamental reasons for SKB's decision to build the Äspö HRL was to provide an opportunity for research, development and demonstration in a realistic and undisturbed rock environment down to the depth planned for a future deep repository.

The primary role of the Äspö HRL in SKB's RD&D activities is to serve as a dress rehearsal for the realization of a deep repository. The research programme is being organized to provide an opportunity to test the steps required to put a deep repository into operation in the Äspö HRL first. The experience gained from the Äspö HRL will then be used in the construction of the deep repository on the selected site.

Important tasks for the Äspö HRL are to

- develop, test, evaluate and demonstrate methods for site characterization, detailed characterization, repository design, construction and deposition of spent nuclear fuel and other long-lived waste,
- develop and test alternative technology with potential to reduce costs and simplify the deep disposal concept without compromising quality and safety,
- increase scientific understanding of the safety margins in the deep repository and furnish input data for safety assessments of the long-term safety of the repository,
- provide experience and train personnel for the execution of different tasks in the deep repository, and
- inform outsiders regarding technology and methods developed for the deep repository.

The work in the Äspö HRL represents a continuation of the tradition of international cooperation and field experiments in a realistic deep repository environment that was begun back in 1977 in the abandoned iron ore mine at Stripa in the Bergslagen district of central Sweden.

To meet the overall schedule for SKB's RD&D work, four stage goals have been set up for the activities at the Äspö HRL. The originally formulated stage goals were revised when the operating phase commenced and were given the following wording in RD&D 95 /14-4/:

1. **Verify pre-investigation methods:** Demonstrate that investigations on the ground surface and in boreholes provide sufficient data on essential safety-related properties of the rock at repository level.

2. **Finalize detailed characterization methodology:** Refine and verify the methods and the technology needed for characterization of the rock in the detailed characterization of a site.

3. **Test models for description of the barrier function of the rock:** Refine and test at repository depth methods and models for describing groundwater flow, radionuclide migration and chemical conditions during the repository's operating period and after closure.

4. **Demonstrate the technology for and function of important parts of the repository system:** Test, investigate and demonstrate on a full scale different components that are of importance for the long-term safety of a deep disposal system and show that high quality can be achieved in the design, construction and operation of system components.

Activities at the Äspö HRL are currently scheduled to continue until the initial operating phase of the deep repository has been concluded. An integrated assessment of experience gained from initial operation and the results obtained from the Äspö HRL will thus underlie an application for a licence for regular operation of the deep repository. An important role for the Äspö HRL in this perspective is to conduct long-term experiments where various aspects of importance for the function of the deep repository have been tested over a long period of time, in some cases up to 15–20 years. The results of such experiments are expected to comprise important supporting material in an application for a licence for regular operation of the deep repository.

The Äspö HRL comprises an important part of the work being pursued within SKB's RD&D-Programme. The quality standard for the work is very high, and a general ambition is that the Äspö HRL should be developed into an internationally leading centre for research, development and demonstration concerning facilities for the deep disposal of high-level waste.

14.3 Executed projects

A brief summary of the main results obtained at the Äspö HRL is provided in this section. More detailed accounts of the results are provided in the project reports referred to below and in the Äspö HRL's annual reports /14-5, 14-6, 14-7, 14-8/.

14.3.1 Verification of pre-investigation methods

An important part of the activities during the pre-investigation and construction phases of the Äspö HRL included development and testing of different pre-investigation methods, plus development and testing of models for description of the function of the rock in the deep disposal system. The goal is to demonstrate that investigations on the ground surface and in boreholes provide sufficient data on essential safety-related properties of the rock at repository level. The results of investigations on the surface and in boreholes are used to gradually construct more detailed models of rock types, geological structures, geohydrology, groundwater chemistry and rock-mechanical conditions on Äspö. When the pre-investigation phase was concluded in the autumn of 1990, models and predictions were presented concerning the rock conditions that would be encountered during construction of the tunnel /14-2, 14-9, 14-10, 14-11/. These predictions have since been checked against the results of the investigations conducted during the construction phase. The results of the stage goal "Verification of pre-investigation methods" were reported in 1997 /14-12, 14-13, 14-14, 14-15, 14-16/. The methods used and experience from their practical use have also been described /14-9, 14-17/.

Pre-investigations or site investigations entail the integration of many different scientific disciplines, as regards both collection of data on the properties of the rock and evaluation of results. Based on an integrated evaluation of measurement results, models are formulated which constitute quantitative or qualitative descriptions of the properties of the rock and the processes that are of importance for the design of a deep repository, its performance during the operating phase, and its long-term safety after closure. A strategy of progressive updating and detailing of the models as new measurement values were obtained was used for the investigations on Äspö. In connection with the updates, renewed evaluations of previously collected measurement values were made. The applied strategy was found to work well and should in all essential respects be used in future site investigations.

The geological model provides a simplified description of rock type distribution, major structures and fracture content. This model comprises the basis for the mechanical, hydrogeological and hydrogeochemical models of a site, since it describes the geometry and properties of the geological structures that are of importance for groundwater flow, chemistry and possible rock movements. The geological model that was developed before the tunnel was begun has in all essential respects been verified by the investigations in the tunnel or in boreholes drilled from the tunnel. As might be expected, the agreement is not exact and discrepancies occur, which is thoroughly commented on in /14-13, 14-14, 14-15/. Despite the fact that the rock type distribution on Äspö is relatively heterogeneous, it was possible to predict the relative proportion and geometric distribution of the main rock types. When it comes to occurrence of rock types that appear as narrow, irregular dykes, such as fine-grained granite and greenstone, it was only possible to predict their relative occurrence. The position, properties and geological character of the major fracture zones proved to coincide well with the observations from the tunnel, see Figure 14-3. The occurrence of minor fracture zones, often steeply dipping with a north-northeasterly strike, was identified in the pre-investigations. The investigations from the tunnel showed that it is not possible to predict the exact location of these minor zones. A good statistical description of them was obtained, however, describing how often they occur and their principal orientation and hydraulic properties.

The hydraulic properties of the rock have been determined by measurements in individual boreholes and by measurements between boreholes (crosshole measurements). Different methods have been used, and measurements have been made on different scales. The measured values have then been used to model groundwater flow and head distribution on Äspö. Several different models, based on different descriptions of how the water flow is distributed in the rock, have been tried (see also section 14.4.2). A stochastic continuum model has mainly been used for calculations of flow distribution on a kilometre scale. This model, which takes into account the influence of differences in water density (different salinities), has given good agreement between calculated and measured groundwater heads, see Figure 14-4, and salinities. The groundwater chemistry investigations have resulted in models of how groundwater composition has evolved since the most recent ice age.

More than 10 years of work characterizing the bedrock on Äspö has shown that relevant models that accurately describe the conditions on a selected site can be developed by application of available methodology of good quality for characterization, data analysis, modelling and integrated assessment. This shows that tools exist for collection of data from the ground surface and in boreholes and for modelling of a site so that its suitability for siting of a deep repository can be assessed. The data collected from Äspö have been used in safety assessments of a hypothetical repository on Äspö, by SKI in the SITE-94 assessment, and by SKB in SR 97. Data on essential safety-related properties of the rock at repository level can thus be obtained from the ground surface and in boreholes. The investigations from the Äspö tunnel have largely verified the models that were made before construction began on the tunnel. The new data obtained from the tunnel have permitted a progressive detailing of the models, but have not changed the fundamental picture of conditions on Äspö.

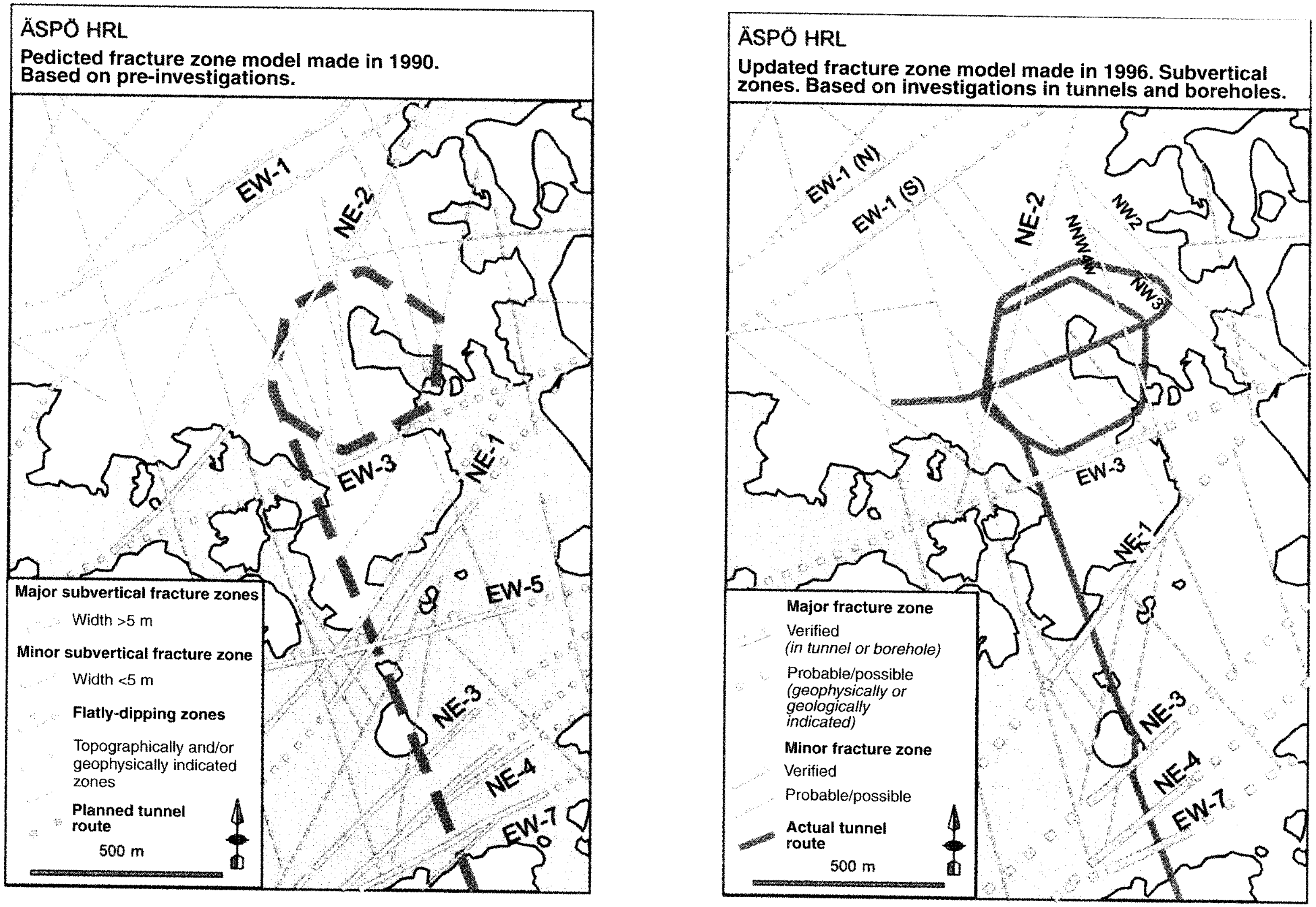

Figure 14-3. *Structural model of Äspö showing the location of the major structures on the ground surface. Model made before (left) and after (right) construction of the tunnel.*

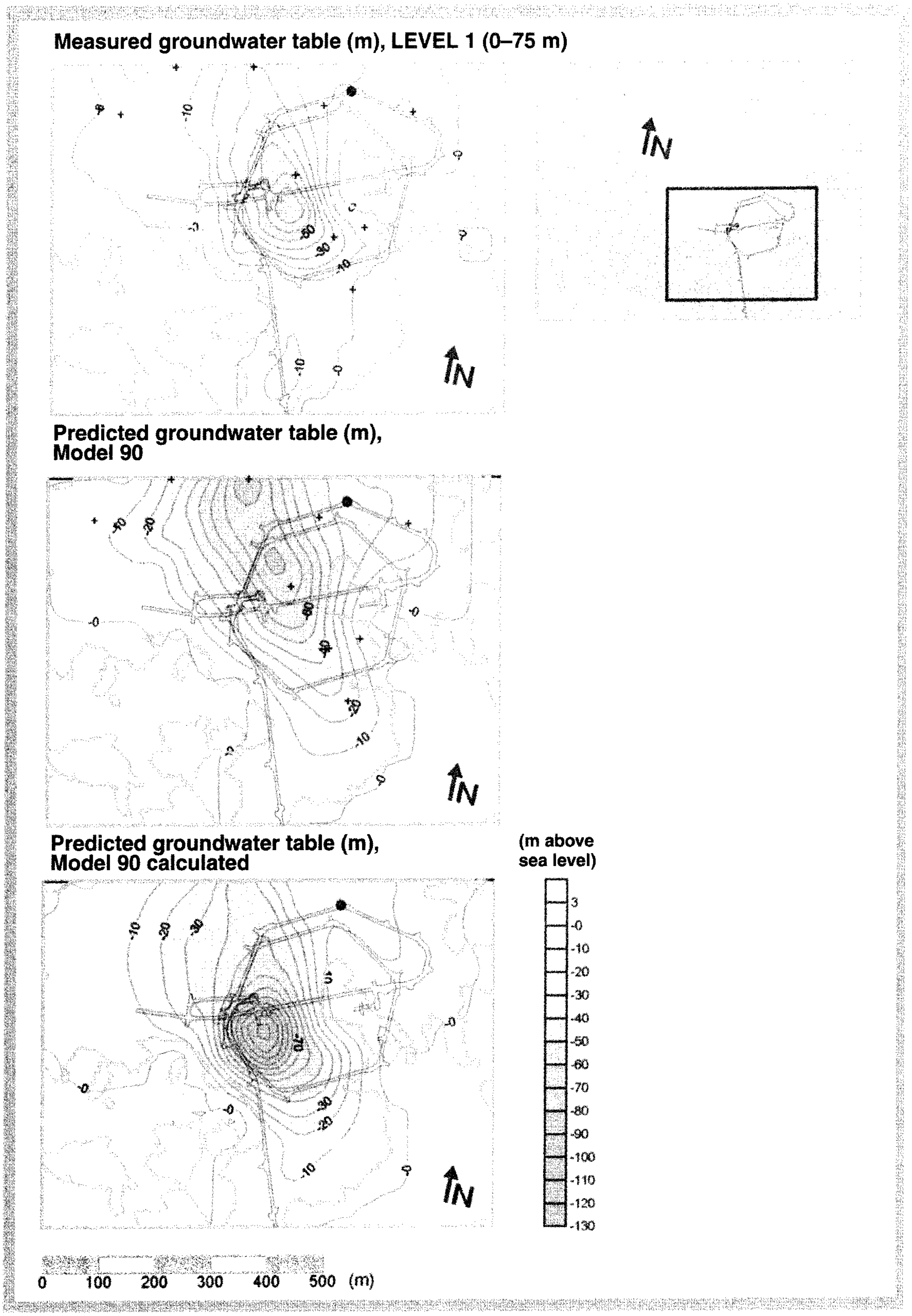

Figure 14-4. *Measured and calculated groundwater tables at the time when the Äspö tunnel reached a depth of 400 m. Measured values (top), calculated values with assumed values of inflow to the tunnel (middle), calculated values based on actual inflow to the tunnel (bottom).*

14.3.2 Finalization of detailed characterization methodology

As regards the second stage goal, finalization of detailed characterization methodology, a great deal of experience has been gained on the application of many different investigation methods underground, in particular as regards coordination of detailed investigations with tunnel construction. The investigation methods used for detailed characterization in conjunction with the construction of the Äspö tunnel will be described in a report similar to the one that summarizes experience from the pre-investigation phase /14-17/. This report will provide an account of experience to date for each method used. Further development of the methods will primarily take place in conjunction with the projects that are carried out in the Äspö HRL.

ZEDEX

The ZEDEX project was carried out to study changes in the properties of the rock in the vicinity of tunnels, in the so-called excavation-disturbed zone (EDZ), which can be of importance for conditions in the repository prior to closure and for long-term repository performance. The objectives of the ZEDEX project were:

- to obtain a better understanding of the mechanical properties of the EDZ with respect to its origin, character, change in properties, geometric extent and dependence on excavation method,
- to carry out investigations to obtain a better understanding of the hydraulic significance of the EDZ, and
- to test equipment and methodology for quantifying the properties of the EDZ.

The ZEDEX experiment was conducted in two parallel tunnels at a depth of 420 m. One tunnel had been mined by boring with a TBM and the other by drill & blast (D&B). Both tunnels had a circular profile and were 5 m in diameter. The final report on the project was published in early 1998 /14-18/. The experiment shows that there is a disturbed and a damaged zone around the tunnels. In the disturbed zone, where the properties of the rock are basically unchanged (Figure 14-5), no new cracks are created as a result of tunnel excavation. The disturbance that is obtained is dependent on the excavation method, but not on the shape of the tunnel, the properties of the rock, or the size and anisotropy of the rock stresses. The changes in rock stresses and associated displacements can lead to changes in the hydraulic properties of existing fractures. Measurements performed before and after tunnel excavation revealed measurable changes in transmissivity in only 10–15% of the tests. The few changes that were observed included both increases and decreases in transmissivity.

In the damaged zone around the drill & blast tunnel, new macro-cracks caused by the stresses were observed. Cracking was extensive in the floor of the tunnel and reached a depth of up to 80 cm. The cracking is more irregular in the wall, but reached a depth of about 30 cm from the tunnel wall in places. The macro-cracks also give rise to increase permeability and reduced seismic velocity. No damages to the rock were revealed in the TBM-bored tunnel by in-situ measurements, but microscopic studies of samples taken from the wall showed cracking up to 3 cm from the tunnel wall. The results show that a systematic increase in permeability around a tunnel is limited to the damaged zone. This means that transport of radionuclides in the rock can be limited by the application of appropriate excavation methods and be stopped by suitably designed plugs.

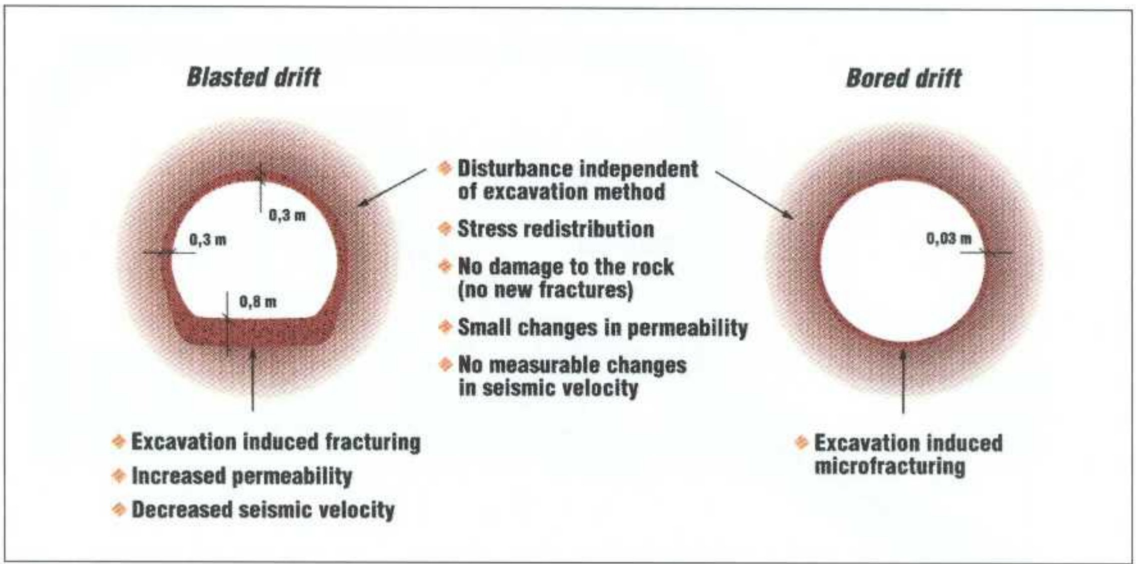

Figure 14-5. Summary of the main findings from the ZEDEX Project.

Hydrotest equipment for underground use

For surface-based measurements, SKB has long had access to what might be called standard equipment for hydraulic injection tests and pumping tests. For underground-based measurements, i.e. measurements performed in boreholes from tunnels or shafts, somewhat different requirements are made in terms of measurement technology, robustness and adaptation to the limitations of the measurement site. The critical requirements in the underground tests have been linked to high pressures and large water flows, a combination that makes greater demands on equipment the deeper down in the rock the measurement site is located. A flexible, easy-to-handle and reliable hydraulic testing system that can quickly be set up at measurement sites under ground has been developed and used with success in several projects, see Figure 14-6 /14-7/.

14.3.3 Testing of models for description of the barrier function of the rock

Three-dimensional models have been developed at the Äspö HRL which can describe flow of groundwater with varying salinity within a volume sufficiently large to be representative of a deep repository /14-2, 14-19, 14-20/. The ability to gather representative data to describe groundwater flow and radionuclide transport is being studied in an international Task Force, where data from Äspö is being used in several fundamentally different groundwater flow models, see section 14.4.2 for a more detailed account. Generally speaking, good agreement has so far been obtained between the models and reality /14-21, 14-22/. Continued work is planned in this field, above all to obtain further data for testing models for transport of radionuclides that react with the minerals in the rock via sorption, resulting in a slower transport of radionuclides compared with transport with the flowing groundwater.

Fracture Classification and Characterization

The goal of the project is to develop relevant concepts and data on fracture properties that can be handled in radionuclide transport modelling and that are based on a sorting of the fractures into a few relevant classes. A detailed mapping has been done of the water-

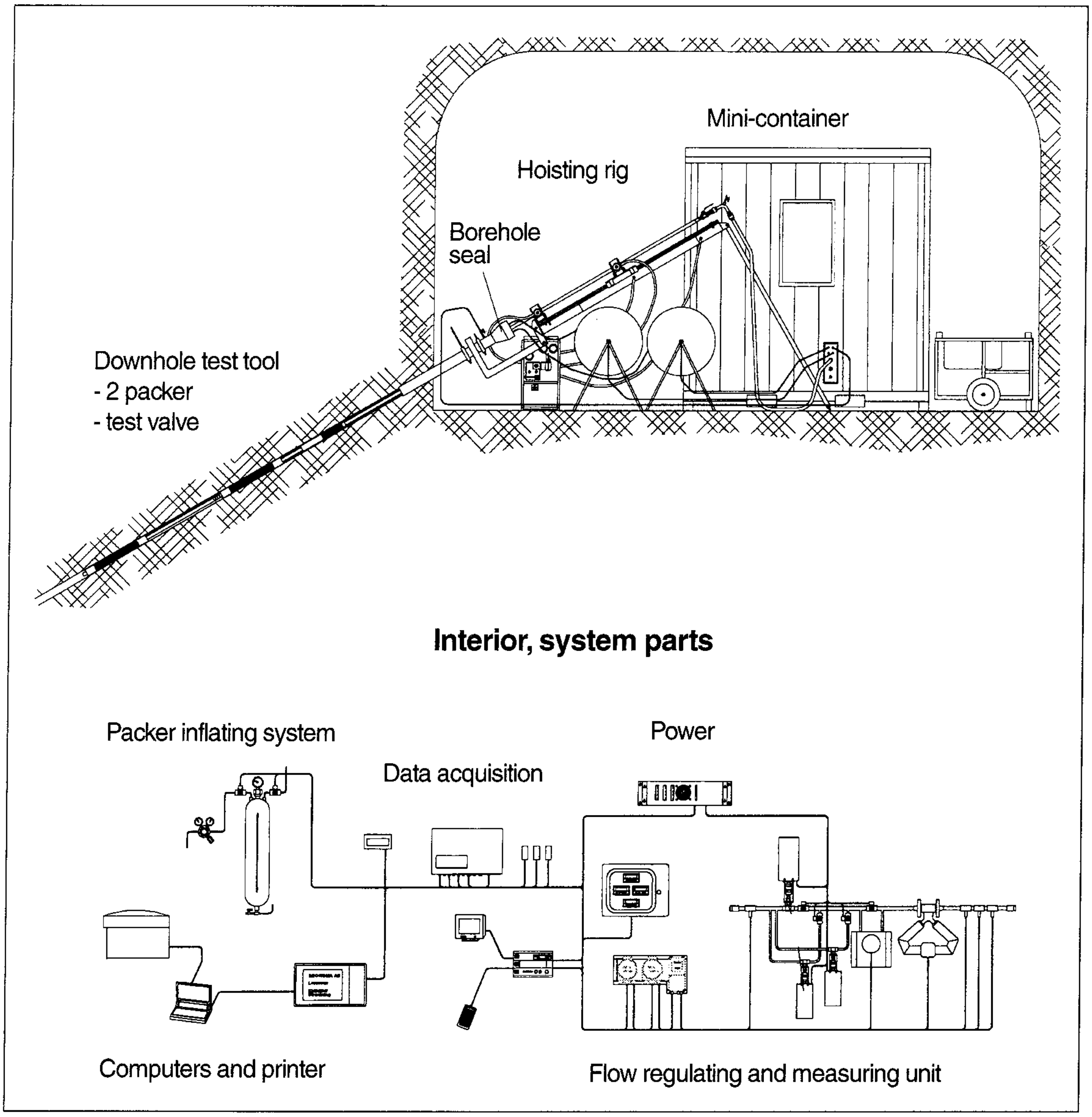

Figure 14-6. The equipment for Underground Hydraulic Testing (UHT-1).

conducting fractures and minor fracture zones that intersect the Äspö tunnel. The results show that the water-conducting features on Äspö consist of steeply dipping faults with a principally northwesterly strike /14-23/. Water-conducting features with a northeasterly strike occur to a lesser extent. The water-conducting features can be divided into 5 classes based on geometric complexity, occurrence of splay cracks, etc. The classification is not unique, since the characteristics of a feature normally vary along its strike. The length of segments with constant properties (belonging to the same class) is in the range of metres to decametres. The developed methodology has then been employed to construct a structural model of the rock volume in which the TRUE-1 experiments are being conducted, see section 14.4.3. The project's final report will be issued during 1998.

REX – Redox Experiment on detailed scale

The groundwater's redox conditions under natural conditions are well known /14-24/. During the tunnel construction and operating phase, the increased water flux can influence the redox conditions beyond what applies under undisturbed conditions. The effect of the rapid transport of oxygenated water down into the rock has been examined in the Block Scale Redox Experiment which was conducted between 1991 and 1993 in the Äspö tunnel. The results show that in this case and others where the concentration of organic matter in the inflowing surface water exceeds 10 mg/l, bacterial processes will consume the oxygen near the ground surface. An expected oxygen breakthrough at a depth of 70 m failed completely to materialize, even though surface water was transported down at the expected rate /14-25/.

Large quantities of oxygen are trapped in the repository at closure. This oxygen is consumed in different ways via reactions with rock, backfill material and bentonite clay. There is, however, a hypothetical possibility that the oxygen will attack the copper canister and cause corrosion. The REX project is studying the reaction kinetics of oxygen reduction by the rock in order to obtain data on how rapidly the oxygen present in the repository at closure will be consumed. Researchers from ANDRA, PNC and SKB are participating in the experiment.

Laboratory experiments aimed at studying oxygen consumption are being performed on rock samples from Äspö where the reaction rate of the oxygen has been determined /14-26/. Laboratory experiments also show that oxygen can be consumed by methanogenic bacteria. Samples have also been taken to determine the natural concentrations of dissolved gases in the groundwater on Äspö. A field experiment to study the reaction rate of the oxygen has been initiated and is expected to be concluded in early 1999.

Degassing of groundwater and two-phase flow

The pressure drop that occurs in the vicinity of tunnels and open boreholes can cause degassing of the groundwater, which gives rise to two-phase flow and thereby to changes in hydraulic properties. Knowledge of these changes is essential to understand the observations of hydraulic properties that are made from drifts and tunnels, to interpret experiments conducted in the vicinity of drifts, and to assess the performance of buffer and backfill materials, especially in conjunction with backfilling and closure of the deep repository.

The laboratory experiments that have been conducted have indicated reductions of the transmissivity of fractures due to degassing (bubbling) by up to a factor of ten. The size of the transmissivity reduction has been found to be a function of the quantity of dis solved gas in the water and the structure of the fracture. A greater reduction is obtained in fractures with variable aperture than in fractures with a smooth surface /14-27, 14-28/.

In the field experiments that have been conducted, transmissivity reductions have not been observed on inflow of natural groundwater to boreholes. A reduction in transmissivity of about 50% was, however, obtained in an experiment where the gas concentration in the groundwater was artificially raised to about 15%. Analysis of obtained results and underlying theory shows that a reduction of the transmissivity on inflow to boreholes is not to be expected at the gas concentrations that occur in the groundwater on Äspö, normally about 3%. Effects due to degassing can, however, be expected around drifts due to their larger diameter /14-28, 14-29, 14-30/. A model for degassing in fractures has been developed that accurately describes the results obtained from the laboratory experiments /14-8/.

The final report on the project will be published in early 1999.

14.4 Results of ongoing projects and research programme 1999–2004

14.4.1 Execution and organization

The research at the Äspö HRL is carried out, like SKB's other R&D work, via contracts to universities, institutes of technology, research institutions, consultants, industrial companies and other Swedish and foreign researchers. This makes it possible to maintain a high level of competence and quality and to choose the most qualified experts for different investigations and experiments. Different alternative methods or models can be tried for certain issues.

Based on the RD&D-programme, annual planning reports giving a relatively detailed description of the next year's work are written. The activities at the Äspö HRL are conducted for the most part in project form. The various research projects are headed by project managers, and the laboratory's personnel are responsible for organizing and executing the work on Äspö.

Figure 14-7 shows the location of the different experiments within the Äspö HRL.

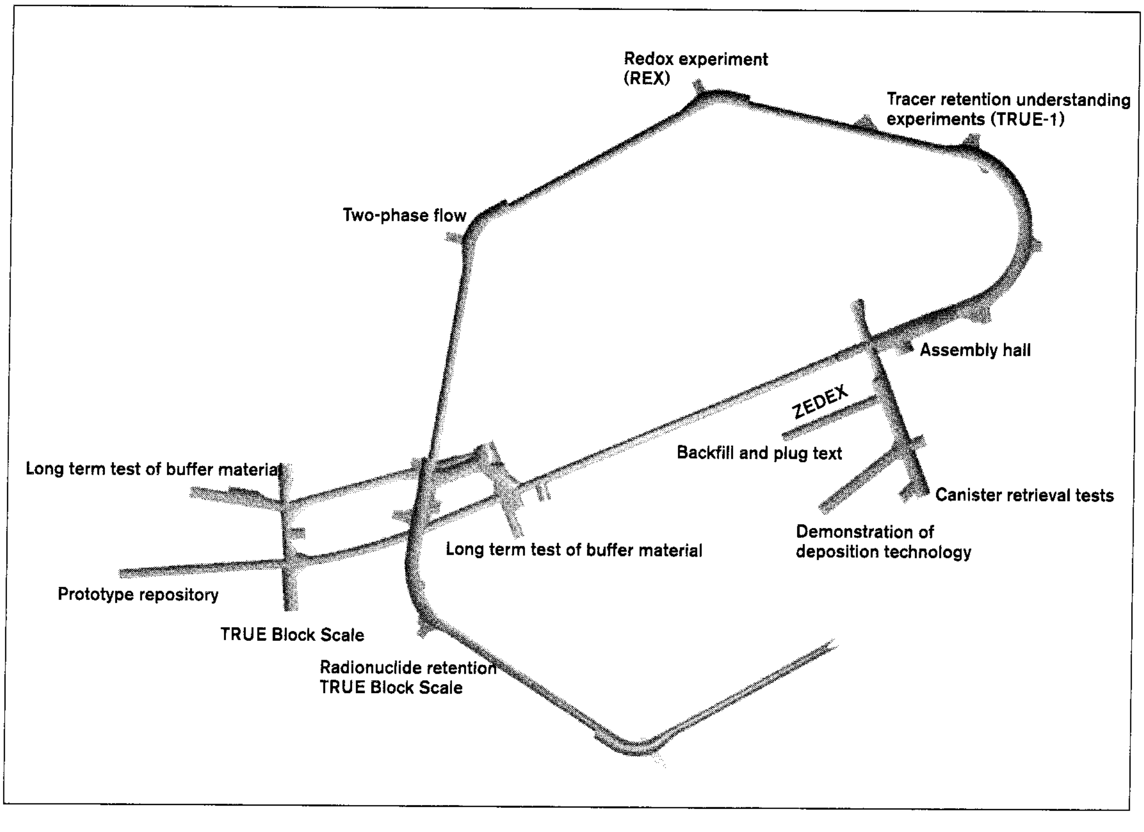

Figure 14-7. The tunnel system under the 300 m level and allocation of experimental sites.

14.4.2 Basic research at the Äspö HRL

Some basic research that is not project-related is conducted at the Äspö HRL. This work is aimed at providing support for the research, development and demonstration projects by conducting and comparing measurements of common interest for all projects, by furnishing results and compiling models from different scientific fields, and by operating and administering SKB's geodatabase.

Geoscientific models

According to SKB's planning, the suitability of geological formations for deep disposal of spent nuclear fuel will be evaluated with the aid of geoscientific models of the site in question, including:

- geological model,
- geohydrological model,
- geomechanical model,
- hydrogeochemical model,
- heat transport model,
- radionuclide transport model.

These models are compiled in conjunction with a site investigation and present an aggregate of existing knowledge on a site.

On Äspö, geoscientific information has been systematically collected during the pre-investigation and construction phases. Data continues to be collected from the various tests and projects that are being conducted. The information that has been gathered up to and including completion of the main tunnel down to a level of 450 metres has been used to devise site-specific models of the conditions on Äspö. The models contain dimensionality, material properties, method for specification of properties in the whole model, boundary conditions, numerical or mathematical tools, and what parameters the model depicts. Structure and content are described in greater detail in /14-16/. The purpose of constructing these models has primarily been to verify our ability to foresee the properties of a rock mass on the basis of information from completed site investigations.

The existing models of Äspö will gradually be revised, particularly in the light of the new information that is constantly obtained from the projects described below. A geomechanical model and a heat transport model will also be developed during the coming three-year period, at the same time as data are gathered for augmentation of the radionuclide transport model that has been used in SKB's safety assessments of a deep repository. The groundwater flow model of Äspö is being further developed to furnish boundary conditions to the experiments described below. Limited efforts are also foreseen in development of the numerical models to simplify and streamline the introduction of boundary conditions and conditioning of models based on measured values.

Monitoring of groundwater head

The work of building a system for monitoring of groundwater heads in boreholes (the Hydro Monitoring System, HMS) on Äspö and nearby areas was begun already during the pre-investigation phase. This system has gradually been extended and now also encompasses a large number of boreholes underground. The boreholes that belong to experiments such as TRUE-1 and TRUE Block Scale have been connected to the system one by one. The groundwater head is normally measured every other hour and the measured values are saved in a database. The system makes it possible to measure disturbances of the groundwater heads caused by various events in the laboratory. These measured values can then be used to refine and evaluate various hydraulic models of Äspö and to check the boundary conditions for different experiments. HMS will be expanded to meet the needs defined by the different projects.

Monitoring of groundwater heads on Äspö is also required by a water court ruling.

Monitoring of groundwater chemistry

Samples of the composition of the groundwater have been taken regularly during the pre-investigation and construction phases of the Äspö HRL as an integral part of development and testing of the hydrogeochemical models. This sampling has continued during the operating phase in order to keep track of changes in groundwater chemistry caused by the facility. Samples are now taken regularly from boreholes above and below ground.

Obtained data serve as a basis for testing models of groundwater flow and groundwater chemistry and for understanding the long-term influence of the facility on geochemical conditions. Data from groundwater chemistry monitoring also serve as input data to Task 5, which is being carried out within the framework of the Task Force (see below). A small expansion of the sampling programme was made during 1998 to also include sampling points from the lower parts of the tunnel.

SKB's geodatabase – SICADA

SKB has been carrying out geological investigations since the end of the 1970s. Data from SKB's investigations, including the measurements performed at the Äspö HRL, are stored in SKB's geodatabase SICADA. Management and administration of investigation data is a demanding task. Safety assessments must be based on correct and relevant data. This means that routines for data management must be designed to meet requirements on traceability, accessibility, data security, user-friendliness and efficiency.

The goal of the administration and further development of SICADA is that the database should be an effective tool for future site investigations and experiments conducted at the Äspö HRL. The system must be kept up-to-date and be developed along with the site investigation programme.

Task Force on Modelling

An international Task Force on Modelling of Groundwater Flow and Transport of Solutes has been tied to the Äspö HRL. The Task Force was initiated by SKB at the end of 1992 for the purpose of evaluating the suitability of different models. The Task Force is supposed to act as a forum for collaboration and discussion of conceptual and numerical modelling of groundwater flow and radionuclide transport for the organizations that are participating in the Äspö HRL. The Task Force meets twice a year.

In the Task Force, the modelling work is linked to ongoing and coming experiments at the Äspö HRL, which enables the experiments to be planned and evaluated better. The work is mainly pursued by having several modelling groups work with the same task. The tasks are therefore defined in such a way that a comparison between the models is possible. The results are then evaluated by representatives of the international organizations participating in the Äspö HRL. In this evaluation, an emphasis is placed on lessons that can be learned for future site investigations and safety assessments. The tasks have so far been:

Task 1: Modelling of LPT-2, a large-scale long-term pumping test with associated tracer test /14-21/.

Task 2: Scoping calculations for planned tracer tests on a detailed scale /14-33, 14-34, 14-35, 14-36, 14-37/.

Task 3: Modelling of the hydraulic impact of the Äspö tunnel /14-22/.

Task 4: Predictive modelling of tracer tests with sorbing and non-sorbing tracers carried out within the TRUE-1 project /14-38, 14-39/.

Task 5: Coupling between hydrogeological and hydrochemical models /14-40/.

Tasks 1-3 have been concluded while Tasks 4-5 will proceed for another few years. The work within the Task Force will continue during the period. New tasks will be defined in cooperation with the foreign organizations that are participating in the Task Force.

14.4.3 Finalize detailed characterization methodology

Detailed characterization includes construction of an access tunnel or shaft to deep repository level and performance of investigations from tunnels or boreholes drilled from tunnels. Detailed characterization for a deep repository of spent nuclear fuel aims at

- confirming the availability of a suitable repository volume,
- furnishing sufficient data for the safety assessment that is needed to obtain a permit for construction of a deep repository, and
- furnishing data so that the disposal system can be optimized with respect to engineered barriers and geometric configuration.

Within the framework of the stage goal, detailed characterization of the excavation-disturbed zone around D&B and TBM tunnels will be carried out, along with development of interactive computer systems for interpretation of measurement data and design of the repository plus instruments for investigations underground.

Rock Visualization System

A rock model for a site is constructed gradually by collection and processing of data. These data will be collected in SKB's geodatabase SICADA. In addition, geological and geophysical map material will be collected in SKB's GIS system. Experience from the investigations at the Äspö HRL shows that it is important during the characterization of a site to have access to an interactive 3D CAD system that permits interactive 3D testing of different possible connections between observations in boreholes and on the ground during the work of building a model of the rock's structure. A rapid visualization of the structural model makes it possible to optimize further investigations on the basis of existing information. In the work of designing a deep repository, the 3D model of the rock will be used to adapt the configuration (layout) of the facility optimally to the geometric structure of the rock. Since several different groups will work with data from a site investigation, it is important to have a common 3D CAD system where all data can be processed and visualized.

To meet these requirements, SKB began development of the interactive 3D CAD tool Rock Visualization System (RVS) at the end of 1994. Version 1 of the system was delivered to SKB in 1997. Since then, the system has gradually begun to be used in the research projects being conducted at the Äspö HRL.

Goal and execution

The goal is to develop an advanced and user-friendly visualization and modelling tool based on a commercially available CAD system and to ensure that the system is well integrated with SKB's database SICADA /14-8/.

RVS is a software application of the commercially available 3D CAD tool MicroStation 95, which can be run under all commonly encountered operating systems. RVS version 1.0 is designed as a single-user system, and the data exchange between RVS and SKB's database SICADA is based on a client/server technique. In RVS, the work is not based on design files and levels as in ordinary CAD systems, but on projects and objects /14-8/. The RVS system contains modules for visualization of boreholes and results from measurements in boreholes, modelling, design of tunnels, animation and production of drawings. Based on experience from about one year's operation of the system and the modification needs identified by the users, a Version 2 of RVS will be produced. Application of the system within the Äspö HRL's projects will lead to demands for changes and new features in the system.

Testing and refinement of investigation methodology for detailed characterization

A programme for detailed characterization will be devised before detailed characterization is initiated on a selected site and construction of the surface and underground portions of the deep repository is commenced. In conjunction with the driving of the Äspö tunnel, several different investigation methods have been tried and the usefulness of these methods for detailed characterization for a deep repository is being evaluated. Preliminary experience from Äspö shows that there is a need for refinement of these methods to enhance the quality of collected data, boost efficiency and improve reliability in a demanding underground environment. Furthermore, the detailed characterization programme needs to be designed so that good coordination is obtained between rock investigations and construction activities.

Goals and completed work

The objectives are:

- to try out existing and new methods to clarify their usefulness for detailed characterization. The methods to be tested are chosen on the basis of their potential use within the detailed characterization programme,

- to refine important methods in a detailed characterization programme to enhance data quality, efficiency and reliability.

Some methods have been tried out within the framework of other projects in the Äspö HRL. For example, radar and seismic methods have been tried out in conjunction with the characterization work that has been carried out for the Prototype Repository Project and tests of different backfill materials /14-41/. The reliability of rock stress measurements performed with the overcoring method has been checked /14-42/. Laser scanning has been tested as a method for documentation of tunnels, both with respect to their geometric dimensions and as a basis for geological mapping /14-43/.

Planned work

Further tests of methods for detailed characterization are mainly intended to be carried out within the framework of ongoing projects. When the necessary data are available, evaluation reports will be compiled which summarize experience gained to date and make recommendations for possible refinement of suitable methods. Methods where some tests have already been made and where evaluation is expected to take place during the coming programme period are measurement of machine parameters during drilling to obtain geological information, water sampling during drilling to obtain undisturbed samples, high-resolution seismic and radar surveys, and methods for accurate position measurement of boreholes. Development of a new system for tunnel mapping will begin during the period.

14.4.4 Testing of models for description of the barrier function of the rock

The rock surrounding the repository constitutes a natural barrier to the release of radionuclides to the biosphere. The most important functions of the rock are to protect the engineered barriers by ensuring long-term stable chemical and mechanical conditions and to limit transport of corrodants and radionuclides by ensuring a slow and stable groundwater flux. In safety assessments, the barrier function of the rock is described with different models.

Within the framework of this stage goal, projects will be carried out for the purpose of evaluating the usefulness and reliability of different models and developing and testing methods for determination of parameters included in the models. An important part of this work is being done in the Äspö HRL's international Task Force on Groundwater Flow and Transport of Solutes, see also 14.4.2. Studies will also be conducted of the disturbance entailed by the construction and operation of a repository in order to ensure that this disturbance does not have a negative impact on the long-term safety of the repository.

Tracer Retention Understanding Experiments – TRUE

The rock constitutes a barrier that limits the transport of different substances. Most substances dissolved in the groundwater are transported more slowly than the average flow velocity of the groundwater. This is due to a number of different processes that cause retardation of the solutes relative to the flowing groundwater. Important processes are dispersion and retention. Retention (retardation) is caused by the following mechanisms:

- Radionuclides sorb on mineral surfaces past which the groundwater flows.

- Radionuclides diffuse out from water-conducting fractures into the stagnant water in micropores in the rock and are sorbed on the mineral surfaces there.

Non-sorbing substances are also retarded due to the fact that they remain in the stagnant water in the micropores and are in this way withheld from transport in the flowing water in water-conducting fractures. Radionuclide retention according to this pattern is important and is often referred to as "matrix diffusion".

To gain a better understanding of radionuclide retention in the rock and create confidence that the radionuclide transport models that are intended to be used in the licensing of a deep repository for spent fuel are realistic, a programme has been devised for tracer tests on different scales. The programme, which has been given the name Tracer Retention Understanding Experiments (TRUE), was devised in 1994 /14-44/.

The basic idea is to carry out a series of tracer tests of progressively increasing complexity. In principle, each tracer test will include a series of activities starting with geological characterization of the test area, followed by hydraulic and tracer tests, and ending with the injection of epoxy or a similar substances into the test volume, which will then be excavated and the rock samples analyzed with respect to flow paths and tracer concentration. Geological characterization, laboratory experiments and modelling are included as integral parts of the project, see Figure 14-8. The first tracer test cycle (TRUE-1), which has been carried out on a small scale, is of limited duration and is aimed primarily at technology development. Subsequent tests will have a longer duration to enable different retention mechanisms to be studied. Tracer tests on both a block scale (10–100 m) and a detailed scale (1–10 m) will be conducted in the same rock volume. This will provide a basis for understanding scaling ratios and testing models for radionuclide transport on the 50 m scale.

The experimental programme is designed to generate data for conceptual and numerical modelling at regular intervals. Regular evaluation of the test results will provide a basis for planning of subsequent test cycles. This should ensure a close integration between experimental and model work. Detailed plans for the tracer tests will be worked out during the course of the programme.

Goals and completed work

The goals of the TRUE programme are:

- to deepen knowledge of radionuclide transport and retention in fractured rock,
- to evaluate the usefulness and feasibility of different model concepts,
- to develop and test methods for determining important transport parameters, and
- to determine values of important transport parameters in-situ.

The first stage of the TRUE experiments (TRUE-1) began in 1994 and is expected to be finished by the end of 1998. The first stage is above all aimed at development of technology for tracer tests on a detailed scale and for characterization of the pore volume by injection of epoxy, plus development of weakly sorbing tracers /14-45/.

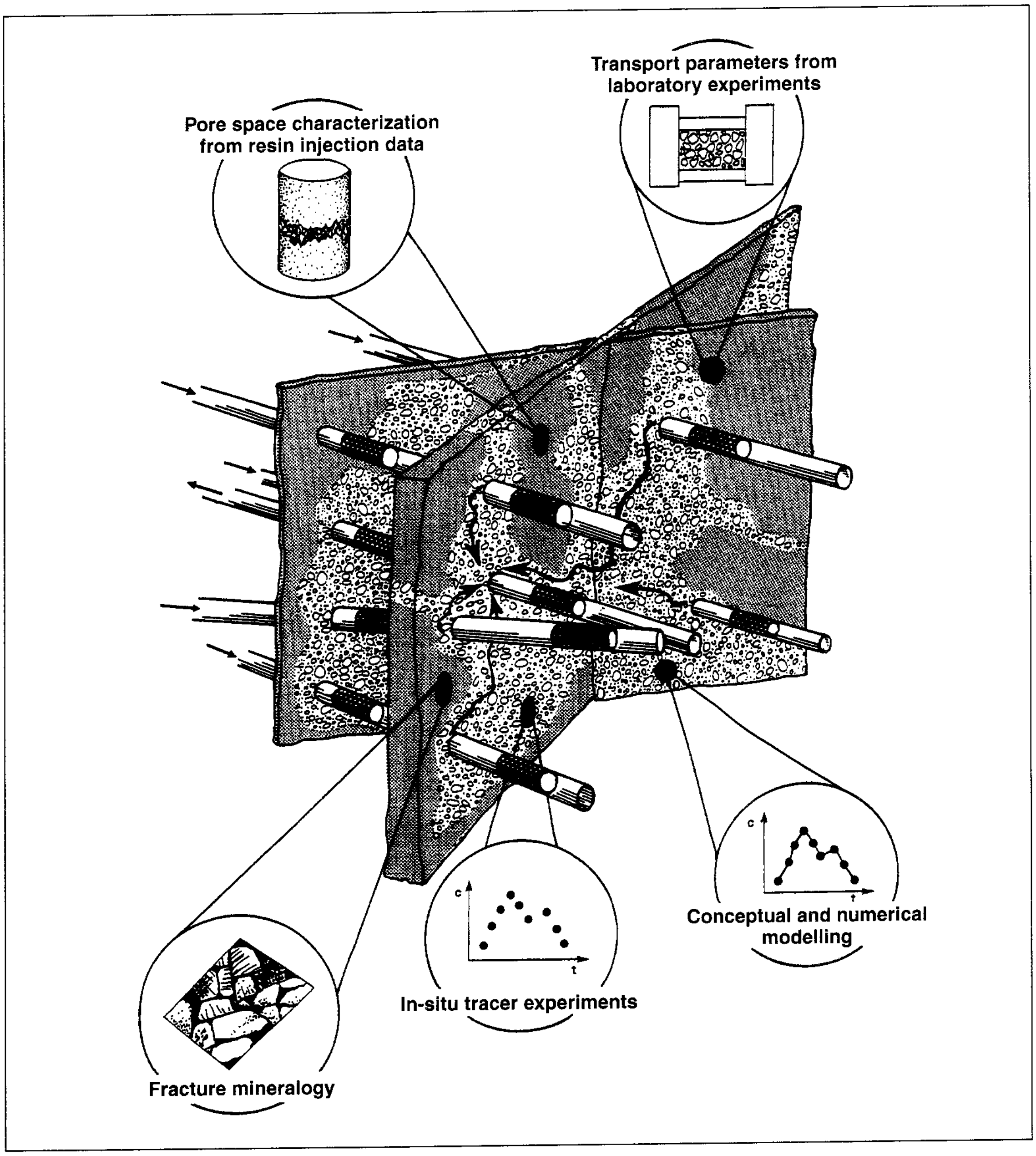

Figure 14-8. *Schematic illustration of the TRUE experiment.*

The TRUE-1 experiment comprises tracer tests in a fracture over a distance of 5-10 m at a depth of about 400 m. Investigations of the rock for selection of a suitable site for performance of the test were commenced in 1994. An area at a depth of about 400 m was selected for performance of the tests at the beginning of 1995 /14-46/. An experimental niche was established, from which four holes were drilled and measurements were performed in these holes to characterize the experimental volume. A fracture at a distance of about 15 m from the experimental niche was identified as suitable. Several tests with non-sorbing tracers were carried out in the selected fracture during 1996 /14-47, 14-48, 14-49, 14-50/.

Experience from the test has shown that the experimental preparations in the form of identification and characterization of suitable experimental volumes are more resource-

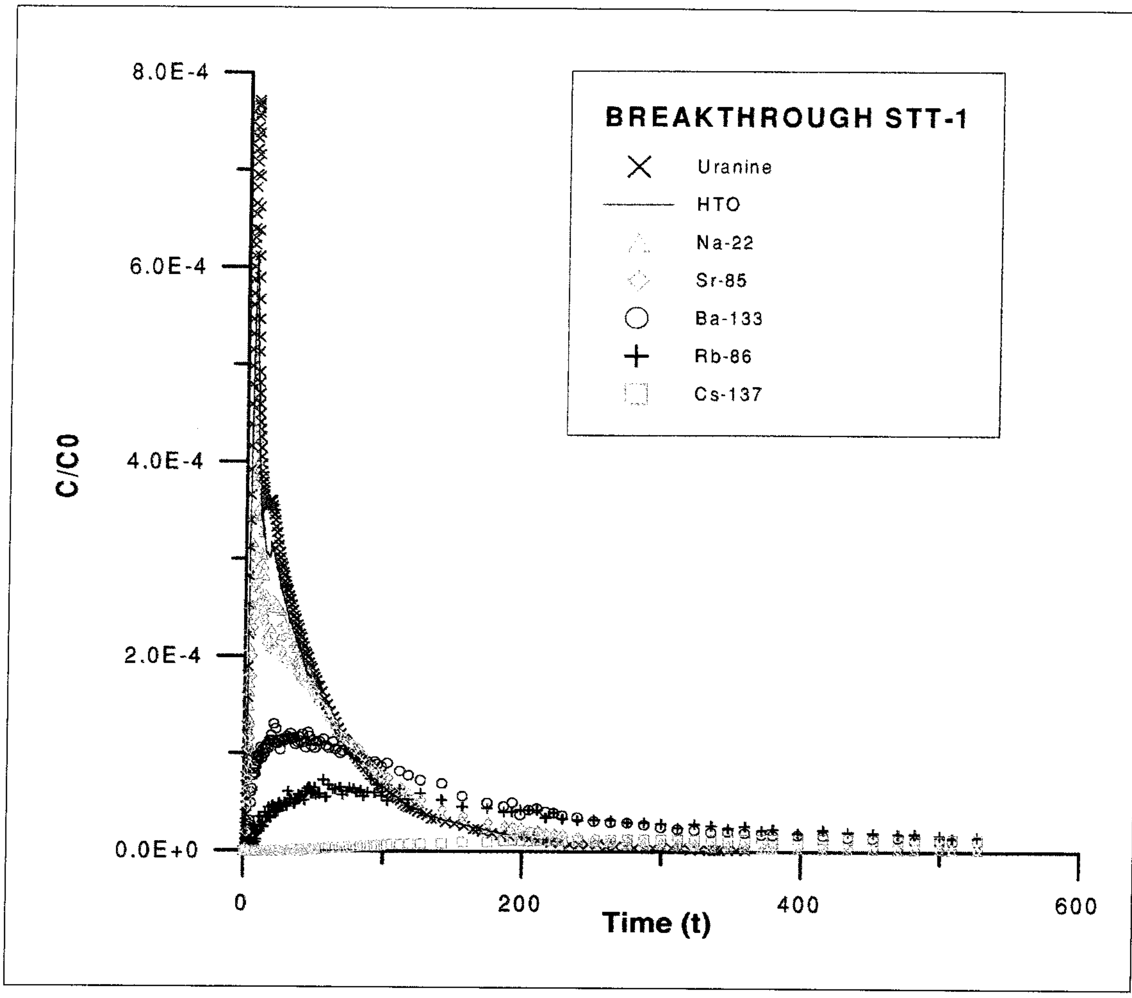

Figure 14-9. Breakthrough curves from a test with sorbing tracers conducted within the TRUE-1 project.

and time-consuming than originally estimated. Since the experimental conditions in the selected experimental volume were judged to be good, a decision was made to supplement the programme and include tests with sorbing tracers in the TRUE-1 project, which had not been planned from the beginning /14-51/. The experimental volume will furthermore be utilized for additional tracer tests before some form of destructive testing, such as injection of epoxy, is carried out.

The first test with sorbing radioactive tracers was begun in July 1997 and concluded in early March 1998. The experiment involved injection of two non-sorbing (Uranine and HTO) and six weakly to moderately sorbing tracers (^{22}Na, ^{85}Sr, ^{86}Rb, ^{47}Ca, ^{133}Ba, ^{137}Cs). The results show relative retardations of the tracer breakthroughs which by and large agree with the values of the sorption coefficients determined in the laboratory. Uranine and tritiated water (HTO) have approximately the same breakthrough time. Thereafter follow in order: ^{22}Na, ^{47}Ca, ^{85}Sr, ^{86}Rb, ^{133}Ba, ^{137}Cs, see Figure 14-9. A preliminary interpretation of the results shows that the sorption of caesium is non-reversible, i.e. that 60-65% of the injected amount of caesium has been retained in the rock /14-8/.

The test has been carried out in close cooperation with the Äspö HRL's Task Force, to which the results of the experiments have been continuously fed back for incorporation in various transport models. To evaluate the reliability of models and underlying data, the modellers have been assigned the task of making predictions of the experimental results in advance of the execution of the experiments /14-52, 14-53, 14-54/. The modellers have also been given an opportunity to influence the design of the tests. This has ensured the close cooperation between experimentalists and modellers that is needed for improvement of models in this area.

In parallel with the field tests, extensive laboratory tests have been conducted to study diffusion and sorption of weakly sorbing substances on rock samples from Äspö. The tests show that the Äspö diorite has a heterogeneous porosity distribution that is closely related to the mineral distribution. The tests have shown that grain boundaries do not constitute migration paths in the diorite matrix. The network in which migration takes place consists of a complex mixture of minerals dominated by biotite, plagioclase and chlorite, all with small grain sizes (<0.5 mm). Quartz and large feldspar grains are judged to be non-porous. The results show that the sorption takes place in the porous minerals. Roughly an order of magnitude lower Kd values were obtained in the diffusion experiments compared with batch experiments performed on crushed rock. This is probably due to the fact that crushing creates greater porosity and a larger sorption surface area. Irreversible sorption has been observed for several of the tested radionuclides. According to the batch tests, a substantial portion of the mass can be sorbed irreversibly and would thus not be transported through the rock /14-8, 14-55/.

A pilot test has been conducted to develop a technique for verifying transport pathways in a real fracture. The test was performed in a fracture that intersects a drift at a depth of 450 m /14-56/. Epoxy was injected into the fracture, which was then sampled by drilling. The samples were then sawed up and the aperture was measured along a dense network of profiles. Two different techniques for measuring the fracture aperture were used /14-8/.

Planned work

Stage 2 of the tracer tests on a detailed scale (TRUE-2) is being initiated in 1998 /14-57/. This stage will be focused on retention processes in an individual fracture and how they can be observed and distinguished in field tests. The duration of the tests will be longer than TRUE-1 so that processes such as diffusion to pores with stagnant water and possibly matrix diffusion will be measurable processes. A principal task in the initial phase of the project will be to identify and characterize yet another individual fracture to carry out the tests in. Within the framework of TRUE-2, additional tests with sorbing tracers will also be carried out in the fracture used for the TRUE-1 tests. Laboratory tests will be conducted to study how diffusion and sorption are influenced by the microstructure of the rock.

Planning and execution of a tracer test on block scale (10-100 m), called the TRUE Block Scale experiment, was begun in 1996 /14-58/. The project is being carried out as an international cooperation project within the Äspö HRL with the participation of ANDRA, ENRESA, PNC, Posiva, UK Nirex and SKB. The goals of this project are:

- to increase our understanding of and ability to predict tracer transport in a fracture network,
- to evaluate the importance of different retention mechanisms in a fracture network, and

- to evaluate the relationship between flow and transport data as a tool for modelling transport processes.

The experiment commenced in 1996 with characterization of the experimental volume, which is situated at a depth of 450-500 m about 100 m south of the TBM tunnel in the southwest part of the laboratory, see Figure 14-7. The rock and its hydraulic properties are described in the form of a deterministic model of identified structures (minor fracture zones), generally with an extent of more than 50 m, and in the form of a stochastic network model that describes the smaller fractures. The models are updated by means of an iterative process whereby information from new boreholes is progressively incorporated in the models /14-8/. Tracer tests with non-sorbing tracers are being commenced during 1998. The project is projected to be finished by the end of 2000.

Long-term test of diffusion in the rock matrix

Radionuclide transport through the fractures in the rock is principally studied within the framework of the TRUE programme. Studies of matrix diffusion, which is an important retention process, require a different experimental design, however. Matrix diffusion is a slow process which is difficult to study within the time frames established for the TRUE projects.

Matrix diffusion has been studied in many laboratory tests. However, it is difficult in a laboratory to reproduce certain experimental parameters such as natural groundwater composition, pressure and an undisturbed rock matrix. Samples that are taken for laboratory tests may be damaged on account of the drilling and the destressing that results from the sampling procedure. It is therefore important to verify the results of laboratory tests performed to date by studies of matrix diffusion in undisturbed rock.

Goals and execution

The goals of the in-situ studies of matrix diffusion are:

- to investigate diffusion of radionuclides in an undisturbed rock matrix that has not been destressed under natural conditions as regards groundwater pressure and composition,
- to obtain data on sorption properties for some radionuclides from undisturbed rock matrix and fresh rock surfaces under natural conditions, and
- to compare sorption data obtained from laboratory tests with data obtained under natural conditions.

The test is carried out in a borehole that has been made in a way that causes little damage to the surrounding rock. The hole is sealed with a packer and groundwater is circulated in the sealed-off section by means of a pump placed at the bottom of the hole. When the chemical composition of the groundwater has stabilized, radionuclides are injected into the borehole. They will then diffuse out into the rock surrounding the hole. Radionuclides with low diffusivity are injected before radionuclides with higher diffusivity so that the radionuclides are kept within a given distance of the hole. The experiment is concluded by overcoring of the test hole and analysis of the rock samples with respect to the presence and distribution of the injected radionuclides. The estimated duration of the field test is about 5 years.

Radionuclide retention

Most radionuclides have a strong affinity for adhering to different surfaces, i.e. a high Kd value. Numerical values that can be used in the safety assessments have been arrived at via laboratory measurements. However, it is difficult in the laboratory to simulate the natural groundwater conditions in the rock when it comes to redox status and concentrations of colloids, dissolved gases and organic matter. Consequently, it is difficult to obtain reliable values in the laboratory for e.g. dissolution or retention of radionuclides in cases where they are strongly dependent on the properties of the groundwater.

Goals and completed work

The goals of the investigations are to:

- validate models and check constants used to describe radionuclide dissolution in groundwater, the influence of radiolysis, fuel corrosion, sorption on mineral surfaces, diffusion in the rock matrix, diffusion in backfill material, transport out of a damaged canister and transport in an individual fracture.
- test the influence of naturally reducing conditions on solubility and sorption of radionuclides,
- test the ability of the groundwater to take up and transport radionuclides with natural colloids, humic substances and fulvic acids.

To carry out the verifying experiments under natural conditions, a borehole probe called CHEMLAB has been created. The design work on the CHEMLAB probe began in 1991 and the probe was delivered to the Äspö HRL in 1996. The CHEMLAB probe is a chemical laboratory that has been incorporated in a borehole probe in which experiments can be conducted under natural conditions as regards groundwater temperature, pressure and composition. Experiments can also be performed with radionuclides without the risk of contaminating surrounding rock and groundwater. The design principles of the probe are illustrated in Figure 14-10. Different types of measurements are planned to be conducted for the next 5 years. Before the in-situ experiments are conducted in the CHEMLAB probe, the experimental set-ups will first be tested in a normal laboratory.

The experiments with diffusion of radionuclides in MX80 bentonite were begun in 1997 and have been carried out for the following nuclides: ^{85}Sr, ^{134}Cs, ^{57}Co, ^{131}I and ^{99}Tc. Figure 14-11 shows the result of an experiment with diffusion of caesium through bentonite. Agreement between expected and obtained results can be regarded as good. In 1997, the CHEMLAB probe was equipped with a computer system for automatic control of the experiments.

Planned work

Coming experiments planned for the CHEMLAB probe include migration of redox-sensitive nuclides, solubility, desorption, migration from buffer to rock (film resistance), radiolysis and dissolution of spent fuel. A preliminary programme for the design of the different experiments has been published /14-59/. A detailed programme will be prepared for the experiments as they are to be conducted.

A radiolysis experiment with Tc will be commenced in 1998 and is expected to be completed by the end of 1999. This experiment will simulate the effect of decomposition

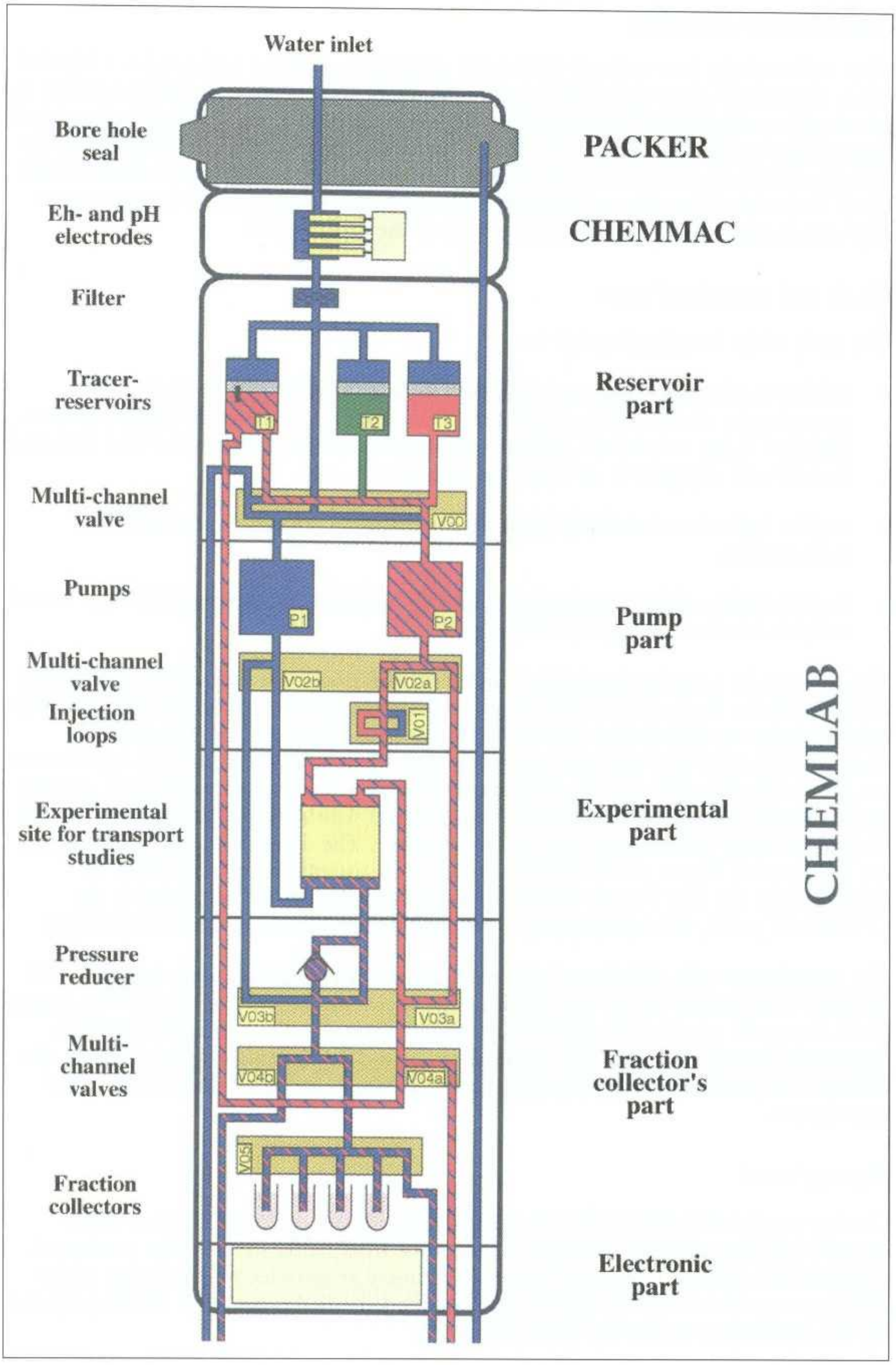

Figure 14-10. Schematic illustration of the CHEMLAB probe.

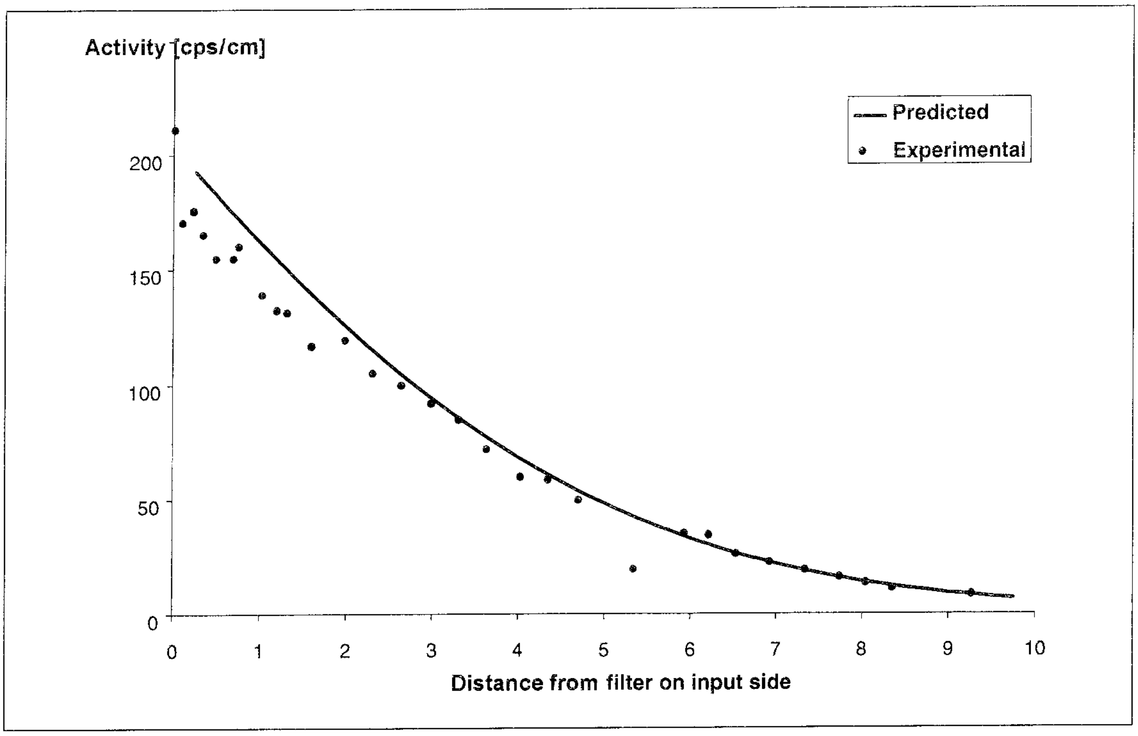

Figure 14-11. *Results from measurement of diffusion of caesium in bentonite.*

of the water molecules by the radiation from the fuel (radiolysis). This gives rise to different substances which can oxidize the redox-sensitive nuclides to forms which are more soluble and more mobile than the reduced form. Two different types of radiolysis experiments are planned. Tetravalent technetium will be used in both experiments.

Radionuclide transport from the bentonite barrier out to a water-conducting fracture will be studied in an experiment where Sr, Cs and I are used as nuclides. The experiment will be conducted to verify theoretical calculations that have shown that the transfer resistance between bentonite and water is an important retardation mechanism. The reason for choosing these nuclides is that they have different diffusivities in bentonite. The experiment is planned to last five months and be conducted during the latter half of 1999 and the first half of 2000.

Sorption reversibility, i.e. the capability of radionuclides that have been sorbed on rock surfaces to be desorbed, will be studied in an experiment using the nuclides Tc, Sr and Cs. It is estimated that the experiment will take just over six months to carry out.

Solubility and sorption are affected by the chemical composition of the water. Particularly significant factors, besides the redox conditions, are concentrations of colloids and microbes, both of which can act as radionuclide carriers. The concentrations are often low and difficult to determine. Their effect can be measured by means of direct solubility and sorption experiments. In relation to the experiments described above, these have lower priority and are therefore planned to come last in order, starting 2001 at the earliest.

An experiment with redox-sensitive nuclides is scheduled to be run during all of 1999 and half of 2000. In cooperation with Institut für Nukleare Entsorgung (which works for BMBF) in Germany, experiments are also planned with americium, neptunium and plutonium. A natural fracture has been cored out in the Äspö HRL. It will be divided up and used for the different experiments. Tests with Tc(VII) and U(VI) are planned to be carried out in a natural cored-out fracture. These experiments, combined with determination of solubilities for Tc(IV) and U(IV), are projected to take ten months. It is assumed that the experiment with americium, plutonium and technetium will take roughly the same length of time.

Experiments with spent fuel will require careful radiological monitoring of preparations, execution and associated transport. Their exact duration cannot be calculated until these questions have been explored. It is reasonable to assume an experimental time of 3-5 years. The goal is to commence the experiments with spent fuel in 2000.

Another borehole probe is required to be able to carry out the planned experimental programme within the scheduled time. A simplified version of the existing CHEMLAB probe will be manufactured during 1998. The new probe will initially be used for the migration tests of redox-sensitive nuclides scheduled to start in 1999.

Hydrochemical stability

The chemical properties of the groundwater are of importance for the durability of various repository components and the solubility and transport properties of radionuclides. The site of the deep repository will be selected where the geochemical conditions at repository depth are favourable. It is therefor important to show that today's favourable conditions will not change significantly in the future. The foundation for an understanding of the future evolution of the geochemical conditions on a repository site lies in a good understanding of the evolution that has led to its present-day state. Hydrogeological and hydrochemical models are important tools for achieving this understanding.

Goals and execution

The overall goal is to obtain a better understanding of the changes in prevailing groundwater systems that might occur in the future (up to 100,000 years) and to develop methodology for integrated hydrochemical modelling.

The modelling work is carried out by modelling groups who work for the organizations that are participating in the Äspö project. The work is performed on investigation data that has for the most part been collected during the pre-investigation phase. The results were reported at workshops in June 1994 /14-60/, 1995 /14-61/ and 1997 /14-62/.

The work is now being carried out primarily within the framework of the Task Force project. Task Force 5 has been established to evaluate and improve the consistency between the hydrochemical and hydrogeological models. The goals of this modelling task have been defined as follows:

- to evaluate the concordance between groundwater flow models and geochemical mixing models by integration and comparison between hydraulic and chemical data obtained before and during construction of the tunnel on Äspö, and
- to develop a methodology for integrating hydrogeological and geochemical information that can be used in the evaluation of possible repository sites.

In this case, the agreement between the hydrogeological and geochemical models can be checked against the change in flow paths and groundwater chemistry to which the construction of the Äspö HRL has given rise.

Within the framework of the project Hydrochemical Stability, SKB is also participating in the EU project EQUIP (Evidence from Quaternary Infills for Palaeohydrogeology). The aim of EQUIP is to deduce previously prevailing hydrochemical conditions from investigations of fracture-filling minerals. The participants in EQUIP are ANDRA, ENRESA, Nirex, Posiva and SKB. The project started in 1997 and is expected to last for 3 years.

Another project with the goal of exploring the origin of the groundwater involves sampling and analysis of water in the microfractures in the rock matrix. Special equipment is being developed for this purpose during 1998. Sampling will take place in a special hole drilled for the purpose. The aim of the study is to clarify whether much saline water has been present on the site during earlier phases. By means of various measurements and calculations, it may be possible to determine whether the salt in the water derives from the rock or whether it has another origin, see section 9.6.

Two-phase flow

Unsaturated or two-phase flow, i.e. simultaneous flow of gas and water, can occur in a deep repository due to 1) release of dissolved gases occurring naturally in the groundwater at the low pressures that occur in the vicinity of drained tunnels, 2) penetration of gas (air and blasting gases) into the rock during construction and from ventilated tunnels or from buffer and backfill material, 3) penetration of gas generated due to corrosion or biological processes, and 4) radioactive gases formed by radioactive decay of the spent fuel.

Studies have so far been carried out of the effect of release of gases dissolved in the groundwater at low pressures, see section 14.3.3 above. The future work will be aimed at studying the transport of gas generated due to corrosion or biological processes. This is of importance above all for other waste, which contains relatively large quantities of corrosive material. Gas generation due to corrosion can also occur in the copper/steel canister if the copper shell has been breached. Corrosion of the steel insert will then give rise to hydrogen. In these contexts it is important to understand how the gas will be transported away from the repository /14-63/.

Goal and execution

The goal is to develop and test models for two-phase flow through fractured rock.

The project is being carried out in cooperation with BMBF, Germany. BMBF is responsible for execution of the field tests in the Äspö HRL and development of three-dimensional numerical models.

The tests are being carried out in a niche at a depth of 360 m in the Äspö HRL, where a vertical fracture has been identified and found suitable for execution of the tests. Geological and hydrogeological characterization of the fracture has been performed. Transport of gas and water in the fracture will then be investigated by means of various experiments. SKB's efforts are mainly focused on model development, analysis of the results of the field tests, and execution of certain laboratory experiments.

14.4.5 Demonstration of technology for and function of important parts of the disposal system

Construction of the Äspö HRL has provided valuable experience regarding refinement and testing of technology for construction of a repository and investigation of the rock in conjunction with construction. This is important experience that is needed for detailed characterization of a site. Since tunnelling has been performed by means of both conventional drill & blast (D&B) and boring with a tunnel boring machine (TBM), valuable experience has been gained for the selection of an excavation method for the deep repository.

The Äspö HRL provides an opportunity to test, investigate and demonstrate on a full scale various components of the deep repository system that are of importance for long-term safety. It is also important to show that high quality can be achieved in design, construction and operation of a deep repository. Within the framework of the stage goal, a full-scale prototype of the deep repository will be built to simulate the function of the repository and interaction between its parts during the initial post-closure period. Demonstration of deposition technology will be done to develop the technology and test different steps in the deposition sequence. Different backfill materials and the method for backfilling of tunnels will be tested in a special experiment. In addition, detailed investigations of the interaction between the engineered barriers and the rock will be carried out, in some cases over long periods of time.

Prototype Repository

Different aspects of the repository concept have been tested in a number of field and laboratory experiments. Models have been developed which describe and predict the function of the repository's components and the system as a whole. However, there is a need to test and demonstrate the execution of the deposition sequence with today's technology on a full scale and to demonstrate that it is possible to understand the processes that are of importance in the different engineered barriers and the surrounding rock.

The idea of building a Prototype Repository in the Äspö HRL has matured over a long period of time. The role of the Prototype Repository has gradually been clarified in relation to the other large-scale experiments that are being conducted in the Äspö HRL and the development of the deep repository programme. As a result, the Prototype Repository project is being focused on testing and demonstration of the function of the disposal system. Certain activities aimed at development and testing of practical engineering solutions for executing deposition have also been included. These activities have, however, been limited since they are included in other projects.

Goals and execution

The main goals for the Prototype Repository are:

- to demonstrate the function and interaction of the different parts of the deep repository and compare the outcome with models and assumptions,
- to develop and test appropriate criteria and quality systems, and
- to simulate applicable parts of the repository design process.

The Prototype Repository should simulate as closely as possible a real repository with respect to geometry, materials and rock conditions. The Prototype Repository is being designed to simulate a KBS-3 repository under what can be described as normal conditions or the reference scenario described in SR-95. The Prototype Repository differs from a real repository in that the heat output will be generated by electric heaters instead of spent nuclear fuel.

The evolution of the Prototype Repository will be followed over a long period of time, possibly up to 20 years. The purpose is to gain experience of a relatively long operating period, which can be cited in applying for a licence for regular operation of the deep repository. Despite a relatively long test period, the Prototype Repository cannot be used to demonstrate the long-term safety of a deep repository.

The Prototype Repository will be built in the inner part of the TBM-excavated tunnel at a depth of 450 m in the Äspö HRL. Preliminary plans call for 6 full-scale deposition holes spaced at a distance of about 6 m, which is the same as in the KBS-3 concept. The distance between the plugs and the nearest deposition hole will be at least 8 m. The proposed configuration is shown in Figure 14-12. The TBM tunnel above the deposition holes will be completely backfilled. The results of the experiment with tests of different

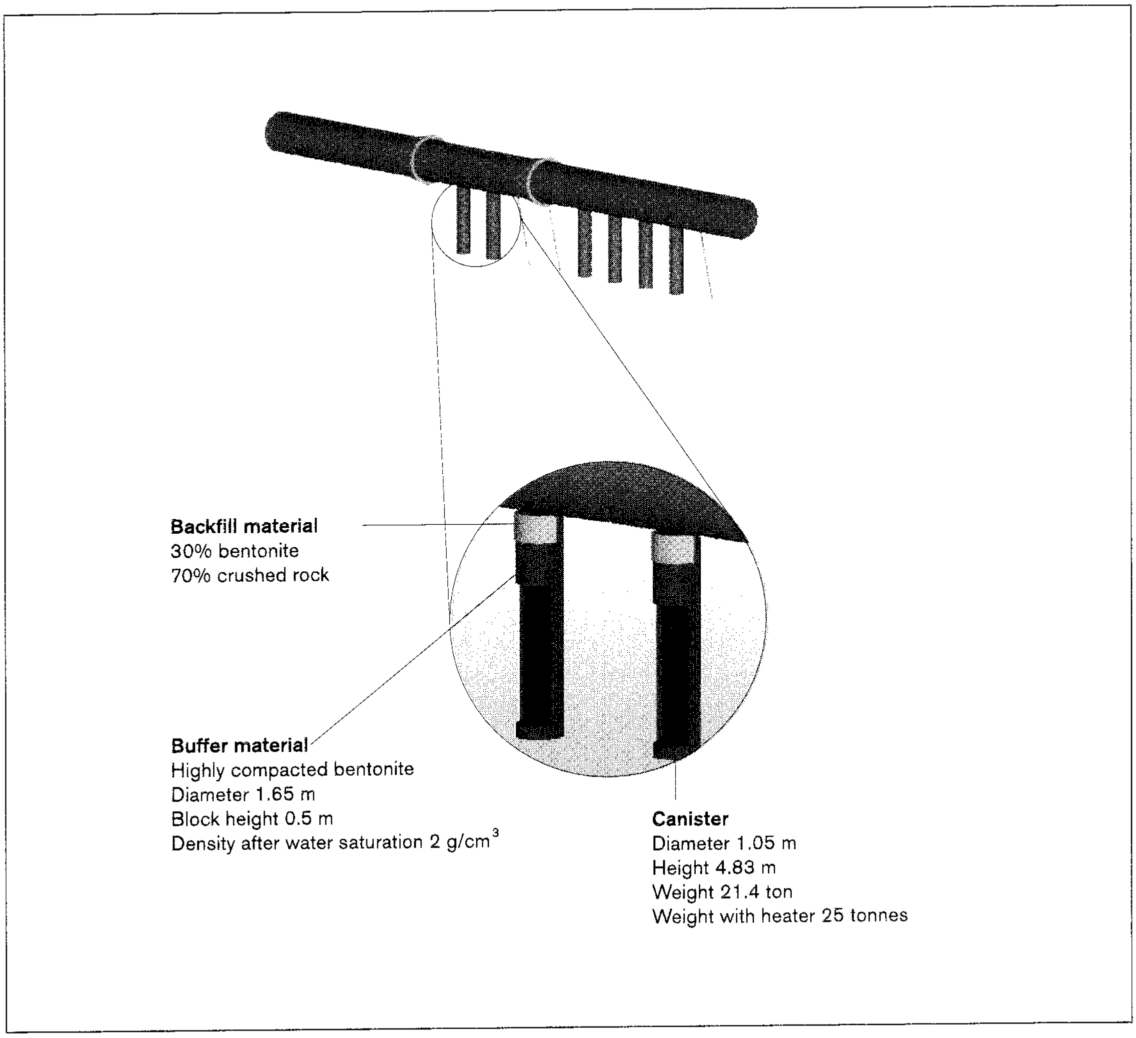

Figure 14-12. *Planned layout of Äspö Prototype Repository.*

backfill materials will be used as a basis for the choice of backfill material in this test. A tunnel plug will separate the outer and inner parts of the test tunnel. The plugs will be designed to withstand the combination of full water pressure and swelling pressure from buffer and backfill material. The outer part of the test is planned to be conducted for about 5 years. Then this part of the test will be discontinued, the plugs demolished, the backfill material and buffer dug out and sampled, and the canister retrieved and examined. The inner part will be left in place and the test there will be continued for another 10–20 years.

The Prototype Repository will be instrumented to permit the following processes and quantities to be studied:

- water uptake in buffer and backfill,
- temperature distribution in canister, buffer, backfill and rock,
- swelling pressure and movements in buffer and backfill,
- rock stresses and movements in surrounding rock, and
- chemical processes.

Testing of different backfill materials

The construction of a deep repository must not result in the creation of new flow and transport pathways that significantly degrade the barrier function of the rock. To this end, the tunnel must be backfilled with a material with low hydraulic conductivity and/or sealed with strategically located plugs. The overriding requirement is that the tunnels should not constitute a significant flow path in relation to the natural flow paths constituted by the fractures in the rock. The requirement on the tunnel backfill must also be regarded in relation to the properties of the damaged zone around the tunnels, since it is the aggregate function that is of importance. These requirements can be met by using a low-permeable tunnel backfill consisting of a mixture of crushed rock and bentonite or a tunnel backfill consisting solely of crushed rock combined with appropriately situated plugs. Another important function of the backfill in the deposition tunnels is to counteract expansion of the buffer from the deposition holes.

Different materials and methodologies for backfilling tunnels in a deep repository have been considered in SKB's development work down through the years. One alternative was based on a backfill material consisting of a mixture of quartz sand ("Bornholm sand") and bentonite deposited in layers and compacted with vibratory equipment. At the top against the roof the mixture was to be blown in, but this results in a lower density in that part of the backfill. The possibility of substituting crushed rock from the mined tunnels in the deep repository for quartz sand has been analyzed /14-64/. The conclusion is that the functional requirements can also be met with crushed rock as a ballast material. In another study /14-65/, the conclusion is drawn that a backfill material consisting solely of sand or crushed rock without bentonite meets the requirements on safety against radionuclide migration if the tunnel does not intersect major fracture zones and the water flow through the tunnel is small. Tests will be conducted with different backfill materials in order to confirm on a full scale the models for the hydraulic and mechanical properties of the backfill material in a deep repository. In conjunction with the testing of different backfill materials, a method for compaction and retrieval (extraction) of backfill material in tunnels will also be developed and tested.

Deposition will proceed one tunnel at a time in the planned deep repository. When deposition has been completed along a tunnel and it has been backfilled, the tunnel must be sealed with a temporary plug. Tests of different backfill materials will also include development and testing of an emplacement method for, and design and function of, a tunnel plug.

Goals and completed work

Testing of different backfill materials (Backfill and Plug Test) is carried out for the following primary purposes:

- to develop and test different materials and compaction methods for backfilling of blasted tunnels,
- to test the function of the backfill and its interaction with surrounding rock on a full scale in a blasted tunnel, and
- to develop and test an emplacement method for and the function of plugs for temporary sealing of deposition tunnels.

An initial test of different materials for backfilling of deposition tunnels was carried out in 1995 and 1996. The primary purpose of the test was to try out a method for backfilling and check what densities can be obtained in practice. The excavation muck obtained from TBM boring of the Äspö tunnel mixed with bentonite was used as a backfill material. Backfilling tests were conducted with uncrushed TBM muck and with crushed TBM muck, as well as with crushed TBM muck mixed with 10, 20 and 30 weight-percent bentonite. A total of about 1,600 tonnes of backfill material was handled. Crushing and mixing of the backfill material worked well. Owing to the relatively large inflow of water to the drift, problems were encountered in compaction of the horizontal layers at the bottom of the tunnel. The method developed for compaction of inclined layers was found to work much better and will be used for the entire cross-sectional area in coming tests. As a consequence of this, the compaction equipment has been modified. Extraction of the compacted tunnel backfill proceeded without problems /14-31/. Laboratory tests have been performed to determine the material properties of the different backfill materials /14-32/.

Planned work

The test will be carried out in the ZEDEX drift, which was excavated by means of normal drill & blast, at a depth of 420 m in the Äspö HRL. The inner test part of the drift will be filled with a mixture of 30 percent bentonite and crushed rock. The outer test part of the drift will be filled with crushed rock containing no bentonite. A layer of pre-compacted blocks consisting of 50 weight-percent bentonite and crushed rock will be placed nearest the roof in this part. The backfill will be compacted with inclined layers, a technique developed in preparatory tests. The experimental tunnel will be sealed with a concrete plug, see Figure 14-13. The backfill will be instrumented and measurements will be made of the sealing capacity of the backfill and the plug. When the measurements are finished, the backfill will be extracted, sampled and analyzed. The design and scope of the test are described in greater detail in /14-66/.

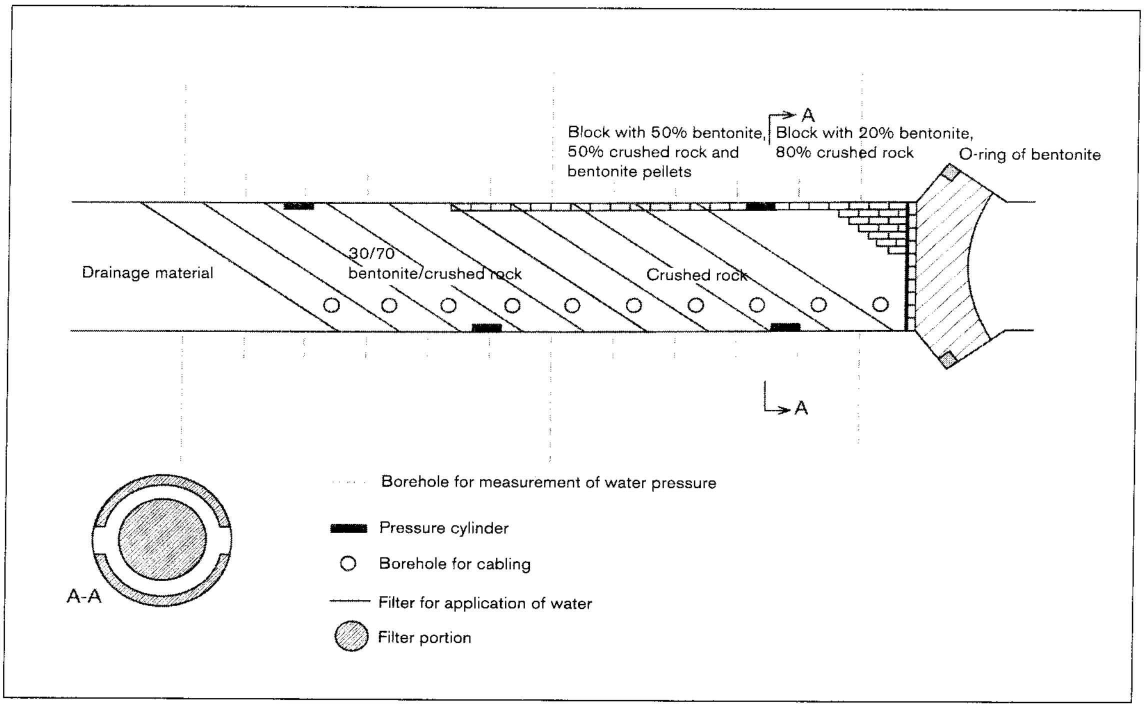

Figure 14-13. *Overview of experimental design for Backfill and Plug Test.*

Demonstration of deposition technology

Development and testing of methodology and equipment for encapsulation and deposition of spent nuclear fuel in a deep repository is an important part of SKB's programme. In addition to the technical aspects, it is also important to be able to demonstrate in a graphic manner the different steps in encapsulation, transport, deposition and retrieval of spent nuclear fuel to specialists and the public. As a part of the overall programme, SKB has established a Canister Laboratory in Oskarshamn, which was put into operation during 1998. Demonstration of deposition and retrieval will be carried out at the Äspö HRL. The demonstration project comprises a complement to the Prototype Repository and the Backfill and Plug Test, which focus on the integral function of the engineered barriers under realistic conditions.

Development of machines for canister deposition does not lie within the Äspö HRL's sphere of responsibility; the Äspö HRL is only responsible for the field activities. The following description focuses on the role of the Äspö HRL in this project.

Goals and execution

The goals of the demonstration of deposition technology are:

- to develop and test methodology and equipment for encapsulation and deposition of spent nuclear fuel,
- to demonstrate in a graphic manner the different steps in deposition and retrieval of canisters to specialists and the public, and
- to develop and test appropriate criteria and quality systems for the deposition process.

Demonstration of deposition technology will be carried out in a drift at the 420 m level. This site provides a realistic environment for execution of the tests while permitting transport of heavy vehicles to the experimental area. The demonstration will include handling and deposition of canisters and bentonite buffer in four full-sized deposition holes. The steps expected to be tested and demonstrated are:

- drainage-pumping of hole,
- application of bentonite buffer,
- deposition of canister,
- application of remaining bentonite buffer above canister,
- filling with water,
- backfilling of deposition hole above bentonite buffer.

Test of retrieval

Due to the stepwise development of the technology for deposition of spent fuel, if the evaluation following the initial operation of the deep repository results in the judgement that the technology is not satisfactory, the canisters may have to be retrieved and handled in some other way. The evaluation will probably be made after the bentonite has become water-saturated and swollen so that the canister is stuck in the hole. To retrieve the canister, the pressure exerted by the bentonite on the canister must first be relieved so that the canister can be lifted up without being destroyed.

Goals and execution

The goals of test of retrieval are:

- to develop and test methodology and equipment for dislodging the canister from the water-saturated and swollen bentonite, and
- to show how a freed canister can be retrieved under realistic conditions.

Test of retrieval will be carried out in a new tunnel at the 420 m level in the Äspö HRL. After geological mapping of the tunnel, two full-sized deposition holes will be drilled. Canisters with electric heaters are then lowered into the hole and surrounded with bentonite blocks and some instrumentation. The holes are sealed with concrete plugs. The tunnel above the holes is not backfilled.

Then the holes are left to become water-saturated. This is expected to take 3-5 years. In the meantime, technology and machines for freeing of the canister from the bentonite are developed. Two different methods may be developed and can be tested, each in its own hole. The methods identified today as feasible are disintegration of the buffer by flushing with salt water, and cooling (and thereby shrinking) of the bentonite /14-68/.

After the bentonite has become water-saturated, the actual retrieval tests commence. The canister is dislodged from the bentonite, gripped by its lid and placed in a radiation shield.

Test of alternative deposition technology

Since the KBS-3 method was presented in 1983, SKB has developed and analyzed some interesting alternatives to the KBS-3 concept (see e.g. the report SKB TR 93-03). A comparison of these alternative methods has shown the KBS-3 method to be the most advantageous. Studies of several alternative designs of the KBS-3 concept have nevertheless continued. The most likely alternatives are horizontal emplacement in medium-long tunnels (MLH = Medium Long Holes) or in holes bored in the tunnel wall (KBS-3H), and emplacement of two canisters in each vertical deposition hole. Besides the actual emplacement of the canister, the study has included analysis and comparison of different deposition methods and different designs of radiation shielding, canister and buffer /14-69/. The result of the comparison is that the KBS-3 method is still the reference alternative, but the MLH method should be further studied to determine whether it offers a realistic alternative to the KBS-3 method.

Goal and execution

The goal is to gather further data to provide a better basis for evaluating horizontal deposition as an alternative to the KBS-3 method.

Compared with the KBS-3 method, the MLH method is based on less tried technical solutions, and a number of systems and technical detail solutions need to be studied. Of essential importance to the method is the development of rational systems for tunnel boring, techniques for sealing and rock support, and methods for canister deposition. Of crucial importance for long-term performance and safety is the method for emplacement of the canister and surrounding bentonite, and the density and homogeneity of the bentonite after closure. More in-depth analyses are required regarding the design of a suitable deposition method and machinery. A review of the size of the deposition holes to allow for the possibility of boring the holes and carrying out deposition of the canister and emplacement of the bentonite is also needed for the MLH method.

As a part of this work, SKB is carefully following the results of the experiment involving horizontal deposition in tunnels, FEBEX, which is currently being conducted in Grimsel. Experience from the experiment in Grimsel, the planned tests of vertical deposition in the Äspö HRL, and the studies reported above ought to provide a good basis for judging whether additional alternatives should be tested on a full scale in the Äspö HRL. A decision on this will be taken during the coming period.

Long-term test of buffer material

The performance of the buffer material was previously tested at Stripa during a time span of up to 5 years /14-67/. These tests were done in water with low salinities, under relatively low water pressures and moderate temperatures (about 80°C). One of the results was that an expected elevated chloride concentration was found in the inner part of the buffer nearest the heater. (The increase in chloride concentration was, however, too small and irregular to be able to be definitely interpreted as an enrichment phenomenon.) A test with French clay was conducted at a temperature of about 180°C, which resulted in a severe deterioration in the buffer properties of the bentonite nearest the heater as a result of a combination of salt enrichment, dissolution of quartz in the bentonite material and cementation (formation of "clay stone"). Different conceivable mineralogical and chemical processes have been studied in laboratory tests. The results show that the negative effects on buffer performance are negligible if the buffer is designed with the density (about 2.0 g/cm^3 after water saturation) that is foreseen in KBS-3, where bentonite blocks are pre-compacted with a high degree of water saturation and the temperature is kept to a moderate level (below 100°C) /14-70/. It is essential to verify the laboratory results and models developed under realistic deep repository conditions over long spans of time, possibly up to 20 years.

Goals and execution

The goals of the long-term tests of the buffer material are:

- to test the performance of the bentonite buffer in the deep repository environment during a long period of time (up to 20 years),
- to test models and confirm results from laboratory experiments concerning transformation of smectite to illite, salt enrichment and influence of high pH,
- to rule out the occurrence of unidentified but possible processes in the deep repository environment.

The long-term tests of bentonite performance are planned to be performed in 4 m deep boreholes with a diameter of about 300 mm. Compacted bentonite blocks with a heater in the middle are lowered into the holes, see Figure 14-14. The holes are instrumented for measurement of temperature, pressure and thermal conductivity (water content) during the duration of the test. To test the buffer under conditions representative of the

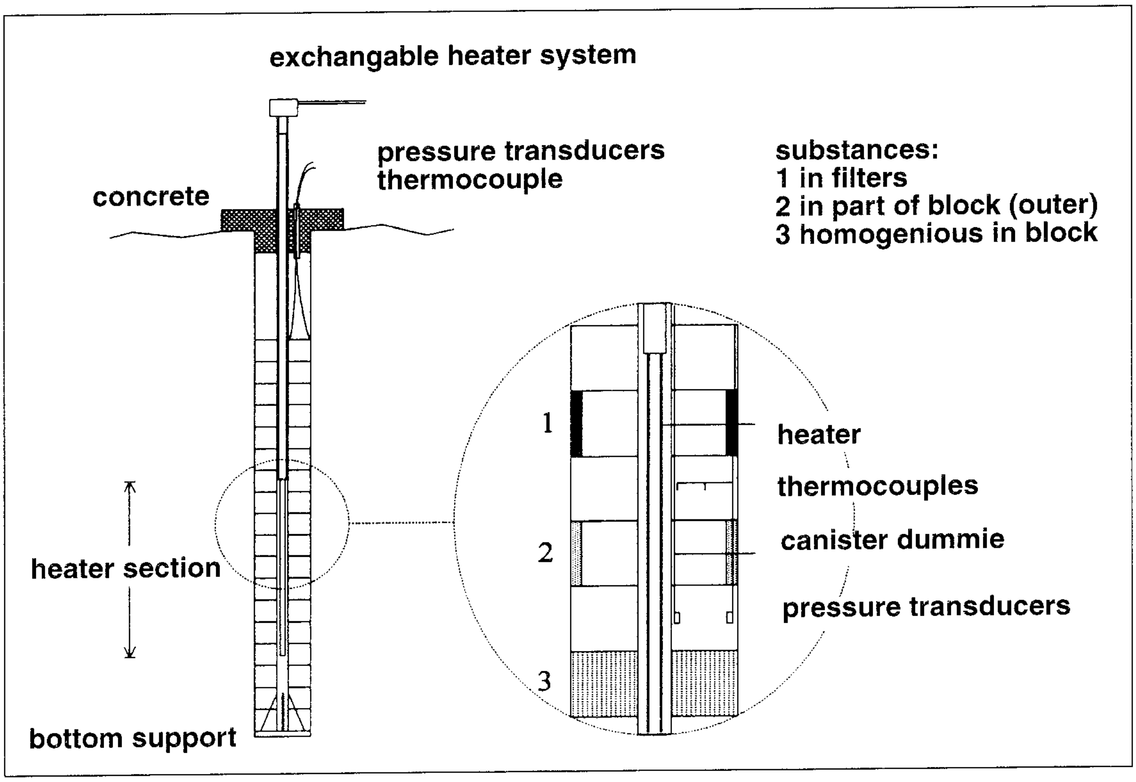

Figure 14-14. Schematic design of long-term tests of buffer material performance.

reference concept, the temperature is driven to a maximum level of about 100°C and the holes are filled with MX-80 bentonite with a high degree of water saturation. For testing under deviant conditions, tests are combined with salt enrichment, cementation and mineral alteration in the same hole. Since these processes are temperature-dependent, these tests are conducted at temperatures higher than 100°C.

The initial phase of the project has been completed. One hole was instrumented in accordance with the reference concept and one hole for testing under deviant conditions. Measurements of buffer performance in the hole were performed during 1 year with maximum temperatures of 90°C and 130°C, respectively. Then the buffer was taken up by overcoring of the test hole. Samples were taken and sent to the laboratory for quantification of parameters of interest, such as water saturation, chemical composition of buffer and pore water, mineral composition, swelling pressure, hydraulic conductivity and shear strength. This hole was utilized primarily as a pilot test for testing of instrumentation and experimental concept before the long-term tests are begun.

It is estimated that the long-term tests will be done in a total of 4 holes, where the tests will be interrupted progressively after 5, 10 or a maximum of 20 years. When the test in a hole is interrupted, the buffer is taken up by overcoring and sampled in a similar manner to that done for the pilot holes. The design and scope of the tests are described in greater detail in /14-71/.

Grouting technology

The programme for development of grouting technology is aimed at gaining additional knowledge of processes and factors that influence the consumption of grouting material and the grouting result obtained, plus development of a practical technique for dealing with conditions that can arise in the deep repository and that cannot be solved in a reliable manner with the commercial methods available today. Know-how and technology need to be verified by tests under realistic conditions.

Goal and execution

The goal is to verify know-how and technology for grouting/reinforcement of large transmissive discontinuities and strongly water-conducting discontinuities of moderate thickness and extent.

For characterization of rock from the grouting viewpoint, development of a purpose-suited hydraulic testing method is planned. Equipment will be tested in the Äspö HRL under well-controlled forms, and a study of the accuracy of the characterization will be carried out by grouting of boreholes.

The stabilizing and sealing effect of the pre-grouting will be studied by investigation of suitable sections in the Äspö tunnel where only pre-grouting has been carried out.

The models that have been developed to predict the result of grouting under different geological conditions will be tested in field tests. First characterization of the rock volume to be grouted is carried out. Based on these data and constructed models, a prediction is made of the expected result. Then grouting is performed and testing to determine the spread and sealing capacity of the grout.

Sealing of exploratory boreholes

In connection with site investigation and detailed characterization, a number of exploratory boreholes will be drilled in order to obtain data on the properties of the rock as a basis for determining the configuration of the repository and assessing its long-term safety. These boreholes have to be sealed prior to closure of the repository so that they do not constitute rapid flow paths from repository depth to the biosphere. This is planned to be done by filling the holes with bentonite or cement. Since most of the boreholes will be instrumented in conjunction with the investigations on a site, reliable technology for cleanout of boreholes so that they can later be sealed is also needed.

Technology for sealing of boreholes has previously been developed and tested within the framework of the Stripa project /14-67/. Two different methods were used to emplace highly compacted bentonite blocks in boreholes with a length of up to 200 m. Very good sealing was obtained. The technology must be further refined to show that boreholes up to 1,000 m in length can be sealed.

Goals and execution

- To develop robust and reliable technology to remove instruments and other obstacles from boreholes.
- To develop robust and reliable technology for sealing of boreholes and verify that the technology provides the desired leaktightness.

The project will commence with an analysis of what requirements should be made on leaktightness. Then available technologies will be examined to determine their potential for meeting these requirements. The most promising technology or technologies will be selected for further development and testing.

There are a large number of exploratory boreholes on Äspö. Equipment is stuck in some of them, and the holes no longer fill any function. One or two of these holes will be selected for testing of technology for cleanout and sealing of holes.

Gas transport in water-saturated buffer

Background

Water can enter a breached canister through the copper shell and corrode the cast iron insert. In a reducing environment, hydrogen forms and can accumulate in a gas bubble with rising pressure if the production rate is higher than the rate of dissolution of the gas in the water. When the pressure becomes sufficiently high, a flow path is opened up through the buffer. The pressure will fall and, if the rate of gas production is sufficiently low, the flow path will close. Comprehensive studies have shown that the critical gas pressure for breakthrough is determined by the sum of the buffer's swelling pressure and the hydrostatic pressure. The flow resistance in the rock is assumed to be less than in the buffer, which would mean that once the gas has passed through the buffer, its further transport out into the geosphere would take place relatively rapidly /14-72/.

Ongoing laboratory tests with small gas flows are studying how gas migrates through the buffer and at what pressures, among other things after repeated pressure build-up and throughflow cycles. Modelling of this transport is under way.

Goal and execution

To study, under realistic conditions and on a full scale, transport of small gas flows through water-saturated bentonite and further out into surrounding rock.

One or more experimental set-ups are planned with bentonite buffer in rock, where the thickness of the buffer is 350 mm, which is equal to the planned thickness of the buffer in the deep repository. On one side the buffer lies up against a copper plate with a nozzle to release gas. The other side is in contact with rock. The gas flow should be able to be adapted to the gas production that is likely in a deep repository. However, helium or argon must be used in the laboratory instead of hydrogen. Experimental set-ups have to be planned with the aid of, among other things, the gas flow model that is being devised within the ongoing GAMBIT project. It is deemed possible that numerical calculations and experimental design can be carried out during the period. Experimental set-up, water saturation of the bentonite and execution of gas tests will not be started until the next three-year period.

Copper corrosion

The corrosion properties of copper are well understood. A summarizing assessment of the state of knowledge regarding copper corrosion is given in /14-73/. The conclusion is that it is highly improbable that general or local corrosion would be the limiting factor for the life of the canister in the deep repository. The influence of groundwater composition on copper corrosion has also been studied. The conclusion is that the corrosion rate is not appreciably affected by the local variations in groundwater chemistry that can be accepted for the choice of repository site or positioning within a selected repository site.

Goal and execution

The goal is to evaluate present-day models for copper corrosion for different groundwaters.

To evaluate models for copper corrosion, long-term tests will be performed where copper is placed in groundwater of varying composition (oxygen content, sulphide content and chloride content). Copper metal is placed in containers traversed by flowing groundwater at different locations in the Äspö HRL. Copper will also be exposed surrounded by bentonite. Comparison is also made with copper corrosion in air.

14.5 Information

Information on the Äspö HRL and its activities is an important and integral part of the laboratory's activities. The public and nearby residents are given information on the site. A special visitor's niche has been arranged in the access tunnel where SKB's activities and the Äspö HRL are presented. Äspö Village also has exhibitions describing the activities and results of the Äspö HRL. Furthermore, general information is provided in the exhibition hall in the village of Simpevarp and along a "nature path" out on Äspö Island. Both are open to the public.

Each spring on Äspö Day, the public is invited to visit the Äspö HRL. More than 500 people normally come. Tours of the Äspö HRL are arranged in the summer in co-operation with OKG and the tourist office in Oskarshamn. Tours of the laboratory can also be arranged by special appointment at other times. The Äspö HRL receives approximately 5,000 visitors annually.

An exhibition on SKB's activities will be built in the new office finished in 1998. This will signal an increased commitment to information on SKB's activities at the Äspö HRL.

14.6 International participation

The activities at the Äspö HRL have attracted great international interest. Agreements on participation exist with Atomic Energy of Canada Limited (AECL); Power Reactor & Nuclear Fuel Development Corporation (PNC), Japan; Central Research Institute of Electric Power Industry (CRIEPI), Japan; Agence Nationale pour la Gestion des Dechets Radioactifs (ANDRA), France; Posiva Oy, Finland; UK Nirex, UK; Nationale Genossenschaft für die Lagerung von Radioaktiver Abfälle (NAGRA), Switzerland; Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie (BMBF), Germany; Empresa Nacional de Residuos Radiactivos (ENRESA); and United States Department of Energy (USDOE), USA.

The international cooperation is coordinated in an International Joint Committee (IJC). Technical Evaluation Forums (TEFs) are organized in conjunction with the meetings of the IJC in order to furnish advice and viewpoints on programmes and results. In addition to the IJC members, technical experts from each organization participating in the Äspö HRL participate in TEFs.

The organizations take part in the practical work via their own personnel on the site who participate in the performance of various experiments. Several of the participating organizations have planned additional investigations and experiments, which have been specified in the agreements concluded with the organizations. These experiments are being conducted in addition to the programme presented here and add considerable value to SKB's activities.

The international cooperation makes it possible to assemble the world's leading experts within many different fields for an exchange of ideas and experience in matters of importance for radioactive waste disposal. This exchange enables all the organizations participating in the Äspö project to keep up with the latest research developments and to participate in a creative interdisciplinary scientific research environment with a potential to advance the frontiers of knowledge. An example of this is the cooperation on models for groundwater flow and radionuclide transport which takes place in a Task Force with members from the participating organizations (see section 14.4.2). An important part of this cooperation is the review performed by SKB's international partners and their experts of the Äspö HRL's plans for the design of different experiments as well as obtained results. Taken together, the international cooperation makes a very valuable contribution to SKB's programme.

The results of the international cooperation are reported in a separate series of reports called Äspö International Cooperation Reports.

15 Natural analogues

The overriding goal of the analogue studies is to validate assumptions and models that are important for the safety of the deep repository /15-1/. The ambition is to find natural examples of processes that are important for long-term safety. Slow or low-intensity processes – such as leaching, weathering and radiolysis – are not always so simple to investigate in the laboratory, but they can be of importance in the long term. Much of the investigation work is being done in the form of large international projects. The advantages of this approach lie not only in the obvious, i.e. the fact that the costs can be divided among a larger number of stakeholders, but also in the fact that the support and involvement of organizations in several different countries can offer a variety of points of view and backgrounds, so that the results can be examined critically.

15.1 Natural analogues and safety assessment

The project form is an effective way to conduct the analogue investigations, but the time frames of the project do not always permit a complete evaluation. Sampling and analysis must be done with the greatest care, which sometimes means that the evaluation phase is rushed or confined closely to its original objectives. For this reason it may be advantageous to go through the material one more time after the project has been concluded. Examples of such "revisiting" of former project data include Poços de Caldas and Cigar Lake. Regarding measurements of trace substances in the groundwater in Poços de Caldas, it was found that better agreement was obtained with calculated values if the effect of co-precipitation was included. It turned out that the solubility of uranium, zinc and rare-earth metals was controlled by iron hydroxide minerals, while strontium was controlled by fluorite. Co-precipitation leads to concentrations that are 2-4 orders of magnitude lower than expected. The same thing would apply to radionuclides of these elements /15-2/.

The evolution of a redox front has been calculated using data from the Osamu Utsumi uranium mine in Poços de Caldas. These calculation models were originally devised to simulate the evolution of the near field around a damaged canister. Many calculations were performed after the Poços de Caldas project had been concluded, and the work is reported in Leonardo Romero's doctoral thesis at the Department of Chemical Engineering at the Royal Institute of Technology, 1995 /15-3/. An essential conclusion is that the redox front from a damaged canister never reaches beyond the bentonite buffer /15-4/.

Another example of "revisiting" is Cigar Lake. The project lasted from 1989 to 1993. After the investigations were concluded and reported, further time and resources were devoted to a more through evaluation of specially selected portions of the material. The following results were arrived at /15-5/:

- A more realistic radiolysis model was developed and tested.
- Hydrothermal calculation models were used to explain the formation of the Cigar Lake ore.
- The role of the clay as a buffer and a barrier around the ore was tested.

The methods that were developed to calculate the radiolysis of water in the Cigar Lake ore were better than the overly conservative models previously used for safety assessments. The geochemical conditions may very well remain reducing despite radiolysis, at least if the intensity of the radiation is as low as at Cigar Lake.

The hydrothermal calculations show that graphite played an important role in the formation of the orebody. That explains why no ore is found at nearby Close Lake where conditions were otherwise similar.

The clay in which the uranium ore lies embedded was compared with bentonite, and the conclusion was arrived at that the Cigar Lake clay acted as an effective barrier to water flow and mass transport, despite its poorer physical properties compared with bentonite. Two factors have contributed most to protecting the ore at Cigar Lake: the low hydraulic conductivity of the clay relative to the surrounding sandstone, and the capacity for preserving reducing geochemical conditions. The clay has been of great importance in both cases.

15.2 Jordan

The Maqarin Project (also called the Jordan Project) started in 1990 with funding from Nagra, Nirex and Ontario Hydro. SKB has participated since 1991. The project is now into its third phase, and supporting organizations are the EA (Environmental Agency, UK), Nagra, Nirex and SKB. The third phase is being coordinated and administered by SKB, and we are in the midst of the final report on phase 3.

Cement and concrete are manufactured by man, and several of the minerals in the cement paste are unusual in nature. The few natural examples that exist are of great interest, since they can tell us something about the long-term properties of the concrete, or how the environment is affected. The latter question, i.e. how the high pH of Portland cement affects the near field, is the principal reason for the interest in hyperalkaline springs. Strongly alkaline springs with a pH of up to 11 exist in areas with ophiolites, for example on Cyprus and in Oman. The high pH value arises when ultramafites in the ophiolitic formations weather to serpentinite. The hyperalkaline springs in Maqarin, Jordan have an entirely different origin, however. Marl, a mixture of clay and calcium carbonate which is present in large quantities in the area and furthermore contains bitumen (15-20%), has burned over large areas and formed a cement-like material. The altered (burnt) zone lies within the original bituminous marl and varies widely in thickness, from a metre or so up to a maximum of 60 m. It is believed that the strata have self-ignited due to oxidation of pyrite, of which there is plenty in the marlstone. Groundwater that has come into contact with the altered zone takes on a composition very close to that of cement pore water, with a pH in the range 12-13 and calcium, sodium and potassium as the dominant cations. The most common anions are sulphate and hydroxide. The water in Maqarin is roughly 10-100 times more alkaline than the water found in Oman and on Cyprus.

The effect the hyperalkaline water has had on the surrounding rock can be seen in Maqarin /15-6/. New minerals are formed, in agreement with theoretical predictions. First zeolites are formed as the pH increases. Then come calcium aluminosilicates (called CASH in the cement industry) and calcium silicates (CSH), see Figure 15-1. Fractures tend to be sealed by the secondary minerals, but there is nothing to indicate that radionuclide retention decreases. The general conclusion is that the water flow in the near field tends to decrease when water-conducting fractures clog up, while the rock behind

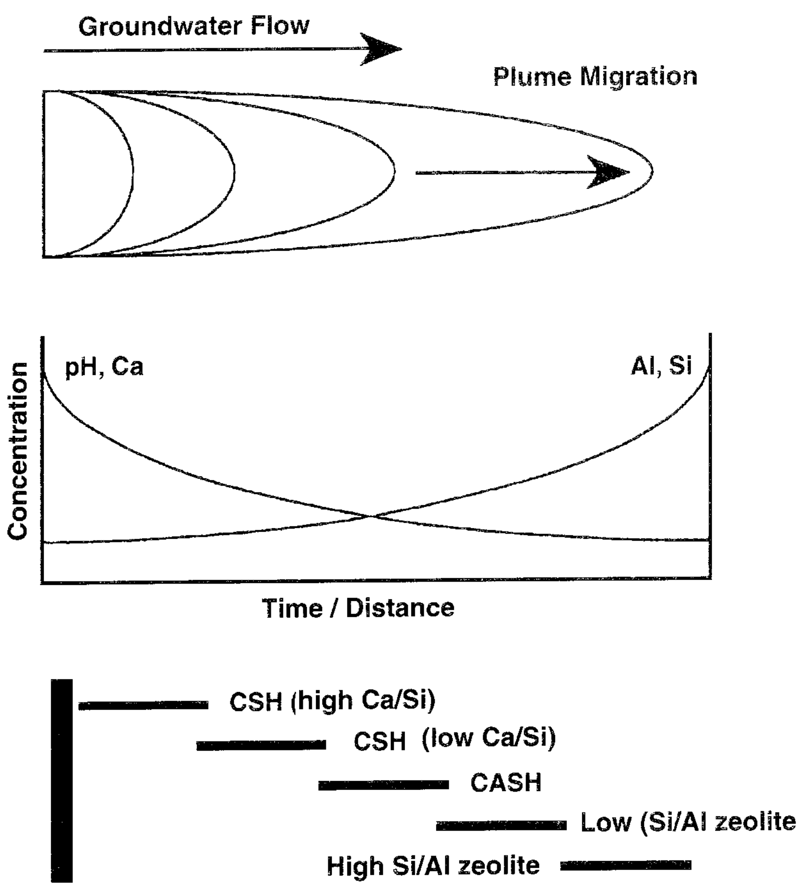

Figure 15-1. Schematic diagram of the extent and reactions in an "alkaline plume" /15-6/.

them remains intact and accessible for retention of radionuclides through matrix diffusion.

Colloids, dissolved organic matter and bacteria are being studied at Maqarin. The concentration of colloids is very low, which agrees with corresponding observations of colloids in concrete pore water and is due to the fact that the water is heavily mineralized (high concentration of calcium, among other minerals). The organic matter differs from the humic substances normally found in groundwater. This is being more thoroughly investigated. Bacteria are found in the hyperalkaline spring water, but they are not alkalophilic, nor active. The actual absence of adaptation suggests that this may be a hostile environment for bacteria as well.

15.3 Oklo

Up to about 25 years ago, all natural uranium was believed to have the same isotope ratio $^{235}U/^{238}U$, but in 1972, during a routine analysis of uranium prior to enrichment, uranium with a lower isotope ratio than normal was discovered. The sample came from a mine in Oklo, Gabon, which contained several deposits of high-grade uranium ore of 20% or more. It was soon discovered that the "abnormal" uranium came from zones in the ore which also contained other elements with an unusual isotope composition. They could only have been formed by fission of ^{235}U, and it must have happened a long time ago. Early investigations in Oklo were concentrated to what is now called zone 2, which is located in the open-cast part of the mine and gave a good picture of how a typical Oklo reactor had worked.

As time passed, the mining at Oklo continued towards greater depths in the open pit and further underground. New reactor zones were found. In 1991, the Oklo Project started to study the reactor zones as natural analogues of a deep repository with high-level waste. The project was run by France's CEA with the support of the EU. Active cooperation was established with SKB and other organizations outside the EU. The work was concentrated to zones 10 and 13, which were located underground in Okelobondo, just south of Oklo, and to the zone located in Bagombé, around 20 km further south. Bagombé was of special interest to SKB since it lies close to the surface and shows traces of oxidative weathering. This project, also called the Oklo Project, Phase 1, was concluded in 1995 and a final report was published in 1996.

When Sweden joined the EU, SKB was also able to participate as a full member in the second phase of the Oklo Project, along with CEA, ENRESA and ANDRA. Phase 2 started officially in June, 1996, and is supposed to last three years. The mining corporation COMUF is discontinuing its operations in Oklo in 1998, after which it may be difficult to do anything more in the mine. Much of the new sampling has been concentrated to Bagombé, which offers the best conditions. Here the reactor has never been exposed, and here there is groundwater that has never been affected by any mining. All sampling takes place via boreholes.

Two billion years ago, natural uranium had an isotope ratio of $^{235}U/^{238}U$ like that in enriched fuel. With enough such uranium in an ore and a suitable moderator such as water, spontaneous criticality could be brought about. Nowadays this is not possible, since ^{235}U has decayed more rapidly than ^{238}U, lowering the isotope ratio. Well-preserved uraninite crystals from reactor zone 10 show by their content of radiogenic lead that the reactor is 1,968 million years old. So far, Oklo is the only place on earth where examples of natural criticality have been found. This is not so strange, since many conditions have to be met before natural criticality can be brought about in uranium ore. Today it is impossible owing to the lower concentration of ^{235}U, but it was sufficiently high two billion years ago. Long before that the isotope ratios were even higher, but then there was too little oxygen in the atmosphere and it is needed in order for concentrated uranium ores to form. Life on earth has thus contributed with leaching (oxidation) and precipitation (reduction) of uranium. Other "fortunate" circumstances coincided at Oklo and contributed towards making the reactors possible. The ore was very rich in uranium, water was present in the right proportions, whereas metals which capture neutrons (reactor poisons) were lacking. The latter is remarkable since vanadium and manganese, both of which are neutron captors, usually accompany uranium, but not at Oklo. To be sure, there are rich deposits of vanadium and manganese in the region, but not at the same places as uranium.

Naudet has thoroughly investigated the criticality at Oklo and described it in his book /15-7/. With permission, SKB has translated parts of the book from French to English /15-8/ and used the material for a comparison between Oklo and the conditions in a deep repository. The very first time the risk of criticality was studied for a repository, reference was made to Oklo /15-9/ and the conclusion then is the same as now: criticality does not occur in a deep repository /15-10/.

A special group (PAIG, Performance Assessment Interface Group) has been established within the Oklo Project to link together the geoscientific evaluation with the safety assessment's need for data. It is a welcome initiative, since the first phase was more general in character.

15.4 Palmottu

The new Palmottu Project started in November 1995. The site being investigated is a uranium deposit by Palmottu Lake in southern Finland. The uranium ore forms a 1-15 m thick, steeply dipping zone that reaches down to about 300 m. It is being studied as an analogue of spent fuel in a repository in granitic rock. Geology, hydrogeology, groundwater chemistry, climate etc. are similar to what can be expected on future repository sites in Finland and Sweden. The project is headed by GTK in Finland, with support from the EU. Besides SKB, ENRESA and BRGM are also participating.

Many of the investigations in Palmottu have made use of the many prospecting holes in the area, but in the new project additional exploratory holes have been drilled with a larger diameter (Ø76 mm), permitting more measurements. The holes have furthermore been positioned to give the best possible results. TV logging has been used, along with radar, spinner measurements of water flows, and hydraulic tests (single-hole and cross-hole tests). SKB's mobile chemistry lab was used for sampling and analysis of groundwater. It has in general been a welcome opportunity for us to test our equipment for logging, hydraulic testing and chemistry measurements, which was either new or modified since the pre-investigation phase on Äspö (1986-1990).

The EU requested that the Palmottu Project be carried out in two separate phases. The goal of phase 1 was a hydrogeological evaluation, and phase 2 was then to proceed with dissolution and mass transport. The EU first granted funds only for phase 1, which was to be reported and approved before funding could be given to phase 2. That is what has happened; phase 1 has been concluded, reported and approved by the EU; funding has been granted for phase 2 and the work has begun /15-11/.

15.5 Goals and programme

15.5.1 Goals of the Oklo Project

The Oklo Project is scheduled to last through 1998. It will probably take a good part of 1999 before the reporting is finished, and some type of supplementary evaluation may be needed. A number of questions to which answers are desired have been formulated for phase 2 of the Oklo Project:

- What fission products and end products of the nuclear reactions are still left?
- Where in the zone, the near field or the rock, have they been retained and in what form?
- What retention mechanisms have been active and for how long?
- What influence have the geological events had on retention?
- What transport mechanisms have been active, and when?

The term "geological events" referred to are magma that has penetrated into and affected some of the zones hydrothermally, and oxidative weathering in Bagombé. Aside from the task of answering the questions, the following goals have also been set:

- To develop models for processes of importance for the function of a repository.
- To test these models on data from the Oklo study.
- To obtain better knowledge of the retention capacity of the natural materials.
- To improve the safety assessment's databases.
- To identify slow processes that could affect radionuclide transport.

These are generally and cautiously formulated goals that reflect some uncertainty as to how far it will be possible to carry the investigation. However, the work within the PAIG group creates hope for a useful result in support of future safety reports.

15.5.2 Goals of the Palmottu Project

The final report on the Palmottu Project is due in 1999. The goals of the project are as follows:

- Provide a quantitative description of the uranium-thorium deposit situated in granitic rock near Palmottu Lake.
- Examine the relative importance of processes that control water flow in crystalline rock.
- Investigate and model the influence of geochemical oxidation and reduction on the mobility of radionuclides in crystalline rock.
- Examine the importance of different mechanisms for radionuclide retardation.
- Investigate the importance of repeated ice ages on the properties of the rock.
- Use knowledge and data from the studies to develop and refine models used in performance and safety assessment.

15.5.3 Maqarin, Oklo and Palmottu

The Natural Analogues programme is primarily focused on carrying out and evaluating the three large analogue projects in which SKB is participating: Maqarin, Oklo and Palmottu. Phase 3 for Maqarin will be completed when the final report is finished, and that work is under way. A continuation has been discussed and the possibilities are currently being explored. The Oklo and Palmottu projects will be finished within the next three-year period, hopefully along with the evaluation of the results. Viewed in a longer time perspective, we assume that analogue investigations will remain a part of the preparation for future safety reports. Their scope and direction may, however, change somewhat with time.

15.6 Competence enhancement

The comprehensive geoscientific investigations within an analogue project contribute towards gathering and training skilled personnel for future site investigations and site evaluations. Since the geology is also the same as at Palmottu, we have an opportunity to try out and develop our equipment for sampling and measurement in boreholes. Extreme conditions such as the hyperalkaline waters in Maqarin and oxidative weathering in Poços de Caldas and Bagombé broaden our experience and make us better equipped to discuss different scenarios where the natural environment of the repository is affected.

15.7 Miscellaneous

Investigations of natural analogues are not entirely restricted to the Natural Analogues programme. Related programmes are often involved in parts of the analogue studies reported here, for example the Oklo Project, where the Fuel programme is participating. On the material side, there is a natural need for examples from nature. Thus, the Encapsulation Project is supporting the studies of native copper in Hyrkkölä in southern Finland.

16 Palaeohydrogeological programme

We know that Sweden has been exposed to repeated, severe glaciations during the past few million years. It can be shown on scientific grounds that the country has been covered by thick ice sheets during approximately 80% of the past 700,000 years. In all probability, we can also expect the greatest changes during the next 100,000 years to be associated with the occurrence of continental ice sheets /16-1/. The changes that can be assumed to be of greatest importance for the performance and safety of the deep repository are loading by the ice cover, deep permafrost, large meltwater flows and high water pressures.

During 1990–91, SKB and TVO in Finland carried out a joint inventory of the international state of knowledge on ice ages /16-2/. Based on this inventory, an ice age scenario was formulated covering the next 130,000 years.

Boulton /16-3/ subsequently proposed an approach whereby SKB/TVO's ice age scenario could be further developed to be used for predictions of future climate-related impact on a repository site. The main proposal in this report entails use of a time-dependent glaciation model driven by a description of the future evolution of the Swedish climate. The first step in such a model run would be to calibrate the model against the past.

In 1996, an international workshop on climate-induced changes in rock stresses, groundwater flow and water chemistry was held within the framework of the Nordic nuclear safety organization NKS /16-4/. Some 90 researchers and officials in the nuclear waste sector took part in the workshop. Both SKB and SKI were involved in the preparatory work and the conduct of the meeting.

16.1 Goals of the programme

Since 1994, SKB has been pursuing a palaeohydrogeological programme for the purpose of:

- identifying and creating an understanding of the processes caused by future climate change which can affect the performance of a deep repository, and
- creating a basis for performance and safety assessments of the repository with a time horizon far in the future.

A detailed description of the programme can be found in Wikberg et al. /16-5/.

16.2 Modelling of glaciations and their impact on the geosphere

As a fundamental part of the palaeohydrogeological programme, SKB has had the University of Edinburgh develop a numerical glaciation model with which the effects of past and future climate changes can be studied. The model can simulate the growth of an ice sheet as a function of time, based on input data in the form of temperature changes and topographical and geological boundary conditions. The glaciation model has been developed stepwise within the framework of five project phases with the following aims:

Project 1: Simulation of the last glaciation cycle and prediction of future glaciations along a transect through Sweden /16-6/.

Project 2: Studies of groundwater flow caused by an ice sheet. Sensitivity studies with respect to various parameters included in the glaciation model /16-7/.

Project 3: Simplifications of the glaciation model. Calibrations of model simulations against reconstructions of the last ice age. Modelling of meltwater flows and rock-mechanical impact /16-8/.

Project 4: Development of a time-dependent site-specific description of the ice sheet and groundwater flow in the Äspö area during the previous glaciation cycle.

Project 5: Development of theories to describe hydrogeological conditions under an ice sheet in three dimensions, including the effects of tunnel flows /16-9/.

In conjunction with these projects at the University of Edinburgh, activities have also been pursued at the Chalmers University of Technology /16-10/ and at various consulting firms /16-11, 16-12/. Svensson, 1996, used the program code PHOENICS to study groundwater flow coupled to an ice sheet above the Äspö area /16-13, 16-14/, using output data from the glaciation model in part as input data.

The glaciation model developed at the University of Edinburgh is available in two versions today, both two- and three-dimensional. The model has been simplified in several respects by means of sensitivity studies and comparisons of model output data with geological observations and our general knowledge of the most recent ice age. Different versions have different advantages and disadvantages and can be used for different purposes. The computing times are moderate today, even when ordinary personal computers are used.

Model runs have been carried out for a number of different cases with regard to both the past and the future. Output data in the form of time-dependent series of different parameters – such as ice thickness, meltwater flow, permafrost depth and water pressure – have been generated for a number of sites. These data can then be used as boundary conditions for detailed modelling of regional/local conditions, or furnish information on differences between sites. The modelling codes must be able to be used as a tool in future performance and safety assessments /16-15, 16-16/.

What drives the advance and retreat of the ice cover is the evolution of the air temperature. The climate system (and thereby the glaciation model as well) is very sensitive to relatively small variations in temperature. Owing to the fact that available climate models are uncertain when it comes the future climate on earth, it necessarily follows that the predictions of future glaciations will also be very uncertain. It is possible to predict with relatively good certainty when future cold periods will fall. However, it is difficult to determine which of these periods will give rise to the a continuous ice cover extending over most of Sweden and thereby covering a repository site. Different glaciation model runs exhibit very great differences in this respect. It cannot be said with certainty today, for example, whether southern and central Sweden will be affected at all by a continental ice sheet during the next 100,000 years.

16.3 Hydrogeological and hydrochemical aspects

Groundwater flow on a regional scale has been modelled for the Äspö area /16-13, 16-14/, whereby the effects of an ice front passing back and forth over a hypothetical repository site were studied. Sensitivity for different assumed conductivity fields and salinity distributions were investigated. The purpose of the model runs was also to study how deep the oxygen-rich meltwater can infiltrate, as well as how mixing of groundwaters of different ages and origins takes place. This type of information is essential for comparisons with hydrogeochemical observations, for example from the 1,700 m deep borehole at Laxemar /16-5/.

Boulton and co-workers have modelled the large-scale pattern of subglacial groundwater flow along a two-dimensional flowline from the Norwegian coast, through Sweden and down to Germany /16-7, 16-8/. These simulations were coupled to the simulation of the advance and retreat of the ice sheet, and the sensitivity of the glaciation model to different parameters was investigated, after which the model was simplified. An important question is, however, how the meltwater produced at the base of the glacier is drained. This also affects the variation of the water pressure in time and space, as well as the subglacial sedimentation processes. The two-dimensional simulations show a transport of water only perpendicular to the ice margin (and in the outer parts in the form of tunnel flows if the bedrock is not sufficiently conductive to absorb all the meltwater that is produced).

Boulton and co-workers recently developed theories for three-dimensional drainage under a glacier or an ice sheet /16-9/. These theories are based on the assumption that the hydraulic system under the glacier is self-organizing with a coupling between pressure distribution, channel flows and the water-conducting properties of the bedrock. The groundwater flow within the meltwater zone of the continental ice sheet is thereby directed to a great extent towards the draining tunnels, i.e. parallel to the ice margin. The proposed theories can explain many of the patterns and the configurations of the esker systems we see today. Through studies and measurements in our present-day large glaciers, observations have been made which confirm the patterns predicted by the theories. Initial modelling of the ice tunnel flows has also been done /16-14/ for the Äspö area.

16.4 Mechanical aspects

The presence of an ice sheet gives rise to a sharp increase in the loading of the underlying bedrock, resulting in a flexure (downwarping) of the crustal area under the ice and a changed state of stress in relation to the present-day situation. Furthermore, shear stresses are created at the base of the ice as it moves over the underlying surface, causing deformation and erosion.

The emphasis within the palaeohydrogeological programme has been on modelling of the growth and properties of the ice sheet and the groundwater flow beneath the ice. Some studies of mechanical impact have also been conducted, however. The downwarping of the bedrock and relative sea level changes are obtained as output data from all model simulations with the glaciation model. Furthermore, attempts have been made to model the erosion and the mass transport, and comparisons have been made with field observations of till thickness with relatively good results /16-6/.

An ice sheet that passes over a site affects both total and effective rock stresses via the combined action of movement, load and water pressure at the base of the ice. Boulton and co-workers have described three fundamentally different causes of mechanical failure induced by an ice sheet /16-8/:

- by the relative movement of the ice against the underlying surface – shear failure,
- by loading – either tensile failure parallel to the greatest principal stress or shear failure due to large deviator stresses,
- by high fluid pressure – hydroshearing and hydrofracturing.

The first of these failure types can only occur very near the ground surface, while the others can theoretically take place at relatively great depths. Boulton and co-workers recently calculated the extent of zones within which failure mechanisms are active for an ice sheet under the assumption of rock-mechanical failure criteria for a homogeneous rock mass /16-8/. However, only lithostatic rock stresses were assumed, which means that the absolute values of the depths are greatly overestimated.

In general, rock-mechanical failures and deformation caused by glaciation/deglaciation primarily take place in existing structures and zones of weakness. Analytical calculations have been carried out of hydrofracturing and hydroshearing underneath an ice front /16-17/. According to these calculations, hydrofracturing of horizontal/subhorizontal fractures can occur a few decametres down in the rock below the actual ice sheet. It is, however, pointed out that conditions at the ice margin may be such that hydrofracturing can take place down to greater depths. Hydraulically induced shear of existing fractures can be expected at relatively moderate pore water pressures.

16.5 Coupled effects of glaciations

The thermal conditions beneath a continental ice sheet have been investigated thoroughly by means of extensive model runs. The results show that three different zones can be distinguished: an ice divide zone where the ground is frozen to fairly great depth and no melting takes place at the base of the ice, a meltwater zone within which large quantities of meltwater are produced and infiltrate, and an ice margin zone where the ground is once again frozen. Furthermore, the model runs indicate an extensive periglacial permafrost that can extend hundreds of kilometres in front of the ice margin. The uncertainties are, however, still rather large regarding how deep down into the rock we can expect permafrost to exist (hundreds of metres). Depending on the chosen input data, very great variations are obtained. The problem here is that we don't have any geological or hydrogeochemical observations that tell us anything about conditions during the most recent ice age. No completed model runs indicate that a deep repository will run any risk of freezing, however.

Studies of groundwater flow within the periglacial permafrost region – where the groundwater's natural flow paths are disturbed, the water's residence time in the bedrock increases and the chemistry changes – have not been conducted within the palaeohydrogeological programme. Modelling has, however, been carried out which shows how glacial meltwater can be transported down to great depths if the vertical conductivity of the bedrock is relatively high. A higher salinity of the groundwater at depth, as well as horizontal fracture zones, can, however, prevent such a deep-going transport. Initial modelling has also been done of how the composition of the groundwater changes with time due to different climate-related events. However, the results are still so uncertain that any more far-reaching comparison with observed water composition has not felt meaningful.

The long-term prospects of being able to do this are deemed to be good, however. This would then offer a method for testing and possibly improving the glaciation model and thereby creating greater confidence in the rest of the output data.

Via their studies and calculations of the drainage conditions in continental ice sheets, Boulton and co-workers have clarified the importance of three-dimensional model runs /16-9/. the lower water pressures that arise along the tunnels are also of great importance for the impact of the ice on mechanical conditions in the bedrock. What remains to be done is to include the theories for tunnel drainage in the glaciation model and to study the hydraulic and mechanical effects thus obtained.

The coupled hydro-mechanical effects of loading and unloading by an ice sheet, including high fluid pressures, are inadequately investigated today. It is particularly difficult to judge the rock-mechanical consequences for a rock mass with a complex fracture structure. The hypotheses recently put forward by Boulton and co-workers are interesting and have development potential with the assumption of a more realistic rock stress situation /16-8/. The type of modelling of "self-regulating" permeability that is proposed where the cycle 'fluid pressure – induced failure – permeability increase – lower fluid pressure' is studied as a transient process is, however, not realistic with present-day knowledge of fracture systems and the mechanical properties of rock fractures.

The rock-mechanical questions have generally played a subordinate role in the completed programme. Relatively simple studies can yield a good understanding of the mechanical impact of the glacier /16-17/. However, coupled hydraulic-mechanical models are probably also required where the bedrock is described as a network of discrete fractures and fracture zones in order to judge the effects at repository depth.

16.6 EQUIP Project

The goal of the EQUIP Project (Evidence from QUaternary Infills for Palaeohydrogeology) is to ascertain and test methods for tracing previously existing hydrochemical and hydrological conditions via investigations of fracture-filling minerals (calcite). Participants in the project are Golder Associates (UK) Ltd., the British Geological Survey (with support from UK Nirex and HMIP), ANDRA, Posiva, SKB, ENRESA and the University of Bristol. Each participant designates one or more sites from which sample material is taken. SKB uses samples from Äspö. Other sites that will be included are Sellafield, Posiva's investigation sites, ANDRA's investigation sites, etc. SKB hope, as do the other participants, to get an idea of how useful new analytical methods are in tracing previously existing hydrochemical conditions. Furthermore, we hope to be able to answer the question of whether the glacial water that exists at great depth at Äspö derives from the most recent deglaciation or whether it has a much earlier origin. The project has a planned duration of 36 months and started in February 1997.

By shedding light on previously existing chemical conditions in this manner, it is possible – with an assumption regarding future climatic conditions – to model future groundwater flow conditions, see PAGEPA.

16.7 PAGEPA Project

The EU project PAGEPA (PAlaehydrogeology and GEoforecasting for Performance Assessment in geosphere repositories for radioactive waste disposal) started in 1997 with SKB as a "subcontractor". SKB is responsible for a task dealing with how palaeohydrogeological information is to be used in safety assessment. The three-year project is being coordinated by the University of Edinburgh in the UK. Other participants are the Chalmers University of Technology in Gothenburg, Sweden, BRGM from France and BGR from Germany.

17 Deep drilling at Laxemar

17.1 Situation report

The state of knowledge with regard to the rock's mechanical stability, hydrochemical environment and capacity for radionuclide retardation is dealt with separately in chapters 7, 8 and 9. In a small integrated project, "Deep Drilling KLX 02 – Laxemar", mechanical, hydraulic, thermal as well as chemical aspects have been studied in the field. The project, which has been carried out on a site separate from but near the Äspö HRL, was initiated in the autumn of 1992 with the goal of broadening knowledge of the composition and properties of the rock at greater depth and obtaining new information regarding the flow pattern and chemical composition of the groundwater in a regional perspective for the Äspö HRL.

Other goals for the project have been:

- to demonstrate the different technical options for exploratory drilling to great depths, and to demonstrate such drilling to a depth of about 1500 m below the surface.
- to demonstrate methods for investigations in boreholes within the depth interval 1000-1500 m.

The drilling of KLX 02 was carried out during the period October-November 1992 to a depth of 1700 m using the wire-line method. An intact drill core exists for the interval 200–1700 m /17-1/. After the drilling, investigation activities have included geological mapping, geophysical measurements, groundwater chemistry and groundwater hydraulics. One rig was modified to measure rock stresses at levels deeper than 1000 m. The borehole also furnishes essential input data to SKB's palaeohydrogeological programme and to the programme that deals with the alternative repository concept "Very Deep Holes", see section 13.2.

All field investigations conducted to date have now been summarized in a compilation /17-2/. Following are examples of some of the results:

- Småland granite comprises 63% of the drill core. Äspö diorite amounts to 25%. Fine-grained granite represents less than 2%. Greenstone sections occur frequently between 600 and 950 metres.
- Fission track studies show that 3000–4000 m thick Devonian sediment strata have previously occurred. These strata consisted of erosion products from the Caledonide mountain range, formed at that time.
- Based on geophysical investigations it is probable that certain fractured sections in KLX 02 have contact with the other deep borehole KLX 01 in the Laxemar area. The distance is about 1000 m.
- Certain sections in the borehole, 600–1200 m and 1550–1700 m, show an elevated fracture frequency.
- The rock stresses do not follow linear relationships with increasing depth. Four separate intervals with stress gradients have been identified for both greatest and smallest principal stress.

- The greatest principal stress runs in the direction N30°W with few exceptions.
- The temperature gradient varies between 14.5 and 17°C/km.
- Transmissivity tests (single-hole tests in 300 m sections) show higher values of transmissivity ($T \gg 1 \times 10^{-4} m^2/s$) down to a depth of about 500 m. Below that level the values are one to two orders of magnitude lower.
- During the interference tests between KLX 02 and KLX 01, a hydraulic contact was noted between the holes.
- The groundwater samples show two obvious water types /17-3/: 1) a superficial brackish water, and 2) brines. The transition occurs at a depth of between 800 and 1100 metres.
- At the bottom of the hole, at a depth of 1700 metres, the chloride concentration is about 50,000 mg/l.

The drilling and the field investigations have been carried out, not without numerous practical difficulties, and have yielded valuable experience for future site investigations. In summary, SKB believes it has achieved its overall goals.

17.2 Goal and programme

The goal for the coming three-year period is to map recharge and discharge conditions at the KLX 02 borehole in Laxemar.

SKB does not intend to conduct any extensive field investigations in the KLX 02 borehole during the coming three-year period. Certain hydrochemical samplings may, however, take place.

18 Science information

The ability to communicate the scientific results that are obtained within the various research programmes to the public and decision-makers is becoming increasingly important in order to obtain popular and political acceptance for a deep repository. We must also be able to show that the facts that are presented in brochures and the like can be easily traced to their source via popularized presentations in various subject areas. With this in mind, a project was carried out during 1996 and 1997 to provide a popular scientific description of the risks to which a deep repository for spent nuclear fuel gives rise. A unit for science information was also created in the summer 1997.

18.1 Risk project

SKB has not succeeded in conveying a realistic description of what risks a deep repository for spent nuclear fuel might pose to man and the environment. Exaggerated depictions of risks and excessive fear of unlikely events, such as nuclear explosions and transport accidents, are frequently encountered in the public debate. A project was therefore started in the spring of 1996, called the Risk Project, for the purpose of describing the properties of spent nuclear fuel and what risks are associated with its management in a popular scientific fashion. The project lasted for all of 1997 and resulted in the following reports (available in Swedish only unless otherwise specified):

- Spent nuclear fuel – how dangerous is it? /18-1/ (available in English)
- Plutonium – data, properties, etc. /18-2/.
- What would an ice age mean for the deep repository? /18-3/
- Spent nuclear fuel – the safety-related importance of the barriers /18-4/.
- Spent nuclear fuel – the function and development of the deep repository /18-5/.
- Spent nuclear fuel – transport /18-6/.
- Dangerous substances in the human environment /18-7/.

The contents of the different reports have then been further popularized and condensed in the form of fact sheets published in the SKB's Facts About series (in Swedish only).

18.2 Function of the unit for science information

Both fact sheets and popular scientific versions of important reports are produced by the unit for science information (in Swedish only). The idea is that there should be traceability from the facts presented in the fact sheets back to the technical reports.

Fact sheets will be published in 1998 dealing with radioactive waste in other countries, other ways to manage and dispose of spent nuclear fuel, decommissioning of nuclear power plants, plutonium, partitioning and transmutation, the nuclear fuel cycle and RD&D 98.

Fact sheets are planned to be published in 1999 dealing with natural analogues, bacteria and safety assessment. The work of revising and updating the material from the risk project will also continue then. Newly won knowledge will be compiled and reported, and new areas may be identified.

To further facilitate the dissemination of information, there are also plans to start a newsletter in 1999. The principal target groups are scientists, trade press journalists and professionals in the environmental field. The question will be further explored in the autumn of 1998.

18.3 Internet

More and more information is being disseminated electronically. The number of people who have access to and use the Internet is increasing at an exponential rate. We must keep up with this trend by expanding our website and increasing its information density. This work was begun in 1997 and has continued during 1998.

18.4 Internal training

All employees at SKB have a responsibility for seeing to it that the knowledge and expertise we have accumulated is made available in digestible form to the general public and experts all over the world. We therefore plan to give all our information officers basic training in communications in the form of a practically oriented course package with components such as how to write reports, presentation techniques, risk communication and media training. The programme was launched in the spring of 1998 with courses in how to write easy-to-understand Swedish.

References

Chapter 1

1-1 RD&D-Programme 98
Treatment and final disposal of nuclear waste. Programme for research, development and demonstration of encapsulation and geological disposal.
SKB, Stockholm, September 1998

1-2 Werme L, 1998
Design premises for canister for spent nuclear fuel.
SKB Technical Report TR 98-08, Stockholm

Chapter 2

2-1 RD&D-Programme 95
Treatment and final disposal of nuclear waste. Programme for encapsulation, deep geological disposal, and research, development and demonstration.
SKB, Stockholm, September 1995

2-2 Skagius K, Ström A, Wiborgh M, 1995
The use of interaction matrices for identification, structuring and ranking of FEPs in a repository system. Application on the far-field of a deep geological repository for spent fuel.
SKB Technical Report TR 95-22, Stockholm

2-3 Coad P, Yourdon E, 1991
Object-Oriented Analysis.
Yordon Press, P T R Prentice-Hall Inc. ISBN 0-13-629981-4

2-4 Shlaer S, Mellor J, 1992
Object Life Cycles; Modelling the World in States.
Yordon Press, P T R Prentice-Hall Inc. ISBN 0-13-629940-7

2-5 SKB, SR 95, 1995
Template for safety reports with descriptive examples.
SKB Technical Report TR 96-05, Stockholm

Chapter 3

3-1 Werme L, Sellin P, Forsyth R, 1990
Radiolytically induced oxidation of spent nuclear fuel.
SKB Technical Report TR 90-08, Stockholm

3-2 Karnland O, 1997
Bentonite swelling pressure in strong NaCl solutions – Correlation between model calculations and experimentally determined data.
SKB Technical Report TR 97-31, Stockholm

3-3 Wieland E, Wanner H, Albinsson Y, Wersin P, Karnland O, 1994
A surface chemical model of the bentonite-water interface and its implications for modelling the near field chemistry in a repository for spent fuel.
SKB Technical Report TR 94-26, Stockholm

3-4 Bond A, Hoch A, Jones G, Tomczyk A, Wiggin R, Worraker W, 1997
Assessment of spent fuel disposal canister – Assessment studies for a copper canister with cast steel inner component.
SKB Technical Report TR 97-19, Stockholm

3-5 Romero L, Moreno L, Neretnieks I, 1991
A compartment model for solute transport in the near field of a repository for radioactive waste (Calculations for Pu-239).
SKB Technical Report TR 91-48, Stockholm

3-6 SKB, SR 95, 1995
Template for safety reports with descriptive examples.
SKB Technical Report TR 96-05, Stockholm

3-7 Hartley L, Boghammar A, Grundfelt B, 1997
Investigation of the large scale regional hydrogeological situation at Beberg.
SKB Technical Report TR 97-, Stockholm (in press)

3-8 Svensson U, 1997
A regional analysis of groundwater flow and salinity distribution in the Äspö area.
SKB Technical Report TR 97-09, Stockholm

3-9 Boghammar A, Grundfelt B, Hartley L, 1997
Investigation of the large scale regional hydrogeological situation at Ceberg.
SKB Technical Report TR 97-21, Stockholm

3-10 SKB, 1996
User's guide to HYDRASTAR 1.5.
SKB Progress Report U-96-15, Stockholm

3-11 Walker D (ed), Eriksson L, Lovius L, 1996
Analysis of the Äspö LPT2 pumping test via simulation and inverse modelling with HYDRASTAR.
SKB Technical Report TR 96-23, Stockholm

3-12 Walker D, Lovius L, Eriksson L, 1997
Verification of HYDRASTAR 1.7: Nugget effect in geostatistical simulations.
SKB Progress Report U-97-22, Stockholm

3-13 Gylling B, Moreno L, Neretnieks I, Birgersson L, 1994
Analysis of LPT2 using the channel network model.
SKB HRL ICR 94-05, Stockholm

3-14 Gylling B, Romero L, Moreno L, Neretnieks I, 1996
Coupling of the near field release to the far field transport – Using NUCTRAN and CHAN3D.
SKB Progress Report U-96-02, Stockholm

3-15 Dershowitz W, Wallmann P, Shuttle D, Follin S, 1996
Canister and far-field demonstration of the discrete fracture analysis approach for performance assessment.
SKB Progress Report U-96-41, Stockholm

3-16 Ström A (ed), 1998
Äspö Modelling Task Force: Key issues in representation of the barrier function of the geosphere as a basis for input to performance assessment.
SKB International Cooperation Report (in preparation)

3-17 Andersson J, Almén K-E, Ericsson L O, Fredriksson A, Karlsson F, Stanfors R, Ström A, 1998
Parameters of importance to determine during geoscientific site investigation.
SKB Technical Report TR 98-02, Stockholm

3-18 Ström A, Andersson J, Almén K-E, Ericsson L O, Svemar C, 1998
Geovetenskapliga värderingsfaktorer och kriterier för platsutvärdering, Lägesrapport augusti 1998.
SKB Report R-98, Stockholm

3-19 Edlund O, 1998
Summary of biosphere research 1967–1997.
SKB Report, Stockholm (manus)

3-20 Smith G M, Watkins B M, Little R H, Jones H M, Mortimer A M, 1996
Biosphere modeling and dose assessment for Yucca Mountain.
EPRI Palo Alto, CA EPRI TR-107190

3-21 BIOMOVSII, 1996
Development of reference biospheres methodology for radioactive waste disposal.
Swedish Radiation Protection Institute (SSI) TR6, Stockholm

3-22 BIOMOVSII, 1996
Uncertainty and validation: Effect of user interpretation on uncertainty estimates.
Swedish Radiation Protection Institute (SSI) TR7, Stockholm

3-23 BIOMOVSII, 1996
Biosphere modelling for dose assessments of radioactive waste repositories: Final Report of the Complementary Studies Working Group.
Swedish Radiation Protection Institute (SSI) TR12, Stockholm

3-24 Zach R, 1997
Nuclear fuel waste management – Biosphere program highlights – 1978 to 1996.
AECL Report AECL-11811, Pinawa, Manitoba, Canada

3-25 Bergström U, Nordlinder S, 1998
Biosmod – a modularized standard biosphere.
SKB Report, Stockholm (manus)

3-26 Nilsson S, Bergström U, Nordlinder S, 1996
Modularized standard biosphere.
Proceedings Intern. Conf. Deep Geol. Disposal of Radioactive Waste, Canada Nuclear Society, pp 4-59 – 4-66, Manitoba, Canada

3-27 Nordlinder S, Bergström U, 1997
Ecosystem specific dose conversion factors for Aberg, Beberg and Ceberg.
SKB Report, Stockholm (manus)

3-28 Lindborg T, Schüldt R, 1998
The biosphere at hypothetical Aberg, Beberg and Ceberg – A description and evaluation of climate, physical geography, ecology, landuse and environment.
SKB Report, Stockholm (manus)

3-29 Thunholm B, Klein Å, 1998
Quaternary deposits and groundwater flow at Aberg, Beberg and Ceberg.
SKB Report, Stockholm (manus)

3-30 Kautsky U, Meili M, Bergström U, 1998
Processer i Biosfären.
SKB Rapport, Stockholm (manus)

3-31 Bergström, U, Nordlinder S, Aquilonius K, 1995
Assessment model validity document. BIOPATH/PRISM: codes for calculating turnover of radionuclides in the biosphere and doses to man.
SKB Arbetsrapport AR 95-19, Stockholm

3-32 Sundblad B, Aggeryd I, 1996
Long-term redistribution of elements within a swamp area – the natural analogue at the island of Äspö.
Proceedings Intern. Conf. Deep Geol. Disposal of Radioactive Waste, Manitoba, Canada

3-33 Nordlinder S, Bergström U, 1995
Osäkerheter i dosberäkningar från förvar av högaktivt avfall.
SKB Utveckling Project Report U-95-15, Stockholm

3-34 Nordlinder S, 1996
Individual doses from inflow of radionuclides via the groundwater from a major fracture zone.
SKB Utveckling Project Report, U-96-23, Stockholm

3-35 Engqvist A, 1997
Water exchange estimates derived from forcing for the hydraulically coupled basins surrounding Äspö island and adjacent coastal water.
SKB Technical Report TR 97-14, Stockholm

3-36 Westman P, 1997
Saliniteten i Östersjön sedan senaste istiden.
Kvartärgeologiska Inst., Stockholms Universitet, Stockholm (manus)

3-37 VAMP, 1996
Validation of models using Chernobyl fallout data from southern Finland. Scenario S. Second report of the VAMP Multiple Pathways Assessment Working Group. International Atomic Energy Agency (IAEA), IAEA-TECDOC-904, Vienna

3-38 Aggeryd I, Aquilonius K, Landström O, Sundblad B, Tullborg E-L, 1996
Long-term transfer of elements across the interface of the biosphere and geosphere – The natural analogue at the island of Äspö.
SKB Utveckling Project Report, U-96-24, Stockholm

3-39 BIOMOVSII, 1996
Model validation studies of water flow and radionuclide transport in vegetated soils using lysimeter data.
Swedish Radiation Protection Institute (SSI), TR15, Stockholm

3-40 Kautsky U, Hedin A, 1998
Accumulated dose – An upper limit of bio-accumulation effects.
High-Level radioactive waste management. Proceedings of the 8th Int. Conf. Las Vegas, NA, May 11–14, 1998. American Nuclear Society, pp 486–488

Chapter 4

4-1 Forsyth R S, Werme L O, 1992
Spent fuel corrosion and dissolution.
J. Nucl. Mat. Vol 190, pp 3-19

4-2 Werme L O, Spahiu K, 1998
Direct disposal of spent nuclear fuel: Actinide chemistry in natural waters under reducing and mildly oxidizing conditions.
J. Metals and Alloys, 1998

4-3 Forsyth R S, Eklund U-B, 1995
Spent nuclear fuel corrosion: The application of ICP-MS to direct actinide analysis.
SKB Technical Report TR 95-04, Stockholm

4-4 Forsyth R S, 1997
Analysis of radioactive corrosion test specimens by means of ICP-MS.
Comparison with earlier methods.
SKB Technical Report TR 97-11, Stockholm

4-5 Spahiu K, Bruno J, 1996
A selected thermodynamic database for REE to be used in HLNW performance assessment exercises.
SKB Technical Report TR 95-35, Stockholm

4-6 SKI evaluation of SKB R&D Program
December 1995

4-7 Forsyth R S, 1997
The SKB spent fuel corrosion Programme. An evaluation of results from the experimental programme performed in the Studsvik "hot cell" Laboratory.
SKB Technical Report TR 97-25, Stockholm

4-8 Forsyth R S, 1996
Spent fuel corrosion: Collected experimental data for the BTC/PTC experiment. Study of the Tc-99 source term for the BWR and PWR reference fuels.
SKB Arbetsrapport AR 94-07, Stockholm

4-9 Forsyth R S, 1995
Spent nuclear fuel. A review of properties of possible relevance to corrosion processes.
SKB Technical Report TR 95-23, Stockholm

4-10 Skålberg M, Eliasson L, Skarnemark G, Torstenfelt B, Forsyth R, Holmer A, Allard B, 1988
Diffusion of radionuclides from spent oxide fuel into compacted bentonite.
Sci. Total Environ. Vol 69, pp 347–365

4-11 Albinsson Y, Forsyth R, Skarnemark G, Skålberg M, Torstenfelt B, Werme L O, 1990
Leaching/migration of UO_2 fuel in compacted bentonite.
Mat. Res. Soc. Symp. Proc. Vol 176, p 559

4-12 Ramebäck H, Albinsson Y, Skålberg M, Werme L O, 1994
Release and diffusion of ^{90}Sr from spent UO_2 fuel in bentonite clay.
Radiochimica Acta, Vol 66/67, pp 475- 478

4-13 Ramebäck H, Albinsson Y, Eklund U-B, Skålberg M, Werme L O, 1995
Analysis of ^{99}Tc at low concentrations, applied in spent fuel leaching and Tc-diffusion experiments.
Radiochimica Acta (accepted for publication)

4-14 Ramebäck H, Skålberg M, 1998
Separation of neptunium, plutonium, americium and curium from uranium with di-(2-ethyl hexyl)-phosphoric acid (HDEHP) for radiometric and ICP-MS analysis.
J. Radioanal. Nucl. Chem. (accepted for publication)

4-15 Ramebäck H, Skålberg M, 1998
A separation procedure for analysis of ^{90}Sr, ^{154}Eu, and the actinides ^{237}Np, ^{239}Pu, ^{241}Am and ^{244}Cm.
J. Radioanal. Nucl. Chem. (submitted for publication)

4-16 Ramebäck H, Skålberg M, Eklund U-B, Kjellberg L, Werme L O, 1998
Mobility of U, Np, Pu, Am and Cm from spent nuclear fuel into bentonite clay.
Accepted for publication in Radiochim. Acta

4-17 Albinsson Y, Christiansen B, Engkvist I, Johansson W, 1991
Transport of actinides and Tc through a bentonite backfill containing small quantities of iron or copper.
Radiochim. acta, 52/53, p 283

4-18 Sato H, Ashida T, Kohara Y, Yui M, Sasaki N, 1992
Effect of dry density on diffusion of some radionuclides in compacted sodium bentonite.
J. Nucl. Sci. Tech., 29/9, p 873

4-19 Carbol P, Engkvist I, 1997
Compilation of radionuclide sorption coefficients for performance assessment.
SKB Report R-97-13, Stockholm

4-20 Eriksen T E, Eklund U-B, Werme L, Bruno J, 1995
Dissolution of irradiated fuel: a radiolytic mass balance study.
J. Nucl. Mater., Vol 227, pp 76– 82

4-21 SKB Annual Report 1995
SKB Technical Report TR 95-37, Stockholm, 1996

4-22 Christensen H, Sunder S, 1996
An evaluation of the water layer thickness effective in the oxidation of UO_2 fuel due to radiolysis of water.
J. Nucl. Mat., Vol 238 , pp 70–77

4-23 Bruno J, Cera E, Duro L, Eriksen T E, Werme L O, 1996
A kinetic model for the stability of spent fuel matrix under oxic conditions.
J. Nucl. Mat., Vol 238 , pp 110–120

4-24 Bruno J, Cera E, Duro L, Eriksen T, Sellin P, Spahiu K, Werme L, 1996
A kinetic model for the stability of spent fuel matrix under oxic conditions: Model development against experimental evidence.
MRS Proceedings, Boston

4-25 Casas I, de Pablo J, Giménez J, Torrero M E, Bruno J, Cera E, Finch R J, Ewing R C, 1996
Uranium in natural systems. The role of pe, pH and carbonate in the solubility of UO_2 and uraninite (UO_{2+x}) under nominally reducing conditions.
Accepted for publication in Geochim. Cosmochim. Acta

4-26 Casas I, Bruno J, Cera E, Finch R J, Ewing R C, 1997
Characterisation and dissolution behaviour of a natural sample of becquerelite from Shinkolobwe (Zaire).
Geochim. Cosmochim. Acta

4-27 E Cera, 1996
Estudis termodinàmics i cinètics de dissolució de fases naturals d'urani representatives d'un procés d'alteració oxidativa de l'òxid d'urani (IV), Ph.D. Thesis, UAB, Barcelona, Spain

4-28 Casas I, Pérez I, Torrero M E, Bruno J, Cera E, Duro L, 1997
Dissolution studies of synthetic soddyite and uranophane.
SKB Technical Report TR 97-15, Stockholm

4-29 Fuger J, 1994
Problems in the thermodynamics of the actinides in relation with the back-end of the nuclear fuel cycle.
J. Nucl. Mater. Vol 201, pp 3–14

4-30 Bunji B, Zogovic B, 1958
Reduction of uranium from carbonate solutions with hydrogen using UO_2 as catalyst. Proceedings of the International Symposium on Peacefull Uses of Atomic Energy, pp 350–355, Stockholm

Chapter 6

6-1 Pusch R, Börgesson L, 1992
Performance assessment of bentonite clay barrier in three repository concepts: VDH, KBS-3 and VLH. PASS project on Alternative Systems Study.
SKB Technical Report TR 92-40, Stockholm

6-2 Pedersen K, Karlsson F, 1995
Investigations of subterranean microorganisms. Their importance for performance assessment of radioactive waste disposal.
SKB Technical Report TR 95-10, Stockholm

6-3 Pusch R (ed), 1997
The Bentonite and Backfill Handbook, Part 2. Materials and Techniques.
SKB Arbetsrapport, Stockholm (under publicering)

6-4 Pusch R, 1998
Transport phenomena in smectite clay explained by considering microstructural features. Proc. MRS Workshop on solute transport in compacted bentonite, Davos (under publicering)

6-5 Pusch R et al., 1998
The Bentonite and Backfill Handbook, Part 3. Models for calculation of processes and behavior.
SKB Arbetsrapport, Stockholm (under publicering)

6-6 Börgesson L, Johannesson L-E, 1995
Thermo-hydro-mechanical modelling of water unsaturated buffer material.
SKB Arbetsrapport AR 95-32, Stockholm

6-7 Johannesson L-E, Börgesson L, Sandén T, 1995
Pressning av bentonitblock för buffertmaterial.
SKB Djupförvar Arbetsrapport AR D-95-001, Stockholm

6-8 Gunnarsson D, Johannesson L-E, Sandén T, Börgesson L, 1996
Field test of tunnel backfilling.
SKB Progress Report PR HRL-96-28, Stockholm

6-9 Kalbantner P, Sjöblom R, 1997
Borttagning av bentonit kring en deponerad kapsel.
SKB Djupförvar Arbetsrapport AR D-97-22, Stockholm

6-10 Pusch R et al., 1985
Final Report of the Buffer Mass Test – Volume II: test results.
Stripa Project Technical Report 85-12, SKB, Stockholm

6-11 Johannesson L-E, Börgesson L, Sandén T, 1995
Compaction of bentonite blocks. Development of technique for industrial production of blocks which are manageable by man.
SKB Technical Report TR 95-19, Stockholm

6-12 Hökmark H, 1994
Plug design – Numerical study of rock. Mechanical conditions.
SKB Djupförvar Project Report PR 44-94-024, Stockholm

6-13 Muurinen A, Lehikoinen J, 1997
Model for diffusion and porewater chemistry.
24 months progress report. EU project Contr. F14WCT950012

6-14 Pusch R, Ranhagen L, Nilden K, 1985.
Gas migration through MX-80 bentonite.
Nagra Tech. Rept. NTB-85-36, Wettingen, Schweiz

6-15 Tanai K, Kanno T, Gallé C, 1997
Experimental study of gas permeabilities and breakthrough pressures in clays.
Symposium on the Scientific Basis for Nuclear Waste Management, XX, Boston, Materials Research Society, pp 1003–1010

6-16 Horseman S T, Harrington J F, 1997
Study of gas migration in MX-80 buffer bentonite.
Nat. Envir. research Council, British Geol. Survey, Report WE/97/7

6-17 Horseman S T, Harrington J F, Sellin P, 1997
Gas migration in Mx80 buffer bentonite. Symposium on the Scientific Basis for Nuclear Waste Management, XX, Boston, Materials Research Society, pp 1003–1010

6-18 Pusch R, 1992
Chemical interaction of clay buffer materials and concrete.
SKBF/KBS Arbetsrapport SFR 82-01, Stockholm

6-19 Karnland O, Pusch R, Sandén T, 1994
Concerning bentonite/cement interaction, 4 months tests.
SKB Arbetsrapport AR 94-22, Stockholm

6-20 Couture R A, 1985
Steam rapidly reduces the swelling capacity of bentonite.
Nature Vol 318, No 6041

6-21 Pusch R, Madsen F, 1995
Aspects on the illitization of the Kinnekulle bentonites.
Clays and Clay Minerals, Vol 43, No 3

Chapter 7

7-1 RD&D-Programme 95
Treatment and final disposal of nuclear waste. Programme for encapsulation, deep geological disposal, and research, development and demonstration.
SKB, Stockholm, September 1995

7-2 SKB Annual Report 1995, 1996
SKB Technical Report TR 95-37, Stockholm

7-3 SKB Annual Report 1996, 1997
SKB Technical Report TR 96-25, Stockholm

7-4 SKB Annual Report 1997, 1998
SKB Technical Report TR 97-, Stockholm (in preparation)

7-5 Ahlbom K, Leijon B, Liedholm M, Smellie J, 1992
Gabbro as a host rock for nuclear waste repository
SKB Technical Report TR 92-25, Stockholm

7-6 Saksa P, Nummela J, 1998
Geological-structural models used in SR 97. Uncertainty analysis.
SKB Technical Report TR 98-, Stockholm (submitted)

7-7 Ericsson L O, Hökmark H, Pusch R, 1998
Mekaniska processer i geosfären. Förslag till hantering i säkerhetsanalys av djupförvar för använt kärnbränsle.
SKB rapport R-98-, Stockholm (submitted)

7-8 Stephansson O, 1996
Coupled thermo-hydro-mechanical processes of fractured media – Mathematical and experimental studies.
Developments in Geotechnical Engineering, 79. Elsevier, Amsterdam

7-9 Leijon B, 1993
Mechanical properties of fracture zones.
SKB Technical Report TR 93-19, Stockholm

7-10 Larsson S-Å, Tullborg E-L, 1994
Tectonic regimes in the Baltic shield during the last 1200 Ma – A review
SKB Technical Report TR 94-05, Stockholm

7-11 Muir Wood R, 1993
A review of the seismotectonics of Sweden
SKB Technical Report TR 93-13, Stockholm

7-12 Muir Wood R, 1995
Reconstructing the tectonic history of Fennoscandia
from its margins: The past 100 million years.
SKB Technical Report TR 95-36, Stockholm

7-13 Tullborg E-L, Larson S-Å, Björklund L, Samuelsson L, Stigh J, 1995
Thermal evidence of Caledonide foreland, molasse sedimentation in
Fennoscandia.
SKB Technical Report TR 95-18, Stockholm

7-14 Cederbom C, 1997
Fission track thermochronology applied to phanerozoic thermotectonic events in
Central and Southern Sweden.
Thesis for Licentiate degree A 25, Dep. of Geology, Earth Sciences Centre,
Göteborg University. Göteborg

7-15 Juhlin C, 1997
Reflection seismic studies on the island of Äspö.
SKB Djuförvar Projektrapport PR D-97-09, Stockholm

7-16 Ljunggren C, Persson M, 1995
Beskrivning av databas Bergspänningsmätningar Sverige.
SKB Djupförvar Projektrapport PR D-95-017, Stockholm

7-17 Ljunggren C, Andersson J, 1998
Bergspänningars representativitet – Mätnoggrannhet och naturliga variationer vid
hydraulisk spräckning och överborrning.
SveBeFo rapport nr. 37, Stockholm

7-18 Ekman L, Ludvigsson J-E, 1998
Project Deep Drilling KLX 02 – Phase 2 Lilla Laxemar, Oskarshamn.
Scope of Activities and Results.
SKB Technical Report TR 98-, Stockholm (submitted)

7-19 Lindfors U, 1996
Experimental study of the mechanics of rock joints.
Licentiate thesis, Div. of Rock Mechanics, Luleå University of Technology, Luleå,
Sweden

7-20 Olsson R, 1997
The effective stress concept in a jointed rock mass. A literature survey.
SKB Report R 97-18, Stockholm

7-21 La Pointe P, Wallmann P, Thomas A, Follin S, 1997
A methodology to estimate earthquake effects on fractures intersecting canister
holes.
SKB Technical Report TR 97-07, Stockholm

7-22 Scherneck H-G, Johansson J M, Elgered G, 1996
Application of space geodetic techniques for the determination of intraplate deformations and movements in relation with the postglacial rebound of Fennoscandia.
SKB Technical Report TR 96-19, Stockholm

7-23 Påsse T, 1996
Lake-tilting investigations in southern Sweden.
SKB Technical Report TR 96-10, Stockholm

7-24 Påsse T, 1996
A mathematical model of the shore level displacement in Fennoscandia.
SKB Technical Report TR 96-24, Stockholm

7-25 Påsse T, 1997
A mathematical model of past, present and future shore level displacement in Fennoscandia.
SKB Technical Report TR 97-28, Stockholm

7-26 Maddock R H, Hailwood E A, Rhodes E J, Muir Wood R, 1993
Direct fault dating trials at the Äspö Hard Rock Laboratory
SKB Technical Report TR 93-24, Stockholm

7-27 Sjöberg R, 1994
Bedrock caves and fractured rock surfaces in Sweden: occurrence and origin.
Doctoral Thesis at Stockholm University

7-28 Andersson J, Almén K-E, Ericsson L O, Fredriksson A, Karlsson F, Stanfors R, Ström A, 1997
Parameters of importance to determine during geoscientific site investigation.
SKB Technical Report TR 98-02, Stockholm

7-29 Ericsson L O, Hökmark H, Pusch R, 1998
Mekaniska processer i geosfären – Förslag till hantering i säkerhetsanalys av djupförvar för använt kärnbränsle.
SKB rapport R-98-, Stockholm (under tryckning)

7-30 Hökmark H, 1991
Distinct element method modeling of fracture behavior in near-field rock.
Stripa Project Technical Report TR 91-01, SKB, Stockholm

7-31 Jing L, Stephansson O, Tsang C-F, Kautsky F, 1996
DECOVALEX – Mathematical Models of Coupled THM Processes for Nuclear Waste Repositories. Executive Summary for Phases I, II and III.
SKI Report 96:58, Stockholm

7-32 Nguyen T S, Selvadurai A P S, 1995
A model for coupled mechanical and hydraulic behavior of a rock joint.
Proc. 1995 Int. Workshop on Hydro-Thermo-Mechanics of Engineered Clay Barriers and Geological Barriers, AECL, Montreal, Canada

7-33 Stephansson O, Jing L, Tsang C-F (eds), 1996
Coupled Thermo-Hydro-Mechanical Processes of Fractured Media.
Developments in Geotechnical Engineering, 79, Elsevier. Amsterdam

Chapter 8

8-1 Andersson P, 1995
Compilation of tracer tests in fractured rock.
SKB Äspö HRL Progress Report PR 25-95-05, Stockholm

8-2 Rehbinder G, Isaksson A, 1996
Large scale flow of groundwater in Swedish bedrock. An analytical calculation.
SKB Utveckling Project Report U-96-11, Stockholm

8-3 Rehbinder G et al., 1997
On regional flow in Baltic shield – An application of an analytical solution using hydrogeologic conditions at Aberg, Beberg and Ceberg of SR97.
SKB Report R-97-17, Stockholm

8-4 Wladis D et al., 1997
Regional characterisation of hydraulic properties of rock using well test data.
SKB Technical Report TR 97-29, Stockholm

8-5 Hakami E, 1995
Aperture distribution of rock fractures, Doctoral Thesis, TRITA-AMI PHD1003, Div. of Engineering Geology, Dep. of Civil and Environmental Engineering, Royal Institute of Technology, Stockholm

8-6 Larsson E, 1997
Groundwater flow through a natural fracture – Flow experiments and numerical modelling.
SKB Technical Report TR 97-16, Stockholm

8-7 Holmén J, 1997
On the flow of groundwater in closed tunnels – Generic hydrogeological modelling of nuclear waste repository, SFL 3-5.
SKB Technical Report TR 97-10, Stockholm

Chapter 9

9-1 Laaksoharju M, Wallin B, 1997
Evolution of the groundwater chemistry at the Äspö Hard Rock Laboratory.
Proceedings of the second Äspö International Geochemistry Workshop, June 6–7, 1995.
SKB International Cooperation Report ICR 97-04, Stockholm

9-2 Rhén I, Gustafson G, Wikberg P, 1997
Äspö HRL – Geoscientific evaluation 1997/5. Models based on pre-investigations and detailed site characterization.
SKB Technical Report TR 97-06, Stockholm

9-3 Banwart S, 1994
Proceedings of The Äspö International Geochemistry Workshop, June 2-3, 1994, Äspö Hard Rock Laboratory.
SKB International Cooperation Report ICR 94-13, Stockholm

9-4 Laaksoharju M, Skårman C, 1995
Groundwater sampling and chemical characterization of the Äspö HRL tunnel in Sweden.
SKB Progress Report PR 25-95-29, Stockholm

9-5 Laaksoharju M (ed), 1995
Sulphate reduction in the Äspö HRL tunnel.
SKB Technical Report TR 95-25, Stockholm

9-6 Smellie J A T, Laaksoharju M, 1992
The Äspö Hard Rock Laboratory. Final evaluation of the hydrogeochemical pre-investigations in relation to existing geologic and hydraulic conditions.
SKB Technical Report TR 92-31, Stockholm

9-7 Svensson U, 1997
A regional analyses of groundwater flow and salinity distribution in the Äspö area.
SKB Technical Report TR 97-09, Stockholm

9-8 Skårman C, Laaksoharju M, 1998
Cross-prediction of the groundwater chemistry at the SKB sites in Sweden.
SKB Rapport R-98-01, Stockholm

9-9 AECL, 1994
Environmental Impact Statement on the concept for disposal of Canada's nuclear fuel waste.
AECL-10711, COG-93-1

9-10 Frape S K, Fritz P, 1987
Geochemical trends for groundwaters from the Canadian shield.
In: Fritz P and Frape S K, Saline water and gases in crystalline rocks. Geol. Assoc. of Canada Spec. Pap., pp 33:19-38

9-11 Lampén, 1992
Saline groundwater in crystalline bedrock – a litterature study.
YJT 92-23, Helsinki, Finland

9-12 Viani B, Bruton C, 1997
Assessing the role of cation exchange in Laaksoharju and Wallin, 1997.
SKB International Cooperation Report ICR 97-04, Stockholm

9-13 Stumm W, Morgan J, 1981
Aquatic Chemistry, 2nd ed. Whiley Interscience Publishers

9-14 Toulhoat P, Beaucaire C, Michard G, Ouzounian G, 1992
Chemical Evolution of Deep Groundwater in Granites, Information Acquired from Natural Systems. Paleohydrogeological Methods and their Applications. Proceedings from an NEA workshop 9–10 November, 1992

9-15 Banwart S (ed), 1995
The Äspö redox investigations in block scale. Project summary and implications for repository performance assessment.
SKB Technical Report TR 95-26, Stockholm

9-16 Malmström M, Banwart S, Duro L, Wersin P, Bruno J, 1995
Biotite and Chlorite weathering at 25°C.
SKB Technical Report TR 95-01, Stockholm

9-17 Pirhonen V, Pitkänen P, 1991
Redox capacity of crystalline rocks. Laboratory studies under 100 bar oxygen gas pressure.
SKB Technical Report TR 91-55, Stockholm

9-18 Banwart S, Laaksoharju M, Skårman C, Gustafsson E, Pitkänen P, Snellman M, Landström O, Aggeryd I, Mathiasson L, Sundblad B, Tullborg E-L, Wallin B, Pettersson C, Pedersen K, Arlinger J, Jahromi N, Ekendahl S, Hallbeck L, Degueldre C, Malmström M, 1995
The Redox experiment in block scale. Final reporting of results from the Three Year Project.
SKB Progress Report PR 25-95-06, Stockholm

9-19 Laaksoharju M, Vuorinen U, Snellman M, Allard B, Pettersson C, Helenius J, Hinkkanen H, 1993
Colloids or artefacts? A TVO/SKB co-operation project in Olkiluota, Finland.
SKB Technical Report TR 93-32, Stockholm

9-20 Tullborg E-L, Wallin B, Landström O, 1991
Hydrogeochemical studies of fracture minerals from water conducting fractures and deep groundwaters at Äspö.
SKB Progress Report PR 25-90-01, Stockholm

9-21 Landström O, Tullborg E-L, 1995
Interactions of trace elements with fracture filling minerals from the Äspö Hard Rock Laboratory.
SKB Technical Report TR 95-13, Stockholm

9-22 Wersin P, Bruno J, Laaksoharju M, 1994
The implication of soil acidification on a future HLW repository.
SKB Technical Report TR 94-31, Stockholm

Chapter 10

10-1 Rydberg J, 1996
Hydrophilic actinide complexation studied by solvent extraction radiotracer technique.
SKB Technical Report TR 96-17, Stockholm

10-2 Cui D, Eriksen T, 1996
Reduction of Tc(VII) and Np(V) in solution by ferrous iron. A laboratory study of heterogeneous redox processes.
SKB Technical Report TR 96-03, Stockholm

10-3 Cui D, 1996
Sorption processes and solubilities of radionuclides in deep granite fracture systems.
Doctoral thesis, Dept of Nuclear Chemistry, Royal Institute of Technology, Stockholm

10-4 Rundberg R, Albinsson Y, 1997
Adsorption isotherms for the sorption of iodate and neptunium(V) onto goethite.
In Proceedings of the Fifth International Conference on the Behaviour of Actinides and Fission Products in the Geosphere, Migration '95, Saint-Malo, France, September 10–15

10-5 Jakobsson A-M, Rundberg R, 1997
Uranyl sorption onto alumina.
Materials Research Society Symposium, Proceedings Vol 465, pp 797–804

10-6 Jakobsson A-M, Albinsson Y, 1998
Sorption of NpO_2^+, Co^{2+} and Th^{4+} onto TiO_2.
Submitted to Radiochimica Acta

10-7 Ohlsson Y, Neretnieks I, 1995
Literature survey of matrix diffusion theory and of experiments and data including natural analogues.
SKB Technical Report TR 95-12, Stockholm

10-8 Eriksen T E, Jansson M, 1996
Diffusion of I^-, Cs^+ and Sr^{2+} in compacted bentonite. Anion exclusion and surface diffusion.
SKB Technical Report TR 96-16, Stockholm

10-9 Carbol P, Engkvist I, 1997
Compilation of radionuclide sorption coefficients for performance assessment.
SKB Report R-97-13, Stockholm

10-10 Ohlsson Y, Neretnieks I, 1997
Diffusion data in granite. Recommended values.
SKB Technical Report TR 97-20, Stockholm

10-11 Yu J-W, Neretnieks I, 1997
Diffusion and sorption properties of radionuclides in compacted bentonite.
SKB Technical Report TR 97-12, Stockholm

10-12 Laaksoharju M, Degueldre C, Skårman Ch, 1995
Studies of colloids and their importance for repository performance assessment.
SKB Technical Report TR 95-24, Stockholm

10-13 Neretnieks I, Ernstson M-L, 1995
A note on radionuclide transport by gas bubbles.
Paper presented at the Fifth International Conference on the Behaviour of Actinide and Fission Products in the Geosphere, Migration '95, Saint Malo, France, September 10–15

10-14 Pedersen K, Karlsson F, 1995
Investigation of subterranean micro-organisms. Their importance for performance assessment of radioactive waste disposal.
SKB Technical Report TR 95-10, Stockholm

10-15 Stroes-Gascoyne S, Pedersen K, Daumas S, Hamon C J, Haveman S A, Delaney T L, Ekendahl S, Jahromi N, Arlinger J, Hallbeck L, Dekeyser K, 1996
Microbial analysis of the buffer/container experiment at AECL's Underground Research Laboratory.
SKB Technical Report TR 96-02, Stockholm

10-16 Pedersen K, Arlinger J, Bruetsch R, Degueldre C, Hallbeck L, Laaksoharju M, Lutz Th, Pettersson C, 1996
Bacteria, colloids and organic carbon in groundwater at the Bangombé site in the Oklo area.
SKB Technical Report TR 96-01, Stockholm

10-17 Ekendahl S, 1996
Deep subsurface ecosystems. Numbers, activity and diversity of groundwater bacteria in Swedish granitic rock.
Doctoral thesis, Dept of General and Marine Microbiology, Göteborg University.

10-18 Pedersen K, Motamedi M, Karnland O, 1995
Survival of bacteria in nuclear waste buffer materials. The influence of nutrients, temperature and water activity.
SKB Technical Report TR 95-35, Stockholm

10-19 Pedersen K, 1997
Investigation of subterranean micro-organisms and their importance for performance assessment of radioactive waste disposal.
SKB Technical Report TR 97-22, Stockholm

10-20 Naturvårdsverket, 1998
Slutförvar av kvicksilver.
Huvudrapport 4752, Naturvårdsverket Förlag, Stockholm

Chapter 11

11-1 Edlund, 1998
Summary of biosphere research 1967–1997.
SKB Report, Stockholm (manus)

11-2 Smith G M, Watkins B M, Little R H, Jones H M, Mortimer A M, 1996
Biosphere modeling and dose assessment for Yucca Mountain.
EPRI Palo Alto, CA. EPRI TR-107190

11-3 BIOMOVSII, 1996
Development of reference biospheres methodology for radioactive waste disposal.
Swedish Radiation Protection Institute (SSI) TR6, Stockholm

11-4 BIOMOVSII, 1996
Uncertainty and validation: Effect of user interpretation on uncertainty estimates.
Swedish Radiation Protection Institute (SSI) TR7, Stockholm

11-5 BIOMOVSII, 1996
Biosphere modelling for dose assessments of radioactive waste repositories: Final report of the complementary studies working group.
Swedish Radiation Protection Institute (SSI) TR12, Stockholm

11-6 Bergström U, Nordlinder S, 1998
Biosmod a modularized standard biosphere.
SKB Report, Stockholm (manus)

11-7 Zach R, 1997
Nuclear fuel waste management – Biosphere program highlights – 1978 to 1996.
AECL Report AECL-11811, Pinawa, Manitoba, Canada

11-8 SSI, 1998
Statens Strålskyddsinstituts föreskrifter om hantering av radioaktivt avfall vid kärntekniska anläggningar. Förhandsremiss.
SSI, Stockholm

11-9 Fitz H C, DeBellevue E B, Costanza R, Boumans R, Maxwell T, Wainger L, Sklar F H, 1996
Development of a general ecosystem model (GEM) for a range of scales and ecosystems.
Ecol. Modeling, Vol 88, pp 263–295

11-10 Gilek M, Björk M, Broman B, Kautsky N, Kautsky U, Näf C, 1997
The role of the blue mussel *Mytilus edulis* L, in the cycling of hydrophobic organic contaminants in the Baltic proper.
Ambio, Vol 26, pp 202–209

11-11 Nilsson S, Bergström U, Nordlinder S, 1996
Modularized standard biosphere. Proccedings Intern. Conf. Deep Geol. Disposal of Radioactive Waste, Manitoba, Canada, Canada Nuclear Society, pp 4-59 – 4-66

11-12 Nordlinder S, Bergström U, 1997
Ecosystem specific dose conversion factors for Aberg Beberg and Ceberg.
SKB Report, Stockholm (manus)

11-13 Kautsky U, Meili M, Bergström U, 1998
Processer i Biosfären.
SKB Rapport, Stockholm (manus)

11-14 Lindborg T, Schüldt R, 1998
The biosphere at hypothetical Aberg, Beberg and Ceberg – a description and evaluation of climate, physical geography, ecology, land use and environment.
SKB Report, Stockholm (manus)

11-15 Thunholm B, Klein Å, 1998
Quaternary deposits and groundwater flow at Aberg, Beberg and Ceberg.
SKB Report, Stockholm (manus)

11-16 Engqvist A, 1997
Water exchange estimates derived from forcing for the hydraulically coupled basins surrounding Äspö island and adjacent coastal water.
SKB Technical Report TR 97-14, Stockholm

11-17 Avila R, Moberg L, Hubbard L, 1998
Modelling of radionuclide migration in forest ecosystems. A literature review.
SSI report 98:07, Stockholm

11-18 BIOMOVSII, 1996
Model validation studies of water flow and radionuclide transport in vegetated soils using lysimeter data.
Swedish Radiation Protection Institute (SSI) TR15, Stockholm

11-19 Aggeryd I, Aquilonius K, Landström O, Sundblad B, Tullborg E-L, 1996
Long-term transfer of elements across the interface of the biosphere and geosphere – The natural analogue at the island of Äspö.
SKB Utveckling Project Report U-96-24, Stockholm

11-20 Aggeryd I, Aquilonius K, Sundblad B, 1996
Biosphere-geosphere interactions. Possible implications for the safety analysis.
ECOSAFE Studsvik, Nyköping (draft)

11-21 Sundblad B, Aggeryd I, 1996
Long-term resistribution of elements within a swamp area – The natural analogue at the island of Äspö. Proccedings Intern. Conf. Deep Geol. Disposal of Radioactive Waste, Manitoba, Canada.
Canada Nuclear Society, pp 4-99 – 4-105

11-22 Konhauser KO, Schultze-Lam S, Ferris F G, Fyfe W S, Longstaffe F J, Beveridge T J, 1994
Mineral preciptation by epilithic biofilms in the Speed River, Ontario, Canada.
Applied and Environmental Microbiology, Vol 60, pp 549–553

11-23 Ferris F G, Fratton C M, Gerits J P, Schultze-Lam S, Sherwood Lollar B, 1995
Microbial preciptation of a strontium calcite phase at a groundwater discharge zone near Rock Creek, British Columbia, Canada.
Geomicrobiology Journal, Vol 13, pp 57–67

11-24 Påsse T, 1997
A mathematical model of past, present and future shore level displacement in Fennoscandia.
SKB Technical Report TR 97-28, Stockholm

11-25 Adcock S T, Dukes M D G, Goodess C M, Palutikof J P, 1997
A critical review of the climate literature relevant to the deep disposal of radioactive waste.
NIREX Report S/97/009, Oxfordshire, United Kingdom

11-26 Boulton G S, Hulton N, Wallroth T, 1996
Impacts of long-term climate change on subsurface conditions: Time sequences, scenarios and boundary conditions for safety assessments.
SKB Utveckling Progress Report U-96-19, Stockholm

11-27 Berger A, Loutre M F, Gallee H, 1996
Sensitivity of the LLN 2-D climate model to the astronomical and CO_2 forcings (from 200 ky BP to 130 ky AP).
Univ. Catholique de Louvain, Louvain-la-Neuve, Belgium. Scientific report 1996/1

11-28 Westman P, 1997
Saliniteten i Östersjön sedan senaste istiden.
Kvartärgeologiska Inst., Stockholms Universitet, Stockholm (manus)

11-29 Stigebrandt A, 1983
A model for the exchange of water and salt between the Baltic and the Skagerack.
J. Phys. Oceano, Vol 13, No 3, pp 411–427

11-30 Losjö K, Johansson B, Bringfelt B, Oleskog I, Bergström S, 1998
Groundwater recharge – Climatic and vegetation induced variations. Simulations in the Emån and Äspö areas in southern Sweden.
SKB Technical Report TR 98-, Stockholm (draft)

11-31 Holmgren K, Karlén W, 1998
Late quaternary changes in climate.
SKB Technical Report TR 98-, Stockholm (manus)

11-32 Vassiljev J, 1997
Simulating the paleorecord of northern European lakes using a coupled lake-catchment model.
Dept. Quaternary Geology, Lundqua Thesis, Vol 41, pp 19+5

11-33 Gaillard M J, Karlén W, Kullman L, Mapny M, 1998
North-South European transect of Holocene paleoclimatic proxy records from northern Scandinavia to the Jura mountains, France: a review and correlation of glacier, tree-limit and lake-level data (manus)

11-34 BIOMOVSII, 1996
Effect of Model Complexity on Uncertainty Estimates.
Swedish Radiation Protection Institute (SSI) TR16, Stockholm

11-35 BIOMOVSII, 1996
Validation Test for Carbon-14 Migration and Accumulation in a Canadian Shield Lake.
Swedish Radiation Protection Institute (SSI) TR14, Stockholm

11-36 Bergström U, Nordlinder S, Aquilonius K, 1995
Assessment model validity document. BIOPATH/PRISM: codes for calculating turnover of radionuclides in the biosphere and doses to man.
SKB Arbetsrapport AR 95-19, Stockholm

11-37 Nordlinder S, Bergström U, 1995
Osäkerheter i dosberäkningar från förvar av högaktivt avfall.
SKB Utveckling Project Report AR 95-15, Stockholm

11-38 Nordlinder S, 1996
Individual doses from inflow of radionuclides via the groundwater from a major fracture zone.
SKB Utveckling Project Report U-96-23, Stockholm

11-39 VAMP, 1996
Validation of models using Chernobyl fallout data from southern Finland. Scenario S. Second report of the VAMP Multiple Pathways Assessment Working Group.
International Atomic Energy Agency (IAEA) IAEA-TECDOC-904, Vienna

Chapter 12

12-1 Wiborgh M (ed), 1995
Prestudy of final disposal of long-lived low and intermediate level waste.
SKB Technical Report TR 95-03, Stockholm

12-2 Forsgren E, Lange F, Larsson H, 1996
SFL 3-5. Layoutstudie.
SKB Arbetsrapport AR-D-96-016, Stockholm

12-3 Holmén J, 1997
On the flow of groundwater in closed tunnels. Generic hydrogeological modelling of the nuclear waste repository, SFL 3-5.
Doctoral thesis at Uppsala University, Earth Science Dept., Uppsala.
SKB Technical Report TR 97-10, Stockholm

12-4 Romero L, Moreno L, Neretnieks I, 1995
Fast multiple path model to calculate radionuclide release from the near field of a repository.
Nuclear Technology, Vol 112, p 89

12-5 Romero L, Moreno L, Neretnieks I, 1995
Release calculations in the SFL 3-5 repositories. Some calculations verifying the model NUCTRAN.
SKB Arbetsrapport AR 95-47, Stockholm

12-6 Lagerblad B, Trägårdh J, 1994
Conseptual model for concrete long time degradation in a deep nuclear repository.
SKB Technical Report TR 95-21, Stockholm

12-7 Engkvist I, Albinsson Y, Johansson-Engkvist W, 1996
The long-term stability of cement – Leaching tests.
SKB Technical Report TR 96-09, Stockholm

12-8 Holgersson S, Albinsson Y, Allard B, Borén H, Pavasars I, Engkvist I, 1998
Effects of gluco-isosaccharinate on Cs, Ni and Pm sorption onto, and diffusion in cement.
Radiochimica Acta (to be published)

12-9 Holgersson S, Albinsson Y, Engkvist I, Rochelle Ch, Pierce J, 1998
Interactions of cement pore fluids with host rock and the effects on HTO, Na and Cs diffusion.
Radiochimica Acta (to be published)

Chapter 13

13-1 Steinberg M, Watsak G, Manowitz B, 1964
Neutron burning of long-lived fission products for waste disposal.
BNL-8558, USA

13-2 Croff A G, 1990
Historical perspective on partitioning and transmutation, in C W Forsberg et al.: Historical perspective, economic analysis and regulatory analysis of the impacts of waste partitioning-transmutation on the disposal of radioactive wastes.
ORNL/TM-11650, USA

13-3 Jameson R A (ed), 1991
Proceedings of the specialist meeting on accelerator-driven transmutation technology for radwaste and other applications, Saltsjöbaden, Sweden 24-28 June 1991.
SKN Report No 54, Stockholm

13-4 RD&D-Programme 92, 1992
Treatment and final disposal of nuclear waste. Programme for research, development, demonstration and other measures.
SKB, Stockholm

13-5 Skålberg M, Liljenzin J O, 1992
Partitioning and transmutation. A review of the current state of the art.
SKB Technical Report TR 92-19, Stockholm

13-6 Gudowski W, Pettersson K, Thedéen T, 1993
Accelerator transmutation of wastes (ATW) – Prospects and safety.
SKB Technical Report TR 93-23, Stockholm

13-7 Skålberg M, Liljenzin J O, 1993
Partitioning and transmutation, the state of the art.
Nuclear Engineering International, Vol 38, No 463, pp 30–33

13-8 Skålberg M et al., 1995
Partitioning and transmutation (P&T) 1995. A review of the current state of the art.
SKB Technical Report TR 95-32, Stockholm

13-9 Enarsson Å et al., 1998
Separation och transmutation (S&T) 1997. En genomgång av nuläget.
SKB rapport 98 (skrivs)

13-10 SKB Annual Report 1993, 1994
SKB Technical Report TR 93-34, Chapter 18, Stockholm

13-11 SKB Annual Report 1994, 1995
SKB Technical Report TR 94-33, Chapter 18, Stockholm

13-12 SKB Annual Report 1995, 1996
SKB Technical Report TR 95-37, Stockholm

13-13 SKB Annual Report 1996, 1997
SKB Technical Report TR 96-25, Chapter 18, Stockholm

13-14 SKB Annual Report 1997, 1998
SKB Technical Report TR 97-, Stockholm (in progress)

13-15 Salvatores M, 1997
Nuclear Engineering Perspective on Accelerator-Driven Transmutation. Lecture at IVA conference on WHY research on accelerator-driven transmutation technology i Stockholm

13-16 Rubbia C et al.
Fast neutron incineration in the energy amplifier as an alternative to geologic storage: The case of Spain.
CERN/LHC/97-01 (EET)

13-17 NEA statement on transmutation.

13-18 Venneri L et al., 1998
Presentation of ATW by LANL at MIT, USA, Jan 15-16

13-19 US National Research Counsil Committee, 1996
Nuclear wastes. Technologies for separations and transmutation.
National Academy Press, Washington D C

13-20 Juhlin C, Wallroth T, Smellie J, Eliasson T, Leijon B, Ljunggren C, Beswick J, 1998
The Very Deep Hole concept – Geoscientific appraisal of conditions at great depth
SKB Technical Report TR 98-05, Stockholm

13-21 Project Alternative Systems Study (PASS)
Final Report
SKB Technical Report TR 93-04, Stockholm

Chapter 14

14-1 RD&D-Programme 86, 1986
Handling and final disposal of nuclear waste. Programme for research, development and other measures.
SKB, Stockholm

14-2 Gustafson G, Liedholm M, Rhén I, Stanfors R, Wikberg P, 1991
Äspö Hard Rock Laboratory. Predictions prior to excavation and the process of their validation.
SKB Technical Report TR 91-23, Stockholm

14-3 RD&D-Programme 92, 1992
Treatment and final disposal of nuclear waste. Background report Äspö Hard Rock Laboratory.
SKB, Stockholm

14-4 RD&D-Programme 95
Treatment and final disposal of nuclear waste. Programme for encapsulation, deep geological disposal, and research, development and demonstration.
SKB, Stockholm, September 1995

14-5 Äspö Hard Rock Laboratory Annual Report 1994, 1995
SKB Technical Report TR 95-07, Stockholm

14-6 Äspö Hard Rock Laboratory Annual Report 1995, 1996
SKB Technical Report TR 96-06, Stockholm

14-7 Äspö Hard Rock Laboratory Annual Report 1996, 1997
SKB Technical Report TR 97-08, Stockholm

14-8 Äspö Hard Rock Laboratory Annual Report 1997, 1998
SKB Technical Report TR 98-, Stockholm (in progress)

14-9 Almén K, Zellman O, 1991
Äspö Hard Rock Laboratory. Field investigation methodology and instruments used in the pre-investigation phase, 1986–1990.
SKB Technical Report TR 91-21, Stockholm

14-10 Wikberg P (ed), Gustafson G, Rhén I, Stanfors R, 1991
Äspö Hard Rock Laboratory. Evaluation and conceptual modelling based on the pre-investigations.
SKB Technical Report TR 91-22, Stockholm

14-11 Smellie J, Laaksoharju M, 1992
The Äspö Hard Rock Laboratory. Final evaluation of the hydrogeochemical pre-investigations in relation to existing geologic and hydraulic conditions. SKB Technical Report TR 92-31, Stockholm

14-12 Stanfors R, Erlström M, Markström I, 1997
Äspö HRL – Geoscientific evaluation 1997/1. Overview of site characterization 1986–1995.
SKB Technical Report TR 97-02, Stockholm

14-13 Rhén I (ed), Bäckblom G (ed), Gustafson G, Stanfors R, Wikberg P, 1997
Äspö HRL – Geoscientific evaluation 1997/2. Results from pre-investigations and detailed site characterization. Summary report.
SKB Technical Report TR 97-03, Stockholm

14-14 Stanfors R, Olsson P, Stille H, 1997
Äspö HRL – Geoscientific evaluation 1997/3. Results from pre-investigations and detailed site characterization. Comparison of predictions and observations. Geology and mechanical stability.
SKB Technical Report TR 97-04, Stockholm

14-15 Rhén I, Gustafson G, Wikberg P, 1997
Äspö HRL – Geoscientific evaluation 1997/4. Results from pre-investigations and detailed site characterization. Comparison of predictions and observations. Geohydrology, groundwater chemistry and transport of solutes.
SKB Technical Report TR 97-05, Stockholm

14-16 Rhén I (ed), Gustafson G, Stanfors R, Wikberg P, 1997
Äspö HRL – Geoscientific evaluation 1997/5. Models based on site characterization 1986–1995.
SKB Technical Report TR 97-06, Stockholm

14-17 Almén K-E, Olsson P, Rhén I, Stanfors R, Wikberg P, 1994
Äspö Hard Rock Laboratory – Feasibility and usefulness of site investigation methods. Experiences from the pre-investigation phase.
SKB Technical Report TR 94-24, Stockholm

14-18 Emsley S, Olsson O, Stenberg L, Alheid H-J, Falls S, 1997
ZEDEX – A study of damage and disturbance from tunnel excavation by blasting and tunnel boring.
SKB Technical Report TR 97-30, Stockholm

14-19 Svensson U, 1994
Flow, pressure and salinity distributions around planned experimental sites at the Äspö Hard Rock Laboratory.
SKB Äspö HRL Progress Report PR 25-94-11, Stockholm

14-20 Svensson U, 1994
Calculation of pressure, flow and salinity fields using measured inflow to the tunnel.
SKB Äspö HRL Progress Report PR 25-94-27, Stockholm

14-21 Gustafson G, Ström A, 1995
The Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes. Evaluation report on Task No 1, the LPT2 large scale field experiments.
SKB International Cooperation Report ICR 95-05, Stockholm

14-22 Gustafson G, Bossart P, Vira J, 1997
The Äspö Task Force on Modelling of Groundwater Flow and Transport of Solutes. Evaluation report on Task No 3, The Äspö tunnel drawdown experiment.
SKB International Cooperation Report ICR 97-06, Stockholm

14-23 Mazurek M, Bossart P, Eliasson T, 1997
Classification and characterization of water-conducting features at Äspö: Results of investigations on the outcrop scale.
SKB International Cooperation Report ICR 97-01, Stockholm

14-24 Grenthe I, Stumm W, Laaksoharju M, Nilsson A-C, Wikberg P, 1992
Redox potentials and redox reactions in deep groundwater systems.
Chemical Geology, 98, 131

14-25 Banwart S (ed), 1995
The Äspö redox investigations in block scale. Project summary and implications for repository performance assessment.
SKB Technical Report TR 95-26, Stockholm

14-26 Rivas Perez J A, 1996
REDOX experiment in the detailed scale (REX). Task 5.1 Laboratory investigations.
SKB Progress Report PR HRL-97-08, Stockholm

14-27 Jarsjö J, Geller J, 1996
Groundwater degassing: Laboratory experiments in rock fracture replicas with radial flow.
SKB Progress Report PR HRL-96-12, Stockholm

14-28 Jarsjö J, Destouni G, 1997
Conditions for fracture transmissivity reduction due to degassing of groundwater: Analytical expressions, numerical simulations and analysis of laboratory and field data.
SKB Progress Report PR HRL-97-03, Stockholm

14-29 Geller J T, Jarsjö J, 1995
Groundwater degassing and two-phase flow: Pilot hole test report.
SKB International Cooperation Report ICR 95-03, Stockholm

14-30 Jarsjö J, Destouni G, 1997. Groundwater degassing: Pilot injection – withdrawal field test with gassaturated water.
SKB Progress Report PR HRL-97-02, Stockholm

14-31 Gunnarsson D, Johannesson L-E, Sandén T, Börgesson L, 1996
Field test of tunnel backfilling.
SKB Progress Report PR HRL-96-28, Stockholm

14-32 Börgesson L, Johannesson L-E, Sandén T, 1996
Backfill materials based on crushed rock. Geotechnical properties determined in laboratory.
SKB Progress Report PR HRL-96-15, Stockholm

14-33 Birgersson L, Widen H, Ågren T, Neretnieks I, Moreno L, 1993
Scoping calculations for the Matrix Diffusion Experiment.
SKB International Cooperation Report ICR 93-03, Stockholm

14-34 Nordqvist R, Gustafsson E, Andersson P, 1993
Scoping calculations for the Multiple Well Tracer Experiment – efficient design for identifying transport processes.
SKB International Cooperation Report ICR 93-04, Stockholm

14-35 Moreno L, Neretnieks I, 1994
Scoping calculations for the Multiple Well Tracer Experiment using a variable aperture model.
SKB International Cooperation Report ICR 94-01, Stockholm

14-36 Svensson U, 1994
The Multiple Well Tracer Experiment – Scoping calculations.
SKB International Cooperation Report ICR 94-03, Stockholm

14-37 Selroos J-O, Winberg A, Cvetcovic V, 1994
Design constraints and process discrimination for the Detailed Scale Tracer Experiments at Äspö – Multiple Well Tracer Experiment and Matrix Diffusion Experiment.
SKB International Cooperation Report ICR 94-04, Stockholm

14-38 Tanaka Y, Hasegawa T, Kawanishi M, 1997
Numerical analysis with FEGM/FERM for TRUE-1 non-sorbing tracer tests.
SKB International Cooperation Report ICR 97-07, Stockholm

14-39 Gylling B, Khademi B, Moreno L, 1998
Modelling of the Tracer Retention Understanding Experiment Task 4C-D using the channel network model.
SKB International Cooperation Report ICR 98-01, Stockholm

14-40 Wikberg P, 1998
Äspö Task Force on modelling of groundwater flow and transport of solutes. Plan for Modelling Task # 5: Impact of the tunnel construction on the groundwater system at Äspö, a hydrological-hydrochemical model assessment exercise.
SKB Progress Report PR HRL-98-07, Stockholm

14-41 Patel S, Dahlström L-O, Stenberg L, 1997
Characterisation of the rock mass in the prototype repository at Äspö HRL stage 1.
SKB Progress Report PR HRL-97-24, Stockholm

14-42 Myrvang A M, 1997
Evaluation of in-situ rock stress measurements at the ZEDEX test area.
SKB Progress Report PR HRL-97-22, Stockholm

14-43 Nilsson A, 1997
Fracture mapping and cross section measurement with laser scanner in the TBM- and ZEDEX tunnels.
SKB Progress Report PR HRL-97-18, Stockholm

14-44 Bäckblom G, Olsson O, 1994
Äspö Hard Rock Laboratory. Program for tracer retention understanding experiments.
SKB Progress Report PR 25-94-24, Stockholm

14-45 Winberg A, 1994
Tracer Retention Understanding Experiments (TRUE). Test plan for the First TRUE Stage.
SKB Progress Report PR 25-94-35, Stockholm

14-46 Winberg A, Andersson P, Hermanson J, Stenberg L, 1996
Result of the Select project. Investigation programme for selection of experimental sites for the operational phase.
SKB Progress Report PR HRL-96-01, Stockholm

14-47 Andersson P, 1996
TRUE 1st stage tracer test program. Experimental data and preliminary evaluation of the TRUE-1 radially converging tracer test (RC-1).
SKB Progress Report PR HRL-96-24, Stockholm

14-48 Olsson O, Winberg A, 1996
The Äspö TRUE experiments.
SKB Progress Report PR HRL-96-27, Stockholm

14-49 Andersson P, Nordqvist R, Jönsson S, 1997
TRUE 1st Stage Tracer Test Program. Experimental data and preliminary evaluation of the TRUE-1 dipole tracer tests (DP-1–DP-4).
SKB Progress Report PR HRL-97-13, Stockholm

14-50 Andersson P, Jönsson S, 1997
TRUE 1st stage tracer test programme. Complementary tracer tests (RC-2, DP-5, DP-6). Experimental description and evaluation.
SKB Progress Report PR HRL-97-23, Stockholm

14-51 Andersson P, Byegård J, Cvetkovic V, Johansson H, Nordqvist R, Selroos J-O, Winberg A, 1997
Experimental plan for tests with sorbing tracers at the TRUE-1 site.
SKB Progress Report PR HRL-97-07, Stockholm

14-52 Ström A (ed), 1996
Äspö Task force on modelling of groundwater flow and transport of solutes. Summary of the predicitve modelling for the RC-1 tracer experiments, Task No 4C.
SKB Progress Report PR HRL-96-23, Stockholm

14-53 Ström A, 1997
Äspö Task Force on modelling of groundwater flow and transport of solutes. Proceedings of the 9th meeting in Cherbourg, France, February 4–6, 1997.
SKB Progress Report PR HRL-97-10, Stockholm

14-54 Ström A, 1997
Äspö Task Force on modelling of groundwater flow and transport of solutes. Proceedings of the 10th meeting in Kamaishi, Japan, November 11–13, 1997. SKB Progress Report PR HRL-98-01, Stockholm

14-55 Johansson H, Siitari-Kauppi M, Skålberg M, Tullborg E-L, 1998
Diffusion pathways in crystalline rock – Examples from Äspö-diorite and fine-grained granite.
Journal of Contaminant Hydrology (accepted)

14-56 Birgersson L, Gale J, Winberg A, 1995
TRUE – Resin injection programme – Test plan for the pilot experiment.
SKB Progress Report PR HRL-96-02, Stockholm

14-57 Olsson O, 1997
Planning report for 1998.
SKB Progress Report PR HRL-97-26, Stockholm

14-58 Winberg A, 1997
Tracer Retention Understanding Experiments (TRUE). Test plan for the TRUE Block Scale experiment.
SKB International Cooperation Report ICR 97-02, Stockholm

14-59 Jansson M, Eriksen T E, 1996
Programme for Chemlab experiments.
SKB Progress Report PR HRL-97-01, Stockholm

14-60 Wikberg P, Banwart S, 1994
Proceedings of The Äspö International Geochemistry Workshop, June 2–3.
SKB International Cooperation Report ICR 94-13, Stockholm

14-61 Laaksoharju M, Wallin B, 1997
Evolution of the groundwater chemistry at the Äspö Hard Rock Laboratory. Proceedings of the second Äspö International Geochemistry Workshop, June 6–7. SKB International Cooperation Report ICR 97-04, Stockholm

14-62 Wikberg P, 1997
Proceedings from Workshop on hydrochemical stability and origin and evolution of deep saline groundwaters. Held in Malå, Sweden, 17–18 March.
SKB Progress Report PR HRL-97-25, Stockholm

14-63 Wikramaratna R S, Goodfield M, Rodwell W R, Nash P J, Agg P J, 1993
A preliminary assessment of gas migration from the Copper/Steel Canister.
SKB Technical Report TR 93-31, Stockholm

14-64 Pusch R, 1995
Consequences of using crushed crystalline rock as ballast in KBS-3 tunnels instead of rounded quartz particles.
SKB Technical Report TR 95-14, Stockholm

14-65 Moreno L, 1995
Repository tunnel filled with fravel – Impact on nuclide transport.
SKB Arbetsrapport AR 95-34, Stockholm

14-66 Börgesson L, 1997
Test plan for backfill and plug test.
SKB Progress Report PR HRL-98-08, Stockholm

14-67 Fairhurst C, Gera F, Gnirk P, Gray M, Stillborg B, 1993
OECD/NEA International Stripa Project 1980–1992. Overview report, Volumes I-III.
SKB, Stockholm

14-68 Kalbantner P, Sjöblom R, 1998
Friläggningstekniker – Slutrapport.
SKB Progress Report (under tryckning)

14-69 Sandstedt H, Munier R, 1998
Projekt JADE – Jämförelse av teknik.
SKB Progress Report (under utarbetande)

14-70 Pusch R, 1995
Selection of buffer materials with special respect to their performance in a long-term perspective.
SKB Arbetsrapport AR 95-21, Stockholm

14-71 Karnland O, 1996
Test plan for long term tests of buffer material.
SKB Progress Report PR HRL-96-22

14-72 Pusch R, 1994
Gas transport through smectite clay and crystalline rock.
SKB Arbetsrapport AR 94-61, Stockholm

14-73 Werme L, Sellin P, Kjellbert N, 1992
Copper canisters for nuclear high level waste disposal. Corrosion aspects.
SKB Technical Report TR 92-26, Stockholm

Chapter 15

15-1 Smellie J A T, Karlsson F, Alexander W R, 1997
Natural analogue studies: Present status and performance assessment implications.
Journal of Contaminant Hydrogeology, Vol 26, pp 3-17

15-2 Bruno J, Duro L, Jordana S, Cera E, 1996
Revisiting Poços de Caldas. Application of the co-precipitation approach to establish realistic solubility limits for performance assessment.
SKB Technical Report TR 96-04, Stockholm

15-3 Romero L, 1995
The near-field transport in a repository for high-level nuclear waste.
Doctoral thesis, Dept of Chemical Engineering, Royal Institute of Technology, TRITA KET R21, Stockholm

15-4 Romero L, Moreno L, Neretnieks I, 1995
Movement of a redox front around a repository for high-level nuclear waste.
Nuclear technology, Vol 110, pp 238–249

15-5 Smellie J, Karlsson F, 1996
A reappraisal of some Cigar Lake issues of importance to performance assessment.
SKB Technical Report TR 96-08, Stockholm

15-6 Alexander W R, Smellie J A T, Crossland I, 1996
Potential effects of hyperalkaline leachates on cementitious repository host rocks: An example from Maqarin, Northern Jordan.
In Proceedings from Chemical containment of wastes in the geosphere, BGS, Nottingham, September 3–4

15-7 Naudet R, 1991
Oklo: Des réacteurs nucléaires fossiles. Études physique.
Collection du CEA, Eyrolles, Paris

15-8 Oversby V O, 1996
Oklo: Des réacteurs nucléaires fossiles (Oklo: The fossil nuclear reactors). Physics study (R Naudet, CEA) – Translation of chapters 6, 13 and conclusions.
SKB Technical Report TR 96-14, Stockholm

15-9 Behrenz P, Hannerz K, 1978
Criticality in a spent fuel repository in wet crystalline rock
SKB Technical Report KBS 108, Stockholm

15-10 Oversby V O, 1996
Criticality in a high level waste repository. A review of some important factors and an assessment of the lessons that can be learned from the Oklo reactors.
SKB Technical Report TR 96-07, Stockholm

15-11 Blomqvist R (ed), 1997
The Palmottu Natural Analogue Project. Hydrogeological evaluation of the Palmottu natural analogue site.
European Commission, Nuclear Science and Technology (submitted)

Chapter 16

16-1 Holmgren K, Karlén W, 1998
Late Quaternary changes in climate.
SKB Technical Report TR 98-, Stockholm (in print)

16-2 Ahlbom K, Äikäs T, Ericsson L O, 1991
SKB/TVO ice age scenario.
SKB Technical Report TR 91-32, Stockholm

16-3 Boulton, G S, 1991
Proposed approach to time-dependent or "event-scenario" modelling of future glaciation in Sweden.
SKB Arbetsrapport AR 91-27, Stockholm

16-4 King-Clayton L, Chapman N, Ericsson L O & Kautsky F (eds), 1997
Glaciation and Hydrology. Workshop on the Impact of Climate Change & Glaciations on Rock Stresses, Groundwater Flow and Hydrochemistry – Past, Present and Future.
SKI Report 97:13, Stockholm

16-5 Wikberg P, Ericsson L O, Rhén I, Wallroth T, Smellie J, 1995
SKB framework for regional groundwater modelling including geochemical-hydrogeological model integration and palaeohydrogeology.
Äspö Hard Rock Laboratory Progress Report 25-95-11, Stockholm

16-6 Boulton G S, Payne A, 1993
Simulation of the European ice sheet through the last glacial cycle and prediction of future glaciation.
SKB Technical Report TR 93-14, Stockholm

16-7 Boulton G S, Caban P, Punkari M, 1995
Sub-surface conditions in Sweden produced by climate change, including glaciation. Project 2: Sensitivity tests and model testing.
SKB Arbetsrapport AR 95-42, Stockholm

16-8 Boulton G S, Caban P, Hulton N, 1998
Sub-surface conditions produced by long-term climate changes, including glaciation. Project 3: Further developments in modelling.
(Manuscript)

16-9 Boulton G S, Zatsepin S, Maillot B, 1998
Sub-surface conditions produced by long-term future climate changes, including glaciation. Project 5: Further developments in the analysis of groundwater flow beneath ice sheets.
(Manuscript)

16-10 Wallroth T, Gustafson G, 1993
Sub-surface conditions produced by future climate changes, including glaciation. Data support for modelling.
SKB Arbetsrapport AR 92-77, Stockholm

16-11 Laaksoharju M, Smellie, J, Skårman C, 1993
Groundwater salinity and density predictions along the Stripa-Äspö transect path.
SKB Arbetsrapport AR 93-37, Stockholm

16-12 Stanfors R, Erlström M, 1995
SKB Palaeohydrogeological Programme. Extended geological models of the Äspö area.
SKB Arbetsrapport AR 95-20, Stockholm

16-13 Svensson U, 1996
SKB Palaeohydrogeological Programme. Regional groundwater flow due to an advancing and retreating glacier – scoping calculations.
SKB Utveckling Progress Report U-96-35, Stockholm

16-14 Svensson U, 1996
SKB Palaeohydrogeological Programme. Simulations of regional groundwater flows, as forced by glaciation cycles.
SKB Utveckling Progress Report U-96-36, Stockholm

16-15 Boulton G S, Hulton N, Wallroth T, 1996
Impacts of long-term climate change on subsurface conditions: Time sequences, scenarios and boundary conditions for safety assessments.
SKB Utveckling Progress Report U-96-19, Stockholm

16-16 Boulton G S, Wallroth T, Morén L, 1998
Impact of long-term climate change on a deep geological repository for spent nuclear fuel.
SKB Technical Report TR 98- , Stockholm (in print)

16-17 Lindblom U, 1997
Hydromechanical instability of a crystalline rock mass below a glaciation front.
SKB Utveckling Project Report U-97-13, Stockholm

Chapter 17

17-1 Andersson O, 1994
Deep drilling KLX 02. Drilling and documentation of a 1700 m deep borehole at Laxemar, Sweden
SKB Technical Report TR 94-19, Stockholm

17-2 Ekman L, Ludvigsson J-E, 1998
Project Deep Drilling KLX 02 – Phase 2 Lilla Laxemar, Oskarshamn.
Scope of Activities and Results
SKB Technical Report TR 98-, Stockholm (in press)

17-3 Laaksoharju M, Smellie J, Nilsson A-C, Skårman C, 1995
Groundwater sampling and chemical characterisation of the Laxemar deep borehole KLX 02.
SKB Technical Report TR 95-05, Stockholm

Chapter 18

18-1 Hedin A, 1997
Spent fuel – How dangerous is it?
SKB Technical Report TR 97-13, Stockholm

18-2 Ahlström P-E, 1997
Plutonium – data, egenskaper m m.
SKB rapport R-97-10, Stockholm

18-3 Wallroth Th, 1997
Vad betyder en istid för djupförvaret?
SKB rapport R-97-11, Stockholm

18-4 Sellin P, 1997
Använt kärnbränsle – Barriärernas säkerhetsmässiga betydelse.
SKB rapport R-97-20, Stockholm

18-5 Morén L, 1997
Använt kärnbränsle – Djupförvarets funktion och utveckling.
SKB rapport R-97-21, Stockholm

18-6 Pettersson L, Ringi M, 1997
Använt kärnbränsle – Transporter.
SKB rapport R-97-22, Stockholm

18-7 Jones C, 1997
Farliga ämnen i människans omgivning.
SKB rapport R-97-23, Stockholm