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Äspö Hard Rock Laboratory

Annual Report 1999

Svensk Kärnbränslehantering AB

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Abstract

The Äspö Hard Rock Laboratory has been constructed as part of the preparations for the deep geological repository for spent nuclear fuel in Sweden.

The Tracer Retention Understanding Experiments are made to gain a better understanding of radionuclide retention in the rock and create confidence in the radionuclide transport models that are intended to be used in the licensing of a deep repository for spent fuel. The TRUE –1 experiment including tests with sorbing radioactive tracers in a single fracture over a distance of about 5 m has been completed. Diffusion and sorption in the rock matrix is the dominant retention mechanism over the time scales of the experiments.

The main objective of the TRUE Block Scale Experiment is to increase understanding and our ability to predict tracer transport in a fracture network over spatial scales of 10 to 50 m. In total six boreholes have been drilled into the experimental volume located at the 450 m level.

The Long-Term Diffusion Experiment is intended as a complement to the dynamic in-situ experiments and the laboratory experiments performed in the TRUE Programme. Diffusion from a fracture into the rock matrix will be studied *in situ*.

The REX project focuses on the reduction of oxygen in a repository after closure due to reactions with rock minerals and microbial activity. Results show that oxygen is consumed within a few days both for the field and laboratory experiments.

A new site for the CHEMLAB experiments was selected and prepared during 1999. All future experiment will be conducted in the J niche at 450 m depth.

The Prototype Repository Test is focused on testing and demonstrating repository system function. A full-scale prototype including six deposition holes with canisters with electric heaters surrounded by highly compacted bentonite will be built and instrumented. Characterisation of the rock mass in the area of the Prototype repository is completed and the six deposition holes have been drilled.

The Backfill and Plug Test includes tests of backfill materials and emplacement methods and a test of a full-scale plug. The backfill and rock has been instrumented with about 230 transducers for measuring the thermo-hydro-mechanical processes. Saturation is in progress and is expected to take 1–2 years.

The Long Term Tests of Buffer Material aim to validate models of buffer performance at standard KBS-3 repository conditions, and at quantifying clay buffer alteration processes at adverse conditions. The 4 long term test parcels and the additional 1-year parcel have been installed.

Nine organisations from eight countries are currently participating in the Äspö Hard Rock Laboratory in addition to SKB.

Sammanfattning

Verksamheten vid Äspölaboratoriet utgör en viktig del av förberedelserna inför lokalisering och byggande av djupförvaret för det svenska använda kärnbränslet. Årsrapporten för 1999 ger en översikt av genomförda arbeten och erhållna resultat.

Spårförsök (Tracer Retention Understanding Experiments, TRUE) genomförs för att erhålla en bättre förståelse för fördröjning av radionuklider i berget samt att öka tillförlitligheten hos de modeller som används för att beskriva radionuklidtransport genom berget. Försöken med sorberande ämnen över avstånd på ca 5 m i en enskild spricka har nu avslutats. Resultaten visar att diffusion och sorption i bergmatrisen som omger sprickan är den dominerande retentionsmekanismen.

Huvudmålet med TRUE Block Scale försöket är att öka förståelsen av och vår förmåga att göra förutsägelser om spårämnestransport i ett spricknätverk över avstånd på 10 till 50 m. För att genomföra försöket har sex stycken 150–200 m långa borrhål borrats i en bergvolym belägen på 450 m djup. Undersökningarna av bergvolymen är nu klara och spårförsöken med sorberande ämnen inleds under år 2000.

Long Term Diffusion (LTDE) försöket utgör ett komplement till TRUE försöken. I LTDE kommer diffusion från en spricka in i bergmatrisen att studeras under så ostörda förhållanden som är möjligt i ett fältförsök.

REX projektet syftar till att utreda hur syre förbrukas i ett förvar efter förslutning på grund av reaktioner med bergets mineral och microbiell aktivitet. Erhållna resultat från försök i berget och på bergprover i laboratorier visar att fritt syre förbrukas inom några dagar.

En ny plats för CHEMLAB experimenten har valts och ställts i ordning under 1999. Alla framtida experiment i CHEMLAB-sonden kommer att genomföras i J-nischen på 450 m djup.

Prototypförvaret syftar till att prova och demonstrera den integrerade funktionen hos djupförvarets olika barriärer. En prototyp i full skala omfattande sex deponeringshål med kapslar innehållande elektriska värmare omgivna av högkompakterad bentonit kommer att byggas och instrumenteras. Karakteriseringen av den bergvolym där Prototypförvaret kommer att placeras är klar och de sex deponeringshålen har borrats.

Backfill and Plug Test innefattar prov av olika återfyllnadsmaterial och packningsmetoder samt prov av en tunnelplugg i full skala. Ungefär 230 mätgivare har placerats i återfyllnadsmaterialet och berget för mätning av termiska, hydrauliska och mekaniska egenskaper under försöket. Vattenmättnad av återfyllnadsmaterialet kommer att pågå under 1–2 år varefter försöken kan inledas.

Långtidsförsök av buffertmaterial syftar till att bekräfta modeller som beskriver buffertens funktion i ett djupförvar under KBS-3 liknande förhållanden samt att kvantifiera processer som kan resultera i omvandling av bufferten under ogynnsamma förhållanden. Under 1999 installerades fyra hål för långtidsprov som är planerade att pågå mellan 5 och 20 år.

Utöver SKB deltar för närvarande nio organisationer från åtta länder i arbetet vid Äspölaboratoriet.

Content

Executive summary

The Äspö Hard Rock Laboratory constitutes an important component of SKB's work to design, construct, and implement a deep geological repository for spent nuclear fuel and to develop and test methods for characterisation of selected repository sites. In the autumn of 1986, SKB initiated field work with the objective to site an underground laboratory in the Simpevarp area in the municipality of Oskarshamn. Construction of the Äspö Hard Rock Laboratory started on October 1st, 1990, after approval had been obtained from the authorities concerned. Excavation work was completed in February 1995.

The Äspö Hard Rock Laboratory has been designed to meet the needs of the research, development, and demonstration projects that are planned for the Operating Phase that started in 1995. The underground part of the laboratory consists of a tunnel from the Simpevarp peninsula to the southern part of Äspö where the tunnel continues in a spiral down to a depth of 450 m.

To meet the overall time schedule for SKB's RD&D work the work has been structured according to four stage goals as defined in SKB's RD&D Program 1995.

Stage Goal 2 – Finalise detailed investigation methodology

The detailed characterisation of a repository will encompass investigations during construction of shafts and tunnels to repository depth. Development and testing of methodology for detailed investigations are the main aim for stage goal 2.

The Rock Visualisation System (RVS) is developed to obtain a tool for interactive 3D interpretation of characterisation data collected in boreholes, tunnels and on the ground surface. The RVS system is linked to SKB's site characterisation data base (SICADA) and it will hence be possible to trace all data that has been used to build a model. The system can also be used for layout of repository tunnels. The final delivery test of RVS version 2.0 was completed 1999-06-07. RVS version 2.0 is adapted for MicroStation/J. Then the programming of version 2.1 started 1999-07-01 and was completed in January 2000. This new version embodies about 30 new or improved existing functions.

Stage Goal 3 – Tests of models for groundwater flow and radionuclide migration

The rock surrounding the repository constitutes a natural barrier to release of radionuclides from a deep repository. The most important function of the natural barrier is to provide protection for the engineered barriers through stable chemical and mechanical conditions and to limit transport of corrodants and radionuclides through slow and stable groundwater flux through the repository and reactions of radionuclides with the host rock. This Stage Goal includes projects with the aim to evaluate the usefulness and reliability of different models and to develop and test methods for determination of parameters required as input to the models.

The development of numerical modelling tools continues with the general objective to improve the numerical models in terms of flow and transport and to update the site-scale and laboratory scale models for the Äspö HRL. The models should cover scales from 1 to

10,000 metres and be developed for the Äspö site, but be generally applicable. Of the modelling concepts tested it seems that SC approach may be most useful for the larger scales while the DFN approach have benefits in the smaller scale. In this work DFN models have been used to generate spatial correlation models for use in SC models. The code PARTRACK has been further developed in order to appropriately model transport in a SC model context. The study of High Permeable Features at the Äspö HRL has been published.

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 program has been devised for tracer tests on different scales. The program has been given the name Tracer Retention Understanding Experiments (TRUE). The experimental program 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 modelling work.

The first tracer test cycle (TRUE-1) constitutes a training exercise for tracer testing technology on a detailed scale using sorbing and non-sorbing tracers in a simple test geometry. In addition, supporting technology development is performed for sampling and analysis techniques for matrix diffusion, and for understanding of tracer transport through detailed aperture distributions obtained from resin injection. The TRUE-1 tests are performed over distances of about 5 m in a fracture at approximately 400 m depth.

The TRUE-1 experiment has now been completed and the final has been prepared. The main conclusions from the TRUE-1 project are:

- Available tracer test methodology has been successfully adapted and applied in the detailed scale at the prevailing conditions (high hydraulic pressures (P >30 bars) and high salinity ([Cl] > 5000 mg/l).
- Sorbing tracers featured by sorption by cation exchange have been successfully applied in laboratory experiments and in *in situ* experiments.
- Breakthrough in the *in situ* experiments has been observed for the sorbing tracers Na^+, Ca^{2+}, Sr^{2+}, Rb^+, Ba^{2+}, Cs^+, K^+ and Co^{2+}. Uranine, tritiated water (HTO), $^{131}I^-$ and $^{82}Br^-$ were used as conservative tracers.
- The sorbtivity of the tracers used in the laboratory experiments on geological material from Äspö, show the following relative order; $Na^+ < Ca^{2+} \approx Sr^{2+} < <Rb^+ \approx Ba^{2+} < Cs^+$. The observed relationship is also consistently observed in the *in situ* test results.
- The developed Lagrangian evaluation framework (LaSAR) has been found suitable for modelling the dominant effects of reactive transport in a single fracture.
- Unlimited diffusion/sorption in the rock matrix is the dominant retention mechanism in Feature A over the time scales of the TRUE-1 *in situ* experiments, particularly so for the more strongly sorbing tracers, eg. Cs. The effects of equilibrium surface sorption, limited sorption in gouge material and diffusion into stagnant zones are not important for strongly sorbing tracers. They are observable, but less important.
- The parameter values for diffusion/sorption estimated for *in situ* conditions have been shown to be enhanced compared to those measured in the laboratory. Enhanced diffusion/sorption in the order of a factor f = 33–50 (excluding Cs) and f = 137 for Cs have been evaluated for the different tracers and experiments. The enhancement is mainly attributed to higher values on matrix porosity and/or diffusivity, and matrix sorption applicable to *in situ* conditions, particularly in the altered rim zone of the fracture, compared to values measured in the laboratory.

- Over time scales relevant to performance assessment, the role of altered rim zone of fractures is assumed to be second order.
- The important processes identified in the TRUE-1 experiment and their relative importance, identified at the experimental time scales are assumed valid also over Performance Assessment time scales. Laboratory data on unaltered rock, not associated with fracture rim zones, are assumed applicable over performance assessment time scales.
- A workable technology and procedure for obtaining pore space/aperture data from *in situ* epoxy resin injection and subsequent excavation and analysis has been developed and applied in a Pilot Resin Injection Experiment (at a different location than the TRUE-1 experiment).

The main objective of the TRUE Block Scale Experiment is to increase understanding and our ability to predict tracer transport in a fracture network over spatial scales of 10 to 50 m. The TRUE Block Scale Experiment is undertaken as a joint project between ANDRA, Enresa, JNC, Nirex, Posiva, and SKB. The total duration of the project is approximately 4.5 years with a scheduled finish at the end of the year 2000. In total six boreholes have been drilled into the experimental volume located at the 450 m level.

During 1999 the focus has been on planning and preparations for the upcoming Tracer Test Stage. This work has included definition of a Tracer Test Programme document. This document includes definitions of the major issues that are to be addressed. Answers to these issues have been formulated in the form of hypotheses to be tested by the by the planned tracer tests. Work in the field was concentrated on verifying interpreted structures. A structural model was developed based on the new field including data from the most recent borehole KI0025F02 to form the March'99 structural model. Assessments of the borehole array in terms of estimated true distances were compiled. The field work also included performance of a Pre-test tracer test campaign which served to demonstrate feasibility of block scale tracer tests in the selected block. Scoping calculations were performed to analyse effects of fracture intersections. A list of actions was recommended by the review team, including drilling of one additional borehole to facilitate verification of the structural model and shorter transport distances.

The Long-Term Diffusion Experiment is intended as a complement to the dynamic in-situ experiments and the laboratory experiments performed in the TRUE Programme. The basic idea is to locate a static tracer experiment to unfractured rock mass with the intention to characterise diffusion of radionuclides into the rock matrix. The experimental concept is based on a large diameter borehole that exposes a fracture surface that is packed of with a cap. Performed scoping calculations using available diffusivity data indicates that axial diffusion will range from mm:s for the strongly sorbing tracers to dm:s for the weakly sorbing tracers considered. A suitable target fracture has been identified in borehole KA3065A02 at a borehole length of 9.81 m. The construction of downhole borehole sampling and monitoring equipment is under way.

The REX project focuses on the reduction of oxygen in a repository after closure due to reactions with rock minerals and microbial activity. Participating funding organisations are ANDRA, JNC, and SKB. The emphasis of the project is on a field experiment involving confined groundwater in contact with a fracture surface. To this aim a borehole (diameter ≈200 mm) has been drilled in the Äspö tunnel at 2861 m. Rock and fracture filling mineral samples that had been collected from the Äspö tunnel are being used for the laboratory experiments. Results from measurements of dissolved gases in groundwater and laboratory tests show that O_2 may be consumed by methanotrophic bacteria in a closed nuclear waste repository. The result from laboratory investigations show that bacteria accelerate weathering processes, and clays were formed in the laboratory reactors only when microbes were added to the system. Results from the *in situ* tests showed that concentrations of O_2 in the range 1 to 8 mg/L were consumed in the experiments within a few days, 5 to 10 days, both for the field and replica experiments.

Laboratory studies under natural conditions are extremely difficult to conduct. Even though the experiences from different scientists are uniform it is of great value to be able to demonstrate the results of the laboratory studies in situ, where the natural contents of colloids, of organic matter, of bacteria etc. are present in the experiments. Laboratory investigations have difficulties to simulate these conditions and are therefore dubious as validation exercises. A special borehole probe, CHEMLAB, has been designed for different kinds of validation experiments where data can be obtained representative for the in situ properties of groundwater at repository depth. The results of experiments in the CHEMLAB probe will be used 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 buffer material, transport out of a damaged canister and transport in an individual fracture. In addition, the influence of naturally reducing conditions on solubility and sorption of radionuclides will be tested.

The manufacturing of the CHEMLAB probe was completed during 1996, and the first experiments were started early in 1997. During 1997 three experiments on diffusion of I, Co, Cs, and Sr in bentonite were conducted. The results of the CHEMLAB experiments with Sr^{2+} and Cs^{+} are in good agreement with results from laboratory experiments with sodium bentonite compacted to 1.8 g cm^{-3} dry density and equilibrated with synthetic groundwater and electrolyte solutions of the same salinity as Äspö groundwater. The discrepancy between the K_d values for Co^{2+} obtained in laboratory diffusion experiments with a synthetic Äspö groundwater is most probably caused by a slightly higher pH in the synthetic groundwater (pH ~7.5) used in the laboratory experiments than in the groundwater at the experimental site at Äspö (pH 7.2). Co^{2+} displays a sorption edge at pH ~6.5 with K_d increasing by two orders of magnitude between pH 6.5 and 8.5. A final diffusion experiment using iodine and technetium has been carried out by yet not evaluated.

The first experiment to be carried out in CHEMLAB-2 is the migration of actinides, Americium, Neptunium and Plutonium, in a rock fracture. Planning and pre-testing is done by Institut fü Nuklear Endsorchung in Karlsruhe (supported by BMWi). INE is also carrying out the experiment at Äspö in cooperation with SKB staff and Nuclear Chemistry at KTH.

A new site for the CHEMLAB experiments was selected and prepared during 1999. All future experiment will be conducted in the J nisch at 450 m depth.

The project Degassing of groundwater and two phase flow was initiated to improve our understanding of observations of hydraulic conditions made in drifts, interpretation of experiments performed close to drifts, and performance of buffer mass and backfill, particularly during emplacement and repository closure. Consistent results between laboratory observations and borehole test observations on the one hand, and model predictions on the other hand, were obtained using the model assumption that the gas re-dissolves as the water pressure increases above the bubble pressure. Based on both observations and model predictions, we conclude more generally that groundwater degassing will not cause considerable inflow reductions in fractures intersecting open boreholes, under natural conditions. The only plausible degassing-based explanation for the observed inflow reductions during the Stripa simulated drift experiment is that the gas re-dissolution was relatively slow, once the gas phase had formed.

The hydrochemical stability programme aims at evaluating the possible changes and evolution of the groundwater chemistry during the repository lifetime. Important questions concern the understanding of the processes that influence and control the occurrence, character and stability of both saline and non-saline groundwater. At present this programme comprises a bilateral cooperation between SKB and Posiva, the technical parts of the SKB participation in the EC EQUIP project and the modelling Task #5 within the framework of the Äspö Task Force for modelling of groundwater flow and transport of solutes.

Calcite from open fractures mainly at Äspö and Laxemar, sampled at depth ranging from 25 to 1600 metres, have been analysed within the EQUIP project. Several generations of calcite can be identified, chemical zoning is common, and the influence on calcite precipitation of fresh or marine water decreases with depth. The depth distribution of different calcite types indicates stability in large-scale groundwater circulation, but in detail large variations in depth may have occurred.

The Matrix Fluid Chemistry project aims at determining the origin and age of matrix fluids. Participating funding organisations are Nagra, Posiva, and SKB. The experiment has been designed to sample matrix fluids from predetermined, isolated borehole sections by specialised equipment. The matrix fluid borehole KF0051A is located in the F-tunnel at the deepest part of the Äspö laboratory. The hole is directed upwards (30-40°) in order to minimise the dead volume and provide the representative groundwater samples in a reasonable time. Since September 1999, activities carried out have involved a continuation of: a) mineralogical studies, b) crush/leaching experiments, c) Äspö diorite permeability test, and d) compilation and interpretation of groundwaters sampled and analysed from the Prototype Repository Experiment. In December 1999, the opening of two sections in the matrix borehole for matrix fluid sampling was carried out. Furthermore, the fluid inclusion programme of study is now in progress.

A "Task Force" with representatives of the project's international participants was formed in 1992. The Task Force is a forum for the organisations supporting the Äspö Hard Rock Laboratory Project to interact in the area of conceptual and numerical modelling of groundwater flow and solute transport in fractured rock. The work in the Task Force is tied to the experimental work performed at the Äspö HRL and is performed within the framework of well defined and focused Modelling Tasks. The Task Force group should attempt to evaluate different concepts and modelling approaches. Finally, the Task Force should provide advice on experimental design to the Project Teams, responsible for different experiments.

Tasks No 4C and 4D concerns predictive modelling of the non-sorbing tracer tests part of TRUE-1. Eight modelling teams representing seven organisations have performed predictive modelling using different modelling approaches and models. An evaluation of the modelling performed for Task 4C&D concluded that:

- many of the modelling teams tested alternative models for evaluating the effect structural geology, transport processes, boundary conditions and heterogeneity,
- the considerable interaction between modelers and experimentalists was vital for experimental setup, understanding results and perform the modelling,
- many of the modelling teams had problems in overpredicitng the drawdown from the radially converging experiment and in finding a suitable relationship between the fracture aperture derived from the hydrological tests and the aperture from the tracer tests,

- the predictive modelling results indicate that the boundary conditions and the flow system was not completely understood at the time of the experiment,
- the methodology to derive the necessary parameters for predictions need development.

Modelling was performed on the transport of the radioactive tracers in Task 4E which utilized weakly sorbing tracers, and in Task 4F with the moderately to strongly sorbing tracers ^{22}Na, ^{47}Ca, ^{42}K, ^{85}Sr, ^{86}Rb, ^{99m}Tc, ^{131}Ba, ^{133}Ba, and ^{134}Cs. The evaluation of the work performed by the Modelling teams in these two tasks started during the year and is planned to be completed in 2000.

Modelling task 5 is an integrated effort to describe the transient groundwater flow and chemistry situation during the tunnel construction. The exercise involves both groundwater flow and hydrochemistry modelling and is considered to be very relevant for site characterisation. It comprises a) predicting water composition expressed as mixing proportions of water types at selected control, b) predict hydraulic head in selected boreholes and c) make an assessment of the chemical evolution during tunnel construction. Predictive Modelling was completed during the year and results presented at a workgroup meeting. So far it has shown the need to obtain both hydrological and hydrochemical data from the same location at approximately the same time.

Stage goal 4 – Demonstration of technology for and function of important parts of the repository system

The Äspö Hard Rock Laboratory makes it possible to demonstrate and perform full scale tests of the function of different components of the repository system, which 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 repository. Within this framework, a full-scale prototype of the deep repository will be built to simulate all steps in the deposition sequence. Different backfill materials and methods for backfilling of tunnels will be tested. 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.

The Prototype Repository Test is focused on testing and demonstrating repository system function. A full-scale prototype including six deposition holes with canisters with electric heaters surrounded by highly compacted bentonite will be built and instrumented. The evolution of the Prototype Repository should be followed for a long period of time, possibly more than 10 years. This is made to provide long term experience on repository performance to be used in the evaluation that will be made after the initial stage operation of the real deep repository. The deposition holes have been mechanically excavated by full face boring, diameter 1.75 m and to a depth of 8 m. The distance between the holes is 6 m. Instrumentation will be used to monitor important processes and properties in the buffer material, backfill and the near field rock. The Prototype should demonstrate that the important processes that take place in the engineered barriers and the host rock are sufficiently well understood.

Detailed planning of the Prototype Repository has been continued during 1999, and the experimental set up of the prototype continuously updated. The application for EC funding of the Prototype Repository project was submitted in October1999 and comprised the time from April 1 of 2000 up to December 2003. The application included eight other organisations. In January 2000 the Commission announced that the application has been selected by EC for funding but only to a smaller amount than was asked for, approximately half of the asked sum. The consequence is a modification of the EC part of the Prototype Repository and minor changes in the over all plans for the whole project.

Boring of the canister holes started in accordance with the overall plan. The inner four holes where completed in early July. And after four weeks off, boring of the two outer holes started in August and where completed in September. The boring machine performed satisfactory and all six holes fulfil well the requirements regarding verticality, straightness and wall smoothness. Equipment for installation of bentonite blocks and canisters are being manufactured and will be tested before start of installation in the Canister Retrieval Test and the Prototype Repository, in a specific test of the deposition process sequences. During the period, planned characterisation work has been performed and analyses and reporting work are in progress. As part of the characterisation of the Prototype Repository, SKB's Rock Visualisation System (RVS) has been used. This system is a powerful tool to visualise data from the SICADA database and model structures in 3D. Total water inflow to canister holes is continuously monitored. Very low flows have been noted. A discrete feature network model (DFN) has been set up to simulate inflow to the canister holes and predict fracture statistics in the Prototype Repository. THM-modelling of buffer material is continuously going on and preliminary results considering time to reach full water saturation at different boundary condition has been presented.

The objectives of the Demonstration of Repository Technology are to develop, test, and demonstrate methodology and equipment for encapsulation and deposition of spent nuclear fuel. The demonstration of handling and deposition will be made in a drift at the 420 m level. The deposition machine was transported to the Äspö HRL in June 1999 and installed in a tunnel prepared with four deposition bore-holes at level 420 m below ground. This tunnel will also be used as an exhibition hall for information about the Swedish Nuclear Waste Management Programme. The design and testing of temporary equipment for handling and deposition of the buffer material and canisters for the Canister Retrieval Test and the Prototype Repository will be completed early 2000.

The Backfill and Plug Test includes tests of backfill materials and emplacement methods and a test of a full-scale plug. It will be a test of the integrated function of the backfill material and the near field rock in a deposition tunnel excavated by blasting. It will also be a test of the hydraulic and mechanical functions of a plug. The test is made in the old part of the ZEDEX tunnel that was excavated by normal blasting. Half the test part is filled with a mixture of 30% bentonite and crushed granite rock. The other half is filled with crushed rock without addition of bentonite, except for the upper 10–20 cm, where a slot was filled with blocks of highly compacted bentonite/crushed rock mixture and bentonite pellets. The backfill was compacted with inclined compaction in layers inclining 35 degrees from the horizontal floor, a technique developed in preparatory field tests. Both the inner and outer parts were divided into sections parted by drainage layers of permeable mats. Outside the backfill an approximately 3 meter thick plug was placed with the required function of both being a mechanical support and a hydraulic seal. The backfill and rock has been instrumented with about 230 transducers for measuring the thermo-hydro-mechanical processes. Participating organisations are SKB and ENRESA.

In 1998 the preparations and all the required work in the rock in the vicinity of the test tunnel were finished. In 1999 the backfilling and plugging were made and the entire test set-up with casting of the final part of the plug was finished in autumn 1999. The water saturation, with water filling of permeable mats, started in late 1999. The saturation is expected to take 1–2 years and the subsequent flow testing about 1 year. The flow testing in the backfill is planned to start after saturation, when steady state flow and pressure have been reached.

The Retrieval Test is aiming at demonstrating the readiness for recovering of emplaced canisters also after the time when the bentonite has swollen. The process covers the retrieval up to the point when the canister is safely emplaced in a radiation shield and ready for transport to the ground surface. A canister surrounded by bentonite blocks will be emplaced in a full size deposition hole. The hole will be sealed with a plug made of concrete and a steel plate as cover. The plug is secured against heave caused by the swelling clay with cable anchored to the rock. The tunnel will be left open for access and inspections of the plug support. Artificial addition of water is provided regularly around the bentonite blocks by means of permeable mats attached to the rock wall. Saturation time for the test is about two-three years in the 350 mm thick buffer along the canister and about 5 years in the buffer below and above the canister.

The boring of the two full-scale holes was carried out successfully in May 1999. Measurement of acoustic events took place during natural pauses in the boring. The results from the acoustic emission measurement and changes in rock stresses around the holes have been evaluated. Interpretation of the stress data reveals an increase of the maximum stress after boring in a direction that is parallel to the direction of the global principal stress in five out of eight investigations. In the other three the direction is perpendicular to the direction of the global principal stress, thus indicating the complex nature of rock stresses and complex impact of tunnel, bored hole and maybe cutters on the boring head. During the second half of 1999 the main activity was preparations for the installation of bentonite blocks and canister by planning for testing of the deposition sequences using the machines manufactured for the installation.

The Long Term Tests of Buffer Material aim to validate models of buffer performance at standard KBS-3 repository conditions, and at quantifying clay buffer alteration processes at adverse conditions. In this context adverse conditions have reference to e.g. super saline ground water, high temperatures, high temperature gradient over the buffer, high pH and high potassium concentration in clay pore water. Further, related processes regarding microbiology, radionuclide transport, copper corrosion and gas transport are also studied. Prefabricated units of bentonite blocks surrounding a copper tube with an electrical heater have been placed in vertical boreholes. The boreholes have a diameter of 30 cm and a length of about 4 m. Participating organisations are SKB and Posiva.

The one year pilot tests A1 and S1 have been completed. Reference material and material from defined positions in the A1 and S1 parcels material have been tested and analysed. The overarching conclusion is that no unpredicted changes were found as a result of the exposure to 90 and 130 C° for 1 year. The 4 long term test parcels and the additional 1-year parcel have been installed. The parcels were placed in percussion drilled boreholes with a diameter of 300 mm and a depth of 4 m in diorite rock at a depth of 450 m below ground. Temperature, total pressure, water pressure and water content are now being measured.

In order to be able to predict the saturation process for the buffer and the tunnel backfill the hydraulic properties of the rock, which is in contact with the buffer and backfill, has to be sufficiently well known. These properties are a result of the structure of the crack network that is created during excavation. A project with the goal to determine the degree of fracturing in the rock wall caused by the mechanical tools during excavation as a function of the force acting on the cutter head in contact with the rock wall started a few years ago. To describe this process the Indentation Crack Model has been developed. Field tests have been conducted in one of the full scale holes in the Canister Retrieval Test area by installation of two instrumented cutters in the bore head, one centre and one gauge cutter, and measurement of the forces acting on them. Fracture systems in the rock wall are examined and the results compared to the measured forces on the cutter in that particular position. The test results indicate that the maximum normal force of the front cutter is much larger than that of the gauge cutter. The magnitudes of the tangential force and side force are, however, similar for both front cutter and gauge cutter.

Facility operation

The operation of the facility has worked properly. A few new projects dealing with security or reliability of the facility have been started. A new rescue chamber has been constructed at the –420 m level. The chamber is sited in an existing niche and will be equipped with a CO_2 scrubber system for cleaning of the used breathing air. The system is designed for 60 people during six hours and will considerably increase the safety at this level. In accordance with the maintenance program for the facility an "five years inspection" was done. The output will result in some extra reinforcement activities, mainly in the deeper parts of the facility.

Information and public relations

The information group's main goal is to create public acceptance for SKB in co-operation with other departments in SKB. This is achieved by giving information about SKB, the Äspö HRL and the SKB siting programme. The visitors are also given a tour of the Äspö HRL. 12,211 visitors visited the Äspö HRL during 1999. The groups have represented the general public, communities where SKB performs feasibility studies, teachers, students, politicians, journalists and visitors from foreign countries.

Data management

One of the main objectives with the Äspö Hard Rock Laboratory is to test and develop techniques before they are applied at the candidate sites. In this context efficient techniques are required to handle, interpret and archive the huge amount of data collected during site characterisation. At present the SICADA data structure contains the sciences engineering, geology, geophysics, geotechnics, groundwater chemistry, hydrology, meteorology and rock mechanics. SICADA is successively updated to accommodate new investigation methods and data sets.

Technical systems

The monitoring of groundwater changes (hydraulic and chemical) during the construction of the laboratory is an essential part of the documentation work aiming at verifying pre-investigation methods. The great amount of data calls for efficient data collection system and data management procedures. Hence, the Hydro Monitoring System (HMS) for on-line recording of these data have been developed and installed in the tunnel and at the surface. Once a year the data is transferred to SKB's site characterisation database, SICADA.

During the course of operating the HMS, fluctuation of groundwater head were observed which correlate with the seismic events that caused the earthquake in Kocaeli, Turkey on 17 August 1999. The event was recorded at Äspö on the same day at 00:09 local time. The earthquake had a magnitude of Mw 7.4. From this earthquake the induced fluctuations in pressure head was as much as 25kPa (=2.5 mH_2O).

Groundwater sampling is performed twice every year, in April and in September, and comprises boreholes drilled from the ground surface and from the underground tunnels. This program provides information for determining where, within the rock mass, hydrochemical changes take place and at what time stationary conditions are established. The monitoring program provides the data for checking the pre-investigation and the construction phase models as well as it provides new data for further development of the hydrogeochemical model of Äspö.

International participation

Nine organisations from eight countries participated during 1999 in the Äspö Hard Rock Laboratory research in addition to SKB. They are:

- POSIVA OY, Finland.
- Agence Nationale pour la Gestion des Déchets Radioactifs, ANDRA, France.
- Japan Nuclear Cycle Development Institute, JNC, Japan.
- The Central Research Institute of the Electric Power Industry, CRIEPI, Japan.
- United Kingdom Nirex Limited, Nirex, Great Britain.
- Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle, NAGRA, Switzerland.
- Bundesministerium für Wirtschaft und Technologie, BMWi, Germany.
- Empresa Nacional de Residuos Radiactivos, ENRESA, Spain.
- US Department of Energy Carlsbad Area Office through Sandia National Laboratories, SANDIA, USA.

Multilateral projects are established on specific subjects within the Äspö HRL program. These projects are governed by specific agreements under the bilateral agreements between SKB and each participating organisation. The TRUE Block Scale Project is an example of such a project.

Below follows a brief summary of tasks undertaken by the international participants that are not covered above. Tasks with a wide international involvement are the TRUE Block Scale Project and the Task Force on groundwater flow and transport of solutes. The work within these projects is not reiterated below.

Posiva

The aim of the joint SKB/POSIVA measurements of the deep borehole KLX02 at Laxemar was to demonstrate Posiva´s new flow measurement and sampling techniques and to compare the results with earlier measurements from this borehole. The overall goal was to increase the information from deep saline groundwater in Sweden and Finland. The equipment used were the Difference flowmeter for hydrogeological determination of the flow situation including also the EC-electrode (to be used for the estimation of TDS), and the PAVE equipment for groundwater sampling.

The difference flow measurements with Posiva Flowmeter at KLX02 was partly run in 1999. The work began with pressure measurements in natural condition and the result was that borehole is fresh water filled down to the depth of 1200 m and there are two relatively homogenous saline layers below 1200 m. The work continued with the difference flow measurements. The result was that the flow direction is from the borehole to the fractures above 1100 m depth. As a result of development of the Posiva Flowmeter the single point resistance was measured simultaneously with the flow. In the year 2000 two campaigns have been planned, including also measurements in detailed mode in order to test possibility of studying individual fractures and detailed flow logging and EC–measurements in the entire borehole.

Groundwater sampling from KLX02 with the PAVE equipment was successfully accomplished during July –December 1999. The exercise showed that the PAVE sampler due to its design and low weight is easy to operate and is robust in its function and samples of good quality for dissolved gases and microbes could be obtained from three sections. The low flow caused sometimes difficulties for the on-line Eh-measurements.

The excavation disturbance caused by boring of the experimental full-scale deposition holes was characterised in the Research Tunnel at Olkiluoto. Characterisation was carried out by using two novel methods: the ^{14}C-PMMA and He-gas methods. The work during 1999 has included development of both the measuring and interpretation techniques in order to study disturbance caused by boring with mini discs, a technique used in the Äspö Hard Rock Laboratory.

In the In Situ Failure Experiment, a hole cored in one of the full-scale deposition holes will be broken by using an artificial stress field large enough to cause failure. After the failure test the observed patterns of failure and the results obtained from the computer model will be compared and evaluated. One of the major tasks carried out in 1999 was the modelling of rock failure by using both a conventional method of modelling without fracture propagation and a more sophisticated method capable of modelling the process of fracture propagation.

Samples have been taken from the ZEDEX tunnel and studied by using the ^{14}C–PMMA technique to study the extent of excavation damage. Studies of the fracturing around blast holes and the increased porosity of the damageded zone using the ^{14}C-PMMA technique have shown that the zone of increased porosity penetrates to a depth of some centimetres, while the penetration of the radial fractures is an order of magnitude deeper.

CRIEPI

CRIEPI conducted groundwater surveys at Äspö HRL in 1995 and 1997, for the purpose of investigating the origin and residence-time of groundwater and estimating changes and stability in groundwater environments during tunnel excavation. On Äspö island, very old groundwater of which the residence time is over one million years has partially remained and it might have maintained palaeohydrological conditions such as stagnant water. However, this is still open for discussion. On the other hand, for some parts of the tunnel groundwater composition has changed due to the intrusion of Baltic seawater via fractures from the tunnelling. The investigation for the past two years indicates that the groundwater flow is very complex in crystalline rocks and depends on the characteristics of fractures. The in-situ production rate of ^{36}Cl in the granite rocks is not negligible compared to that of cosmogenic ^{36}Cl.

BMWi

The activities related to the two-phase flow experiment carried out by GRS and BGR were continued. Hydraulic investigations with gas and water were performed to characterise the flow conditions in the tunnel near field at the experimental niche at 2,715 m. The code ROCKFLOW was used to model the flow conditions of a system consisting of a water saturated continuous fracture and the adjacent rock matrix. The code MUFTE-UG was developed further to be used in 3-dimensional simulations of a multiphase-multicomponent system, and the computer code "GMTM Tracer Transport by Gas Flow" was tested.

TUC's work addresses the mobility of radionuclides in crystalline rocks. The investigations deal with 1) mobilization and immobilization of selected trace elements in different granitic rocks and fluids and 2) mobilization behaviour of Uranium and Thorium as a natural analogue for the mobility of actinides in granitic rocks.

The geoelectrical measurements along the walls of the ZEDEX-drift and the DEMO-tunnel as well as the tomography in the rock between both galleries were continued. The results show clearly short time resistivity changes which could be related to saturation changes resulting from drilling activities in this area.

ENRESA

The purpose of ENRESA's contribution is:

- to develop and test a dynamic pore water pressure sensor based on the piezocone principle, for the direct measurement of local saturated permeability in the backfill,
- to model a particular section of the backfill, including the hydration process and the hydraulic tests to be performed.

The dynamic pore pressure sensors and the measurement system required to control the sensors and to perform the pulse tests, were installed in the Backfill and Plug Test in 1999.

Regarding the modelling work, an effort has been made to incorporate the effect of salt concentrations of Äspö water in the simulation of the hydration process. So far, only a preliminary approach has been adopted, as additional laboratory tests are going to be performed in order to understand the coupling between hydraulic properties and salt concentration of water in the backfill.

1 General

1.1 Background

The Äspö Hard Rock Laboratory constitutes an important component of SKB's work to design and construct a deep geological repository for spent fuel and to develop and test methods for characterisation of selected repository site. The role of the Äspö Hard Rock Laboratory is to provide input to the performance assessments that have to be supplied as part of each license application and to develop, test, and evaluate methods for site investigations, detailed investigations, repository construction, and deposition before they are applied within the deep repository program. The Äspö HRL should also provide experience and train staff in performing the various tasks within the deep repository program. Äspö HRL also offers the opportunity to test various aspects of repository performance during a long time, up to 20 years, and will hence provide valuable input to the evaluation made in conjunction with application for regular operation of the deep repository.

In 1986 SKB decided to construct an underground rock laboratory in order to provide an opportunity for research, development, and demonstration in a realistic and undisturbed underground rock environment down to the depth planned for a future deep repository. In the autumn of 1986, SKB initiated field work for the siting of an underground laboratory in the Simpevarp area in the municipality of Oskarshamn, see Figure 1-1. At the end of 1988, SKB decided in principle to site the laboratory on southern Äspö about 2 km north of the Oskarshamn power station. Construction of the Äspö Hard Rock Laboratory started on October 1st, 1990 after approval had been obtained from the authorities concerned. Excavation work was completed in February 1995.

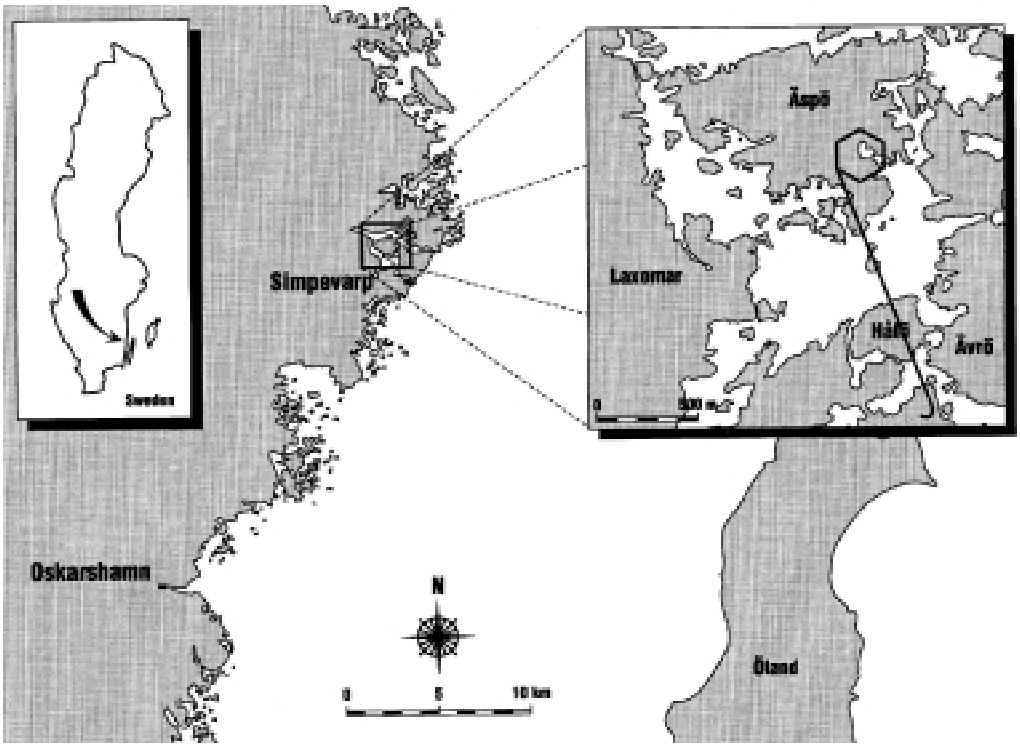


Figure 1-1. *Location of the Äspö HRL.*

The Äspö Hard Rock Laboratory has been designed to meet the needs of the research, development, and demonstration projects that are planned for the Operating Phase. The underground part of the laboratory consists of a tunnel from the Simpevarp peninsula to the southern part of Äspö where the tunnel continues in a spiral down to a depth of 450 m, see Figure 1-2. The total length of the tunnel is 3600 m where the last 400 m have been excavated by a tunnel boring machine (TBM) with a diameter of 5 m. The first part of the tunnel has been excavated by conventional drill and blast techniques. The underground tunnel is connected to the ground surface through a hoist shaft and two ventilation shafts. Äspö Research Village is located at the surface on the Äspö Island and it comprises office facilities, storage facilities, and machinery for hoist and ventilation, see Figure 1-3.

The work with the Äspö Hard Rock Laboratory, Äspö HRL, has been divided into three phases: the pre-investigation phase, the construction phase, and the operating phase.

During the **Pre-investigation phase, 1986-1990,** studies were made to provide background material for the decision to locate the laboratory to a suitable site. The natural conditions of the bedrock were described and predictions made of geological, hydrogeological, geochemical etc. conditions to be observed during excavation of the laboratory. This phase also included planning for the construction and operating phases.

During the **Construction phase, 1990-1995,** comprehensive investigations and experiments were performed in parallel with construction of the laboratory. The excavation of the main access tunnel to a depth of 450 m and the construction of the Äspö Research Village were completed.

The **Operating phase began in 1995**. A preliminary outline of the program for the Operating phase was given in SKB's Research, Development and Demonstration (RD&D) Program 1992. Since then the program has been revised and the basis for the current program is described in SKB's RD&D Program 1998.

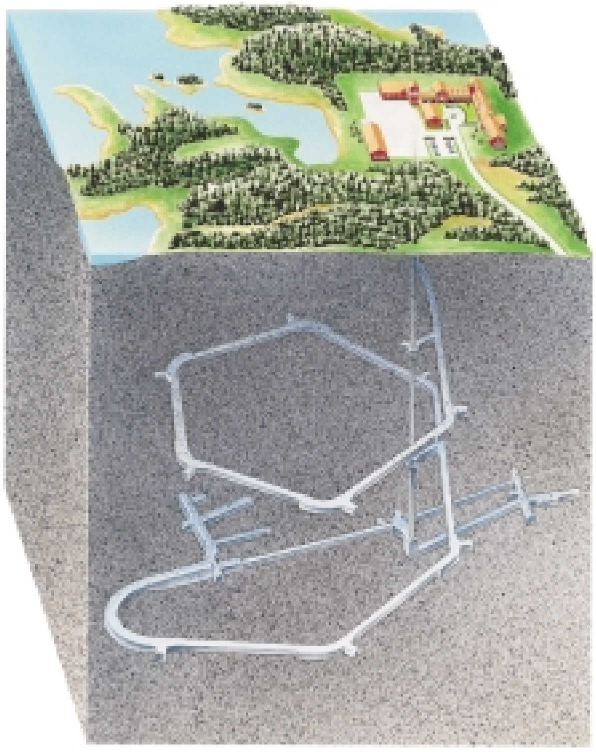


Figure 1-2. *Overview of the Äspö Hard Rock Laboratory Facilities.*

Figure 1-3. *Overview of the Äspö Research Village.*

1.2 Goals

SKB decided to construct the Äspö Hard Rock Laboratory for the main purpose of providing an opportunity for research, development and demonstration in a realistic and undisturbed underground rock environment down to the depth planned for the future deep repository. Important tasks for the Äspö Hard Rock Laboratory are:

- to increase scientific understanding of the safety margins of the deep repository,
- to test and verify technology that provide cost reductions and simplifies the repository concept without compromising safety,
- to demonstrate technology that will be used in the deep repository,
- to provide experience and training of staff, and
- to inform about technology and methods to be used in the deep repository.

To meet the overall time schedule for SKB's RD&D work, the following stage goals have been defined for the work at the Äspö Hard Rock Laboratory.

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, and
2. **Finalise detailed investigation methodology;** refine and verify the methods and the technology needed for characterisation of the rock in the detailed site investigations.
3. **Test models for description of the barrier function of the host rock;** further develop and at repository depth test methods and models for description of groundwater flow, radionuclide migration, and chemical conditions during operation of a repository and after closure.
4. **Demonstrate technology for and function of important parts of the repository system;** test, investigate and demonstrate on a full scale different components of importance for the long-term safety of a deep repository system and to show that high quality can be achieved in design, construction, and operation of system components.

1.3 Organisation

1.3.1 Repository Technology and the Äspö Hard Rock Laboratory

The Äspö Hard Rock Laboratory and the associated research, development, and demonstration tasks are managed by the Director of Repository Technology (Olle Olsson). The International Cooperation at the Äspö Hard Rock Laboratory is the responsibility of the Director of Repository Technology, Olle Olsson, and SKB's International Coordinator, Monica Hammarström.

The Repository Technology unit is part of the Safety and Technology division that is responsible for technical development of the repository system, research, and safety assessments see Figure 1-4.

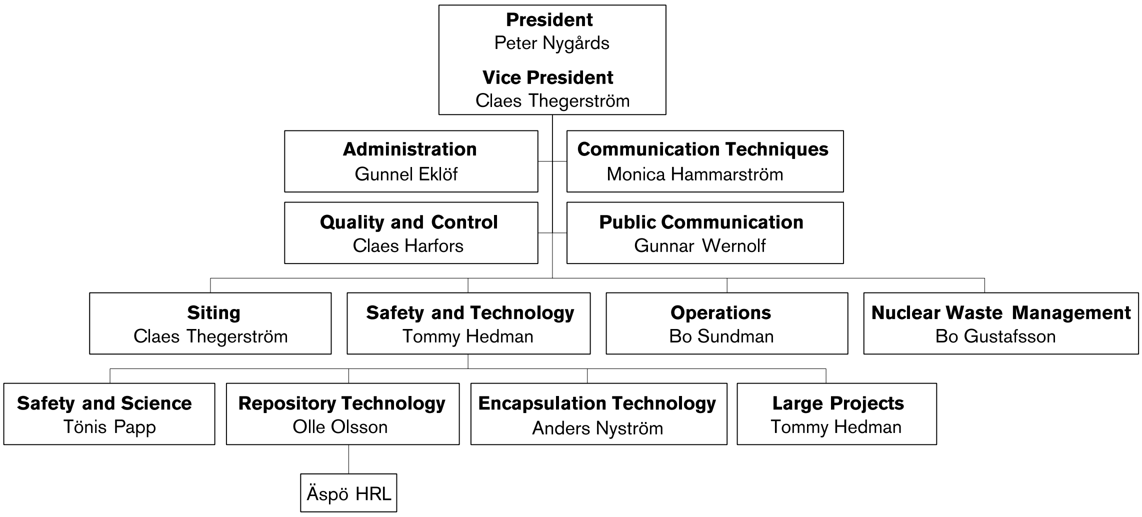


Figure 1-4. *Organisation chart for SKB.*

The Repository Technology unit is organised as a matrix organisation with three Senior Project Managers with responsibility to define the programme and manage the projects within their respective areas of responsibility (Figure 1-5). The three main tasks are:

- Site investigations with responsibility to provide an appropriate site investigation program, methods, equipment, and a competent organisation for site and detailed investigations to be applied when needed.
- Repository technology with responsibility for development, testing, planning, design, and demonstration of the technology and the methods needed to construct a deep repository.
- Natural barriers with responsibility for management and performance of research projects at the Äspö Hard Rock Laboratory aimed at resolving issues concerning the function of the natural barrier.

The Senior Project Managers report directly to the Director of Repository Technology.

The staff is organised into the following groups:

- The Technology and Science group is responsible for maintaining knowledge about the characterisation and experimental methods that have been used and the results that have been obtained from work at Äspö. The group is also responsible for the successive updates of the geoscientific models of Äspö based on new data from the experiments.
- The Experiment Service group is responsible for the co-ordination of projects undertaken at the Äspö HRL and providing service (design, installations, measurements etc.) to the experiments undertaken at Äspö HRL. They are also responsible for operation and maintenance of monitoring systems and experimental equipment at Äspö.
- The Computer Systems group is responsible for operation and maintenance of computer hardware at SKB's offices in Oskarshamn. They are also responsible for the further development and administration of SKB's geoscientific database, SICADA, and the Rock Visualisation System (RVS).
- The Facility Operations group is responsible for operation and maintenance of the Äspö HRL offices, workshops and underground facilities.

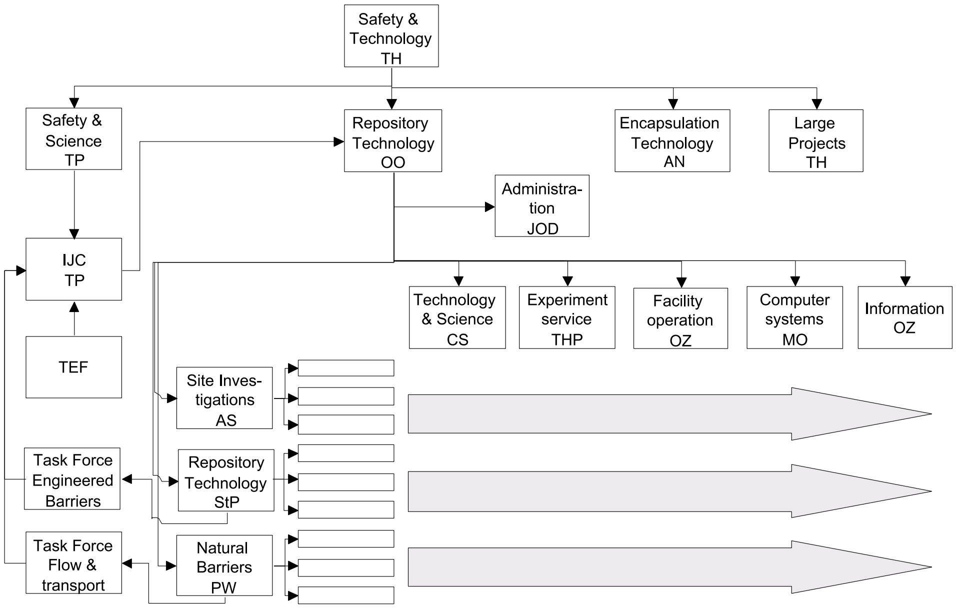


***Figure 1-5.** Organisation of Repository Technology.*

- The Information group is responsible for arranging visits to SKB's facilities and providing information to visitors to Äspö HRL and SKB's other facilities in Oskarshamn.
- The Administration group is responsible for providing administrative service and quality systems.

Each major research and development task is organised as a project that is led by a Project Manger who reports to one of the Senior Project Managers. Each Project Manager will be assisted by an On-Site Co-ordinator from the Äspö HRL with responsibility for co-ordination and execution of project tasks at the Äspö HRL. The staff at the site office provides technical and administrative service to the projects and maintains the database and expertise on results obtained at the Äspö HRL.

1.3.2 International participation in Äspö HRL

The Äspö Hard Rock Laboratory has so far attracted considerable international interest. As of February 2000 nine foreign organisations are participating in the Äspö HRL in addition to SKB. These organisations are: Japan Nuclear Cycle Development Institute (JNC), Japan; Central Research Institute of Electric Power Industry (CRIEPI), Japan; Agence National Pur la Gestion des Dechets Radioactifs (ANDRA), France; POSIVA Oy, Finland; UK Nirex, United Kingdom; Nationale Genossenschaft für die lagerung von radioaktiver Abfälle (NAGRA), Switzerland; Bundesministerium für Wirtschaft und Technologie (BMWi), Germany; Empresa Nacional de Residuos Radiactivos (ENRESA), Spain, and United States Department of Energy, Carlsbad Area Office (USDOE/CAO).

1.3.3 Advisory Groups

The international partners and SKB reached a joint decision to form the Äspö International Joint Committee (IJC) to be convened in connection with Technical Evaluation Forum (TEF) meetings. The role of the IJC is to co-ordinate the contributions of organisations participating in the Äspö HRL. The TEF meetings are organised to facilitate a broad scientific discussion and review of results obtained and planned work. Technical experts from each participating organisation and the IJC delegates participate in the TEF meetings. Chairman of IJC/TEF is Tönis Papp and secretary is Monica Hammarström (February 2000).

For each experiment the Äspö HRL management will establish a Peer Review Panel consisting of three to four Swedish or International experts in fields relevant to the experiment.

1.3.4 Task Force on modelling of groundwater flow and transport of solutes

The Technical Co-ordinating Board (TCB) which preceded the IJC established the Task Force on modelling of groundwater flow and transport of solutes. The Task Force reviews and or proposes detailed experimental and analytical approaches for investigations and experiments at Äspö HRL. The group convenes twice a year. Approximately ten different modelling groups are now actively involved in the work. Chairman (February 2000) is Gunnar Gustafson, CTH and secretary is Mansueto Morosini, SKB.

1.4 Allocation of experimental sites

The rock volume and the available underground excavations have to be divided between the experiments performed at the Äspö HRL. It is essential that experimental sites be allocated so that interference between different experiments is minimised. The current allocation of experimental sites within the Äspö HRL is shown in Figure 1-6.

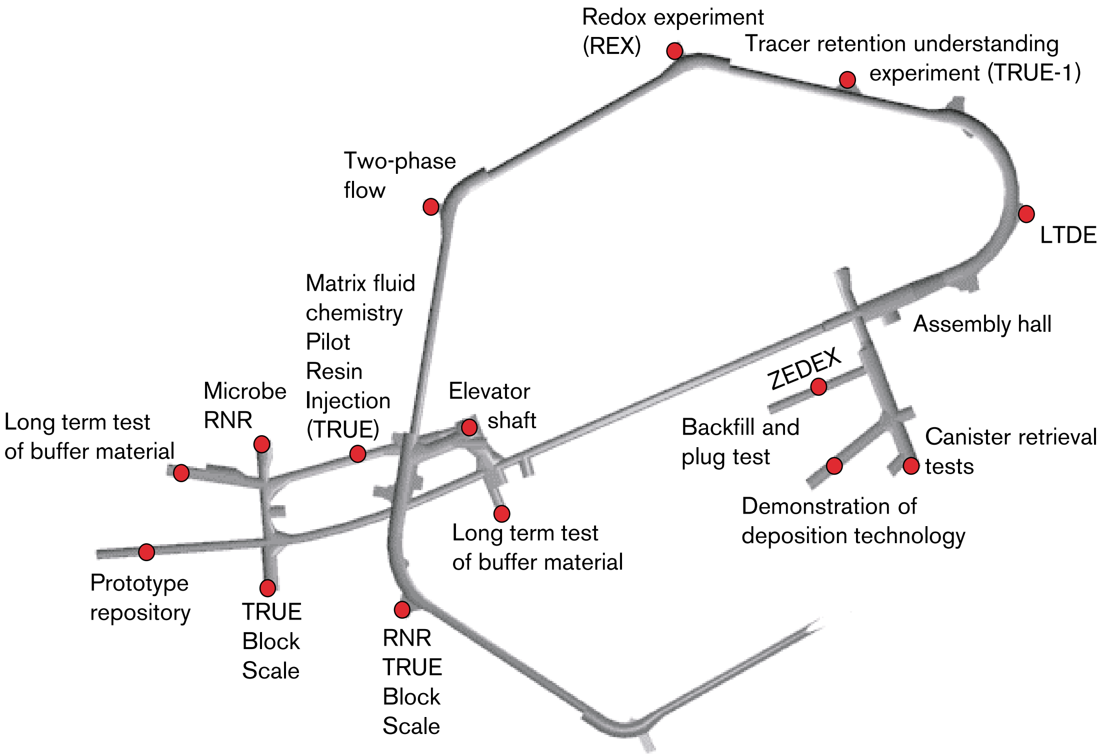


Figure 1-6. *Underground excavations at the 300–450 m levels and current allocation of experimental sites.*

2 Methodology for detailed characterisation of rock underground

2.1 General

A programme for detailed characterisation will be devised before detailed characterisation 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 characterisation 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 characterisation programme needs to be designed so that good co-ordination is obtained between rock investigations and construction activities.

The objectives are:

- to try out existing and new methods to clarify their usefulness for detailed characterisation. The methods to be tested are chosen on the basis of their potential use within the detailed characterisation programme,
- to refine important methods in a detailed characterisation programme to enhance data quality, efficiency and reliability.

Detailed characterisation will facilitate refinement of site models originally based on data from the ground surface and surface boreholes. The refined models will provide the basis for updating the layout of the repository and adapting it to local conditions. Due to the heterogeneity of the rock, the layout of the repository needs to be adapted to the gradually refined model of rock conditions. This approach has a long tradition in underground construction and it should be used also for a deep repository. During 1999 an updating of the geoscientific models of Äspö HRL was initiated.

2.2 Updating of the geoscientific models of Äspö HRL

2.2.1 Background

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. 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,
- groundwater chemical model,
- geomechanical 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 now 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 /Olsson et al, 1994/. Structure and content are described in greater detail in Rhén et al /1997/. 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 geological, geomechanical, geohydrological and groundwater chemical models of Äspö will gradually be revised, particularly in the light of the new information that is constantly obtained from the projects described later. A test plan for this modelling exercise, which was given the name GeoMode, was presented during mid 1999. The rock mass to be modelled cover the last tunnel spiral from the level of 340 m down to 460 m.

A heat transport model and a radionuclide transport model will also be developed but outside the GeoMode project.

2.2.2 Objectives

The aim of the project was to develop tools for constructing geological, geomechanical, geohydrological and groundwater chemical models as a basis for the different experiments to be conducted at Äspö HRL. The specific objectives were:

- describe the rock volume in the last tunnel spiral,
- define the initial and boundary conditions of importance to the different experiments,
- integrate the knowledge for the different disciplines,
- develop and refine tools for the model construction.

The main goal is to construct an integrated model by June 2001. The individual geological, geomechanical, geohydrological and groundwater chemical models should be presented in June 2000. Necessary tools for input and visualisation of data, e.g. RVS and SICADA, should be further developed until September 2000.

2.2.3 Results

A definition of the boundary conditions for the different subjects has been performed. A screening of data for the different subjects has also be performed. The first visualisation mainly in chemistry has started up.

2.2.4 Planned work

Complementary input of data will follow and visualisation will be performed in June 2000.

2.3 Underground measurement methods and methodology

2.3.1 Background

Detailed investigation for SKB deep repository will include a characterisation step involving one candidate site, subsequent following the site investigation which will be carried out on at least two sites. Detailed investigations will mostly include investigations from the underground.

During the Construction phase of the Äspö HRL documentation, measurements and testing activities from underground were performed. Other underground investigation methods have been used, and will further on be used, during the Operational phase. Preliminary experiences shows that methods and instruments in some cases have to be improved, with regard to correctness in data, efficiency and robustness.

2.3.2 Objectives

The aim is to evaluate the feasibility and usefulness of the methods used, define areas, methods and instruments where improvements have to be made. The work also includes testing of other methods (mainly commercially available) which have not been used before. Tests of methods for detailed characterisation are mainly intended to be carried out within the framework of ongoing projects.

2.3.3 Results

Some methods have been used within the framework of ongoing projects in the Äspö HRL project. Borehole radar and seismics have been used in the characterisation work within Prototype repository and TRUE project.

2.3.4 Planned work

A report on underground investigation methods used during the construction phase of the Äspö HRL will be published during mid 2000. The report will describe the different methods used with regard to instrument or other working tools and measurement methodology. Resolution and accuracy of the measured values as well as general aspects of errors will be discussed. The evaluation part will address the usefulness and feasibility of the methods. Recommendations on possible modifications etc. will also be given.

Based on the report, but also on the basis of other project evaluation and validation reports, further testing of existing methods, testing of new methods, etc. will be planned.

2.4 Rock Visualisation System

2.4.1 Background

A digital three dimensional rock model is built by successive collection, processing and interpretation of site data. All site data will be stored in SICADA (SKB's Site Characterisation Database). Furthermore all geological and geophysical maps will be available in SKB's GIS database. Advanced software applications are need to create the rock model based on correct and well documented sets of investigation data.

2.4.2 Objectives

The experiences obtained from SKB's site investigations and at Äspö HRL have shown that it is very important to have the possibility to test interactively in 3D different possible connections between observations in boreholes, tunnels and on the ground surface. By effectively visualising the rock model, based on available site data in SICADA, it is also possible to optimise new investigation efforts. Finally, during the design of the Deep Repository, the rock model, also used as a basis in the safety assessment, will be the basis for adaptation of the tunnel layout to the different rock characteristics at the site.

To fulfil the above strategy and requirements SKB are developing the Rock Visualisation System. The Principal Investigators in the Äspö project and other geoscientific experts in SKB's organisation have been deeply involved in defining the functions needed in the system.

2.4.3 System concept

SKB's Rock Visualisation System is based on the CAD-system MicroStation/J. It is designed as a single-user system, but the data exchange link between RVS and SKB's Site Characterisation Database System (SICADA) is based on a client/server technique. There is also a database engine (MS/Access 97) required on each RVS workstation. An open architecture based on the ODBC data exchange concept is used. Hence, by using ODBC, it will be easy to quit MS/Access 97 if another database is needed in the future.

In the Rock Visualization System, in contrast to standard MicroStation, the work is not based on design files (drawing files) and levels but on projects and objects. In order to work in an organised matter, and for practical reasons, it is for *larger projects* highly recommended to separate the visualisation work into three sub-projects:

• Data project	(Containing visualisations of background data)
• Model project	(Containing modelled objects)
• Construction project	(Containing underground constructions)

Hence, data, model and construction can be handled separately which is a great advantage, mainly regarding version handling, when data are updated continuously and much more often than the model. The project with background data is then attached as a background project to the model project. The background data project can be labeled with the attribute *data* by the user to ensure traceability between model and data project.

For *small projects*, limited in time and extension, it could, however, be more efficient to gather all information in one project, but independent of how the total set of objects are managed they can be mixed arbitrary when displayed on the screen. An example of that is shown in Figure 2-1. By using the *object selector*, an unique feature in the system, objects can be turned on (visible) or off (not visible).

From the users point of view the system can be divided in five main parts, namely:

- Borehole Visualisation
- Tunnel design
- Modelling
- Animation
- Drawings

An overview description of these system parts have been presented in the Annual Report for 1997.

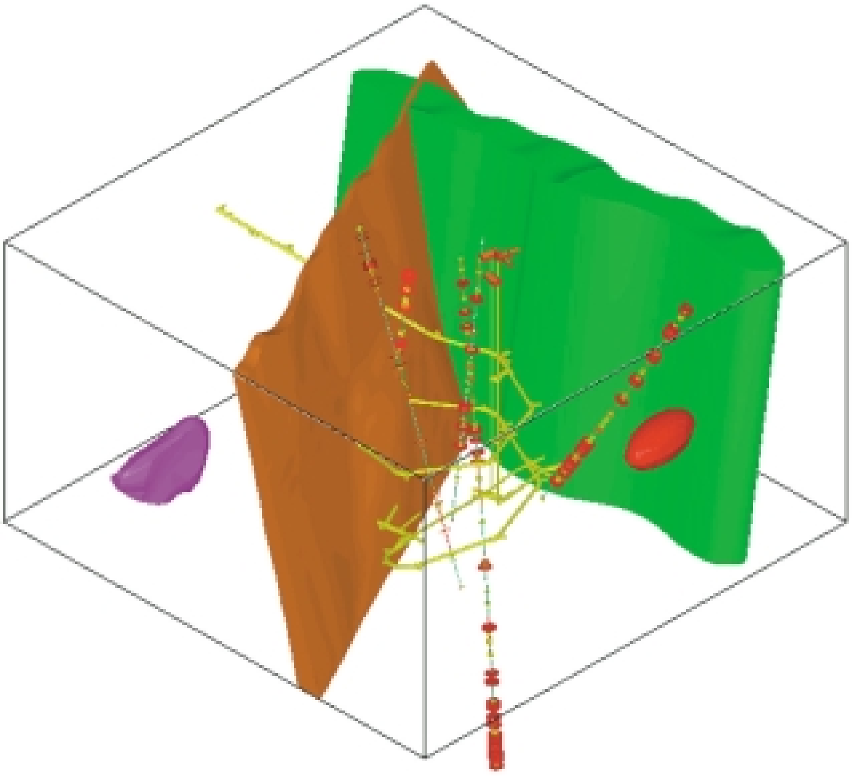


Figure 2-1. *Objects can be turned on (visible) or off (not visible), by using the object* ***selector****. The rock mass visualised in this case includes visible objects of several types including borehole data, modelled objects (a fracture zone in brown, a lens in red and two arbitrary rock bodies in purple and green) and construction objects (tunnels in yellow).*

2.4.4 Results

The final delivery test of RVS version 2.0 was completed 1999-06-07. Then the programming of version 2.1 started 1999-07-01 and will be completed in January 2000.

RVS version 2.0 is adapted for MicroStation/J compared to version 1.3 which was based on MicroStation 95. MicroStation/J includes SmartSolid and SmartSurface creation and edit functionality, based on the Parasolid®modelling kernel. This was the major reason why MicroStation 95 and MicroStation Modeler was left behind by the RVS project. The Parasolid® modelling kernel have several advantages compared to the ACISÒ modelling kernel included in MicroStation Modeler. The flexibility and the performance of Parasolid is impressing. This upgrade procedure resulted in a project delay of 5 months. Hence, there were no possibilities to extend RVS with new functions during this period of time.

RVS version 2.1 is ready to be delivered for final testing. This new version embodies about 30 new or improved existing functions. Some of these functions are described briefly in the following text.

The unique *Object List* has been improved. As a result it will be more easy to have an overview of all active objects in a model or set of visualisations. As an example all borehole visualisations are stored as sub-objects to the borehole it self. A new column, named *user*, has also been inserted in the Object List. This column stores the name of the person who have created a certain object in the model. Some other columns in the list has been renamed in order to be more understandable.

The new feature *Work Set* has been introduced to make it possible for the user to reduce the amount of borehole data in the local database. As an additional positive effect the number of boreholes in some lists are shortened as wanted.

In the previous version a discontinuity surface, describing a single fracture plane, was automatically extended to the borders of the modelled rock mass. This restriction has been removed. *A discontinuity is now extended by rules given by the user.* It is also possible to *remodel discontinuities.*

Earlier imported *DGN-files can now be reloaded* if they have been updated in standard MicroStation/J during the modelling process.

November 24th a RVS seminar was held in Stockholm. The status and abilities of the system was first presented as a background, and then a discussion was held around the subject: Programming of interfaces between RVS and software packages used in the complete range of numerical modelling used until now. During 2000 this seminar will be followed up by intensifying the dialogue with the modelling groups. General interfaces between RVS and the numerical modelling packages are needed in the future safety assessments.

3 Test of models for description of the barrier function of the host rock

3.1 General

The Natural Barriers in the deep geological repository for radioactive wastes are the bedrock, its properties and the on-going processes in the rock. The function of the natural barriers as part of the integrated disposal system can be presented as *isolation*, *retention* and *dilution*. The common goal of the experiments within Natural Barriers is to increase the scientific knowledge of the safety margins of the deep repository and to provide data for performance and safety assessment calculations. The priority for the on-going experiments on the natural barriers is to concentrate the efforts on those experiments which results are needed for the planning of the future candidate site investigations, planned to start in 2002.

Isolation is the prime function of the repository. It is obtained through the co-function of the engineered and the natural barriers. In the KBS-3 disposal concept the copper canister is expected to remain unbroken for millions of years, in case it is intact at deposition. The bentonite clay barrier will further protect the copper canister by minimising the flow of water to the canister and thereby minimise the transport of possible corrodants to the canister. For other waste types, not insulated by copper, the flow of water to the canister/waste containment is largely determining the magnitude at which the corrosion and the dissolution of the waste form can take place. For a good isolation it is thus necessary to minimise the groundwater flow to the waste containment.

Additional conditions that affect the isolation are the chemistry of the groundwater and the mechanical stability of the rock. Present day hydrochemistry is favourable for a low corrosion rate of the canister. These conditions can be expected to persist up to, at least, the next major glaciation. The host rock should provide mechanical protection for the engineered barriers and future rock movements should not jeopardise the integrity of the engineered barriers. This can be achieved by proper repository design and emplacement of spent fuel away from active faults.

Conceptual and numerical groundwater flow models have been developed through the entire Äspö project up to now, Further development of the tools for groundwater flow and transport calculations is made to meet the needs of the site characterisation phase.

Hydrochemical stability and potential variability is assessed within several ongoing projects. These aim at explaining possible chemical conditions in a repository host rock based on assumption of different climate conditions in the future.

The *retention* of radionuclides dissolved in groundwater is the second most important barrier function of the repository. Retention will be provided by any system and process that interacts with the nuclides dissolved in the groundwater when eventually the water has come in contact with the waste form and dissolved radionuclides. Retention is provided by the physical and chemical processes, which occur in the nearfield and farfield. Some elements are strongly retarded while others are escaping with the flowing groundwater. The major emphasis in the safety assessment calculations has therefore been on the weakly retarded nuclides even if they are not dominating the potential hazard of the waste.

The large amount of activity in a repository is caused by the fission products, Cs, Sr, I, Tc, and the transuranic elements Am, Np, and Pu. The transuranics, Cs, and Tc are, if dissolved, effectively sorbed in the near field. However, in case neptunium and technetium are oxidized to neptonyl and pertechnetate by radiolyses from the waste they might be transported into the bentonite buffer before they are reduced to the insoluble tetravalent state.

Strontium and all negatively charged elements will be transported through the bentonite buffer by diffusion. They will then be retarded by the interaction with the fracture minerals in the flow paths of the rock and through the diffusion into the rock matrix. The effective retention of these nuclides is a combination of radioactive decay, sorption and diffusion. The more long-lived and the weaker the sorption of the nuclide, the more important is the actual groundwater flow for the migration. The chemical composition of the groundwater is important for the magnitude of sorption for some of the nuclides. Negatively charged nuclides are retarded from the groundwater flow only through the diffusion into the stagnant pores of the rock matrix.

Tracer tests are carried out within experiments in the TRUE-projects. These are conducted at different scales with the aim of identifying detailed scale (5 m) and block scale (50 m) flow paths, retention of weakly and moderately sorbing tracers and the effect of matrix diffusion. During 2000 the goals are to complete the experimental part of TRUE Block Scale and to start the Long Term Diffusion Experiment (LTDE). Modelling of the experiments is done by several groups associated to the Äspö Task Force for modelling of groundwater flow and transport of solutes.

CHEMLAB experiments are conducted with the moderately and highly sorbing nuclides. Experiments are carried out in simulated near field conditions (bentonite) and in tiny rock fractures. During 2000 experiments including effects of radiolysis will be carried out in the CHEMLAB 1 unit. In the CHEMLAB 2 unit experiments with actinides will be started.

Microbes are of particular interest since they can directly influence the chemistry of the groundwater, and indirectly transport nuclides attached to them. For continuing the basic studies of the microbes in the Äspö laboratory, a site has been allocated in the J-niche at 450 m depth.

Dilution is the third barrier function. It will take place in the rock volume surrounding the repository. The magnitude of dilution is very much depending on the site specific conditions, and for performance assessment calculations on the conceptualisation of the flow. In the geosphere the dilution is caused by the dispersion in the groundwater flow.

No specific experiment is focussing on dilution. However, this process is included in a proposal for the next-coming modelling task within the Äspö Task Force for groundwater flow and transport of solutes.

3.2 Numerical modelling

3.2.1 Background

Mathematical model for groundwater flow and transport are important tools in the characterisation and assessment of underground waste disposal sites. SKB has during the years developed and tested a number of modelling tools and at Äspö HRL several modelling concepts as Stochastic Continuum (SC) and Discrete Fracture Network (DFN) concepts has been used. SC approach has been used for the regional and site scale models /Svensson, 1997a,b/ and in the laboratory scale model the starting point has been a fracture network for assigning hydraulic properties to a SC model /Svensson, 1999a/. The methodology of how to transform the fracture network to the SC was shown in Svensson (1999b). This is called the GEHYCO concept. Based on the new data available since the Äspö model 1996, reported in Rhén et al (1997b), and the new concept of generating the conductivity field /Svensson,1999b/, it is planned to update the site, laboratory and (possibly) the regional models of Äspö area.

Tests of embedded grids have been made with the PHOENICS code. The purpose was to see if it was feasible to generate local dense grids to get high resolution and better possibilities to define small features in the model. The technique is expected to be useful for regional, site and laboratory scale models. Both the non-uniform and BFC (Body Fitted Co-ordinates) grids generates cells with high aspect ratio, i.e. $\Delta_x/\Delta_y >>1$, which is a disadvantage when spatial assignment method for hydraulic conductivity is chosen. The advantage with embedded grid is that the cells are cubic which is considered better base for choosing spatial assignment method.

3.2.2 Objectives

The general objective is to improve the numerical model in terms of flow and transport and to update the site-scale and laboratory scale models for the Äspö HRL. The models should cover scales from 1 to 10,000 metres and be developed for the Äspö site, but be generally applicable.

The specific objectives with the updated models are:

- test and improve new methodology of generating a conductivity field based on a fracture network in a continuum modelling approach,
- develop models for transport and dispersion,
- improve the methodology for calibration and conditioning the model to observed conductive features of the groundwater flow models,
- improve the handling of the inner boundary conditions in terms of generating the tunnel system and applying boundary conditions,
- improve the data handling in terms of importing geometrical data from RVS to the numerical code for groundwater flow and to export modelling results to RVS,
- increase the details in the models based on new knowledge of the Äspö site collected during the last years.

3.2.3 Modelling concept

The modelling of groundwater flow and transport in sparsely fractured rock is made with three different concepts: Stochastic Continuum (SC), Discrete Fracture Network (DFN) and Channel Network (CN). The last modelling approach has similarities with the SC approach. Experiences gained from international modelling tasks within the Äspö Task Force on modelling of groundwater flow and transport of solutes have shown that the different concepts are all useful but there are needs to develop both the codes in terms of data handling and visualisation. It is also necessary to continue developing and testing the concepts /Gustafson and Ström, 1995; Gustafson et al, 1997/. The model code intended to be used is PHOENICS, which has been used in regional scale, sites cale and laboratory models /Svensson 1997a,b and 1999a/

The results from the construction phase of the Äspö HRL showed a relatively high number of events with a high inflow rate during drilling. Features with a high transmissivity were drilled through at a number of times and these features were in several cases not a part of the deterministically defined major discontinuities. This has also been seen in boreholes made in the operation phase of the Äspö HRL. These features were called High Permeability Feature (HPF). The spatial distribution of these features, and features with lower transmissivity, has been studied and are a base for modifying the modelling concepts /Rhén and Forsmark, 1999; Rhén et al 1997b/.

High Permeability Feature (HPF), as defined in Rhén and Forsmark (1999) consist of a fracture, system of fractures, or a fracture zone with an inflow rate (observed during drilling or flow logging) which exceeds 100 l/min or alternatively show a transmissivity $T \geq 10^{-5}$ m^2/s. Some of the conclusions from the study of the data from the pre-investigation and the construction phase of the Äspö HRL are presented in Rhén and Forsmark, 1999.

3.2.4 Results

The different modelling concepts have their benefits and drawbacks. It seems that SC approach may be most useful for the larger scales and the DFN approach have benefits in the smaller scale. The use of the SC approach demands that spatial correlation models can be established. The use of conventional geo-statistical methods has indicated problems when tests from boreholes have been used. These methods do not take into account the support scale in proper manner and the long distances between boreholes are a problem when a 3D-correlation structure is to be established. It was also stressed in Rhén et al (1997a/ the need to develop better spatial correlation models useful for the SC approach. One way of doing this is to incorporate geometrical models of the fracture network for the generation of the correlation model or directly create the conductivity field in a SC model. The first approach has been used by Hoch et al (1998) and the second approach has been used by Svensson (1999a). Important data for the test of the model in Svensson (1999a/ is the statistics of hydraulic conductivity based on the injection tests made with 3 m packer spacing but also the statistics of the distances between conductive features exceeding a specified limit of the transmissivity. The last type of statistics was for Äspö data presented in Rhén et al (1997b) and later the analysis was updated with more data but focussed on High Permeability Features (HPF/ /Rhén and Forsmark, 1999/. Both the results from Hoech et al (1998) and Svensson (1999a,b) seem promising in terms of the possibilities of generation anisotropic conditions as well as a more realistic correlation structure in the SC models. In Figure 3-1 shows a fracture network at the percolation threshold when the network only connects two opposite faces of a flow domain modelled (Svensson, 1999b/. A more advanced way of performing a geo-statistical analysis also indicate good correspondence between statistical model based on the injection tests made with 3 m packer spacing and the conductivity field in the laboratory model /Painter, 1999; Svensson, 1999a/.

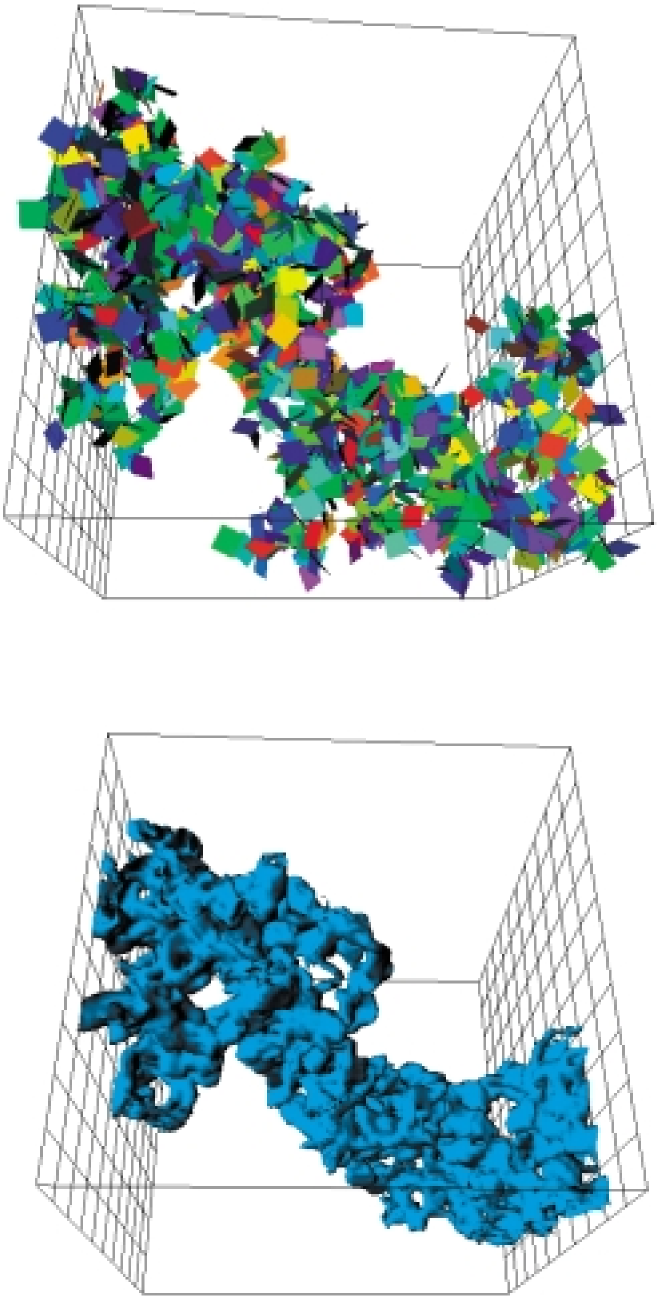


Figure 3-1. *A fracture network that connects two opposite faces of the box (top) and the corresponding flow channels. Fracture density at the percolation threshold. Fracture size is 5 m. The two connected sides of the box have been marked with grids.*

Transport properties was only briefly studied during the pre-investigation and construction phase of Äspö HRL. During the operation phase of the Äspö HRL much more effort are made to increase the knowledge of the transport properties in fracture crystalline rock. Some of the results concerning transport properties in fracture crystalline rock was compiled in Rhén et al (1997b) and was also used in the modelling (Svensson, 1997b/. These relations are approximate and uncertain but still considered useful for assigning properties to the rock mass on a large scale. More relevant transport data are now available from mainly the TRUE project /Winberg, 1996/ and later reports from the project. Tests of modelling concepts for transport in SC have also been made. In Svensson (1992, 1994/ it was tested how micro-dispersion and sorption could be incorporated into a particle tracking routine. It was further developed and tested in Svensson (1999c/. The recent development in Svensson (1999c/ is focused on description of physical and chemical processes. The basic idea in PARTRACK is that a particle can have two states "moving" or "non-moving". A frequency pair determines the rates by which a particle should change state. Obviously it is possible to describe sorption in this way but it has also been demonstrated that Taylor dispersion can be exactly parameterised by the two states. Up to now it has however not been possible to handle more than one process that causes dispersion. The recent development allows for several physical and chemical processes working in parallel. It is thus possible to simulate the movement of a particle that is exposed to, for example; Taylor dispersion when moving in the flow, diffusion into a stagnant pool, sorption on the walls of that pool and perhaps even diffusion into the rock matrix. The recent development of PARTRACK is employing some concepts and formulations from the Multi-rate model of diffusion (Haggerty and Gorelick (1995/ and also the applications of McKenna (1999). Presently the mathematical derivations, software development and some basic tests been carried out. It can be expected that future work should be directed to implementation of relevant physical and chemical processes.

In the site and regional models /Svensson, 1997a,b/ the tunnel has been modelled as a line and the flow into the tunnel has been prescribed according to the measurements and distributed in the deterministic Hydraulic Conductor Domains. This has been considered to be a simple and straightforward technique and to give sufficiently good results in the regional and site scales. In the laboratory scale it is difficult to get a realistic pressure and flow field near the tunnels with the technique used for the site and regional scale models. The size of the tunnel, the smaller side tunnels or nisches should be modelled properly and a reasonable flow distribution along the tunnel must be given or generated by applying a pressure-boundary condition. It is difficult to define a distributed flow along the tunnel as the exact measurements are made "only" every 150 m along the tunnel. There have been tunnel mapping of flowing feature that can be a base for defining a stochastic distribution but after that it still remains to find a way of applying it to the generate conductivity field around the tunnel. Probably a better way is to have a pressure boundary condition and try to define a generalised Skin factor that gives correspondence between the measured inflow to the tunnel and the generated conductivity field. This has been tested in the laboratory scale model but has to be improved /Svensson, 1999a/. In the laboratory scale model it is also possible and useful to define minor conductive features close to the tunnels. Mapping and hydraulic tests along the tunnel, mostly at the experimental sites, give information of smaller conductive features that can be geometrically defined. If they are considered "certain" it may be a reason to include them in the laboratory model. There is also information of where conductive features intersect longer core holes. This information is used to calculate the statistics of these features /see Rhén and Forsmark, 1999/ and is very useful for the calibration of models. It can also be used to condition the model along the boreholes. It is how ever difficult because the orientation and size of the features are not always known and it is difficult to define an effective methodology for conditioning-calibration.

The study of the High Permeable Features at Äspö HRL was presented briefly in Äspö Annual Report 1998 and is now published in Rhén and Forsmark (1999).

3.2.5 Planned work

The main tasks up to 2002 are:

- feasibility project A, Flow modelling,
- feasibility project B, Transport,
- HPF, part 2,
- update the regional scale model,
- update the site model,
- update the laboratory model.

The two first tasks aims at developing and testing the numerical code for the flow and transport calculations, which is made before the models are updated. The third task aims at compiling some site-specific hydrogeological data useful for the updating of the models. The three first tasks are the basis for the three last tasks.

3.3 Tracer Retention Understanding Experiments

3.3.1 TRUE-1

Background

A programme has been defined for tracer tests at different experimental scales, the so-called Tracer Retention Understanding Experiments (TRUE), Bäckblom and Olsson (1994). The overall objective of the TRUE experiments is to increase the understanding of the processes which govern retention of radionuclides transported in crystalline rock, and to increase the credibility in the computer models for radionuclide transport which will be used in licensing of a repository. The basic concept is that tracer experiments will be performed in cycles with an approximate duration of 2 years. At the end of each test cycle, results and experience will be evaluated and the programme revised.

The basic idea is to perform a series of tracer tests with progressively increasing complexity. In principle, each tracer experiment will consist of a cycle of activities beginning with geological characterisation of the selected site, followed by hydraulic and tracer tests, after which resin will be injected. Subsequently the tested rock volume will be excavated and analysed with regards to flow path geometry, and tracer concentration.

The first tracer test cycle (TRUE-1) constitutes a training exercise for tracer testing technology on a detailed scale using non-reactive tracers in a simple test geometry, see Figure 4-1. In addition, supporting technology development is performed for sampling and analysis techniques for matrix diffusion, and for understanding of tracer transport through detailed aperture distributions obtained from resin injection. The TRUE-1 cycle is expected to contribute data and experience, which will constitute the necessary platform for subsequent more elaborate experiments within TRUE.

The stated objectives of the first tracer test cycle (TRUE-1) are Winberg (1994):

- to conceptualise and parametrize an experimental site on a detailed scale (L=5 m) using non-reactive tracers in a simple test geometry,
- to improve tracer test methodologies for non-reactive tracer tests on detailed scale,

- to develop and test a technology for injection of epoxy resin on a detailed scale and to develop and test techniques for excavation (drilling) of injected volumes,
- to test sampling and analysis technologies to be employed in the analysis of matrix diffusion.

During 1995 work within the TRUE experiment has mainly been devoted to site characterisation of the site where the tracer experiments during the First TRUE Stage will be conducted, and development of resin injection technology.

Late 1995 SKB identified the need for early data on reactive tracer transport and took the strategic decision also to include reactive transport experiments during the First Tracer test cycle. Early 1997 preparatory work at the site commenced at the test site with furnishing of two containers to host the injection and pumping equipment. A series of design tests (PDT-1 through PDT-3) were performed during the Spring. The first of the tests with radioactive sorbing tracers (STT-1) was started up mid July 1997 and comprised injection of Na. Ca, Sr, Rb, Ba and Cs in the flow path KXTT4–>KXTT3. The results showed a strong retardation of Cs-137. Late 1997 it was decided to prolong the study of Cs breakthrough. It was also decided to conduct an additional injection in the same flow field, but in a different flow path (KXTT1–>KXTT3). The latter injection included the same tracers as in STT-1 with the exception that Cs-137 and Br-133 were not included, and with the addition of the two radioactive conservative tracers, I-131 and Br-82, the sorbing tracer Co-58 and the redox-sensitive tracer Tc-99m. The latter test is denoted STT-1b.

During 1998 the flow path between KXTT4 and KXTT4 was revisited with a new test with sorbing tracers using a flow rate of 0.2 l/min, i.e. 50% of the flow rate employed during STT-1. Apart from radioactive sorbing tracers employed during STT-1 and STT-1b, also the K-42 and the redox-sensistive tracer Tc-99m were used, the latter which did not show breakthrough. The breakthrough curves, unlike the ones observed for STT-1, show dual peaks, most distinctively in the breakthrough of the conservative tracers, indicating transport in two flow paths. Indeed, two intercepts have been interpreted in section KXTT4:R3. The fact that a dual peak is observed in STT-2, and not in STT-1 is attributed to the 50% reduction in pumping rate, sufficient to activate the subordinate flow path not mapped by STT-1.

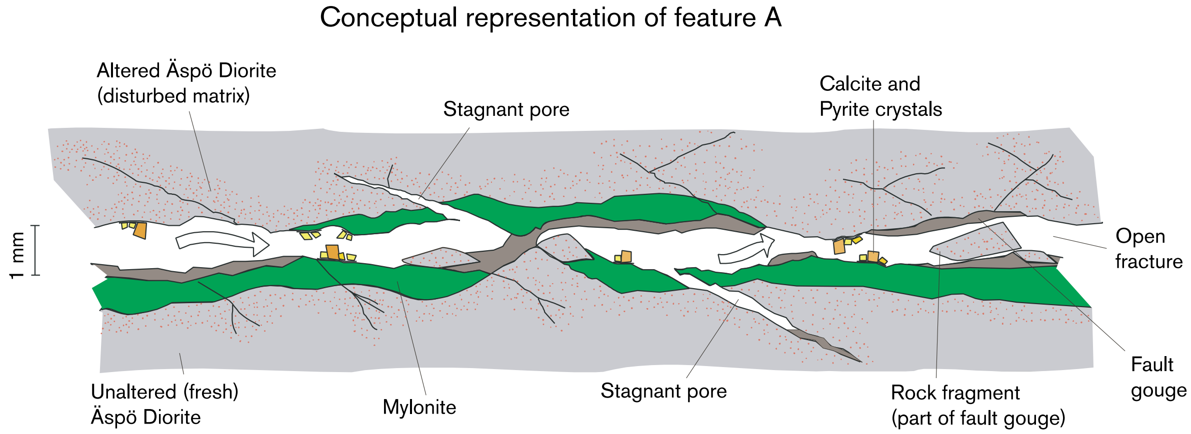
Evaluation of the tests has been performed using what we refer to as the Lagrangian Stochastic Advection Reaction model (LaSAR) /Cvetkovic et al, 1999/. In this approach the flow path is viewed as part of an open fracture /e.g. Neretnieks, 1993/. The key processes are spatially variable advection and mass transfer, the latter assumed linear, and the coupled effect is obtained by convolution. To account for dispersive effects, the convoluted result for a single flow path is integrated over different flow paths, described by a distribution of τ and β. The parameter β [T/L] is flow-dependent, integrating the inverse of the velocity-weighted aperture along the a flow path, and τ is the water residence time. The product $q\beta$ [L^2] provides an estimate of the area over which the tracer is in contact with the rock matrix ("flow-wetted surface", Moreno and Neretnieks, 1993/, where q [L^3/T] is the volumetric flow rate carrying the tracer. The parameters β and τ have been shown to be significantly correlated for generic conditions /Cvetkovic, et al, 1999/ and also for Feature A specific conditions, such that an approximate linear (deterministic) relationship $\beta = k \cdot \tau$ is applicable. Using Monte Carlo simulations of flow and particle transport in Feature A, we estimated $k_0 \approx 3{,}400$ m^{-1} as an ensemble average. For the strict assumption of linear relation between β and τ, k is equivalent to the "flow wetted surface per volume of water" (a_w) as defined and used in the recently concluded safety analysis SR-97 /SKB, 1999/. The sorption parameters for the fracture are the distribution coefficients for surface sorption K_a and sorption in gouge K_d^g. The key parameter group controlling sorption/diffusion into the rock matrix is $\beta\kappa\ [T]^{½}$ where $\kappa = \theta[D(1+\rho K_d^m/\theta)]^{1/2} = \theta(DR_m)^{1/2} = (\theta F D_w R_m)^{1/2}$, where θ is the porosity of the rock matrix (note that no distinction is made between the "total porosity" and the "diffusion porosity"), F is the formation factor and D and D_w are the pore diffusivity in the rock matrix (θD is the effective diffusion coefficient in the rock matrix) and the diffusivity in water, respectively. K_d^m is the sorption coefficient in the rock matrix. The evaluation includes determination of the water residence time distribution $g(\tau)$ by deconvoluting breakthrough curves for HTO. The reactive breakthroughs are evaluated using $g(\tau)$. One of the stated hypotheses is that the laboratory-derived value of k may not be representative of the corresponding value in the field.

Results – Main conclusions from the First TRUE Stage

In the following the main conclusions presented in the final report of the TRUE-1 experiment /Winberg et al, 2000/ are reviewed. Preliminary conclusions were presented at a combined review meeting for the planned LTDE (see 3.3.3) and TRUE-2.

Conceptual model of Feature A

- Feature A follows a reactivated mylonite, bounded by a rim zone of altered Äspö diorite, cf. Figure 3-2.
- Different mineralogical composition, grain size and porosity in the two units.
- Main mineral assemblage: calcite, fluorite, k-feldspar and pyrite.
- Indications of clay minerals suggest presence of gouge material.
- Total thickness including rim zone estimated to 0.05–0.09 m.
- Transmissivity T varying between $8 \cdot 10^{-9}$ to $4 \cdot 10^{-7}$ m^2/s



Fracture aperture to scale. Other geological units not to scale.

Figure 3-2. *Conceptual cross section of the investigated Feature A.*

Tracer test methodology

- Available **tracer test methodology** has been successfully adapted and applied in the detailed scale at the prevailing conditions (high hydraulic pressures (P >30 bars) and high salinity ([Cl] > 5000 mg/l).
  - Feature A is found to be connected in a transport sense over its investigated area.
  - The use of tracer dilution tests in combination with pumping has proven to be a good tool for identification of workable injection sections and subsequent tracer test design.
  - The existing natural gradient in the investigated Feature A (10%) controls the background flow and makes it difficult to perform high-recovery tracer tests over longer distances (>5 m) and at low pump flow rates (< 0.2 l/min).
  - Two flow paths in Feature A qualified for tests with radioactive sorbing tracers have been successfully used.

Experiments with cationic tracers

- **Cationic sorbing tracers** featured by sorption by cation exchange have been successfully applied in laboratory experiments and in *in situ* experiments.
  - The sorbtivity of the exposed geological material is shown to depend on the concentration of biotite.
  - The sorption in the batch laboratory experiments is observed to be time depend ent, ie. the evaluated K_d increase with increasing contact time. This finding is attributed to chemical kinetics, mass transfer (intra-particle diffusion) or geohemical changes in the solid phase, or combinations thereof.
  - Breakthrough in the *in situ* experiments has been observed for the sorbing tracers Na^+, Ca^{2+}, Sr^{2+}, Rb^+, Ba^{2+}, Cs^+, K^+ and Co^{2+}. Uranine, tritiated water (HTO), $^{131}I^-$ and $^{82}Br^-$ were used as conservative tracers.
  - The sorbtivity of the tracers used in the laboratory experiments on geological material from Äspö, show the following relative order; $Na^+ < Ca^{2+} \approx Sr^{2+} < <Rb^+ \approx Ba^{2+} < Cs^+$. The observed relationship is also consistently observed in the *in situ* test results.
  - Laboratory results indicate that the sorption of the more sorbing species, Rb, Ba and Cs, are affected by slowly reversible processes. Similarly, the performed *in situ* experiments show a similar behaviour for Co, Ba and Cs. At the time of termina tion of STT-2 in October 1998, after some 10,870 hours of pumping, approximately 63% of the ^{137}Cs mass injected as part of STT-1 still remained sorbed in the injection section and the fracture. With the data presently available, no distinction is possible between reversible and irreversible contributions to the sorption of Cs.

Main transport processes

- The developed Lagrangian **evaluation framework** (LaSAR) has been found suitable for modelling the dominant effects of reactive transport in a single fracture.
  - Unlimited diffusion/sorption in the rock matrix is the **dominant retention mechanism** in Feature A over the time scales of the TRUE-1 *in situ* experiments, particularly so for the more strongly sorbing tracers, e.g. Cs. The effects of equilibrium surface sorption, limited sorption in gouge material and diffusion into stagnant zones are not important for strongly sorbing tracers, are observable, but less important.
  - The relative importance of the processes included in the evaluation of the TRUE-1 *in situ* experiments are also assumed valid over time scales relevant to performance assessment.
  - A key result is the derivation of the parameter β which integrates the inverse velocity-weighted aperture along the flow path. It controls surface sorption and diffusion/sorption into the matrix, accounting for the effect of aperture variability on retention. A linear relationship $\beta = k \cdot \tau$ was found suitable for modelling retention in Feature A. A representative estimate of *k* obtained from simulations is $k_0 \approx 3{,}400\ \mathrm{m}^{-1}$.
  - Assuming a strict linear relation between β and τ, the proportionality factor *k* is equivalent to the "flow wetted surface" per volume of water" (a_w). The value *k* is within bounds of a_w reported in the literature.

Transport parameters

- Values of **parameters for the main retention processes** included in evaluation concept (LaSAR) have been obtained either from laboratory data, or through estimation using *in situ* data and the calibrated parameter group ($\kappa = \theta[D(1+\rho K_d^m/\theta)]^{1/2}$) which controls diffusion/sorption in the matrix rock.
  - The parameter values for diffusion/sorption estimated for *in situ* conditions have been shown to be enhanced compared to those measured in the laboratory. Enhanced diffusion/sorption in the order of a factor $f = 33–50$ (excluding Cs) and $f = 137$ for Cs have been evaluated for the different tracers and experiments. The enhancement is mainly attributed to higher values on matrix porosity and/or diffusivity, and matrix sorption applicable to *in situ* conditions compared to values measured in the laboratory. A minor contribution to the enhancement is attributed to the flow-dependent parameter *k* in the $\beta = k \cdot t$ relationship, hence being higher in the field than what has been interpreted from performed Monte Carlo simulations.
  - The parameters related to sorption in gouge material have been calibrated using *in situ* breakthrough data. Effects of sorption onto gouge material have been found to be most evident for the weakly sorbing tracers Na and Sr, since for these tracers, matrix diffusion/sorption is relatively small.

Predictive capability

- The **representative laboratory data set (MIDS) and $k_0 \approx$ 3,400 m^{-1}** constitute a basis for robust predictions of reactive tracer breakthrough in the TRUE-1 experiments. Relatively accurate *first arrival* is obtained while the *peaks* are overestimated by approximately one order of magnitude.
  - This provided that the water residence time distribution (conservative breakthrough) is known (can be assessed) and that variability in the b parameter is accounted for, cf. Figure 3-3.

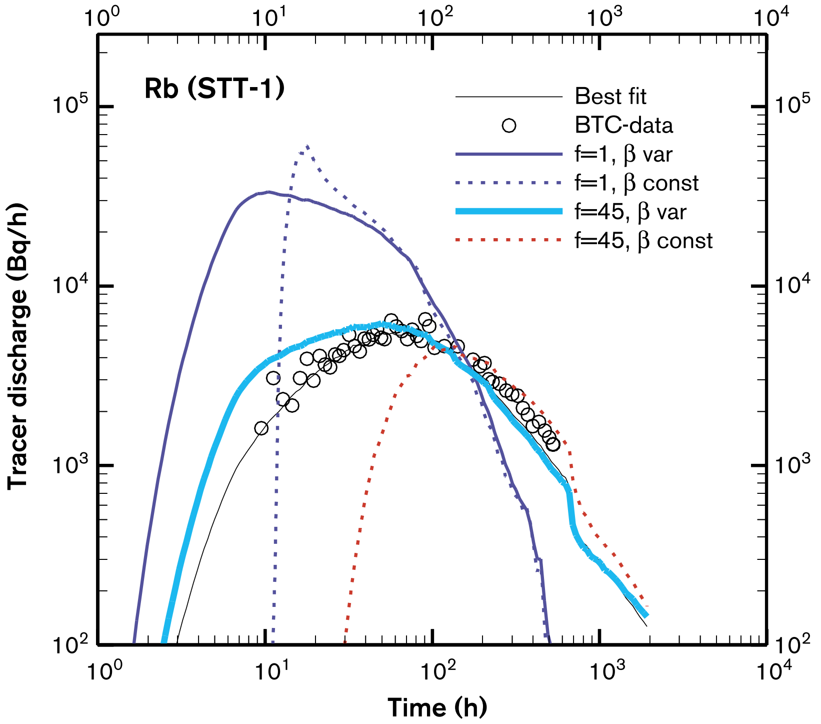


Figure 3-3. *Predictive capability and effect of variability in β exemplified using a) Rb and b) Cs breakthrough in the STT-1 test. Only matrix diffusion/sorption and surface sorption are considered except in the "best fit" curve where sorption in gouge is added.*

Properties of the rim zone

- The **altered rim zone** along the studied feature is interpreted to show enhanced, albeit variable, porosity/diffusivity in relation to the unaltered matrix rock, and is important for the tracer retention over the time scales of the TRUE-1 experiments.
  - The rim zone is interpreted to be made up of primarily of altered Äspö diorite and mylonite, the latter with a lower porosity/diffusivity.
  - The average range of porosity of the parts of the rim zone of Feature A which is accessible over the time scales of the *in situ* experiments is estimated to be 2–2.4%. Independent information and new site-specific data indicate that this estimate is realistic.

  - Analysis e.g. indicate that performed 36 day batch sorption tests on 1–2 mm size fractions of generic Äspö diorite material capture, in an average sense, the variability in sorption along the studied flow paths, over the time scales of the *in situ* experiments.
  - The tested flow path is only known at its respective intercepts in the injection and pumping borehole. The actual distribution of transport properties along the flow path can only be analysed in detail when the fracture excavated, preceded by injection of epoxy resin.
  - Over time scales relevant to performance assessment, the role of altered rim zone of fractures is assumed second order. Over the PA time scales the diffusivities from the through-diffusion experiments on unaltered geological material (cf. MIDS data set) are assumed applicable for predictions.

Performance assessment

- The performance assessment related conclusions based on the results of the TRUE-1 experiments can be summarised as follows:
  - The important processes and their realtive importance, identified at the experimental time scales are assumed valid also over PA time scales.
  - Laboratory data on unaltered rock, not associated with fracture rim zones, are assumed applicable over performance assessment time scales.
  - A value on "flow wetted surface per volume of water" $a_w = k_0 \approx 3{,}400 \text{ m}^{-1}$ has been estimated based on *in situ* experiments and associated modelling. This value is in parity with previous estimates found in the literature.
  - Bounding values of the "flow wetted surface per volume of water" can be estimated using the tracer injection flow rate and the hydraulic aperture. The former estimate is in this context regarded as conservative.

Pore space analyses

- A workable technology and procedure for obtaining **pore space/aperture data** from in situ epoxy resin injection and subsequent excavation and analysis has been developed and applied in a Pilot Resin Injection Experiment (at a different location than the TRUE-1 experiment).
  - A fracture system with a one order of magnitude lower transmissivity than Feature A has been subject to resin injection.
  - The average aperture of the analysed samples are 240 and 270 µm, respectively with a coefficient of variation of about 40%.
  - Evaluated variograms of the aperture mapped by the epoxy indicate practical ranges varying between 0.003 to 0.005 m.

Site characterisation/Next TRUE Stage

- The performed characterisation provides a powerful set of tools for assessment of conductive geometry and connectivity in future preliminary **site characterisation**, and in particular during future detailed site characterisation.
  - The use of borehole TV imaging in combination with detailed flow logging identifies the conductive features in a borehole.
  - Cross-hole pressure interfere testing, including observations during drilling of a new borehole, provide information on how the conductive features connect.
  - The tracer test methodology developed and used in this work is applicable to charactrisation work in various phases of repository development.

3.3.2 TRUE Block Scale

Background

Work on the TRUE Block Scale Project started in mid 1996. This subproject of TRUE broadens the perspective from an address of a singular feature in TRUE-1, to flow and transport processes in a network of fractures and a spatial scale between 10 and 50 m. The specific objectives of the TRUE Block Scale Project are to /Winberg, 1997/:

1. increase understanding and the ability to predict tracer transport in a fracture network,
2. assess the importance of tracer retention mechanisms (diffusion and sorption) in a fracture network,
3. assess the link between flow and transport data as a means for predicting transport phenomena.

A set of desired experimental conditions have been defined and a flexible iterative characterisation strategy has been adopted (Winberg, 1997/. The project is divided into a five basic stages:

- Scoping Stage.
- Preliminary Characterisation Stage.
- Tracer Test Stage.
- Evaluation (and reporting) Stage.

The total duration of the project is approximately 4.5 years with a scheduled finish at the end of the year 2000.

The project was originally organised as a multi-partite project involving ANDRA, NIREX, POSIVA and SKB. During 1997, also ENRESA and PNC has joined the project.

Until late 1997 in total three boreholes, KA2563A, K10025F and K10023B, have been drilled into the selected rock volume. In addition an already existing borehole, KA2511A, has been used for characterisation and pressure registration.

During 1998, one additional borehole, K10025F02, has been drilled and used for site characterisation. A comprehensive 3D seismic measurement campaign has been carried out with seismic sources distributed in the near proximity tunnel system and with the seismic receiver system distributed along the length of borehole K10025F02. The obtained data has subsequently been co-interpreted with existing old seismic data from the investigated rock block. During the year a comprehensive cross-hole interference, tracer dilution and tracer test programme has been carried out. During the year the POSIVA flow meter has been employed in a detailed mode for the first time in borehole K10025F02.

Tentative modelling work started up during 1997 using a discrete feature network model (DFN. During 1998, the modelling work has diversified with the inclusion of stochastic continuum and channel network modelling.

Also the groundwater chemical data collected from the packed off sections have been used in the integrated interpretation of groundwater flow in the studied block. During the year one structural model update has been produced (Sep'98 model/.

The characterisation and data integration work up till October 1998, including most of the work in K10025F02 is presented in a position report prepared for the 2nd TRUE Block Scale Review Meeting, Winberg (1999/.

Overview of work performed during 1999

During 1999 the focus has been on planning and preparations for the upcoming Tracer Test Stage. This work has included definition of a Tracer Test Programme document. This document includes definitions of the major issues which are to be addressed. Answers to these issues have been formulated in the form of hypotheses to be tested by the by the planned tracer tests. Work in the field was concentrated on veryfying interpreted structures. A structural model was developed based on the new field including data from the most recent borehole K10025F02 to formthe March'99 structural model. Assessments of the borehole array in terms of estimated true distances were compiled. The field work also included performance of a Pre-test tracer test campaign which served to demonstrate feasibility of block scale tracer tests in the selected block. Scoping calculations were performed to analyse effects of fracture intersections. A list of actions was recommended, including drilling of one additional borehole to facilitate verification of the structural model and shorter transport distances. This list of actions was discussed at the 3rd TRUE Block Scale Review Meeting October 27, 1999.

Results of site characterisation

A series of flow measurements have been performed in borehole KA2563A using a double packer system with simsultaneous observation of pressure responses in the adjacent borehole sections. Subsequently POSIVA flow loggingin a continuous mode has been carried out in KA2563A and KA2511A. The results complements the corresponding results from K10025F02 and KA3510A. Further POSIVA logging during open and closed borehole conditions has been carried in KA2563A, when flowing and not flowing Structure #9 in section K10023B:P6. The latter with the intention to identify the existence or not of Structure #9 in KA2563A. The tests clearly identified Structure "20 and #13, but the results regarding Structure #9 remained inconclusive/uncertain. As a result a so called "flow inhibition" test was conducted where a double packer straddle without a permeable screen was lowered to seal off selected depth intervals in KA2563A in an otherwise free-flowing KA2563A. The reduction in inflow before and beyond the straddle, and pressure responses in adjacent holes were monitored. The tests confirmed Structure #13, but no further evidence was provided regarding Structure #9 in KA2563A. A final confirmation test with a four packer system in KA2563A was devised to confirm the observed pressure responses associated with Structure #9 in KA2563A when a hydraulic disturbance is applied in sections containing Structure #20. The conclusion of the test is that the structure (candidate for Structure #9) at 265 m in KA2563A is not associated with structure

#20 and the pressure responses monitored in previous cross-hole tests were artefacts induced by the instrumentation. The structure (candidate for Structure #9) at 230 m in KA2563A is not in good hydraulic contact with structure #20 and is therefore not considered to be of interest for future tracer experiments.

March'99 structural model

The results shows that the structure #9 has limited extent and hydraulic significance and cannot be assumed to provide connectivity between the main components of the target fracture network, Structure #20 and #13. However, the detail added by the new POSIVA flow logs in combination with the BIPS, has allowed identification of alternative structures which may provide the observed connection between Structures #13 and #20. Two NNW structures, #21 and #22, were interpreted as a result, and are together with the two main NW structures, #13 and #20, assumed make up the target fracture network. The resulting deterministic structural model is shown in Figure 3-4.

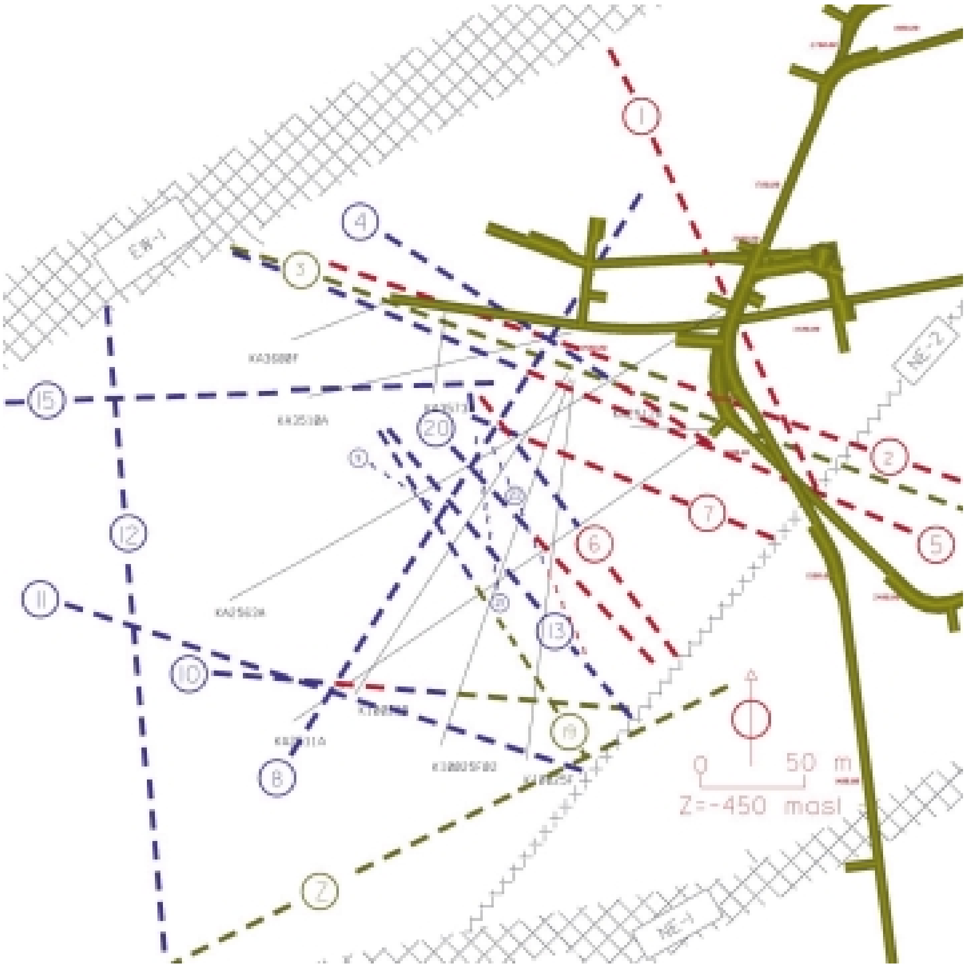


Figure 3-4. Structural model of the TRUE Block Scale site as of March 99. The numbered structures are discussed in the text.

Spring'99 tracer pre-tests

The pre tests performed during the Spring 1999 had two principle goals, first to complement the existing series of tracer dilution data, and in particular for the new sections resulting from the reinstrumentation of the borehole array performed in March 1999. Second, to provide firm demonstration of feasibility of tracer tests in the block scale. In total three pumpings (PT-1, PT-2 and PT-3) were performed in sections containing Structures #13, #21 and #20, respectively, with the purpose of collecting pressure interference data and tracer dilution data. Between 6 to 12 sections were tested with tracer dilution techniques, before and during pumping in each case. Out of a total of 28 separate tracer dilution tests, using 14 different sections and three sink sections, 16 (57%) show a significant increase in flow under pumped conditions compared to ambient conditions.

During a subsequent PT-4, the PT-2 situation with pumping in Structure #21 in KI0023B was revisited with performing tracer injections in neighbouring sections containing Structures #22, #13/#21 and #20. The results of these tests show mass recovery from all sections, representing multiple structure pathways over distances ranging between about 15–100 m, and very high recovery for the tracers injected in KI0025F02:P3 (#13/#21) and KI0025F02:P6 (#22), ranging between 76–80%, assumed to have shown full recovery had the experiment been prolonged, cf. Figure 3-5.

The prospects for block scale tracer tests were consequently considered very promising.

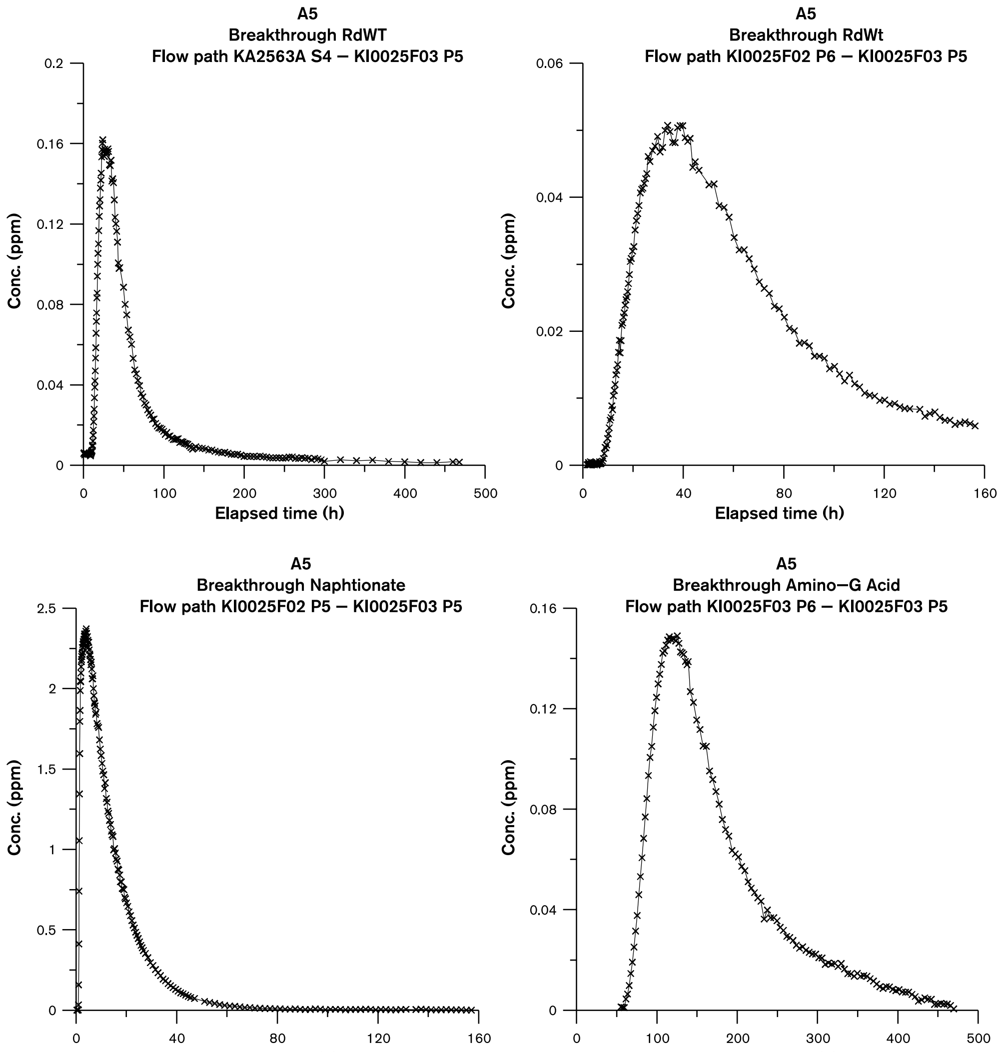


Figure 3-5. *Tracer breakthrough in KI0023B:P6 during PT-4. Note that the scales of the axes differ between the plots.*

Hydraulic reconciliation of the March'99 model

The hydraulic reconciliation of the March'99 structural has involved analysis of drilling records of the most recent borehole, KI0025F02, and associated pressure responses. In addition, available flow logging and flow and pressure build-up tests have been used. Finally the results of the tracer dilution tests have been utilised.

The hydraulic reconciliation overall confirm the principal structures contained in the March'99 structural model. Structures #10, #19, #20 and #6 appear hydraulically in a consistent manner with the structural model, cf. Figure 3-6. Structure #13 appears in KA2563A and KI0023B, but may not continue southeastward to KI0025F. Feature #22 is interpreted to appear in KI0023B and KI0025F02, but does not extend to KA2563A. Structure #21 is still difficult to interpret over larger distances based on the hydraulic information. The tracer dilution data, however, indicate connection between KI0025F02:P3 and KI0023B:P6. Additional connecting fractures between Structures #13 and #20 are likely to exist, and evidence for additional conductors have been presented.

Identification of issues and hypotheses

Hypotheses are usually derived from our previous experiments and experiences. Some of our previous experiments show that tracer tests have particular kinds of breakthroughs, or have particularly low recoveries, or have no breakthrough at all. We consider these data and wonder "why?" We also observe fractures in boreholes and underground openings. We develop detailed models of these features in three-dimensions and we wonder, "How does this network geometry affect groundwater movement and solute transport?" Our observations lead us to a series of "why", "how", and "what if" questions. Hypotheses are possible answers to these questions. As scientists, our job is to develop experiments that test the validity of these hypotheses. We must develop these experiments carefully, because the results of our tests may reflect complicated interactions of flow geometry and flow processes. A valid interpretation of our results may require separating the effects of these interactions.

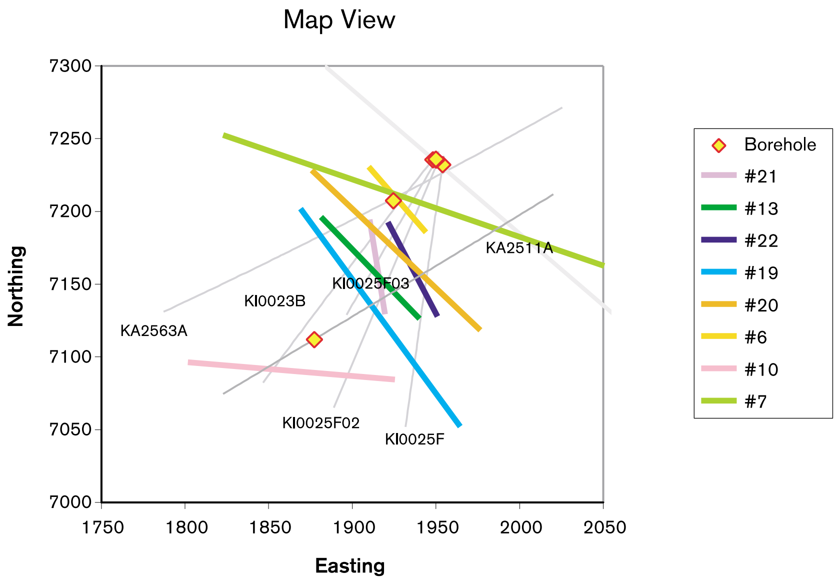


Figure 3-6. Reconciled March'99 structural model of the TRUE Block Scale rock volume. Plan view at Z=-450 masl.

We are proposing three basic questions and hypotheses for the planned future tracer tests are compiled in Table 3-1.

Table 3-1. Identified issue/question and associated hypothesis to be addressed by in situ experiments.

Identified issue or question	Associated hypothesis
1. "What is the conductive geometry of the defined target volume for tracer tests within the TRUE Block Scale rock volume? Does the most recent structural model reflect this geometry with sufficient accuracy to allow design and interpretation of the planned tracer tests?"	1. "*The major conducting structures of the target volume for tracer tests in the TRUE Block Scale rock volume trend northwest and are subvertical. Being subvertical, and subparallel, they do not form a conductive network in the designated target volume. For the purpose of testing fracture network flow and transport effects in the current borehole array, second-order NNW features are required to provide the necessary connectivity between the major conducting NW structures!*"
2. "What are the properties of fractures and fracture zones that control transport in fracture networks?"	2a. "*Fracture intersections have distinctive properties and have a measurable influence on transport in fracture/feature networks. These distinctive properties may make the intersection a preferential conductor, a barrier, or a combination of both!*" *Or* *2b.* "*In-plane heterogeneity and anisotropy have a measurable influence on transport of solutes in a block scale fracture network!*"
3. "Is there a discriminating difference between breakthrough of sorbing tracers in a detailed scale single fracture, as opposed to that observed in a fracture network in the block scale?"	3. "*It is not possible to discriminate between breakthrough curves of sorbing tracers in a single fracture from those obtained in a network of fractures*"*!*

Drilling and characterisation of KI0025F03

The new 76 mm borehole KI0025F03 was drilled in early August collared and oriented between KI0023B and KI0025F02, cf. Figures 3-4 and 3-6, to a depth of 141.7 m. The borehole has an inclination of 30 degrees down. The projected locations of interpreted structures have largely been verified by observed structures and inflows in the borehole, as well as observed pressure responses in neighbouring packed-off boreholes.

The performed site characterisation comprise BIPS borehole TV logging, BOREMAP core logging, POSIVA continuous mode flow logging. Flow and pressure build up tests combined with observations of pressure responses in neighbouring boreholes. Some 12 tests with a flow period of 30 minutes have been performed. The target fractures for the tests comprise both identified structures and fractures belonging to the so-called background fracture population. The pressure responses were interpreted quantitatively and plotted in diagnostic pressure response diagrams and in time distance diagrams. The observed responses were also compiled in a response matrix. The qualitative interpretation shows that the responses in general are consistent with the reconciled March'99 structural model. The dominating flow regimes are (pseudo-)radial which in some cases transform to leaky (pseudo-) spherical flow by the end of the tests.

The results of these measurements have been used to select a suitable configuration of the multi-packer system. The system is made up of all together 9 sections where pressure will be monitored. Five sections will be equipped to allow injection/abstraction of water and tracer. Two sections will be equipped with steel tubing to allow injection of dissolved He gas as a tracer without risking diffusion through the lines.

Phase A tracer tests

The principle objectives of the Phase A tests are to provide the basis for selection of the best main sink to be used in the subsequent experimental phases. In addition, the database of tracer dilution data is complemented using sink sections in the new borehole. Subsequently two tracer tests have been performed. One using the previously used sink in KI0023B:P6 (Structure #21) and injection points in the new borehole, and one test in KI0025F03::03 (Structure #20) with injection in 5 sections in adjacent holes.

The database with tracer dilution test data at ambient and pumped conditions amount to a total of 70 sections after performing tests A-1 to A-3. The results in terms of pressure responses and flow data have been distributed to the modelling teams as conditioning information for predictions of A-4 (sink in KI0023B:P6, #21) and A-5 (sink in KI0025F03:P5, #20).

The tracer test in A-4 performed by pumping in structure #21 (KI0023B:P6) resulted in tracer breakthrough from two of three injection points, KI0025F03:P5 (Structure #20) and KI0025F03:P6 (#22). No breakthrough was observed from injection in section KI0025F03:P7 (denoted #23). The tests cover distances ranging between 15–100 m (distances along structures). The tracer mass recoveries are not very high (40–50%) but a large portion of the tail of the breakthrough curves still remained to be recovered when sampling was finished for time reasons, and therefore it is likely that the mass recoveries would have increased by another 20–30% had the tests been prolonged.

The tracer test in A-5 performed by pumping in structure #20 (KI0025F03:P5) resulted in tracer breakthrough from four of five injection points, KI0025F02:P5 (structure #20), KI0025F02:P6 (#22), KI0025F03:P6 (#22) and KA2563A:S4 (#20). No breakthrough was observed from injection in section KI0025F02:P3 (#13, 21). The tests cover distances ranging between 10 to 65 m (distances along structures).

Modelling work related to fracture intersection zones

The main modelling activities performed during the year are scoping calculations of fracture intersections zone effects and predictive modelling work related to the Phase A tracer test. As part of the panning for the Tracer Test Stage, design calculations have been performed by JNC/Golder with the purpose to investigate the possibility to detect and distinguish effects of fracture intersection zones (FIZ) from the other types of heterogeneity present in a fracture network. Two types of modelling have been performed, one generic model focused on a fracture intersection, and one site-specific focused on the Structure #20/#21 intersection in the TRUIE Block Scale rock volume.

In both simulation cases tracer tests have been simulated along, across, and diagonally across the FIZ. In addition the sensitivity to transmissivity contrast between the FIZ and the structures forming it, heterogeneity and degree of heterogeneity in the structures, distance from borehole intercept to FIZ, have been analysed.

The results of the simulation shows that it will be difficult, if not impossible to distinguish the effects of the FIZ from the overall, heterogeneity. The use of sorbing tracers may in this context add a beneficial effect. One aspect which eg. has not been studied is the heterogeneity and spatial continuity within the FIZ itself.

Predictive modelling Phase A

The tests will be subject to prediction using the updated stochastic continuum, discrete fracture network and channel network models.

Stochastic Continuum

The new structural model has been implemented. A hydraulic conductivity data base is built for each fracture plane and for the background. For the matrix conductivity the flow logging data on 5 m intervals were used. For the fracture plane conductivities the compiled data set with transmissivities for the main fracture planes were used.

The simulated hydraulic conductivity for a grid cell is only conditioned to hydraulic conductivity data taken in the fracture plane to which the cell belongs. The hydraulic conductivity variogram model is not estimated from the data but is adopted according to expert knowledge since too few data are available to estimate variogram models for all fracture planes.

The 3D hydraulic conductivity fields are inversely conditioned to hydraulic head data by sequential self calibration. First, the conductivity field is conditioned to steady state hydraulic head data from July 1999. Second, the field is conditioned to a series of selected transient interference tests.

The prescribed heads on the boundaries are also calibrated using the steady state head data, since the hydraulic head has changed over the period of experimentation. The inverse conditioning is carried out for two different scenarios related to fracture intersection zones (FIZ); (1) Treating the FIZ as a separate zone, (2) Treating the FIZ as belonging to multiple fracture planes. Four simulations for the two scenarios have been performed so far. Each of them is conditioned to the most recent structural model, hydraulic conductivity data, steady state head data and five short term interference tests. The reproduction of the measured hydraulic head is better than in previous calculation results. The correspondence is better for the scenario in which the FIZ are treated separately. The updated conductivities show an important spatial variance inside the fracture planes with important differences in average conductivities between planes representing individual deterministic structures.

Discrete feature network

A basic local DFN model of the TRUE Block site has been constructed based on the so-called March'99 model. This includes a parameterised structural model (primarily based on transmissivity measurements arising from the pre-testing of the key structures) of the basic reconciled geometrical model. A development has been completed to enable the DFN code NAPSAC to include small-scale variability, potentially down to a 5 cm scale, to be included in an efficient way. It has been demonstrated that it is possible to perform detailed scale calculations. Work is progressing on calibration approaches and the integration of data on various length-scales, which will eventually result in prediction of the Phase A tests. During the year DFN based calculations have been relayed from Golder (S) to AEA Technology (UK).

PAWorks Channel Network Model

During the fourth quarter of 1999 and the first quarter of 2000, JNC/Golder are in the process of updating their PAWorks Channel Network model for use in prediction of the "Phase A" tracer tests. The following modifications were made during the fourth quarter of 1999:

- CN Model Features: Borehole KI0025F03 was added to CN Model.
- Virtual Packers: Virtual Packer locations based on Doe (1999) were implemented into the model 8 this to account for planar interpretation of structures based on individual intercepts).
- Background Fracturing: The background fracturing in the model was updated using values determined, see above.
- Boundary Conditions: Boundary conditions were implemented for PT-1 through PT-4 and A-1 through A-3 interference and tracer test simulations.
- Simulations using these updated models will be carried out during the first quarter of 2000.

Miscellaneous

A study has been performed with the purpose of providing a quantitative basis for modelling of background fracturing in the immediate vicinity of Features #13, #20, #21, and #22 (TTS region) which are the focus of the Tracer Test Stage (TTS) of the TRUE Block Scale experiment. Based on this analysis statistics have been derived for conductive background fracturing in the studied rock volume.

The analysis is based on a correlation of Posiva flow log features with fractures identified in borehole (BIPS) logs in boreholes KI0025F02, KI0025F03, KA2563A, and KA2511A. Analyses were carried out on data (a) adjusted to remove numbered deterministic structures, and (b) Terzaghi corrected for orientation biases.

As study has been performed with the purpose of testing and comparing various conservative (non-reactive) tracers. Four tests have been performed at the TRUE-1 site in Feature B. The first test was focused on a number of metal complexes earlier used in Stripa and also at Äspö, The second test focused on the feasibility of using dissolved Helium gas (performed in co-operation with ANDRA and Solexperts, Switzerland). The third test also included Helium, a number of fluorescent dyes and Deuterium. The final test focused on five different fluoro-benzoates.

The results of the first test with metal complexes, show that most of the complexes behave similar to the reference conservative tracer Uranine. However, two of the injected tracers, Phloxine B and Ni-EDTA, show significant losses (>50). A preliminary assessment of the feasibility test of Helium indicates that it is possible to use as a tracer in the Äspö environment.

Work with development of enrichment techniques for fluorescent dye tracers has resulted in a method applying solvent extraction. From a slightly acidified (0.003M HCl) water phase, fluorescein (uranine) and some substituted fluoresceins have been found to extract quantatively into a hexanol organic phase. A water phase volume of 100 ml, an organic phase volume of 5 ml and a tracer concentration of 1μM were used. Measurements were performed using absorbance spectrophotometry and it was found that the absorbance was increased 16–50 times.

Planned work

- Performance of Phase B and Phase C of planned tracer tests.
- Prediction of Phase C tracer tests.
- Evaluation of results.
- Reporting.

3.3.3 Long-Term Diffusion Experiment

Background

The Long-Term Diffusion Experiment is intended as a compliment to the in-situ dynamic experiments and the laboratory experiments performed within the TRUE Programme.

The objectives of the planned experiment are /Byegård et al, 1999/:

- to investigate diffusion into matrix rock from a natural fracture in situ under natural rock stress conditions and hydraulic pressure and groundwater chemical conditions,
- to obtain data on sorption properties and processes of some radionuclides on natural fracture surfaces,
- to compare laboratory derived diffusion constants and sorption coefficients for the investigated rock fracture system with the sorption behaviour observed in situ at natural conditions, and to evaluate if laboratory scale sorption results are representative also for larger scales.

The updated test plan presents an experimental concept centred on establishment of an experimental (large diameter) borehole which exposes a fracture surface. This fracture surface is packed off with a cap, similar to the one used in the REX experiment, cf. Figure 3-7. The intention is to establish an experimental chamber in which a tracer solution is circulated over a period of four years. Performed scoping calculations using available diffusivity data indicates that axial diffusion will range from mm:s for the strongly sorbing tracers to dm:s for the weakly sorbing tracers considered. Apart from tracers used in the TRUE-1 experiment, also PA-relevant tracers (^{99}Tc, ^{237}Np and ^{241}Am) are being proposed. The principal feat of the experiment is to establish axial diffusion from a natural fracture, through the rim zone of fracture minerals and alteration, into the unaltered rock matrix, without any advective component (towards the tunnel). This is resolved using a multi-packer system which effectively shields off the gradient. In addition, an intricate pressure regulation system is devised which will effectively allow the pressure in the experiment chamber to adapt to the ambient conditions without causing pressure differences, and hence no advetive transport. The reference pressure is obtained from a packed-off pilot borehole in the immediate vicinity of the large diameter experimental borehole. The former borehole has also been used to identify the target fracture to be investigated.

The characterisation of the large diameter borehole includes ia. measurements with various electrical geophysical logs (resistivity). The idea being to enable coupling between the electrical resistivity and diffusivity. In addition the core will be analysed using mineralogical, petrophysical and geochemical methods.

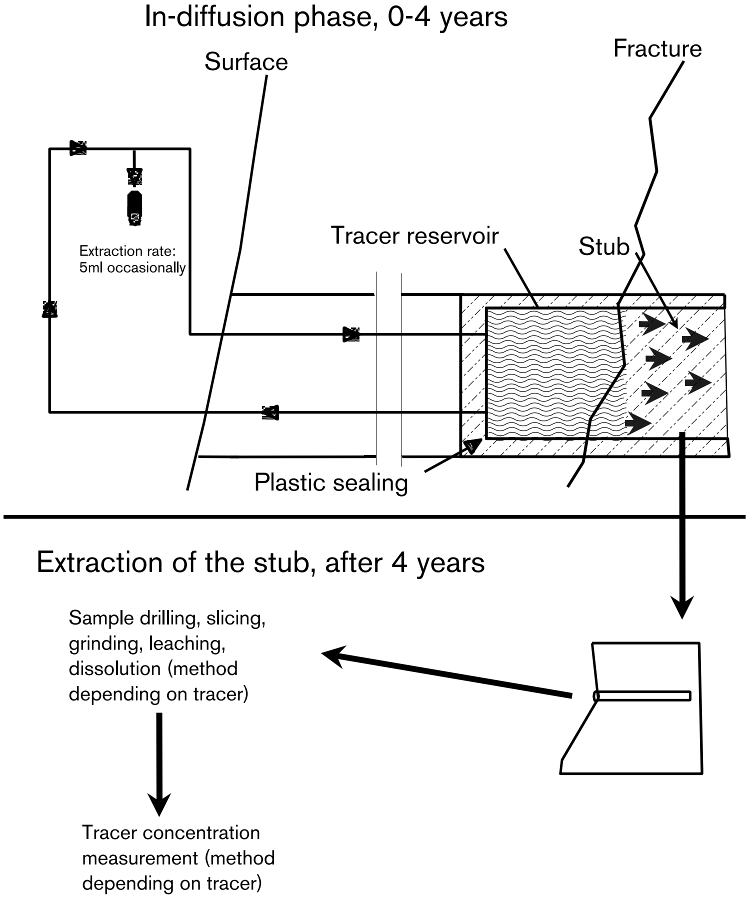


Figure 3-7. *Schematic of LTDE experimental concept including injection borehole in contact with a fracture surface, combined with excavation and penetration profile studies.*

Results

Site characterisation

During the period a formal decision has been taken by SKB to run LTDE as laid out in the developed test plan for the project.

A suitable target fracture was identified in borehole KA3065A02 at a borehole length of 9.81 m. This structure constitutes a chlorite splay (141/81) to a main fault, the latter on which slicken lines on the surface are evident. It shows mylonitic character in diorite/greenstone with an increasing alteration towards the fault centre. The total inflow at this zone is about 16 l/min. The target structure constitutes the delimiting structure of the zone and is followed by a long > 0.5 m long intact portion of Äspö diorite.

The plan is to target the target feature some 0.3 away from the intercept in the existing pilot borehole (KA3065A02). Prior to conduction the actual drilling of the LTDE experimental hole, a trial drilling with the selected 196.5 mm core barrel selected for the final part of the borehole check that the surfaces will be smooth enough to enable satisfactory sealing. In addition the ability to drill short uptakes and break the core at selected depth will be tested.

The drilling of the telescoped experimental borehole will be done with a strong element of interactive site characterisation (borehole imaging) and structural modelling using the RVS system. After each uptake, borehole TV imaging will be performed and compared with the corresponding image from the pilot borehole some 0.3 m away, and the structural and geological extrapolations made on the basis of the developed model. The structural and geological model will be updated successively and the projected depth to the target structure will be adjusted accordingly. The drilling of the LTDE borehole constitute a first attempt at Äspö to interactively and on-site steer the drilling using site characterisation and structural and geological modelling.

Equipment

The construction of downhole borehole and sampling and monitoring equipment is under way. A schematic layout of the equipment ius shown i Figure 3-8.

Samples of the proposed material used for the downhole equipment (PEEK and polyurethane) have been sent to CTH-Nuclear Chemistry in Gothenburg in order to test sorption characteristics and possible influence on the experiment. As a result CTH have confirmed usage of the tested materials for the sealing. A mock-up borehole has been manufactured of a steel tube trying to imitate the inner part of the borehole involving the core stub. A first prototype of the sealing rubber (shore 60–90 deg) has been manufactured and tested. The rubber withstands a differential pressure of about 0.5 MPa. A new sealing rubber (shore 45–70 deg) is going to be delivered week early 2000. The new rubber is expected to withstand about 0.8 MPa in the mock-up borehole. The final construction, manufacturing and testing are going to be done when the actual geometry of the stub in the LTDE borehole is known.

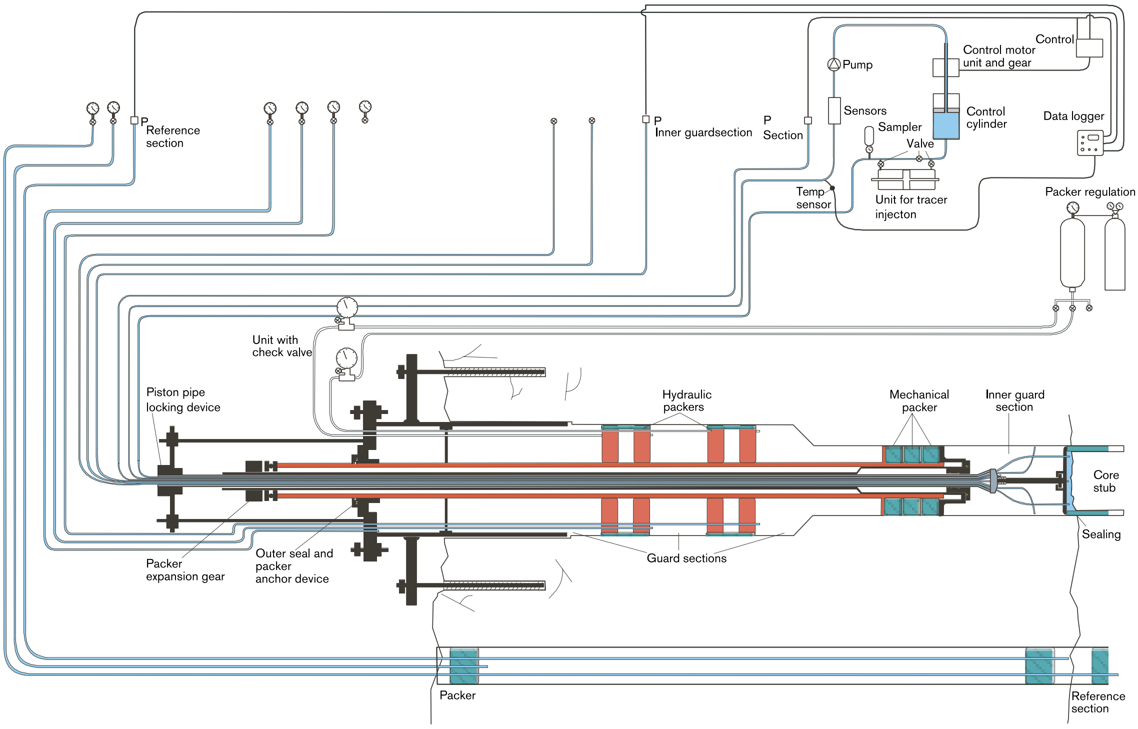


Figure 3-8. *Schematic layout of regulation and sampling equipment and downhole equipment.*

3.4 The REX-experiment

3.4.1 Background

A block scale redox experiment was carried out in a fracture zone at 70 m depth in the entrance tunnel to Äspö /Banwart, 1995/. In spite of massive surface water input, the fracture zone remained persistently anoxic. The main conclusion from that study was that the increased inflow of relatively organic-rich shallow groundwater instead of adding dissolved oxygen, it added organic compounds that acted as reductants in the deeper parts of the fracture zone. These conclusions are specific to this particular fracture zone, experimental conditions and the time scale (3 years) of the experiment, but are probably also relevant for other conductive fracture zones.

The detailed scale redox experiment (REX) was planned to focus on the question of oxygen that is trapped in the tunnels when the repository is closed. Questions regarding the role of oxygen in this context are:

- Will oxygen penetrate into the rock matrix during construction and operation?
- If yes, how much of the rock will be oxidised and how long time will it take before oxygen is consumed?
- What happens to the oxygen in the backfill/buffer: how much is consumed by the rock, and how much by the buffer?

The REX project focuses on the first two of these questions, especially the second one. The third question is not included in the experiment.

The objectives of the experiment are:

- How does oxygen trapped in the closed repository react with the rock minerals in the tunnel and deposition holes and in the water conducting fractures?
- What is the capacity of the rock matrix to consume oxygen?
- How long time will it take for the oxygen to be consumed and how far into the rock matrix and water conducting fractures will the oxygen penetrate?

3.4.2 Experimental concept

The emphasis of the project was on a field experiment involving confined groundwater in contact with a fracture surface. To this aim a ≈200 mm borehole was drilled in the Äspö tunnel at 2,861 m. Field data (hydrochemical and bacteriological) were obtained to establish the boundary conditions for the experiments.

The field study was supported by laboratory experiments to determine oxygen reaction rates and mechanisms with Äspö samples (both for inorganic and microbially mediated processes). A replica experiment was performed at CEA, France, with the other half of the fracture surface obtained in the drilling procedure.

3.4.3 Results

Four laboratory groups participated in the REX-experiment: Dept. of Civil & Environmental Engineering of the University of Bradford (UK); the Fluid Processes Group of the British Geological Survey (UK, financed by PNC, Japan); Centre d'Etudes Nucléaires Cadarache (France, financed by ANDRA); and Dept. of General and Marine Microbiology of the Göteborg University. Additionally several consultants in Sweden participated in the project.

Rock and fracture filling mineral samples collected from the Äspö tunnel wall were used within the research program at Bradford. Fracture-filling minerals were also collected from the NW-3 fracture zone using the "triple tube" technique in a 3 m long borehole (KA3066A). The core from this borehole was characterised and the sieved fractions were also used in the laboratory testing at the University of Bradford. Oxygen consumption rates were determined for these samples.

Measurements of dissolved gases (CH_4, H_2, etc) in Äspö groundwaters have been performed. These data were combined with measurements of bacteriological oxygen consumption in Äspö groundwater. These results showed that O_2 may be consumed by methanotrophic bacteria in a closed nuclear waste repository. The results on bacteriological oxygen consumption experiments performed at the Äspö tunnel have been reported /Kotelnikova et al, 1999/.

The British Geological Survey studied the microbial effects on rock-groundwater interactions using samples from Äspö. The result from the laboratory investigations have been reported /West et al, 1998/. Bacteria were found to accelerate weathering processes, and clays were formed in the laboratory reactors only when microbes were added to the system /Bateman et al, 1998/.

The REX field experiment was being conducted in a single fracture at 8.81 m from the tunnel wall (borehole KA2861A, $\Phi \approx 200$ mm). The drillcore was sent to CEA (Cadarache, France) where a replica of the field experiment has been performed /Lartigue et al, 1997/.

The aim of the field study was to isolate the innermost part of the borehole and to monitor the consumption of O_2 as a function of time. The set-up for the REX field experiment is illustrated in Figure 3-9 /Puigdomenech et al, in print/.

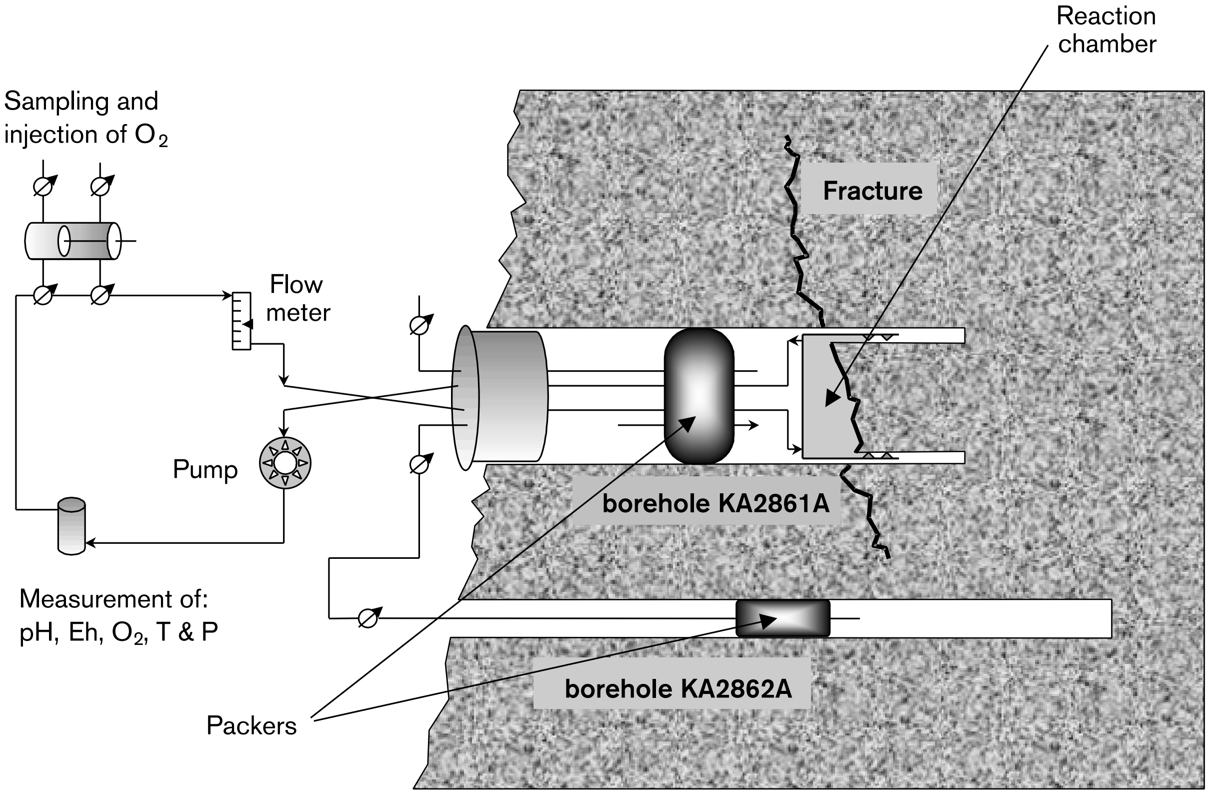


Figure 3-9. *Schematic illustration of the REX field experiment.*

A series of O_2 injection pulses were performed in the REX field and replica experiments. The results showed that concentrations of O_2 in the range 1 to 8 mg/L were consumed in the experiments within a few days, 5 to 10 days, both for the field and replica experiments. Data for O_2-pulses are shown in Figure 3-10 for the field experiment and in Figure 3-11 for the replica experiment.

The final report for the REX project is being drafted, and publications in the open literature are planned.

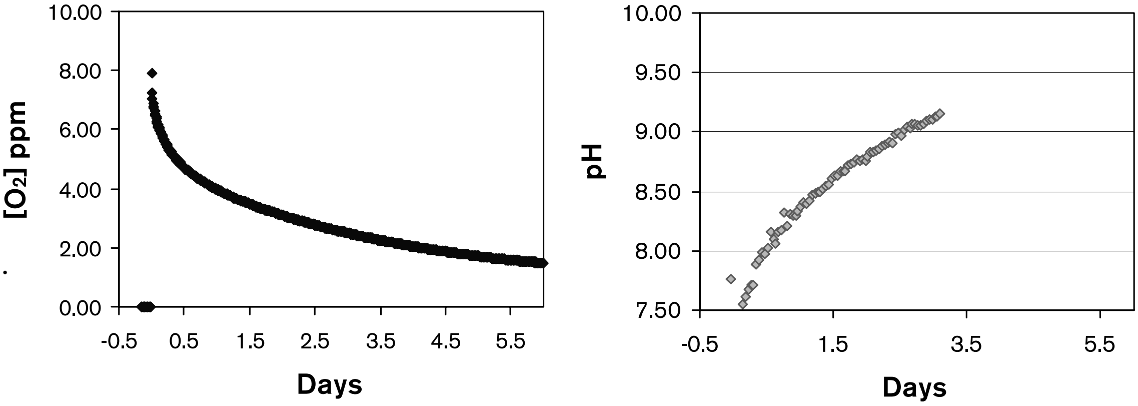


Figure 3-10. *Results from one of the O_2-pulses in the REX field experiment.*

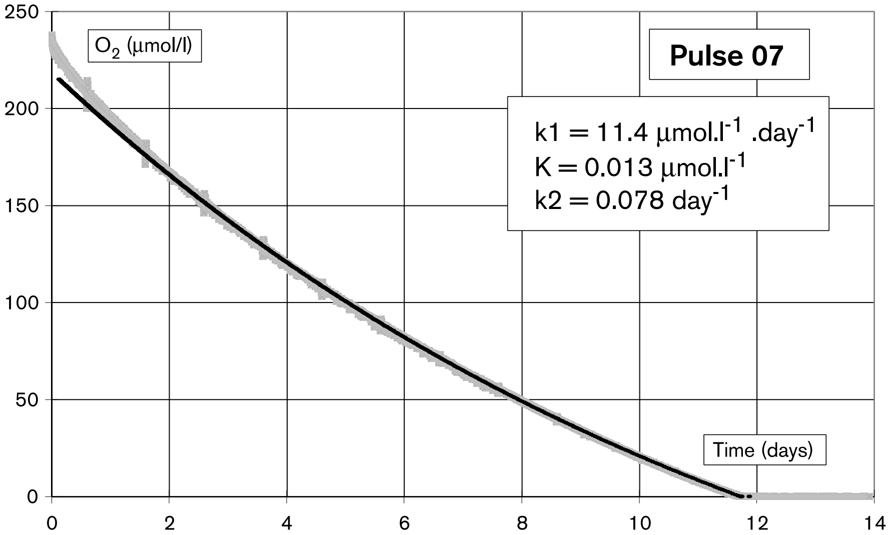


Figure 3-11. *Dissolved O_2 evolution during a pulse in the replica experiment.*

3.5 Radionuclide retention (include CHEMLAB)

3.5.1 Background

The retention of radionuclides in the rock is the most effective protection mechanism if the engineering barriers have failed and the radionuclides have been released from the waste form. The retention is mainly due to the chemical properties of the radionuclides, the chemical composition of the groundwater, and to some extent also by the conditions of the water conducting fractures and the groundwater flow.

Laboratory studies on solubility and migration of the long lived nuclides e.g. Tc, Np, and Pu indicate that these elements are so strongly sorbed on the fracture surfaces and into the rock matrix that they will not be transported to the biosphere until they have decayed. This very strong retention could well be an irreversible sorption process. In such a case the migration of the nuclides, released from a waste containment, will stop as soon as the source term is ending.

Laboratory studies have been undertaken with this kind of nuclides even though natural conditions are extremely difficult mimic. Even though the experiences from different scientists are uniform it is of great value to demonstrate the results of the laboratory studies in situ, where the natural contents of colloids, organic matter, bacteria, etc. are present in the experiments. Laboratory investigations have difficulties to simulate these conditions and are therefore dubious as validation exercises. The CHEMLAB borehole probe has been constructed and manufactured for validation experiments in situ at undisturbed natural conditions. Figure 3-12 illustrates the principles of the CHEMLAB 1 and CHEMLAB 2 units.

3.5.2 Objectives

The objectives of the Radionuclide Retention (CHEMLAB) experiments are:

- to validate the radionuclide retention data which have been measured in laboratories by data from in situ experiments in the rock,
- to demonstrate that the laboratory data are reliable and correct also at the conditions prevailing in the rock,
- to decrease the uncertainty in the retention properties of relevant radionuclides.

3.5.3 Experimental concept

CHEMLAB is a borehole laboratory built in a probe, in which migration experiments can be carried out under ambient conditions regarding pressure and temperature and with the use of the formation groundwater from the surrounding rock.

Initially one “all purpose” unit was constructed in order to meet any possible experimental requirement. This unit CHEMLAB 1 has been used for the “diffusion in bentonite” experiments and will now be used for similar experiments including the effects of radiolysis. Others to follow are:

- migration from buffer to rock,
- desorption of radionuclides from the rock,
- batch sorption experiments.

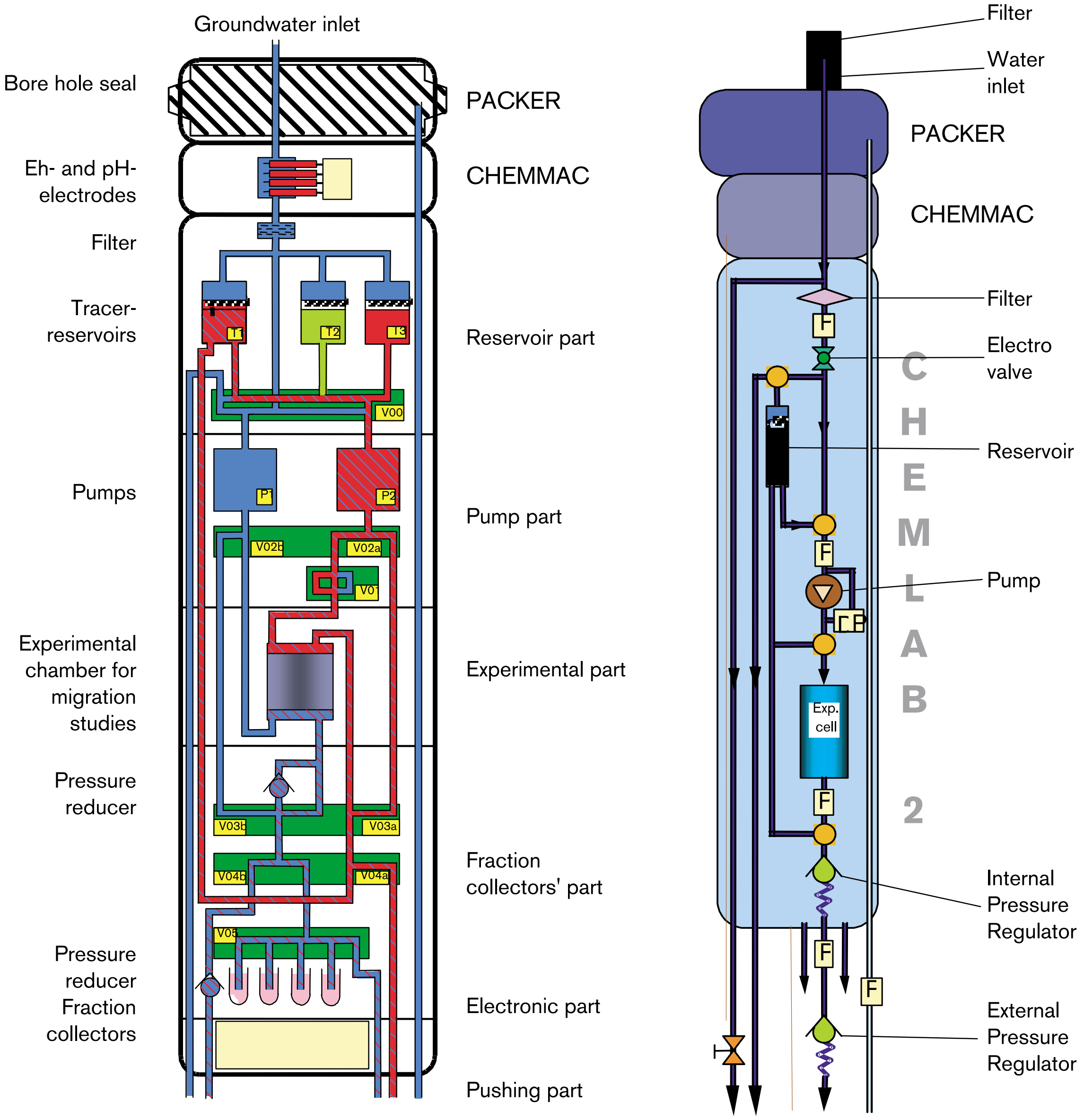


Figure 3-12. *Schematic illustration of CHEMLAB 1 and 2.*

The CHEMLAB 2 unit is a simplified version of CHEMLAB 1, designed to meet the requirements by experiments where highly sorbing nuclides are involved. These are:

- migration of redox sensitive radionuclides and actinides,
- radionuclide solubility,
- spent fuel leaching.

3.5.4 Results

During spring and summer 1997 the first radionuclide in-situ experiments with CHEMLAB were performed at Äspö Hard Rock Laboratory. These included cation diffusion in compacted bentonite with the tracers Co-57, Sr-85 and Cs-134. The experiments were carried out, partly to gain experience in the novel experimental technique, but mainly to validate diffusion and sorption data obtained in laboratory experiments.

The selected nuclides are expected to exist predominantly as non-hydrolysed cations that are not influenced by pH or Eh. Cs^+ and Sr^{2+} have been extensively studied in laboratory and the diffusive and sorptive properties are reasonably well known /Eriksen and Jansson, 1996; Yu and Neretnieks, 1997; Ooch, 1997; Muurinen, 1994/. Of critical importance for their sorption and diffusion in bentonite is the concentration of major ions (Na^+, K^+, Mg^{2+}, Ca^{2+}) and for Sr^{2+} also the pH.

The sorptive and diffusive properties of Co^{2+} are less well known, but Co^{2+} is primarily sorbed by surface complexation on the montmorillonite and pH is of critical importance in the pH-range 7 to 10 /Eriksen and Molera, 1997/.

Two experiments were performed. In the first one Co-57 was used and in the second one Sr-85 and Cs-134 were used. The radionuclides were added in their ionic form (Co^{2+}, Sr^{2+} and Cs^+) to a reservoir in CHEMLAB in a 5 ml solution of degassed, filtrated Äspö ground water. The first step in the experiments was to dilute this stock solution to 100 ml with ground water direcly from the rock. In the Co^{2+} experiment the 5 mm thick bentonite clay was then saturated with ground water from both ends of the cell for 14 days. The tagged Co^{2+} solution was then circulated at the front end of the cell, while the back end was flushed to the fraction collectors of CHEMLAB in intervals to remove and collect all radionuclides that had diffused through the cell.

In the Sr^{2+}, Cs^+ experiment a 10 mm long cell was used. After diluting the radionuclide solution, the bentonite clay was saturated with ground water from one side of the cell. The radioactive solution was recirculated at the front end of the cell, while the back end was blocked, allowing the radionuclides to diffuse into, but not through, the cell.

To obtain the concentration profiles in the bentonite, the cell was dismantled at the end of the experiments and the bentonite cut into thin sections. Each section was weighted and the activity measured by γ-counting using a germanium detector and multichannel analyzer. The concentration profiles in the bentonite were simulated using a finite difference based computer code ANADIFF /Eriksen and Jansson, 1996/.

The measured and calculated concentration profiles for Cs^+, Sr^{2+} and Co^{2+} are plotted, see Figures 3-13 to 3-15. It should be pointed out that the measured Co^{2+} profile is expected to be somewhat low at the inlet/bentonite interphase due to a pump failure after 8 days diffusion.

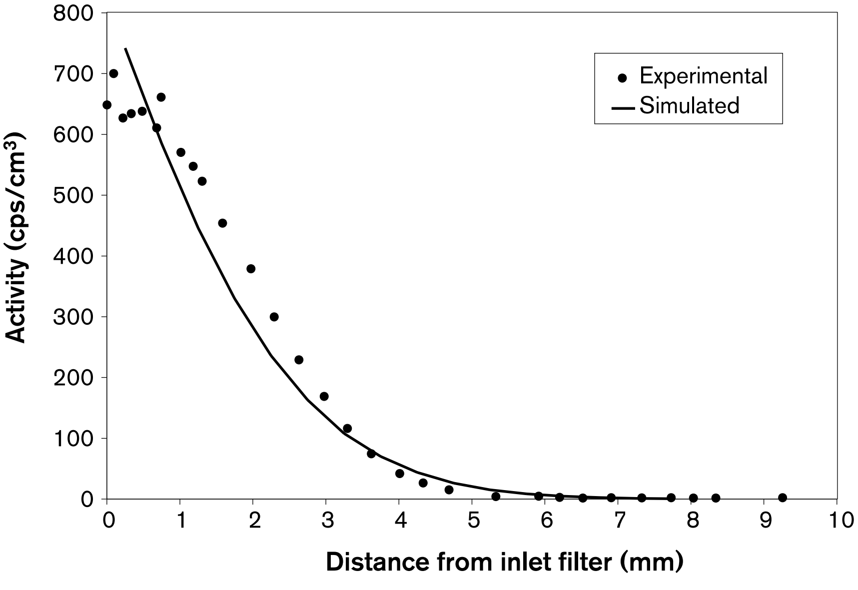


Figure 3-13. *Measured and simulated activity profiles for* Cs^+ *in bentonite. Diffusion time 15 days,* $D_a = 2 \cdot 10^{-8}\ cm^2\ s^{-1}$, $K_d = 60\ g\ cm^{-3}$.

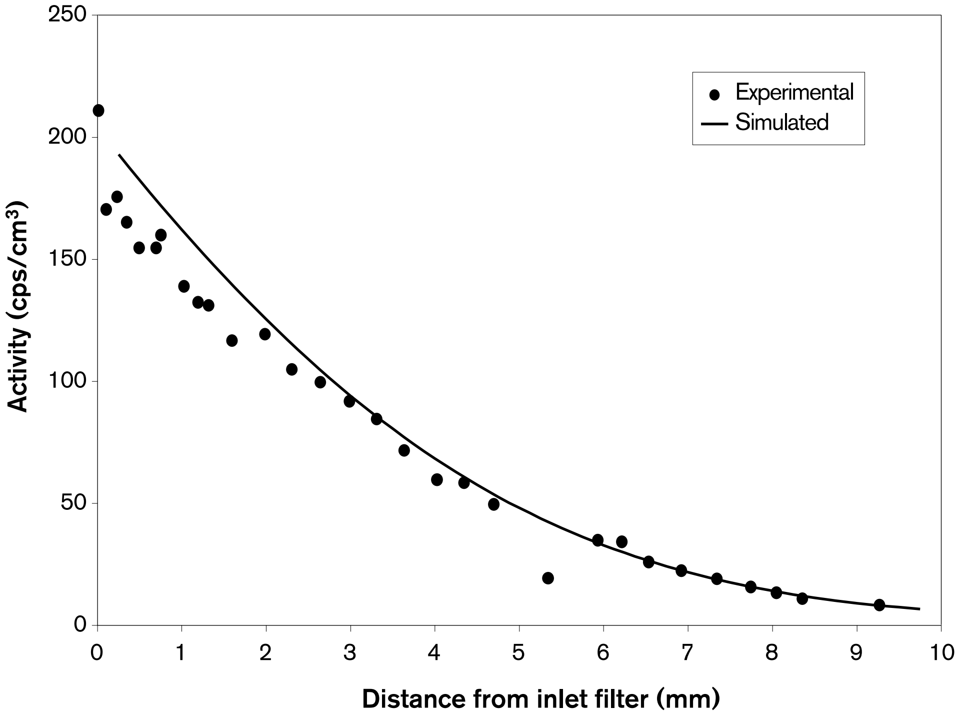


Figure 3-14. *Measured and simulated activity profiles for Sr^{2+} in bentonite. Diffusion time 15 days, $D_a = 7 \cdot 10^{-8}$ cm² s⁻¹, $K_d = 13$ g cm⁻³.*

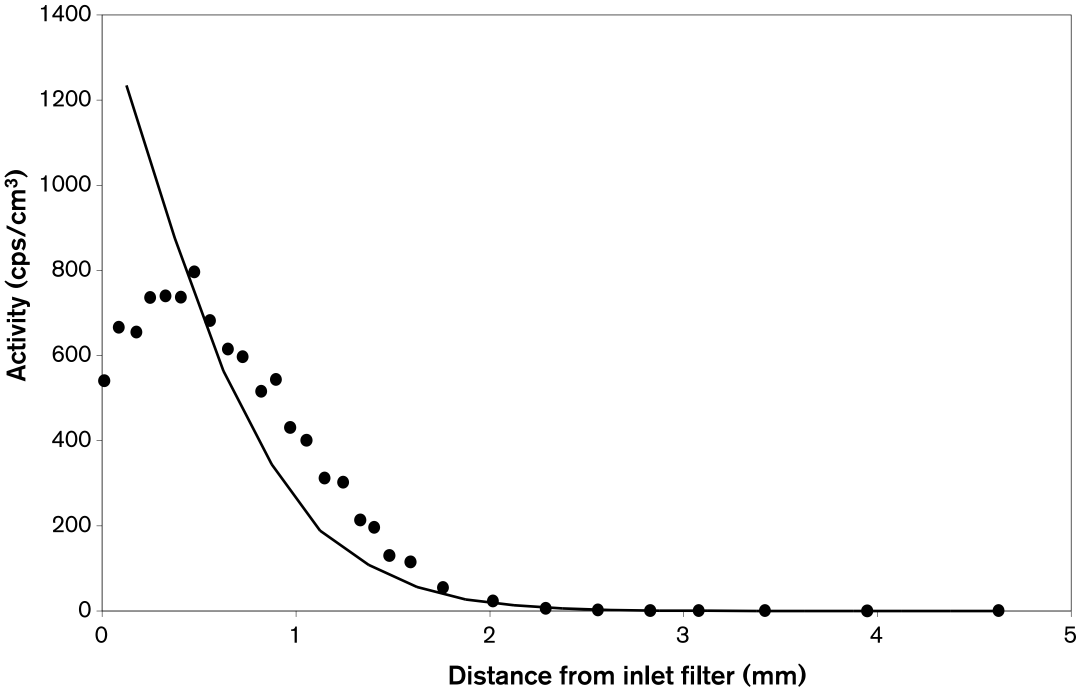


Figure 3-15. *Measured and simulated activity profiles for Co^{2+} in bentonite. Diffusion time 15 days, $D_a = 4 \cdot 10^{-9}$ cm² s⁻¹, $K_d = 250$ g cm⁻³.*

The K_d and D_a values used in the computer simulations are given in Table 3-2. For comparison expected K_d values for Cs^+, Sr^{2+} obtained by regression analysis of sorption data from experiments with solutions and groundwaters with different salinity /Eriksen and Jansson, 1996/ as well as apparent diffusivities are also given in Table 3-2. The corresponding Co^{2+} values obtained in our laboratory are also given in the table.

The results of the downhole experiments with Sr^{2+} and Cs^+ are in good agreement with results from laboratory experiments with sodium bentonite compacted to 1.8 g cm^{-3} dry density and equilibrated with synthetic groundwater and electrolyte solutions of the same salinity as Äspö groundwater. It ought to be pointed out that the Sr^{2+} concentration in the Äspö groundwater is fairly high ($\sim 2 \cdot 10^{-4}$ mole/l) so the $^{85}Sr^{2+}$ sorption observed is really isotope exchange between sorbed Sr^{2+} and Sr^{2+} in the porewater in an equilibrated system.

The discrepancy between the K_d values for Co^{2+} obtained in laboratory diffusion experiments with a synthetic Äspö groundwater is most probably caused by a slightly higher pH in the synthetic groundwater (pH ~7.5) used in the laboratory experiments than in the groundwater at the experimental site at Äspö (pH 7.2). Co^{2+} displays a sorption edge at pH ~6.5 with K_d increasing by two orders of magnitude between pH 6.5 and 8.5. Corresponding sorption edges on Na-montmorillonite for Ni, Zn and Ca have been modelled assuming the formation of surface complexes /Bradbury and Baeyens, 1997/.

A final diffusion experiment using iodine and technetium has been carried out but yet not evaluated.

A new site for the CHEMLAB experiments was selected and prepared during 1999. All future experiment will be conducted in the J nisch at 450 m depth.

The planning of an experiment with radiolyses was started in 1999. It will be started during 2000. The experimental setup is similar to the previous diffusion experiment.

The first experiment to be carried out in CHEMLAB-2 is the migration of actinides, Americium, Neptunium and Plutonium, in a rock fracture. Planning and pre-testing is done by Institut für Nuklear Endsorchung in Karlsruhe. INE is also carrying out the experiment at Äspö in cooperation with SKB staff and Nuclear Chemistry at KTH.

Table 3-2. K_d values and apparent diffusion coefficients from CHEMLAB and laboratory experiments

Cation	CHEMLAB experiments		Laboratory experiments	
	log K_d [cm^3 g^{-1}]	D_a [cm^2 s^{-1}]	log K_d [cm^3 g^{-1}]	D_a [cm^2 s^{-1}]
Cs^+	1.8	$2 \cdot 10^{-8}$	2 ± 0.35	$(2 \pm 1) \cdot 10^{-8}$
Sr^{2+}	1.1	$7 \cdot 10^{-8}$	1.56 ± 0.32	$(9 \pm 1) \cdot 10^{-8}$
Co^{2+}	2.4	$4 \cdot 10^{-9}$	3.3 ± 0.3	$(2 \pm 1) \cdot 10^{-9}$

3.6 Degassing and two-phase flow

3.6.1 Introduction

Two-phase flow conditions, i.e. a mixed flow of gas and water, may develop in the vicinity of a repository situated in a regionally saturated rock mass. The main sources of two-phase flow conditions are 1) gas generation in the repository due to corrosion or biological processes, 2) exsolution of gas (bubble generation) due to pressure decrease, and 3) entry of gas (air) into the rock mass from ventilated tunnels. The presence of a gas phase in the repository before and after closure must be understood in relation to its effect on repository performance. Waste-generated gas may affect repository integrity and hazardous material may be transported in the gas phase.

Understanding evolution and characteristics of two-phase flow conditions near drifts is essential for interpreting observations of hydraulic conditions in drifts, interpretation of experiments performed close to drifts, and performance of buffer mass and backfill, particularly during emplacement and repository closure.

The objectives for the project on degassing and two-phase flow are:

- to show if degassing of groundwater at low pressures has significant effects on measurements of hydraulic properties in boreholes and drifts,
- to study and quantify other processes causing two-phase flow near excavations such as air invasion due to buoyancy and evaporation,
- to show under what conditions two-phase flow will occur and be significant. Conditions expected to be of importance are gas content, chemical composition of groundwater, fracture characteristics (aperture distribution and transmissivities), and flow conditions,
- to get an idea of the time scales required for resaturation of a repository,
- to develop technology for measurement of saturation.

During 1999, we considered all available degassing-related experimental investigations, and tested various hypotheses underlying a theoretical degassing model for a wide range of boundary conditions, interpreting previous degassing observations in boreholes (see Section 3.6.2 below) and drifts (Section 3.6.3). In parallel with the interpretation of the experimental investigations, a final summarising degassing report was prepared, synthesising results from both experimental and theoretical degassing studies. We also investigated the applicability of the developed unsaturated flow/ degassing relations, considering conditions relevant for gas injection tests, see further Section 3.6.5.

3.6.2 Interpretation of borehole experiments

Table 3-3 shows the parameter values used in the modelling of the degassing experiments in boreholes (see further Section 3.2 of Jarsjö and Destouni, 1998, for a description of the degassing model). The values of the fracture boundary pressure p_{bound}, the borehole pressure during the degassing test p_{bh}, the bubble pressure p_b and the borehole radius r_w correspond to experimental conditions reported in Geller and Jarsjö (1995) and Jarsjö and Destouni (1997a). We have assumed radial flow conditions and a radius of influence R of 150 metres in all cases. We also assumed a standard deviation value of ln a ($s_{\ln a}$, where a denotes the fracture aperture) of 0.8 in all cases. This is within the range of standard deviation values for rock fracture apertures previously reported by Hakami (1995). Furthermore, we estimated the mean value of ln a ($m_{\ln a}$) on basis of measured fracture transmissivity values, through the cubic law.

Table 3-3. Parameter values used in the modelling of the degassing experiments in boreholes (Figure 3-16)

Experiment	r_w (mm)	R (m)	$\mu_{\ln a}$	$\sigma_{\ln a}$	p_{bound} (kPa)	p_b (kPa)	p_{bh} (kPa)
SWT/P2[a]	28	150	-3.8	0.8	2000	160	36
SWT/P4[b]	28	150	-4.0	0.8	1000	121	115
DT/P4-P8[c]	28	150	-4.0	0.8	1000	957	107
PHT[d]	42.5	150	-2.2	0.8	3000	167	120

[a] Single-well test in borehole P2 (Jarsjö and Destouni, 1997a).
[b] Single-well test in borehole P4 (Jarsjö and Destouni, 1997a).
[c] Dipole test – boreholes P4 and P8 (Jarsjö and Destouni, 1997a).
[d] Pilot hole test in borehole KA2512A (Geller and Jarsjö, 1995).

Figure 3-16 shows that the modelled relative transmissivity values T_{rel} (i.e., the transmissivity under degassing conditions divided by the saturated transmissivity) agree well with the experimental observations in the different boreholes. However, some of the parameters used in the modelling of the relative transmissivity (Table 3-3) were based on rather rough and non site-specific estimates, such as the R-value and the $\sigma_{\ln a}$-value. With the aim to investigate whether or not the model results shown in Figure 3-16 are sensitive to the assumed values of these parameters, and whether or not more general conclusions can be drawn regarding degassing effects in the vicinity of boreholes, we will in the following show more generally how the modelled relative transmissivity is affected by different plausible parameter values (given in Table 3-4). We then consider a range of parameter values that are relevant for rock fractures intersecting boreholes at depths between 20 and 600 metres (Table 3-4). We have furthermore used the borehole pressure during the degassing test p_{bh} as a reference point at 0 kPa and assumed a value of 0.2 for the model parameter a. It was previously shown that the model results are relatively insensitive to α, at least for values between 0.05 and 0.4. The results are furthermore not affected by the absolute values of the parameters r_w and R, but depend only on the ratio r_w/R.

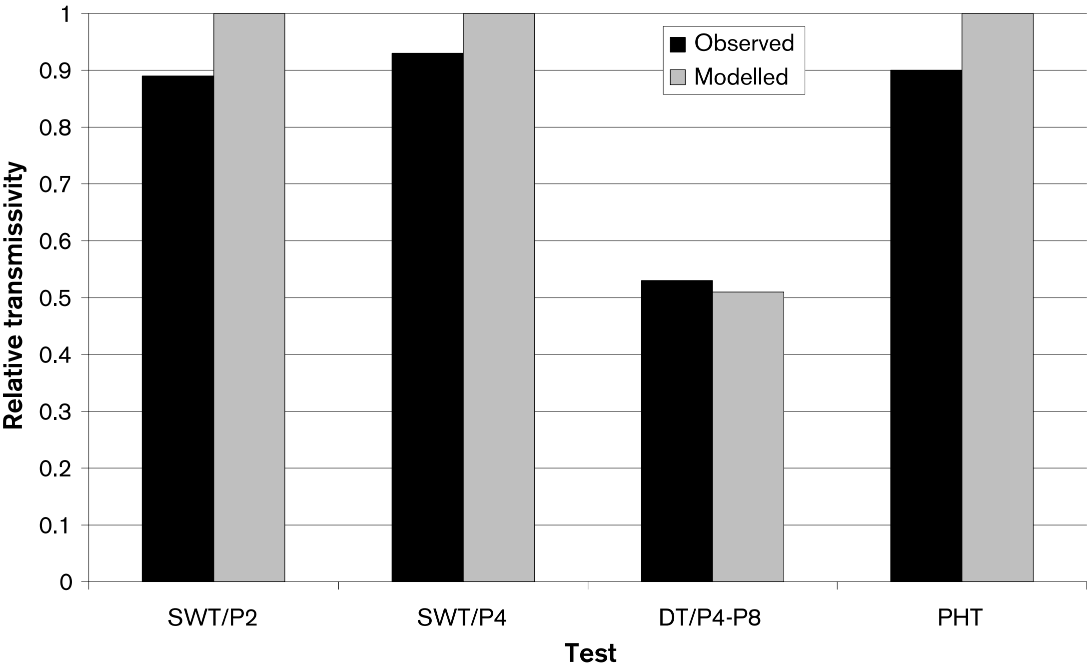


Figure 3-16. Observed (black bars) and modelled (grey bars) relative transmissivities for the degassing experiments in boreholes.

Table 3-4. Parameters for the modelled cases in Figure 3-16 Numbers in bold indicate differences from Case 1

Case	r_w/R	R (m) for r_w=0.03m	μ_{lna}	σ_{lna}	p_{bound} (kPa)	p_b (kPa)
1	$2 \cdot 10^{-4}$	150	–4	0.8	2000	0 to 2000
2	$2 \cdot 10^{-4}$	150	**–1**	0.8	2000	0 to 2000
3	$2 \cdot 10^{-4}$	150	–4	**0.2**	2000	0 to 2000
4	$2 \cdot 10^{-4}$	150	**–1**	**0.2**	2000	0 to 2000
5	**$2 \cdot 10^{-3}$**	**15**	–4	0.8	2000	0 to 2000
6	**$2 \cdot 10^{-5}$**	**1500**	–4	0.8	2000	0 to 2000
7	$2 \cdot 10^{-4}$	150	–4	0.8	**200**	**0 to 200**
8	$2 \cdot 10^{-4}$	150	–4	0.8	**6000**	**0 to 6000**

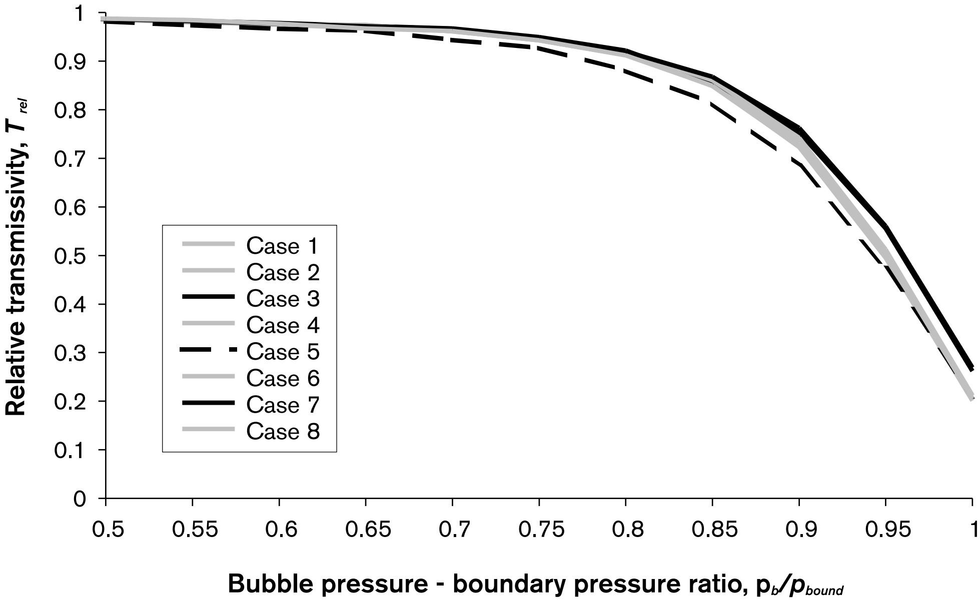


Figure 3-17. *Relative transmissivity as a function of the bubble pressure – boundary pressure ratio, for the different hypothetical fractures and boundary conditions listed in Table 3-4.*

Figure 3-17 shows the modelled relative transmissivity for the eight hypothetical cases listed in Table 3-4, as a function of the bubble pressure (normalised by the boundary pressure). The figure shows that the relative transmissivity curves are very similar for the different cases 1 to 8, which indicates that the model results are insensitive to the r_w/R, $\mu_{\ln a}$, $\sigma_{\ln a}$ and p_{bound} values within the considered ranges. This also implies that the model predictions of the borehole tests (Figure 3-16) are robust for these parameter ranges.

As Figure 3-17 furthermore shows, the p_b/p_{bound} ratio (on the x-axis) considerably influences the relative transmissivity, but only if the ratio is relatively large (more than about 0.8). For values below 0.8, T_{rel} is close to unity and flow reductions due to groundwater degassing are negligible. Under natural conditions at the Äspö HRL, the gas contents at atmospheric pressure are relatively low, around 3% (sometimes even considerably lower). The gas consists mainly of nitrogen, implying bubble pressure values of about 260 kPa for a gas content of 3%. At 200 metres depth, the borehole pressure at no flow (or boundary pressure p_{bound}) is approximately equal to the hydrostatic water pressure of 2000 kPa. The above-mentioned p_b/p_{bound} ratio is hence around 0.13, which is far below the value of 0.8. Hence, based on both the borehole test observations and the consistent model predictions, we conclude more generally that groundwater degassing will not cause considerable inflow reductions in fractures intersecting open boreholes, under natural conditions.

3.6.3 Interpretation of drift observations

The relatively large inflow reductions observed during the Stripa simulated drift experiment /SDE; see Olsson, 1992/ were possibly a result of groundwater degassing, although there were also other possible causes for the observed flow reductions. The gas content in the water was about 3% and the hydrostatic water pressure was 2300 kPa, implying a bubble pressure p_b of 260 kPa and a relatively low p_b/p_{bound} ratio (see previous section) of 0.11. Both experimental and model results show that degassing would not cause considerable transmissivity or flow reductions around boreholes for such a low ratio. In this section, we consider the different conditions that may prevail around drifts, and model the outcome of the Stripa SDE.

Drifts and tunnels intersect more fractures per unit length than boreholes. The hydraulic conditions in the vicinity of drifts and tunnels may be quite complex, with considerable variability in the hydraulic properties. Furthermore, as shown in Jarsjö and Destouni (1997b), the water pressures around drifts are typically significantly lower than those around open boreholes at the same radial distances. This implies that for a given bubble pressure, the extent of the low-pressure zone X_{low} (where degassing can occur; defined as the zone where the water pressure is lower than the gas bubble pressure) is considerably larger around drifts than around boreholes. Hence, a developed gas-containing zone is likely to be larger around drifts than around boreholes, which may affect the local conditions within that zone. For instance, a larger gas containing zone extent implies that less flowing volume of water is available per unit volume of gas, such that gas re-dissolution may take longer time as the pressures increase above the bubble pressure again.

Considering the above-mentioned differences between drifts and boreholes, we investigated:

- the effect of increased variability in the transmissive properties, and
- the effect of slow gas re-dissolution

in the modelling of degassing around drifts.

We modelled the Stripa SDE, first assuming that the transmissivity was higher close to the drift wall than further away from the drift wall. We further assumed a fracture boundary pressure p_{bound} of 2300 kPa, a borehole pressure during the degassing test p_{bh} of 110 kPa and a bubble pressure p_b of 260 kPa, which is consistent with the experimental conditions reported in Olsson (1992). For this case, Figure 3-18 shows the modelled water pressures before groundwater degassing (black line) and after (grey line). The x-axis shows the relative distance x/x_{infl} from the drift wall, located at $x/x_{infl}=0$; x_{infl} is the distance to the outer boundary, at which water pressures no longer are influenced by the drawdown in the drift. The grey line indicates that the water pressure gradient is much steeper close to the drift wall after degassing. The reason is that the transmissivities are reduced locally close to the wall, due to the presence of a gas phase, for water pressures that are lower than the bubble pressure (of 260 kPa). Because of this steepness, the zone of reduced transmissivities is small ($x/x_{inf}<0.033$; Figure 3-18) and the effective, relative transmissivity T_{rel} for the whole domain ($0<x/x_{inf}<1$) is close to unity (0.94). The transmissivity reduction is hence negligible in this case. Similar results were obtained also for other assumptions than the above-mentioned regarding the variability of the transmissive properties of the rock mass. For instance, assuming a lower transmissivity close to the drift wall, we obtained a T_{rel}-value of 0.96. The results are in contrast to the Stripa SDE observations of considerable transmissivity reductions.

We now modified the degassing model to account for the possible effect of a relatively slow gas re-dissolution around drifts (see discussion above). We assumed, as we also did in

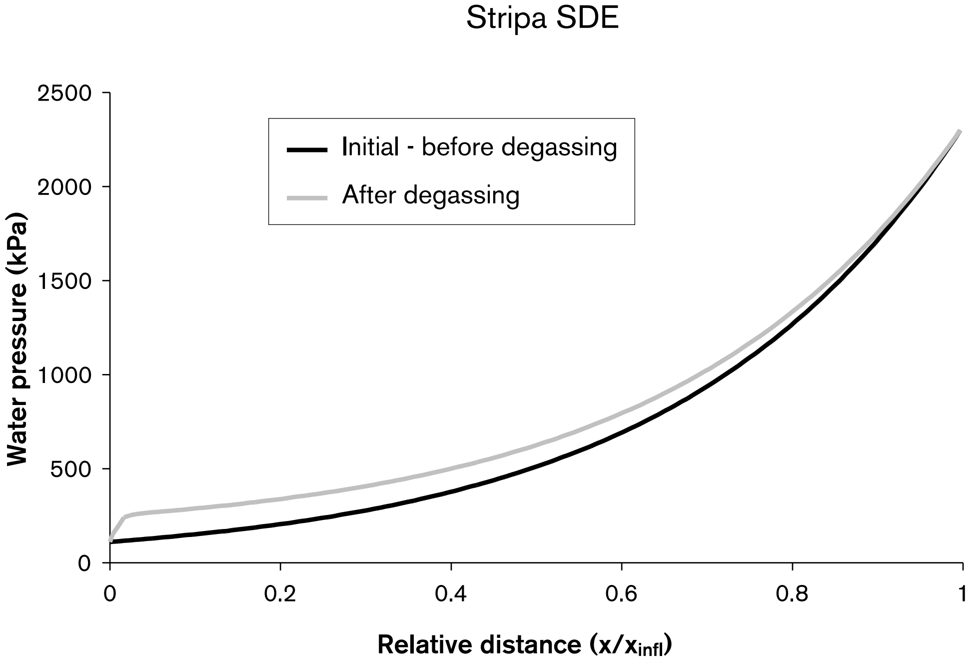


Figure 3-18. *Water pressures before groundwater degassing (black line) and after (grey line) as a function of the relative distance from the drift wall, located at* $x/x_{inf} = 0$*. The modelled relative transmissivity was close to unity (0.94).*

the previous modelling, that gas initially forms where the water pressure is lower than the bubble pressure. For the example shown in Figure 3-19, with a bubble pressure p_b of 260 kPa, gas then forms in the zone where the initial pressure (black line) is lower than p_b, i.e., for $x/x_{inf}<0.28$. As a result of this gas phase formation, the transmissivity is reduced along the distance $x/x_{inf}<0.28$, resulting in increased pressure gradients. Assuming that no gas is re-dissolved due to this local pressure increase, the pressures at degassing conditions is indicated by the grey line in Figure 3-19. The resulting relative transmissivity T_{rel} is then 0.44, indicating considerably reduced flowrates.

The modelled conditions are exactly the same in Figure 3-18 as in Figure 3-19, except that in Figure 3-18, the gas is assumed to re-dissolve as soon as the local pressure increases above the bubble pressure, resulting in a considerably smaller zone of reduced transmissivities. Whereas the model assumption used in Figure 3-18 resulted in consistent results between degassing model predictions and borehole and laboratory observations, the model does not reproduce the observations of the Stripa simulated drift experiment, unless relatively slow gas re-dissolution is assumed; Figure 3-19 shows the limiting case that the gas is not re-dissolved at all.

3.6.4 Concluding remarks

In summary, consistent results between laboratory observations and borehole test observations on the one hand, and model predictions on the other hand, were obtained using the model assumption that the gas re-dissolves as the water pressure increases above the bubble pressure. Based on both observations and model predictions, we conclude more generally that groundwater degassing will not cause considerable inflow reductions in fractures intersecting open boreholes, under natural conditions. The only plausible degassing-based explanation for the observed inflow reductions during the Stripa simulated drift experiment is that the gas re-dissolution was relatively slow, once the gas phase had formed.

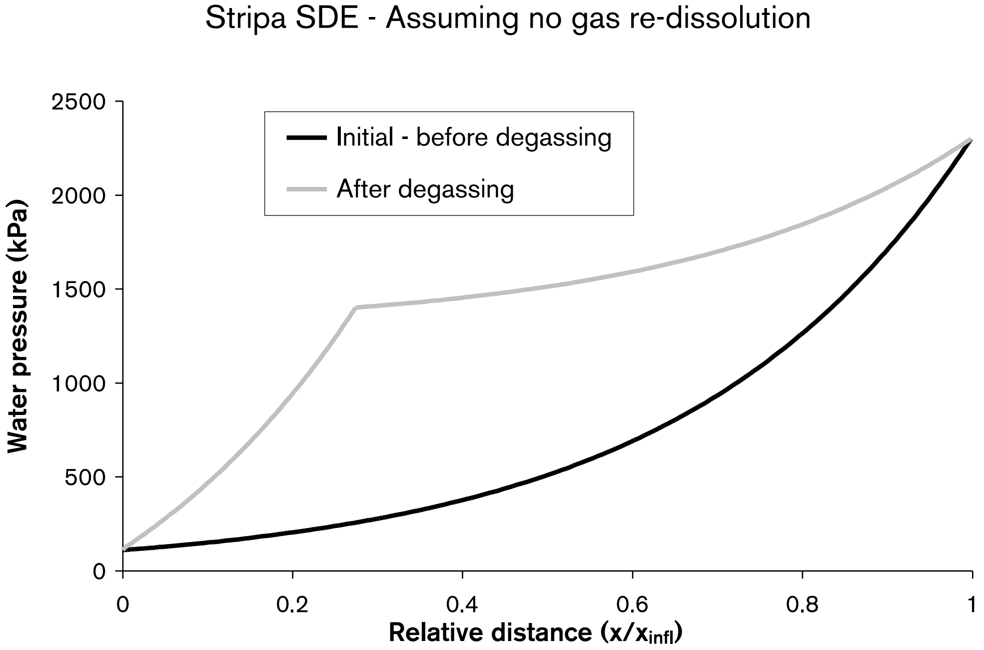


Figure 3-19. *Water pressures before groundwater degassing (black line) and after (grey line) as a function of the relative distance from the drift wall, located at* $x/x_{inf} = 0$*. Conditions are the same as in Figure 3-18, except for an assumption of no gas re-dissolution. The modelled relative transmissivity is in this case 0.44.*

3.6.5 Scaling of unsaturated flow/degassing relations

We have investigated the applicability of the unsaturated flow relations, originally developed for degassing applications /see Jarsjö and Destouni, 1998/, for the interpretation of unsaturated flow occurring for other reasons than degassing. Specifically, we consider gas injection tests, which for instance have been performed at Äspö HRL by the German organisation BGR. For reproducing such field experiments, a key issue is how to use (limited) field measurements of the physical fracture aperture and its variability (as well as hydraulic test data) in the modelling.

The unsaturated flow relations/characteristic curves of Jarsjö and Destouni (1998) are based on physical fracture aperture statistics. Hence, for fracture regions where such aperture statistics is not available, one must find alternative procedures to estimate the characteristic relations. In the following, we outline such an alternative procedure (modified from the porous medium Leverett-scaling procedure), and test its relevance and applicability for fractured media.

The following site-specific information is needed for the above-mentioned scaling procedure:

(i) More detailed statistics on the physical fracture aperture for one subregion (corresponding to a “cell” in the numerical model).

(ii) Some information/statistics on either the mean aperture width, or the saturated transmissivity value, for the other subregions/cells.

We further assume that the fracture apertures within each subregion/cell are log-normally distributed.

The Leverett scaling relation, originally developed for scaling of characteristic curves in porous media (see p. 446 in Bear, 1972), may be expressed as:

$$p_c(S_w)_2 = p_c(S_w)_1\sqrt{k_1/k_2} \tag{3-1}$$

where subscripts 1 and 2 refer to the two different media. Hence the (unknown) capillary pressure p_c at a particular water saturation S_w in medium number 2 can be estimated on basis of the corresponding (known) capillary pressure at the same water saturation in medium number 1, and the permeability ratio k_1/k_2 between the media.

However, the most relevant measure of the hydraulic properties in fractured media is transmissivity (*T*), rather than permeability (*k*). With the aim to obtain a scaling relation based on fracture transmissivities, we therefore recall the following relation between permeability and transmissivity (originally developed for flow between parallel plates):

$$k = \frac{\mu T}{\rho g a_h} \tag{3-2}$$

where μ is the liquid viscosity, ρ is the liquid density, g is the gravitational constant and a_h is the hydraulic fracture aperture. Then, one can use the corresponding relation between a_h and k, $a_h = \sqrt{12k}$ to eliminate a_h from the above expression and obtain

$$k = \sqrt[3]{12}\left(\frac{\mu T}{\rho g}\right)^{2/3} \tag{3-3}$$

which, when inserted in relation (1) results in the following scaling relation:

$$p_c(S_w)_2 = p_c(S_w)_1\sqrt[3]{T_1/T_2} \tag{3-4}$$

How does then the proposed scaling procedure of the characteristic curves, through (3-4), perform in comparison with direct estimates of the characteristic curves, based on fracture aperture data? Through numerical experiments, we showed that the scaling using equation (3-4) is relevant for fractures of different mean apertures, as long as the aperture standard deviations do not differ too much. For fractures with different mean apertures and exactly the same aperture standard deviation, the characteristic curve obtained by scaling coincided with the curve estimated directly from aperture data.

3.6.6 Planned work

The finalisation of the summarising technical report on groundwater degassing was delayed and is now scheduled for the end of March, 2000. This report will also include findings regarding the relevance of various two-phase flow relations for fractured rock applications, in a more general sense (including the relations originally developed for degassing applications). This latter work is carried out within the German-Swedish programme at the Äspö HRL, mainly in cooperation with the group of R. Helmig at the Institute for Computer Applications in Civil Engineering (CAB), Braunschweig, Germany.

3.7 Hydrochemistry modelling / Hydrochemical stability

3.7.1 Background

The chemical properties of the groundwater affect the canister and buffer stability and the dissolution and transport of radionuclides. It is therefore important to know the possible changes and evolution of the groundwater chemistry during the repository life time. Important questions concern the understanding of the processes which influence and control the salinity, occurrence, character and stability of both saline and non-saline groundwaters.

At present this project is carried out within the framework of the Äspö agreement between SKB and Posiva. It also covers the technical parts of the participation in the EC EQUIP project and the modelling Task #5 within the framework of the Äspö Task Force for modelling of groundwater flow and transport of solutes.

3.7.2 Objectives

The objectives of this project are:

- to clarify the general hydrochemical stability (= groundwater chemistry of importance for canister and bentonite durability and radionuclide solubility and migration),
- to describe the possible scenarios for hydrochemical evolution at Äspö over the next 100,000 years, separated into time slabs of 0–100, 100–1,000, 1,000–10,000 and 10,000–100,000 years,
- to develop a methodology to describe the evolution at candidate repository sites, e.g. Olkiluoto.

3.7.3 Model concepts

Geochemical interpretation of groundwater-rock interaction along flow paths makes use of the results from groundwater chemical investigations, i.e. chemical constituents, isotopes and master variables pH and Eh in combination with the existing mineralogy, petrology and termodynamic data. Useful tools for these calculations are reaction path codes like NETPATH and equilibrium-mass balance codes like EQ 3/6. These codes are frequently used in hydrochemical studies.

A newly developed concept and code, M3, start from the assumption that it is mixing and not chemical reactions that is the dominating process affecting the chemical composition of the groundwater within the investigated system. The principal assumptions behind this concept is that the varying hydraulic conditions of the past have created the complex mixing pattern presently observed. When the effects of mixing has been evaluated, mass balance calculations (resulting from chemical reactions) are then made to explain the difference between the ideal mixing and the observations. A good description of the different modelling approaches is found in the Applied Geochemistry Journal, vol 14, No 7, Sept. 1999.

The modelling strategy for the Hydrochemical Stability project involve:

- identification of the dominant (chemical) processes for Finnish and Swedish sites,
- geochemical mixing for Äspö and Olkiluoto,
- site intercomparison and comparison between the M3 and NETPATH techniques based on data from Olkiluoto,
- transient hydrodynamic modelling for Äspö and Olkiluoto.

The intention with the strategy is to be able to compare the results of the traditional hydrochemical modelling with the results from M3 and to compare the outcome of the hydrodynamic modelling with the results from M3. The latter comparison is done within the Task #5 of the Äspö Task Force for modelling of groundwater flow and transport of solutes.

The Equip project has the specific objective to trace the past hydrochemical conditions through investigation of (calcite)fracture filling minerals. The outcome will be compared to the results from the hydrogeological and hydrochemical models and thus provide an independent check of the long term stability of the groundwater flow and chemistry.

3.7.4 Results

Task#5

The time for the integrated modelling of Task#5 has been prolonged and the results of the individual modelling teams will be reported by the middle of this year. The evaluation of the entire Task#5 will start and be ended in 2001.

Table 3-5 summarises the presentations of modelling results given at the 13th Task Force Meeting in February 2000.

Table 3-5. Task 5 technical presentations at the 13th Task Force Meeting

Title	Organisation	Presenter
Groundwater mixing and geochemical reactions – an inverse modelling approach	POSIVA	A Luukkonen, VTT
M3 predictions of the groundwater changes associated with the construction of Äspö HRL	SKB	M Laaksoharju, INTERA
The origin and composition of groundwater leaking into the Äspö tunnel	SKB	U Svensson, CFE
Integration of hydrogeology and hydrochemistry at the Äspö site	ENRESA	J Molinero, ULC
A hydraulic transport model of the large-scale fracture system in the Äspö Hard Rock Laboratory consisting of ten intersecting macro-elements	BMWi	L Liedtke, BGR
Geochemical Modeling Plan and Preliminary Results	CRIEPI	T Hasegawa, CRIEPI
Executive summary of Task 5 modelling	JNC	W Dershowitz, Golder
Modelling work of CEA/DMT for Task 5	ANDRA	C Grenier, CEA
Task 5 modelling	ANDRA	J Wendling, ANTEA
Task 5 Modelling, Executive Summary	ANDRA	D Billaux, ITASCA
Comments on predictions	SKB	I Rhén, VBB-VIAK
Modelling of the REDOX Zone experiment	ENRESA	J Molinero, ULC

The conclusions so far is that Task#5 is very relevant for site characterisation. There is a need to obtain information on both hydrological and hydrochemical properties from the same location at the same time. Even though there is a huge database on hydrochemistry, many modellers still would have needed more time series observations from more observation points.

In general there is an agreement that the hydrochemical information has helped constraining the groundwater flow models.

EQUIP

Calcite from open fractures mainly at Äspö and Laxemar, sampled at depth ranging from 25 to 1,600 metres, have been analysed within the Swedish part of the EQUIP programme. The results have been interpreted with respect to past and present groundwater regimes /Laaksoharju et al, 1999/.

The studies reveal that several generations of calcite can be identified, chemical zoning is common, and the influence on calcite precipitation of fresh or marine water decreases with depth. The different methods are variably good in recognising different generations and zoning. It can be concluded that fine scale zoning, possible dissolution/redistribution of calcite, and the disturbances caused by drilling (where loose material probably containing young calcite precipitates was lost), introduce difficulties in the separation of different calcite generations. Thus, the timing of different calcite generations is hard to establish.

A compilation of the existing data results in identification of 6 different calcite generations:

1. Calcite precipitated from meteoric water at low temperature conditions most common in the upper part 50 to 100 metres of the bedrock but may exist down to 1,000 m.
2. Calcite precipitated from brackish water (Baltic sea water?) at low temperatures is found down to a depth of approximately 500 m and is possibly (or partly) of postglacial age.
3. Calcite precipitated from oceanic water is found down to a depth of 300 metres. This calcite may as youngest be Eemian in age (117,000 to 130,000 years) but may well be considerable older.
4. Calcite precipitated from glacial/cold climate water.
5. Calcite precipitated from brine water at temperatures between 60 and 150°C.
6. Calcite precipitated from hydrothermal solutions usually associated with epidote, quartz, adularia and fluorite.

The occurrence of calcite types 1 to 4 decrease with increasing depth, whereas calcite of type 6, and to some extent calcite of type 5 increase with depth. Calcite generations of type 5 and 6 constitute the thickest precipitations (mm thickness) whereas the low temperature calcite constitutes extremely thin coatings or rims (mm thickness) on older hydrothermal calcite precipitates. Reliable age determinations of the low temperature precipitates are therefor very difficult to obtain.

It is remarkable that calcites precipitated from brackish and marine water are only found down to ca 500 m depth whereas calcites with meteoric/cold climate recharge signatures can be traced to larger depth, possibly as deep as 1,000 m. One explanation for this may be differences in hydraulic head: Durig periods when Äspö/Laxemar was covered by sea (brackish or oceanic) the hydraulic driving force would not allow deep penetration of the marine water. In contrast when the area is situated above sea level the hydraulic situation is more in favour of recharge into large depths.

A tentative model of the past and present groundwater circulation is shown in Figure 3-20. Three different zones can be recognised. The upper 0–100 metres is characterised by a dynamic situation including dissolution and precipitation of new calcite. During some periods the biogenic input has been significant, whereas during others periods, oxidising conditions may have prevailed. At depth below 100 m down to c. 700 m (or possibly down to 1,000 m) mainly precipitation (or recrystallisation) of calcite is detected. Several generations are common at these depths. Redox conditions have probably been stable (reducing) and biogenic input is detected in terms of low carbon isotope values and high Mn, La and Ba values. At even larger depth recent calcite precipitation is rare and the biogenic input seems to be insignificant.

The observed distribution pattern of the different calcite generations is the net effect of calcite/fluid interaction (and during long periods also subsurface microbiological activity) during the entire geological history of the Äspö granitoids. The hydrothermal calcite (type 6) is the most widespread fracture calcite precipitation. It is probably related to the regional hydrothermal alteration along fractures and fracture zones that occurred early in the geological history of Äspö. The subsequent dissolution and replacement of the hydrothermal calcite by calcite from younger groundwater regimes have been repeated during periods since then. When the sedimentary cover on the shield was thick (e.g. during the Late Palaeozoic) the temperatures may have been high enough to precipitate calcite from a brine type of water (calcite 5).

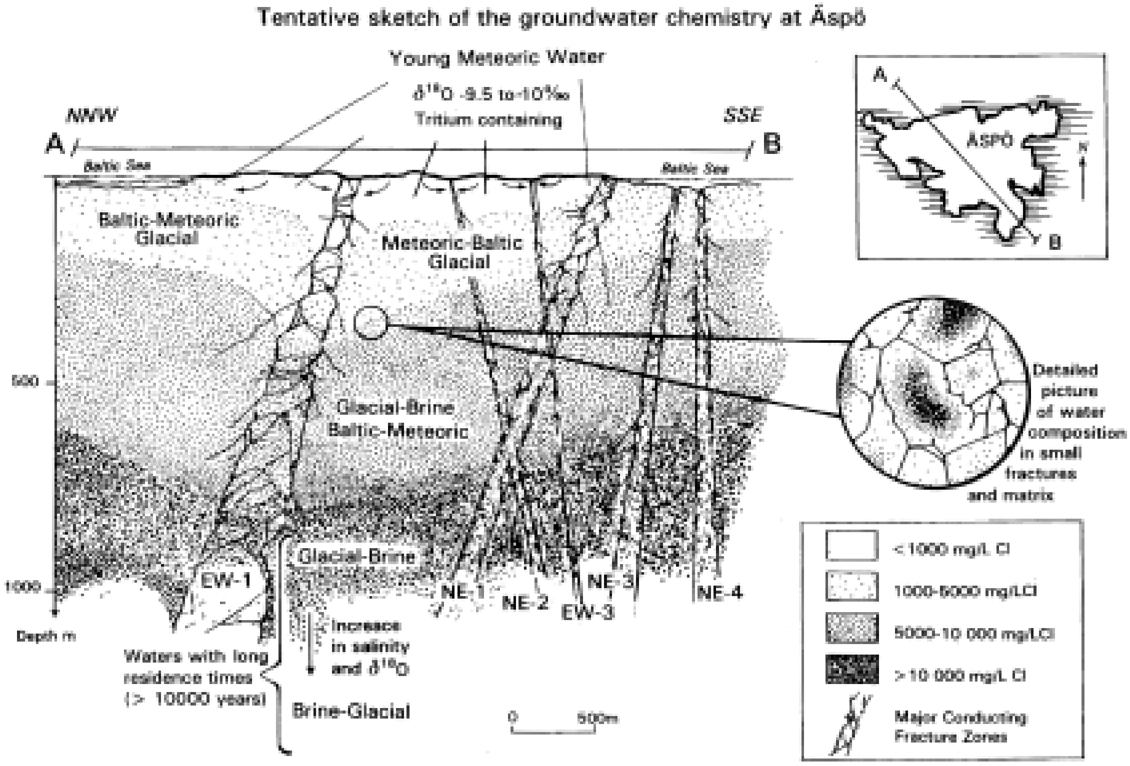


Figure 3-20. Tentative sketch of calcite/groundwater interaction at various depth (see text).

The depth distribution of different calcite types indicates stability in large-scale groundwater circulation, but in detail large variations in depth may have occurred. For example, the attempts to correlate calcite/groundwater pairs from the same fracture/borehole depth, indicate that there is no equilibrium with the present groundwater. Nevertheless, the large scale pattern of calcite types and the ground water chemistry are in rough correspondence (presence of meteoric-, Baltic-, and cold-climate, recharge water followed at depth by brine water corresponding to the less dynamic zone described above).

Modelling

The project "Hydrochemical Stability" will be reported during 2000. In addition to the individual modelling efforts, the final report will assess the stability/variability with respect to the potential danger in the waste in the different time slabs. That reporting will then identify possible further needs for model development.

The hydrochemistry of the very first period after closing of the repository will be completely depending on the site specific conditions and on the type and amounts of construction and stray materials left in the repository.

The period of 100 to 1,000 years is most important for the performance of a HLRW repository. During this period, the activity of the waste decreases by two orders of magnitude from what it was at deposition. The hydrochemical stability of a repository site is therefore most important for the first 1,000 years.

Expected hydrochemical conditions during the first 1,000 years: Stable groundwater flow conditions, giving steady state mixing and reaction processes.

What could change this picture during a 1,000 to 10,000 year period? Man-made climate changes could change local precipitation regimes, and thus affect slightly groundwater flow conditions. Slow global cooling will change the hydrological regime in the long run. Fennoscandinavian land upheaval will also affect the groundwater paths.

During 10,000 to 100,000, the hydrochemical conditions will be influence by the local climatic conditions which will probably have large variations during this period. The process that affects hydrochemical stability is varying groundwater flow conditions. These variations will introduce changes in groundwater flow and mixing patterns. At this time the activity and potential hazard of the waste has also decreased to less than 0.1% of the initial activity at disposal.

3.8 Matrix Fluid Chemistry

3.8.1 Background

Groundwater sampled from the Äspö site has been collected from water-conducting fracture zones with hydraulic conductivities greater than K = 10^{-9} ms^{-1}. The chemistry of these groundwaters probably results from mixing along fairly rapid conductive flow paths, being mainly determined by the hydraulic gradient, rather than by chemical water/rock interaction. In contrast, little is known about groundwater compositions from low conductive parts (K< 10^{-10} ms^{-1}) of the bedrock (i.e. matrix fluids), which are determined mainly by the mineralogical composition of the rock and the result of water/rock reactions. As rock of low hydraulic activity constitutes the major volume of the bedrock mass in any granite body, matrix fluids are suspected to contribute significantly to the salinity of deep formation groundwaters. It is considered expedient therefore to sample and quantify such fluids and to understand their chemistry and origin.

Such knowledge of matrix fluids and groundwaters from rocks of low hydraulic conductivity will complement the hydrogeochemical studies already conducted at Äspö. It will also provide a more realistic chemical input to near-field performance and safety assessment calculations, since deposition of spent fuel will be restricted to rock volumes of similar hydraulic character.

3.8.2 Objectives

The main objectives of the task /Smellie, 1999/ are:

- to determine the origin and age of the matrix fluids,
- to establish whether present or past diffusion processes have influenced the composition of the matrix fluids, either by dilution or increased concentration,
- to derive a range of groundwater compositions as suitable input for near-field model calculations, and
- to establish the influence of fissures and small-scale fractures on fluid chemistry in the bedrock.

3.8.3 Experimental concept

The experiment has been designed to sample matrix fluids from predetermined, isolated borehole sections see Figure 3-21. The borehole was selected and drilled on the basis of: a) rock type, b) mineral and geochemical homogeneity, c) major rock foliation, d) depth, e) presence and absence of fractures, and f) existing groundwater data from other completed and on-going experiments at Äspö. Special equipment has been designed to sample the matrix fluids ensuring: a) an anaerobic environment, b) minimal contamination from the installation, c) minimal dead space in the sample section, d) the possibility to control the hydraulic head differential between the sampling section and the surrounding bedrock, e) in-line monitoring of electrical conductivity and uranine content, f) the collection of fluids (and gases) under pressure, and g) convenient sample holder to facilitate rapid transport to the laboratory for analysis /Smellie, 1999/.

Migration of matrix fluids will be facilitated by small-scale fractures and fissures. Therefore the matrix fluid chemistry will be related to the chemistry of groundwaters present in hydraulically-conducting minor fractures ($K = 10^{-10}–10^{-9} ms^{-1}$), since it will be these groundwaters that may initially saturate the bentonite buffer material.

3.8.4 Results

During the latter part of 1999 a Feasibility Study was carried out on solid drillcore material representing one of the borehole sections (Section 2) isolated for sampling matrix fluid Figure 3-20. The first stage of the study comprised the basic mineralogy and major and trace element geochemistry to generally characterise the rockmass. These data were then used to initially characterise fluid inclusion populations and to identify which relevant elements and isotopes to be determined. Crush/leach experiments were conducted also to indicate the nature of the matrix fluid. A 'Matrix Fluid Experiment Workshop' was held at Äspö on September 6/7 when initial results of the Feasibility Study were presented and discussed, and future plans were laid.

Since September 1999, activities carried out have involved a continuation of: a) mineralogical studies, b) crush/leaching experiments, c) Äspö diorite permeability test, and d) compilation and interpretation of groundwaters sampled and analysed from the Prototype Repository Experiment. In December 1999, the opening of two sections in the matrix borehole (Sections 1 and 4) for matrix fluid sampling was carried out. Furthermore, the fluid inclusion programme of study is now in progress.

Mineralogy

General mineralogical characterisation of the drillcore from borehole Section 4 (4.66–5.26 m), now sampled for matrix fluid (see below) has been carried out by the University of Bern, Switzerland and by Terralogica AB, Sweden. Additional samples from borehole Section 2 (8.85–9.55 m), earmarked for fluid sampling, are now being prepared for mineralogical, fluid inclusion and petrophysical studies. Preliminary results from the complete drillcore suggests that two main rock-types may be present (possibly of differing porosity), an Äspö porphyritic diorite type adjacent to the tunnel, and an Ävrö Granite type away from the tunnel, with the transition being located somewhere between borehole Sections 2 and 4. Furthermore, there is a suggestion of partly open, small-scale fractures (~1 mm) intersecting (and parallel to) the borehole close to Section 4. This feature, together with possible porosity differences, may be an explanation why borehole Section 4 has already been filled with water, whilst Section 2 is still accumulating fluid. It may explain also why fracture-type waters have been found in Section 4, rather than matrix fluid (see below).

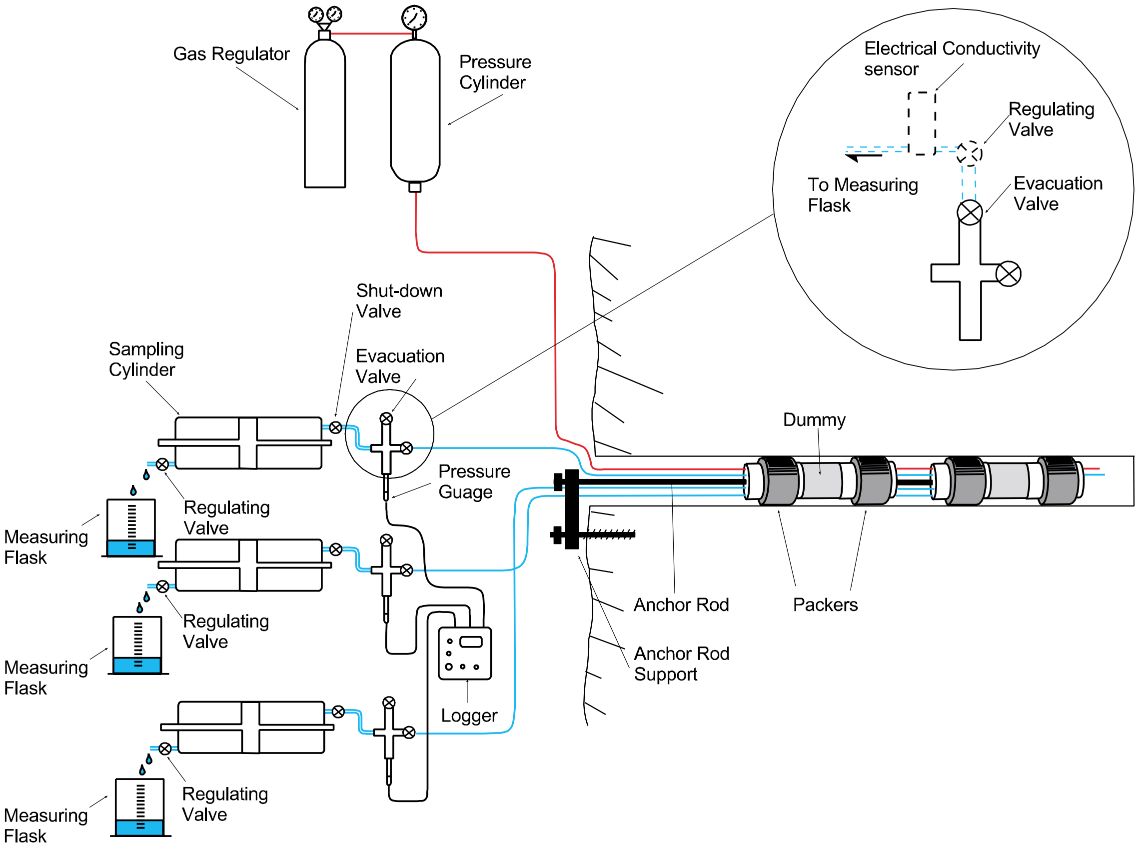


Figure 3-21. *Experimental configuration for sampling matrix fluids. Note that the casing has not been included.*

Crush/leaching experiments

Three crush/leach sequences from the same drillcore material (immediately adjacent to Section 4 towards the tunnel) have been completed by the University of Waterloo and, independently, two sequences by the University of Bern on the same material. There was good agreement between the first crush/leach of Waterloo and the Bern sample; both samples represented approximately similar size fractions.The composition of the *in situ* pore water (i.e. matrix fluid) from the Bern sample, calculated from these experiments, ranged from 61,000 to 89,000 mg/L Cl; the Waterloo calculations are forthcoming.

Permeability test

Since August 1999 a high pressure experimental set-up has been operating at the University of Waterloo. This experiment is essentially trying to force double distilled (Ultrapure) water through a drillcore portion (100 · 50 mm) in order to extract unbound, intragranular matrix fluid. The drillcore portion, selected adjacent to Section 4, has been mounted in a moisture proof membrane with an applied hydrostatic stress of 11.7 MPa (i.e. equivalent to the lithostatic stress at the Matrix Borehole location in Tunnel 'F') and a pore pressure of 6 MPa has been applied to the distilled water. Up until October 1999 no movement was observed and the pore pressure was accordingly increased to 9.5 MPa. Some activity was observed in November, which subsequently slowed down. Monitoring is continuing.

Sampling and analysis of matrix fluid

Attempts were made in December 1999 to determine the presence of any accumulated matrix fluid after a time period of 18 months. Borehole Section 1 (10.55–11.80 m), initially intended only for pressure monitoring, was opened. No fluid emerged, only a release of gas with a distinct smell of H_2S. The absence of fluid was not altogether surprising since this borehole section is rather long and not instrumented for sampling (total volume of 5,461 µL). Initially some 65 µL of fluid would need to accumulate (because of the geometry of the borehole) prior to discharging from the borehole section outlet tube.

This was followed by opening borehole Section 4 (4.66–5.26 m), initially demarcated for sampling, which had shown a steady build-up and a levelling-off of pressure over the 18 month period. Some 160 µL of water were collected under an inert N_2 atmosphere. This was out of a total borehole section volume of 210 µL, of which 35 µL was considered inaccessible because of the geometry of the borehole and the nature of the instrumentation. The analytical protocol was prioritised according to the amount of sample available. The sample is presently being analysed, but preliminary data suggest a nearby fracture origin for the water, via suspected intersecting small-scale fractures, possibly combined with some contribution from interconnected pore flow or diffusion into the sampling section, rather than matrix derived. Comparison of the matrix water with typical fracture-derived groundwaters (i.e. Prototype Experiment – see below) indicate, in general, similar ranges of major and trace element values. There is significantly more Mg in the fracture-derived groundwaters which may reflect a small marine influence caused by the hydraulic drawdown during tunnel construction.

Unfortunately the ^{14}C data cannot be used since sample contamination occurred. Rubber corks used to seal the flask during collection of the matrix water, obtained from the laboratory at the nearby nuclear power facility, were subsequently shown to be contaminated. The $\delta^{13}C$ value of –26.8‰ PDB indicates biogenic activity, probably *in situ*; this is supported by the high HCO_3 content (170–200 mg/L).

Microbial activity is generally evidenced, probably due to some residual contamination in the sampled section following borehole activities. Viable counts of sulphate-reducing bacteria (SRB), which gave rise to the smell of H_2S, and iron-reducing bacteria (IRB), were both positive. It can be speculated that most of the metabolic activity occurred at the beginning of the experiment. SRB and IRB would be responsible for the high carbonate concentration observed, which indicates that degradable organic material was present in the section. Other chemical parameters possibly affected by microbial activity are S, SO_4, Mn, Fe-speciation, organic carbon content, pH and alkalinity. For prolonged sterilisation, a sustainable bacteriocidal substance is required (e.g. mercury chloride or silver chloride). This was not considered in the initial planning phase for fear of chemically contaminating the borehole. In retrospect, this risk will have to be taken in future long-term experiments to 'avoid' undesireable microbial activity.

Borehole Section 2 (8.85–9.55 m) has been showing a small, but steady pressure increase since February 1999, with a slightly more marked increase since October, 1999. This will be allowed to continue until adequate matrix fluid has accumulated (total section volume of 245 μL). Sampling will then be carried out; this time a more sophisticated sampling approach will be planned, including gas analysis. The much slower accumulation of fluid in this section, plus the absence of large fluid volumes in the adjacent Section 1 (already opened), may suggest a more representative matrix fluid composition than collected from borehole Section 4.

Fracture groundwaters sampled within the Prototype Experiment

Groundwater samples have been collected from fractures of low transmissivity in coordination with the Prototype Experiment. The analyses are still incomplete but the data indicate that there is no clear correlation between transmissivity (sampled fractures ranged from 10^{-10}–10^{-6} m^2s^{-1}) and the major ion chemistry; all samples have been influenced by the hydraulic drawdown caused by tunnel construction. This is evidenced by the general incursion of young, meteoric-derived water and perhaps some marine component. Trace element and isotopic data have still to be evaluated fully; these data might still reveal some features that may reflect some kind of hydraulic control on groundwater chemistry. Irrespective, the results to date show that even lower transmissivities ($< 10^{-10}$ m^2s^{-1}) need to be studied.

Fluid inclusion studies

The nature of the matrix fluid may be strongly influenced by leakage of saline fluids from fluid inclusions which, at Äspö, are commonly included in matrix quartz. Four research groups (Universities of Stockholm, Bern and Waterloo, together with a group from Kivitieto, Oulu, Finland, sponsored by Posiva) will participate in characterising the fluid inclusions; this collaboration will also function as an interlaboratory exercise with the intention of deriving a common methodology for the description, analysis and interpretation of fluid inclusion populations.

Some preliminary fluid inclusion studies have already been reported by the University of Bern, Switzerland. Highly saline fluid inclusion populations (indicating the presence of a Na-Ca-(Mg)-Cl type fluid) have been identified in coarse-grained magmatic quartz and in fine-grained recrystallised quartz. Salinity ranges from 8.2–20.9 wt% $NaCl_{eq}$ in the former types and from 4.3–10.8 wt% $NaCl_{eq}$ in the latter types. In addition, several other fluid inclusion types containing NaCl and $CaCl_2$ (± $MgCl_2$) were found to be common to both quartz hosts. Non-fluorescent gas-rich inclusions (CO_2 or CH_4) have also been revealed.

Combining the results from the crush/leach experiments (described above), the aqueous extracts yield salinities in the range of the highly saline fluid inclusions. These results, together with Br/Cl and Sr-isotope data, indicate that a mixture of interstitial water and fluid inclusion fluid could act as a high salinity source, potentially explaining the presence of deep, highly saline groundwaters at Äspö.

Hydraulic considerations

Hydraulic characterisation of the bedrock matrix hosting the borehole is an important repository performance assessment issue since little is known about the transmissive nature of crystalline rock in the interval 10^{-14}–10^{-10} m^2s^{-1}. The matrix experiment provides this opportunity. Long-term monitoring of the various isolated borehole sections, coupled with known times of water accumulation, have confirmed earlier predictions of matrix transmissivity (i.e. around 10^{-14} m^2s^{-1}). In addition, predictions of matrix water volume expected after a time interval of up to a year, based on a transmissivity of 10^{-14} m^2s^{-1}, was close to that finally obtained in Section 4, even though the presence of a partly open microfissure is suspected.

Calculations are presently being carried out to further constrain flow/diffusion rates in the bedrock hosting the matrix borehole. These calculations will also address the estimated transmissivity of the small-scale fractures that appear to have contributed to the water chemistry obtained in borehole Section 4.

3.9 The Task Force on modelling of groundwater flow and transport of solutes

3.9.1 Background

The work within the Äspö Task Force constitutes an important part of the international co-operation within the Äspö Hard Rock Laboratory. The group was initiated by SKB in 1992 and is a forum for the organizations to interact in the area of conceptual and numerical Modelling of groundwater flow and transport. The work within the Task Force is being performed on well-defined and focused Modelling Tasks and the following have been defined so far:

- **Task No 1**: The long term pumping test (LPT-2) and tracer experiments. Site scale.
- **Task No 2:** Scoping calculations for a number of planned experiments at the Äspö site. Detailed scale.
- **Task No 3:** The hydraulic impact of the Äspö tunnel excavation. Site scale.
- **Task No 4:** Modelling of radionuclide transport in a hydraulic feature based on data from the Tracer Retention and Understanding Experiment 1st stage (TRUE-1). This involves non-reactive and reactive tracer tests at a detailed scale of 5 m.
- **Task No 5:** Impact of the tunnel construction on the groundwater system at Äspö, a hydrological and hydrochemical model assessment exercise. It is conducted at the site scale of about 1 km.

During 1999 eight foreign organizations in addition to SKB were participating in the Äspö HRL Task Force. These organizations are: Japan Nuclear Cycle Corporation (JNC), Japan; Central Research Institute of Electric Power Industry (CRIEPI), Japan; Agence National Pour la Gestion des Déchets Radioactifs (ANDRA), France; Posiva Oy, Finland;

Nationale Genossenschaft für die Lagerung von radioaktiver Abfälle (NAGRA), Switzerland; Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie (BMWi), Germany , Empresa Nacional de Residuos Radiactivas (ENRESA), Spain and US DOE/ Sandia National Laboratories.

3.9.2 Objectives

The Äspö Task Force is a forum for the organizations supporting the Äspö HRL Project to interact in the area of conceptual and numerical Modelling of groundwater flow and solute transport in fractured rock. In particular, the Task Force shall propose, review, evaluate and contribute to such work in the Project. The Task Force interacts with the *Principal Investigators* responsible for carrying out experimental and Modelling work for the Äspö HRL in areas of particular interest for the members of the Task Force.

3.9.3 Results

Modelling for Task 1-3 were completed in previous years. Results are presented for Task 4 and 5 only. A web site has been constructed for the Task Force and was officially launched in 1999. The site is a mean to inform on the work done and a channel for data distribution. It has public pages as well as member pages. The address is **http://www.skb.se/omskb/forskning/aspo/tf/.**

Task 4

Modelling was done on Task 4C, D, E and F where C&D are based on conservative tracers and E&F on radioactive sorbing tracers.

Data from a radially converging tracer test (Task4C) was utilized in order to determine the transport parameters (flow porosity, dispersivity and fracture conductivity) and to test the connectivity of the selected hydraulic feature (Feature A). Data from a dipole test constitute the base for the Modelling in Task 4D which was undertaken with the purpose to obtain results for intercomparison with the results of the previously performed preliminary tracer tests (PTT) and the radially converging test (RC-1). Furthermore, the dipole tests should increase the understanding of the properties of the target feature (Feature A) and how the boundary conditions affects solute transport in that feature. As an example of the Modelling results Figure 3-22 show the predicted mass flux by different Modelling teams.

An evaluation of the modelling performed for Task 4C&D /Elert, 1999/ concluded that:

- many of the modelling teams tested alternative models for evaluating the effect structural geology, transport processes, boundary conditions and heterogeneity,
- the considerable interaction between modelers and experimentalists was vital for experimental setup, understanding results and perform the modelling,
- many of the modelling teams had problems in overpredicitng the drawdown form the radially converging experiment and in finding a suitable relationship between the fracture aperture derived from the hydrological tests and the aperture from the tracer tests,
- the predictive modelling results indicate that the boundary conditions and the flow system was not completely understood at the time of the experiment,
- it was found beneficial to utilize several models based on different concepts and of varying complexity for the modelling predictions and evaluations,
- the methodology to derive the necessary parameters for predictions need development.

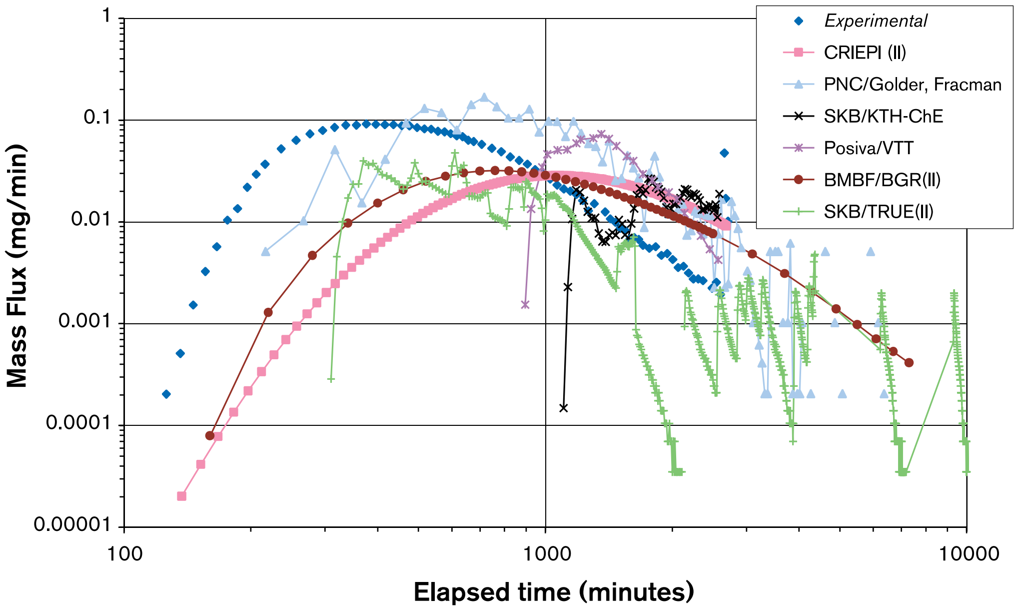


Figure 3-22. *Breakthrough curve from dipole test between the injection borehole (KXTT1 R2) and the withdrawal borehole (KXTT3 R2) in the DP-1 test. The distance between injection and withdrawal is 5.03 m.*

Modelling was performed on the transport of the radioactive tracers in Task 4E which utilized weakly sorbing tracers, and in Task 4F with the moderately to strongly sorbing tracers ^{22}Na, ^{47}Ca, ^{42}K, ^{85}Sr, ^{86}Rb, ^{99m}Tc, ^{131}Ba, ^{133}Ba, and ^{134}Cs. The evaluation of the work performed by the Modelling teams in these two tasks started during the year and is planned to be completed in 2000.

Deconvolution of breakthrough curves

It is often difficult to discriminate between heterogeneity, processes and methodological artifacts. In order to facilitate the evaluation of the transport properties from the tracer tests it is important to have a well-defined injection source term that is short in comparison with the tracer travel time. In practice this may be difficult to achieve.

To evaluate the breakthrough curves excluding the effects caused by the injection procedure a mathematical treatment of the tracer test data can been done. This treatment, called deconvolution, uses the experimental tracer injection curves and breakthrough curves to evaluate what the breakthrough curve would have looked like if the injection was performed as a pulse with unit mass and zero duration (Dirac function). Ideally, all features of the resulting curve – the unit response function – are caused by processes occurring during the transport. In reality experimental errors may cause oscillations or mathematical artifacts in the unit response function. Therefore, mathematical manipulation of the experimental curves in the form of smoothing or curve fitting may be needed. Therefore, a deconvolution of the experimental results used in Modelling Task 4E was undertaken, Elert (1999). An example of the results from the deconvolution study is shown in Figure 3-23, where STT1b data is used. Here the deconvolved unit response function and the convoluted breakthrough curve for ^{86}Rb matched with the measured breakthrough data are presented.

It is concluded that deconvolution is a useful approach to evaluate tracer experiments in order to identify features in the breakthrough curves caused by transport processes. In particular they can be used for comparison with unit response curves obtained from

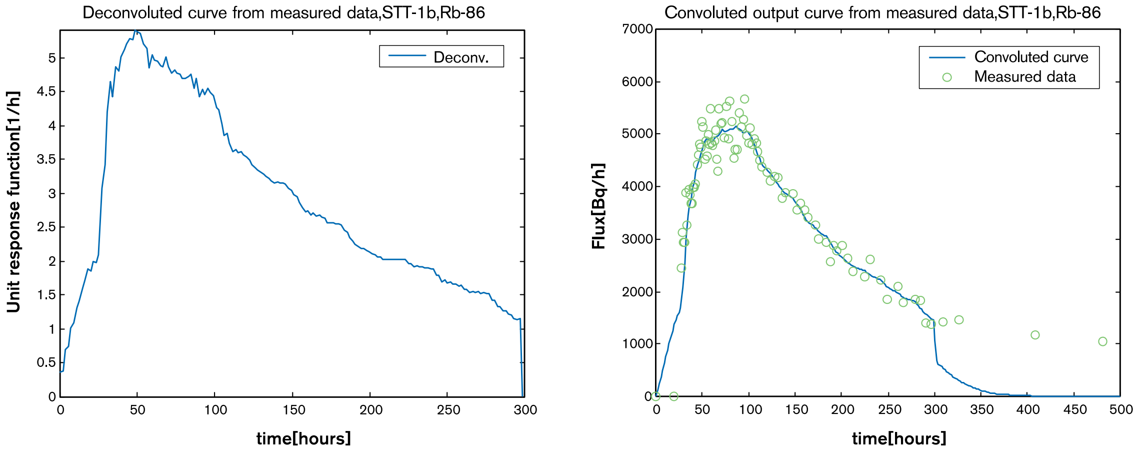


Figure 3-23. *Unit response function and convoluted curve for Rb-86 in STT-1b compared with measured data.*

model predictions. The method presently used for deconvolution has successfully deconvoluted most of the tracers used in Task 4E (STT-1 and STT-1b tests). However, there is a need for further improvement of the method in order to handle curves with large experimental errors.

Task 5

The Modelling task 5 consisted of a) predicting water composition expressed as mixing proportions of water types at selected control, b) predict hydraulic head in selected boreholes and c) make an assessment of the chemical evolution during tunnel construction. Predictive Modelling was completed during the year and results presented at a workgroup meeting. An example of preliminary result for the prediction is shown in Figure 3-24 where the measured and predicted hydraulic head in section 191–290 m in borehole KAS07 is shown.

In Figure 3-25, an example of the prediction made on the water compositions is shown. The composition is specified as relative fraction between the different water types glacial, meteoric, Baltic and brine.

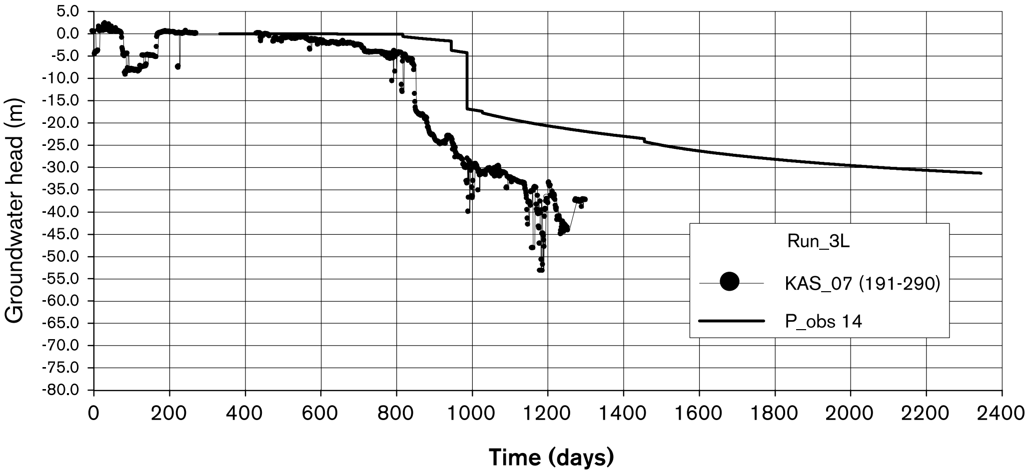


Figure 3-24. *Temporal evolution of predicted and measured hydraulic head values in borehole KAS07 (191–290 m) by ENRESA/ULC. The time period cover the duration of the tunnel construction.*

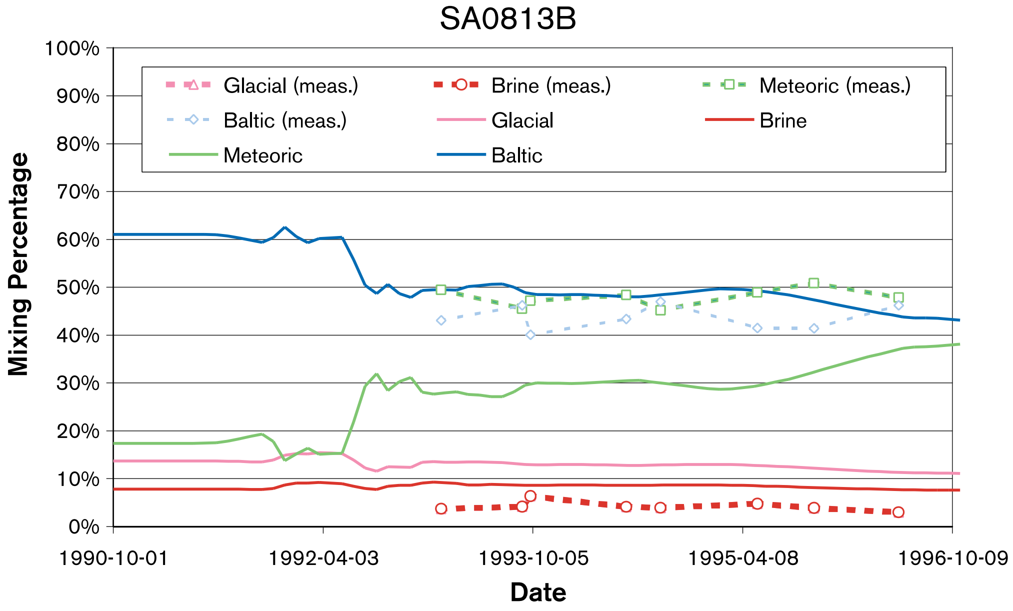


Figure 3-25. *Temporal evolution of predicted and measured watertypes in borehole SA0813B by JNC/Golder.*

Reports

During 1999 the following reports were produced within the framework of the Äspö Task Force:

Elert M, 1999. Evaluation of the TRUE-1 radially converging and dipole tests with conservative tracers. Äspö Task Force, Task 4C and 4D. SKB TR-99-04.

Elert M, 1999. Deconvolution of breakthrough curves from TRUE-1 tracers tests (STT1 and STT1b) with sorbing tracers. Äspö Task Force, Task 4E. SKB IPR-99-35.

Morosini M (ed), 1999. Proceeding from the 12th Task Force meeting at Gimo, Sweden, April 20-22, 1999. SKB IPR-99-22.

Selroos J-O, Cvetkovic V, 1998. Prediction of the TRUE-1 radially converging and dipole tracer tests. Äspö Task Force, Task 4C and 4D. SKB HRL ICR 98-07.

Ström A, 1998. Issue Evaluation Table 1997/1998. Äspö Task Force.
SKB HRL ICR98-05.

Worraker W, Holton D, Cliffe KA, 1998. Modelling TRUE-1 (RC-1) tracer tests using a heterogeneous variable aperture approach. Äspö Task Force, Task 4C.
SKB HRL ICR98-06.

4 Demonstration of technology for and function of important parts of the Repository system

4.1 General

Stage goal 4 of the Äspö HRL is to demonstrate technology for and function of important parts f the repository system. This implies translation of current scientific knowledge and state-of-the-art technology, into engineering practice applicable in a real repository.

It is important that development, testing and demonstration of methods and procedures, as well as testing and demonstration of repository system performance, is conducted under realistic conditions and at appropriate scale. A number of large-scale field experiments and supporting activities are therefore planned to be conducted at Äspö HRL. The experiments focus on different aspects of engineering technology and performance testing, and will together form a major experimental program.

With respect to technology demonstration important overall objectives of this program are:

- to furnish methods, equipment and procedures required for excavation of tunnels and deposition holes, near-field characterisation, canister handling and deposition, backfilling, sealing, plugging, monitoring and also canister retrieval,
- to integrate these methods and procedures into a disposal sequence, that can be demonstrated to meet requirements of quality in relation to relevant standards, as well as practicality,

With respect to repository function, objectives are:

- to test and demonstrate the function of components of the repository system,
- to test and demonstrate the function of the integrated repository system.

4.2 The Prototype Repository

4.2.1 Background

Many aspects of the repository concept (KBS-3) have been tested in a number of in-situ and laboratory tests. Models have been developed that are able to describe and predict the behavior of both individual components of the repository, and the entire system. However, processes have not been studied in the complete sequence, as they will occur in connection during repository construction and operation. There is a need to test and demonstrate the execution and function of the deposition sequence with state-of-the-art technology and in full-scale and to demonstrate that it is possible to understand and qualify the processes that takes place in the engineered barriers and the surrounding host rock. It is envisaged that this technology can be tested, developed and demonstrated in the Prototype Repository.

The execution of the Äspö Prototype Repository is a dress rehearsal of the action needed to construct a deep repository from detailed characterisation to resaturation of deposition holes and backfilling of tunnels. The Prototype is focused on testing and demonstrating the system function of the KBS-3 concept and will provide a full-scale reference for test of predictive models concerning individual components as well as the complete repository system. The Prototype should demonstrate that the important processes that take place in the engineered barriers and the host rock are sufficiently well understood.

Activities aimed at contributing to development and testing of practical engineering measures to rationally perform the steps of a deposition sequence are included. Efforts in this direction are limited since handling can not be made as in a real deep repository. However, it is believed that experience on handling will be gained to some extent. Handling matters are further addressed in other project such as Technology Demonstration and Retrieval Test.

4.2.2 Objectives

The main objectives for the Prototype Repository are:

- to test and demonstrate the integrated function of the deep repository components under realistic conditions in full-scale and to compare results with models and assumptions.
- to develop, test and demonstrate appropriate engineering standards and quality assurance methods.
- to simulate appropriate parts of the repository design and construction processes.

The evolution of the Prototype Repository should be followed for a long time, possible up to 20 years. This is made to provide long term experience on repository performance to be used in the evaluation that will be made after the initial operation stage in the real deep repository. The Prototype Repository will in this context provide operating experience for 10–20 years longer than will have been achieved with deposited canisters containing spent fuel.

4.2.3 Experimental concept

The Prototype Repository is set up to simulate a part of the KBS-3 type repository under what can be described as normal conditions, which is essentially the same as the reference scenario described in Research, Development and Demonstration Programme 98. The Prototype Repository is planned to simulate, to the extent possible, the real deep repository system, regarding geometry, materials, and rock environment. The test arrangement is planned to be such that artificial disturbance of boundary conditions or processes governing the behaviour of the engineered barriers and the interaction with the surrounding rock are kept to a minimum.

Important limitations with respect to the possibilities to simulate a repository situation are:

- the test site area is given and the location in conjunction with certain conditional criteria is therefore limited,
- no spent fuel, or any other form of nuclear waste, will be used. Canisters equipped with electrical heaters will be used to simulate encapsulated spent fuel,
- the Prototype Repository cannot demonstrate long-term safety, since the experiment considered will be extended in time at most tens of years.

In the deep repository, the plan is that localisation of the repository, deposition tunnels and final canister positions shall be determined by a step-by-step characterisation system followed by a detailing of the repository layout. Each step is based on data from characterisation of the host rock, which contribute to adjustment of localisation in relation to data as major and minor discontinuities and their orientation, water conditions, magnitude and orientation of rock stresses etc. The site of the Prototype Repository is given. However, methods for characterisation of the rock mass in the test site are expected to contribute to the assessment of methods for characterisation of the rock mass and the canister positions in a real deep repository.

Different alternatives as regards location and layout of the Prototype Repository have been considered. The test location chosen is the innermost section of the TBM tunnel at 450 m depth. The layout involves six deposition holes with a centre distance of 6 m see Figure 4-1. The distance is evaluated considering the thermal diffusivity of the rock mass and a maximum temperature of 90°C on the canister surface.

The deposition holes have been mechanically excavated by full-face boring, diameter 1.75 m and to a depth of 8 m. Performance of the boring machine and the boring technique will be analysed. Special considerations are taken to investigate the geometric results, surface roughness, and the disturbed zone (EDZ) i.e. induced fracturing.

A massive concrete plug designed to withstand full water- and swelling pressures will separate the test area from the open tunnel system. A second plug will be placed such that it divides the test into two sections, comprising four and two canister holes. This layout will in practice provide two more or less independent test sections.

Canisters with dimension and weight according to the current plans for the deep repository and with heaters to simulate the thermal energy output from the waste will be positioned in the holes. The plan is that decay heat will be controlled by real power output.

The buffer surrounding the canisters will be made of highly compacted Na-bentonite blocks, see Figure 4-2. The blocks will fill up the space between the rock and the canister but leave an outer slot of about 50 mm and a 10 mm slot between the blocks and the canister. The blocks will be made in full diameter 1.65 m and with a height of 0.5 m. The outer slot is planned to be filled with bentonite pellets. The final average density of the buffer in the deposition holes after water saturation will be about 2 ton/m^3 which represent a confined swelling pressure of approximately 5 MPa. The deposition tunnel will be backfilled with a mixture of 20–30% Na-bentonite and 70–80% crushed rock dependent on the salt content in the ground water; 10–15% Na-bentonite being the normal grade in fresh water.

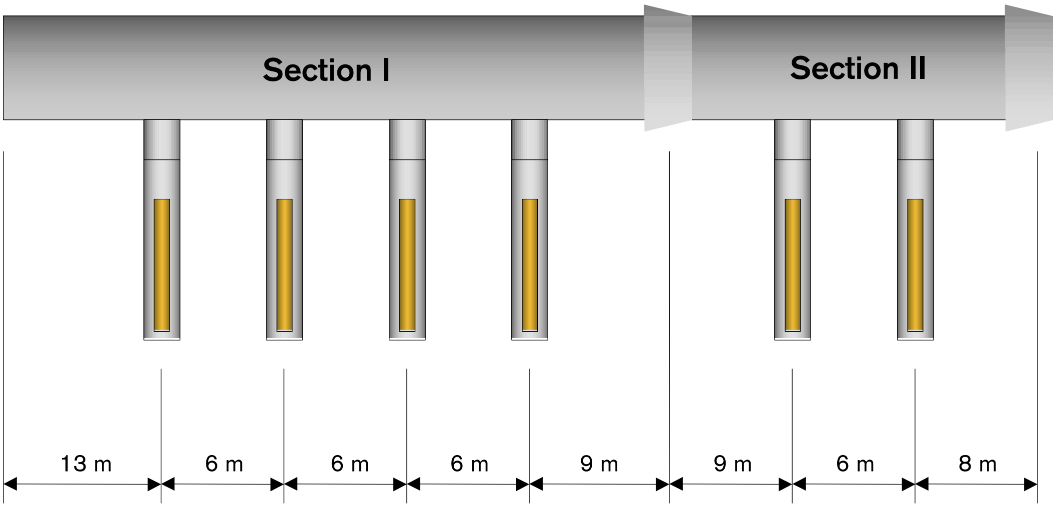


***Figure 4-1.** Schematic view of the layout of the Prototype Repository (not to scale).*

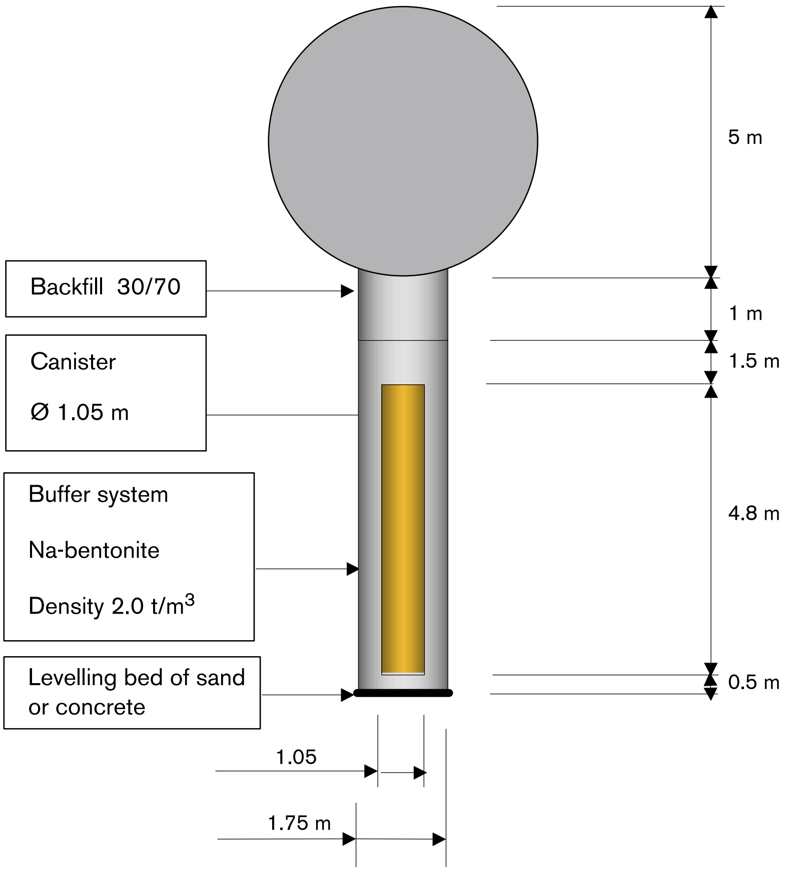


Figure 4-2. *Schematic layout of the deposition holes (not to scale).*

Decision as to when to stop and decommission the test will be influenced by several factors, including performance of monitoring instrumentation, results successively gained, and also the overall progress of the deep repository project. It is envisaged that the outer test section (Section II) will be de-commissioned after approximately five years to obtain interim data on buffer and backfill performance through sampling. The inner section (Section I) will be designed for an operational life time of 20 years.

Instrumentation will be used to monitor processes and properties in the buffer, the backfill and the near-field rock. The intention to minimise disturbance will, however, add restrictions to the monitoring possible.

Processes that will be studied include:

- water uptake in buffer and backfill,
- temperature distribution in canisters, buffer, backfill and rock,
- displacements of canisters,
- swelling pressure and displacement in buffer and backfill,
- stresses and displacements in the near field rock,
- water pressure build-up and pressure distribution in rock,
- chemical processes in rock, buffer and backfill,
- bacterial growth and migration in buffer and backfill.

4.2.4 Results

Detailed planning has been continued during 1999, and the experimental set up of the prototype continuously updated.

Time table

In December it was obvious that the equipment for handling bentonite blocks and for handling canisters in the installation would not be ready in time. In addition a possible EC funding would not be negotiated before the middle of year 2000. The start of installation in Section I was therefore postponed until January 2001 and in Section II to October 2001. The consequence is that the inner section can not be in full operation until the end of year 2001, when the construction of the inner plug is completed, and the outer section not until early 2002.

EC project

The application for EC funding of the Prototype Repository project was submitted in October1999 and comprised the time from April 1 of 2000 up to December 2003. The application included eight other organisations and asked for 50% funding of SKB' costs during that period and between 10% and 100% funding for the other organisations contributions. In January 2000 the Commission announced that the application has been selected by EC for funding but only to a smaller amount than was asked for, approximately half of the asked sum. The consequence is a modification of the EC part of the Prototype Repository and minor changes in the over all plans for the whole project. Contract signing is now estimated to take place around July 1st, 2000. Some of the organisations which were listed as subcontractors in the application shall, according to EC regulations, be partners in the contract instead (executing scientific work compared to supplying equipment or other goods). The list of participants then is 13 as follows (9 in the application):

- SKB
  - GeoDevelopment
  - VBB VIAK
  - Clay Technology
- POSIVA, Finland
  - VTT
- ENRESA, Spain
- AITEMIN, Spain (associated with ENRESA)
- CIMNE, Spain (associated with ENRESA)
- GRS, Germany
- BGR, Germany
- UWC (University of Wales)
- JNC, Japan

Construction

Boring of the canister holes started in accordance with the overall plan. The inner four holes where completed in early July. And after four weeks off, boring of the two outer holes started in August and where completed in September. The boring machine performed satisfactory and all six holes fulfil well the requirements regarding verticality, straightness and wall smoothness. The deviation of the centre point varied between 1 to 7 mm, which should be compared to the requirements where the maximum deviation of the centre point, for an 8.5-m deep hole, was 25 mm.

Manufacturing of canisters is proceeding as planned. The final design of the electrical heater system and other details needed for power output is in progress.

Equipment for installation of bentonite blocks and canisters are being manufactured and will be tested before start of installation in the Canister Retrieval Test and the Prototype Repository, in a specific test of the deposition process sequences.

Planning and detail design of the instrumentation and sampling program for monitoring of processes in rock, buffer and backfill have continuously going on during the period. The principal design has been presented and number and type of instruments selected.

Characterisation

During the period, planned field activities have been performed and analyses and reporting work are in progress. Geological characterisation of the canister holes, regarding lithology, structural and water leakage data has been performed. Digitalisation and analyses of data is in progress. The data will be compared to earlier predictions based on characterisation of tunnels and investigation holes.

Total water inflow to canister holes is continuously monitored. Very low flows have been noted. Maximum flow has been measured in canister hole 1 ($8 \cdot 10^{-2}$ litre/minute) and minimum in canister hole 4 ($7 \cdot 10^{-4}$ litre/minute). The holes are numbered from the tunnel front, i.e. from left to right on Figure 4-3.

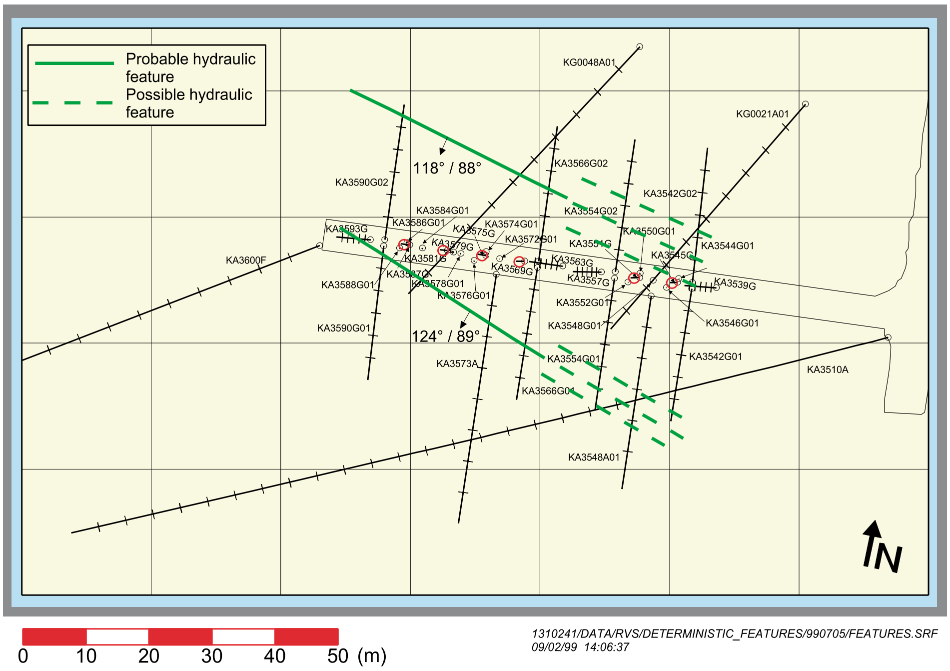


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Figure 4-3. *Major hydraulic features observed during interference tests.*

During 1999 fourteen hydraulic interference tests were made, where flowing of a borehole section was done before closing the section to register the pressure recovery. The pressure response during these tests were registered, in addition to the flow section, in up to 61 observation sections. Two almost vertical major features, one on the south side and one on the north side of the repository, were observed and strikes approximately 120°. The transmissivity of these hydraulic features is within the range $5–10 \cdot 10^{-8}$ m^2/s.

In addition to this major hydraulic test campaign 39 injection tests were done in the upper part of 13 borehole within the Prototype Repository area.

Monitoring

Prior to boring of the two outer holes, i.e. Section II, a number of instruments where installed to monitor the rock mechanical and hydraulic response during the construction phase of the canister holes. The system included instrument for:

- registration of acoustic emission and ultrasonic wave velocity,
- monitoring of stress and strain changes and deformation of intact rock and across joints,
- hydraulic pressure response during boring of the six canister holes.

Vertical displacement of tunnel floor was measured by surveying before and after the holes where completed. Horizontal displacements where measured before and after boring by a tape extensometer between six bolts evenly distributed around each canister hole.

Figure 4–4 shows the configuration of holes for acoustic emission and ray paths for ultrasonic surveys, including the biaxial stress meters installed around each canister holes, 0.3 m away from the periphery of the planned holes.

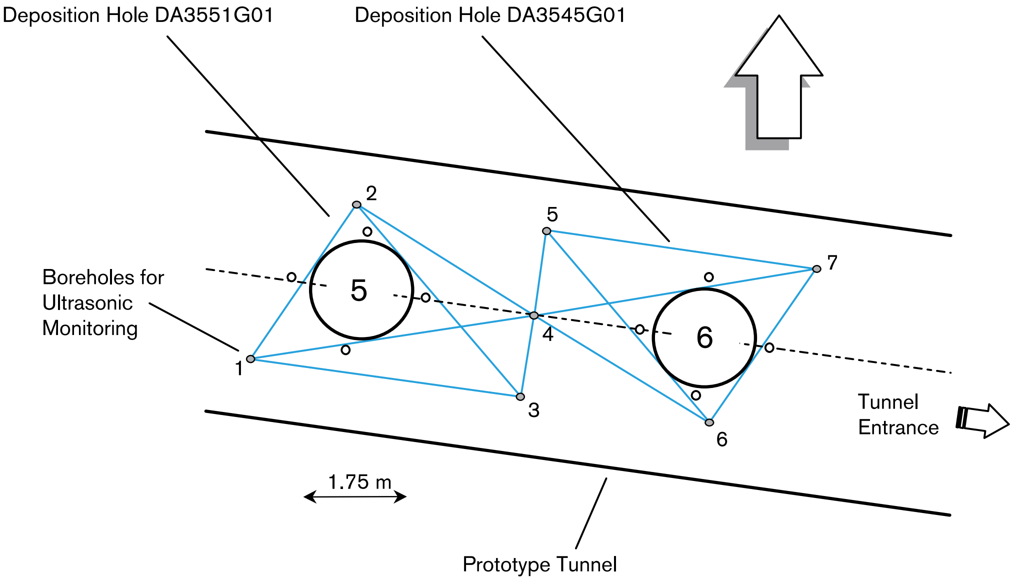
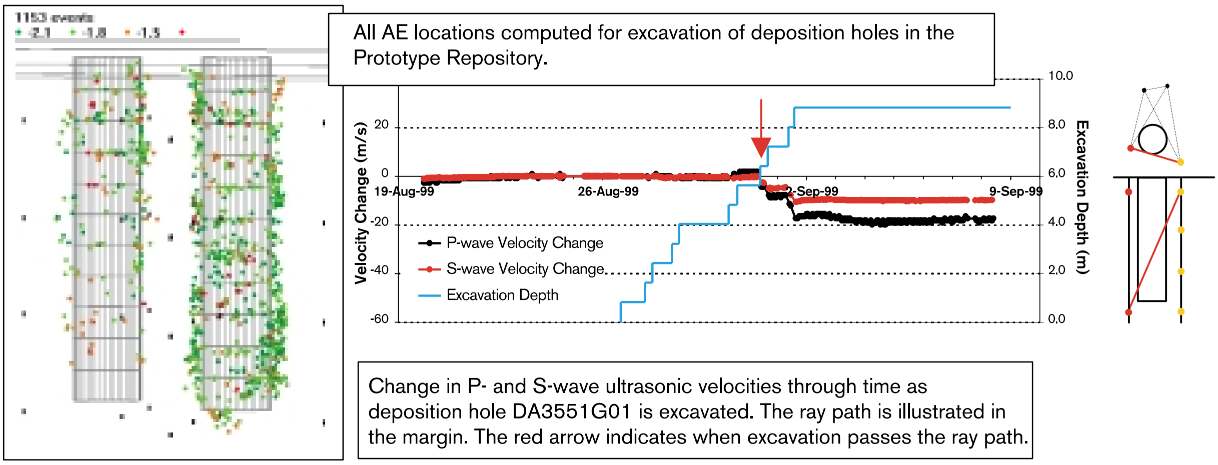


Figure 4-4. *Plan view of the array geometry for the two canister holes in the prototype Repository, including location of the biaxial stress meters.*



All AE locations computed for excavation of deposition holes in the Prototype Repository.

Change in P- and S-wave ultrasonic velocities through time as deposition hole DA3551G01 is excavated. The ray path is illustrated in the margin. The red arrow indicates when excavation passes the ray path.

Figure 4-5. *Example of results from acoustic emission and ultrasonic monitoring of deposition hole excavation in the Prototype Repository.*

All instruments performed satisfactory, and evaluation and interpretation of data are in progress. The acoustic emission monitoring and the ultrasonic survey showed AE locations around the deposition hole and variation in ultrasonic velocities through the rock mass. Figure 4-5, shows a compiled example of results.

Monitoring of stress changes around the canister holes clearly demonstrated a prompt response when the boring reached the level of instrument location. Evaluation has been made of the change in orientations and magnitudes of the maximal stress increase and maximal stress reduction.

Modelling

As part of the characterisation of the Prototype Repository, SKB's Rock Visualisation System (RVS) has been used. This system is a powerful tool to visualise data from the SICADA database and model structures in 3D. RVS is an application based on Bentley's Microstations CAD software.

The process of characterisation has involved geological data from tunnel mappings, core logs, detailed mapping of the tunnel floor and hydrological data. A first draft was made from the tunnel mappings and as additional data have been made available, these have been added to the visualisation and subsequent updating of the model has been made. Hydrological data have been processed in a similar way.

Processing of deposition hole data and mappings and interpretation of hydrological data are under way and they will be included in the final model that is due for presentation in late spring, 2000.

Data from SICADA can be visualised in several ways in RVS. An example is shown in Figure 4-6, where section transmissivities in core holes have been visualised as cylinders. Higher transmissivities have been visualised with a larger diameter and different colour. In Figure 4-7, modelled joint planes are shown. These have been coloured differently depending on origin and water observations.

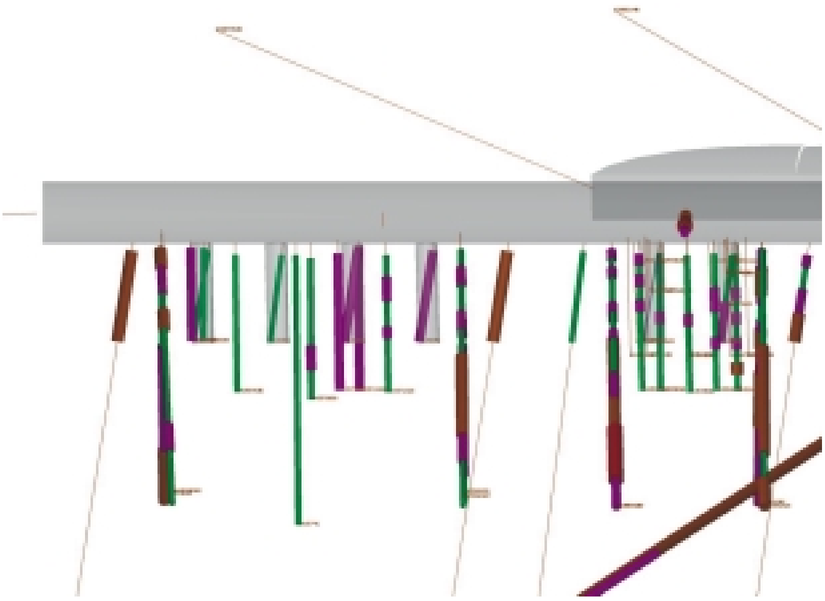


Figure 4-6. *Section transmissivities visualised as cylinders.*

Modelling in 3D with RVS has shown to be a technique that can speed up the process of visualising database records significantly. However, since RVS is quite new, development is still under progress. Future versions of RVS will take advantage of better modelling and graphic tools available in Microstation.

A discrete feature network model (DFN) has been set up to simulate inflow to the canister holes and predict fracture statistics in the Prototype Repository. Results from the first stage of modelling have been presented and a second stage will be reported early year 2000.

The thermal model has been adjusted to the experimental set up configuration and updated thermal properties. In the thermal calculations three cases where investigated with respect to water bearing capacity of the rock and water or no water in the outer slot. The calculation was stopped at a simulation time of 6 years and the highest temperature (dry rock condition and no water in the slot) on the canister surfaces was 90.3°C at 4.5 years and occurred on canister No. 3.

THM-modelling of buffer material is continuously going on and preliminary results considering time to reach full water saturation at different boundary conditions has been presented.

The first modelling on rock mechanical response due to stress redistribution and thermal loading has been reported. The mechanical response has been modelled with the Finite Element method. The possibility to use the Particle Flow Code (PFC) to analyse the mechanical response has been tested.

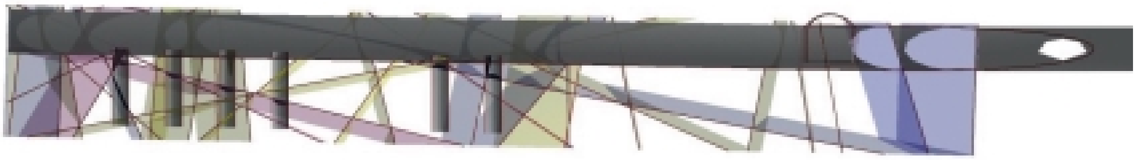


Figure 4-7. *Visualisation of mapped and interpreted joint planes.*

The scope for 2000 is to further detail the planning, prepare the site and furnish key components to the Prototype Repository. Major activities planned are:

- detail planning of layout, material and monitoring, including furnishing etc.,
- finalise the characterisation of the deposition holes and the host rock,
- installation of the inner section,
- evaluation of the characterisation work and reporting,
- prediction modelling.

4.3 Demonstration of Disposal Technology

4.3.1 Background

SKB decided 1996 that the all transport and handling of the copper canister with spent fuel from the encapsulation plant to the deep repository should be carried out with full radiation shielding. Also the handling of the canister in the deposition tunnel should be done with full radiation shielding. A feasibility study for the development of a full size deposition machine started late 1996 and a number of different concepts were investigated. Mid 1997 the preferred concept for the deposition machine was selected and the work with conceptual design and engineering design of the deposition machine started. Early 1998 the manufacturing drawings and specifications for the main parts of the machine was completed and could be ordered for manufacturing.

The assembly of the deposition machine for testing on a test bed at the manufacturing workshop started in December 1998. The workshop tests were completed in May 1999. The deposition machine was transported to the Äspö HRL in June 1999 and installed in a tunnel prepared with four deposition bore-holes at level 420 m below ground. This tunnel will also be used as an exhibition hall for information about the Swedish Nuclear Waste Management Programme.

The development of the equipment needed for the handling of the buffer material and canisters with heaters for the two planned engineering experiments at Äspö HRL, the Canister Retrieval Test and the Prototype Repository, has been ongoing in parallel.

4.3.2 Objective

The main objective with the ongoing work is to develop and demonstrate the techniques and equipment needed for handling and deposition of the buffer material and copper canister with spent fuel as well as the emplacement of the backfill material and sealing of the deposition tunnels.

4.3.3 Results

The full size deposition machine for deposition of copper canisters is installed during 1999 and will be used for demonstration at Äspö HRL. Figure 4-8 shows the deposition machine on the test bed at the manufacturing workshop in May 1999.

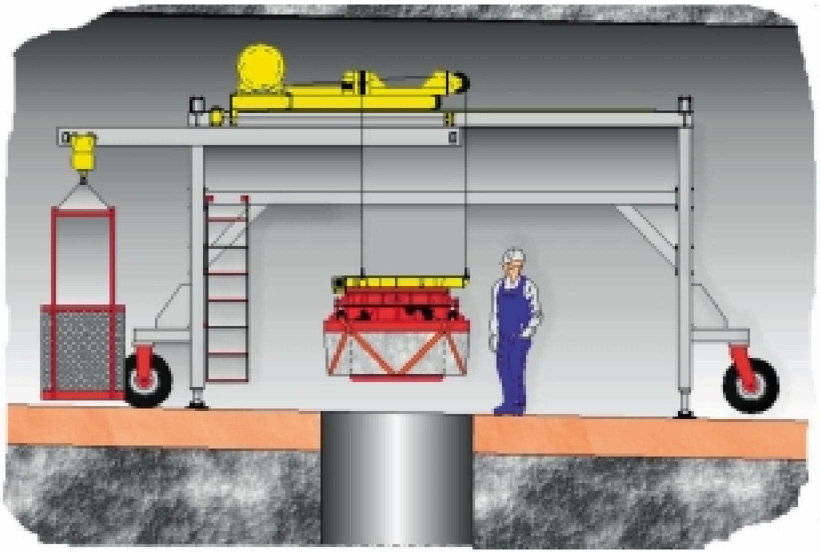
The design and testing of temporary equipment for handling and deposition of the buffer material and canisters for the Canister Retrieval Test and the Prototype Repository will be completed early 2000.

The main data of the deposition machine are as follows:

Height: 4.6 m
Width: 3.7 m
Length: 11.5 m
Weight: 160 metric tons including the weight of the copper canister.
The total weight of the demonstration machine at Äspö is about 150 metric tons.

Figure 4-8. *Picture of the deposition machine on the test bed in the workshop.*

The gantry crane with tools for emplacement of the bentonite buffer into deposition hole and the small deposition machine that will be used for these experiments are shown in the illustrations Figures 4-9 and 4-10.

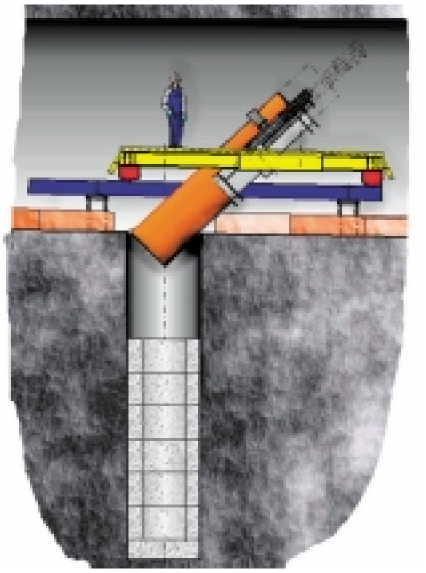


The main data and features of the gentry crane are as follows:

Height: 4.3 m
Width: 2.8 m
Length: 8.5 m
Lifting capacity: Main hoist = 3 metric tons. Auxiliary hoist = 1 metric tons.

The auxiliary hoist with the small circular working cage can be lowered inside the pile of bentonite rings down in the deposition hole. One ring of compacted bentonite is shown in the lifting tool of the gentry crane.

Figure 4-9. *Illustration of the gantry crane for handling of the compacted buffer material.*



The main data and features of the deposition machine are as follows:

Height:	3 m
Width:	3.5 m
Length:	8.7 m
Weight:	13 metric tons excluding the copper canister.

The limited height in the prototype repository requires that the canister is tilted down into the deposition hole.

Figure 4-10. *Illustration of the small deposition machine.*

Development work of the equipment needed in the future deep repository will continue based on experiences from the ongoing work at Äspö. The different machines, transport and auxiliary equipment will be developed to a feasibility or conceptual stage as part of the ongoing design studies of the deep repository. Some of the equipment may later also be designed and constructed and tested at the Äspö HRL for verification of the function and suitability of the equipment.

4.4 Backfill and Plug Test

4.4.1 Background

The *Backfill and Plug Test* includes tests of backfill materials and emplacement methods and a test of a full-scale plug. It is a test of the integrated function of the backfill material and the near field rock in a deposition tunnel excavated by blasting. It is also a test of the hydraulic and mechanical functions of a plug. The test is partly a preparation for the Prototype Repository.

In 1998 the preparations and all the required work in the rock in the vicinity of the test tunnel were finished. In 1999 the backfilling and plugging were made and the entire test set-up with casting of the final part of the plug was finished in autumn 1999. The water saturation, with water filling of permeable mats, started in late 1999.

4.4.2 Objectives

The main objectives of the Backfill and Plug Test are:

- to develop and test different materials and compaction techniques for backfilling of tunnels excavated by blasting,
- to test the function of the backfill and its interaction with the surrounding rock in full scale in a tunnel excavated by blasting,
- to develop technique for building tunnel plugs and test the function.

4.4.3 Experimental concept

Figure 4-11 shows an axial section of the test layout. The test region, which is located in the old part of the ZEDEX drift, can be divided into the following three test parts:

1. The *inner part* filled with backfill containing 30% bentonite (sections A1-A5 and B1).
2. The *outer part* filled with backfill without bentonite and bentonite blocks at the roof (sections B2-B5).
3. The *plug*.

The backfill sections are applied layer wise and compacted with vibrating plates that were developed and built for this purpose. It was concluded from preparatory tests that inclined compaction should be used in the entire cross section from the floor to the roof and that the inclination should be about 35 degrees.

The inner test part is filled with a mixture of bentonite and crushed rock with a bentonite content of 30%. The composition is based on results from laboratory tests and field compaction tests. The outer part is filled with crushed rock with no bentonite additive. Since the crushed rock has no swelling potential but may instead settle with time, a slot of a few dm is left between the backfill and the roof and filled with a row of highly compacted blocks with 100% bentonite content, in order to ensure a good contact between the backfill and the rock. The remaining irregularities between these blocks and the roof are filled with bentonite pellets.

The two test parts are about 14 meter long and divided by drainage layers of permeable mats in order to apply hydraulic gradients between the layers and to study the flow of water in the backfill and nearfield rock. The mats are also used for the water saturation of the backfill. The mats are installed in both backfill parts with the individual distance 2.2 m. Each mat section is divided in three units in order to be able to separate the flow close to the roof from the flow close to the floor and also in order to separate the flow close to the rock surface from the flow in the central part of the backfill.

The outer section ends with a wall made of prefabricated beams for temporary support of the backfill before casting of the plug. Since in situ compaction of the backfill cannot be made in the upper corner, this triangle is instead filled with blocks of bentonite/sand mixture with 20% bentonite content.

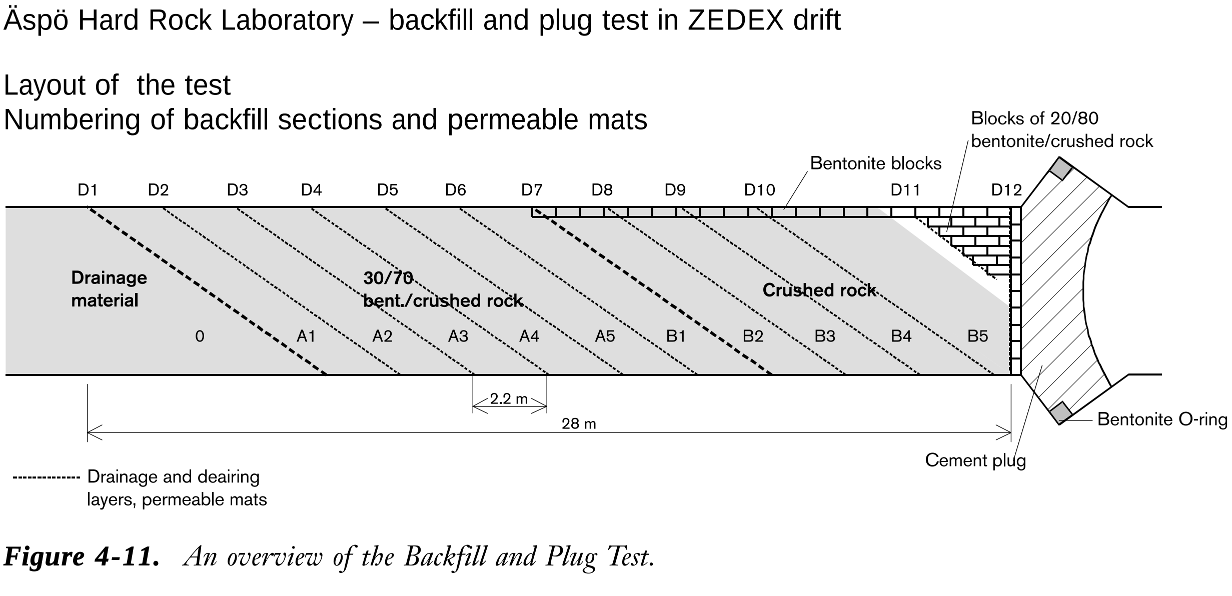


Figure 4-11. *An overview of the Backfill and Plug Test.*

The backfill and rock are instrumented with piezometers, total pressure cells, thermocouples, moisture gauges, and gauges for measuring the local hydraulic conductivity. The axial conductivity of the backfill and the near field rock will after water saturation be tested by applying a water pressure gradient along the tunnel between the mats and measuring the water flow. All cables from the instruments are enclosed in Tecalan tubes in order to prevent leakage through the cables. The cables are led through the rock to the data collection room in bore holes drilled between the test tunnel and the neighbouring Demo-tunnel.

The *plug* is designed to resist water and swelling pressures that can be developed. It is equipped with a filter on the inside and a 1.5 m deep triangular slot with an "O-ring" of highly compacted bentonite blocks at the inner rock contact.

The saturation is expected to take 1–2 year and the subsequent flow testing about 1 year. The flow testing in the backfill is planned to start after saturation, when steady state flow and pressure have been reached.

4.4.4 Results

The test setup has been completed and the water saturation phase and the data collection have started during 1999:

- The innermost 18 meters of the test drift were filled with drainage material in the beginning of 1999. This part will not be used for the tests.
- 2 pumps were installed in order to keep the inner part free from water during the construction phase. Each pump was placed in a concrete tube with lid. The capacity of each pump is 5 l/min or equal to the measured inflow into this part of the drift.
- An inclined concrete wall was built outside the drainage material in order to separate this part from the test sections. The concrete was cast in contact with the rock except for at the roof where rubber foams were placed between the roof and the concrete with the purpose to act like an O-ring and prevent backfill from penetrating into the drainage material.
- The backfilling started in February. Six sections were backfilled and compacted with the mixture of 30% bentonite and 70% crushed rock (A1-A5 and B1). Section B1 was originally intended to be made of crushed rock but it was decided to change the backfill material in that section. Each section contains 6 layers with the axial thickness 35 cm and the inclination 35 degrees. The vibrating plate compactor and the vibrating "roof compactor" were used during the compaction of each layer.
- Sections B2–B5 were backfilled with 100% crushed rock and compacted according to the schedule and the 10 cm gap at the roof was filled with bentonite blocks and bentonite pellets. The pellets were placed with a "pellets blowing machine".
- Three permeable mats (one large mat in the centre and two smaller mats at the roof and floor respectively) were installed on top of the inclined concrete wall and between all backfill sections according to the plans.
- The instruments were gradually installed in the backfill according to the plans. The sensors were placed from the surface of each layer.
- Twelve packages with cables and Tecalan tubes from instruments and mats were installed in the through connection tubes during the backfilling and led from the test drift to the Demonstration drift. After installation the through connections were leakage tested.

- The data collection house was built and the cables and tubes were led on cable ladders into the data collection systems in the house.
- About 4 m^3 blocks of brick-size with 20% bentonite and 80% sand were installed in the triangular space left between the roof and the retaining wall, where compaction of backfill material could not be made. The final space of about 1.7 m^3 was filled with bentonite pellets, with the purpose to “buffer” the swelling pressure of the blocks. Installation of all backfill material was finished on June 30.
- About 1,300 bentonite blocks ($25 \cdot 25 \cdot 8$ cm^3) were installed in the inner $0.5 \cdot 0.5$ m^2 space between the first part of the plug and the rock wall to form the O-ring around the plug. In order to prevent concrete from penetrating between the blocks the tangential slots were caulked. The radial slots were filled with bentonite paste.
- The mould for part 2 of the plug was built and required reinforcement installed see Figure 4-12. Tubes for grouting between the concrete and the rock were also installed as well as cooling tubes. Finally the plug was cast on September 23 by pumping about 70 m^3 concrete into the mould.
- The panels and the tube system for measuring water pressure in the rock and for the flow testing were installed in the data collection house. Registration of data from the 200 gauges started gradually.
- The filling of the concrete at the crown of the slot were checked by drilling a hole and studying the rock/concrete contact with borehole television. A small slot of about 1 cm could be seen but was considered to be acceptable.
- The arrangement for filling and pressurising the permeable mats was installed. It consists of three 1.6 m^3 water tanks, three 150–500 litre hydrofors, three gas tubes with nitrogen gas, two pressure regulators, and four flow meters.
- The water saturation started on November 29. Every second mat in the sections with bentonite/crushed rock were filled with water with the salt content 1.6% and pressurised with 100–150 kPa. The mats at the roof were left unfilled in order to minimise the risk of having piping between the backfill and the roof.
- The reading of the instruments is in full progress. It seems as we are receiving acceptable data from almost all instruments.

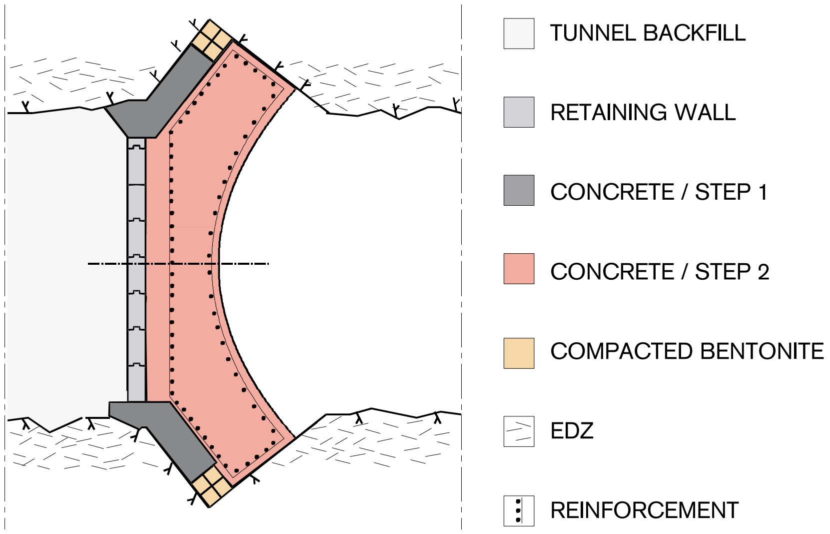


Figure 4-12. *Layout of the Plug.*

Fig 4-13 shows a 3D visualisation of the experimental setup.

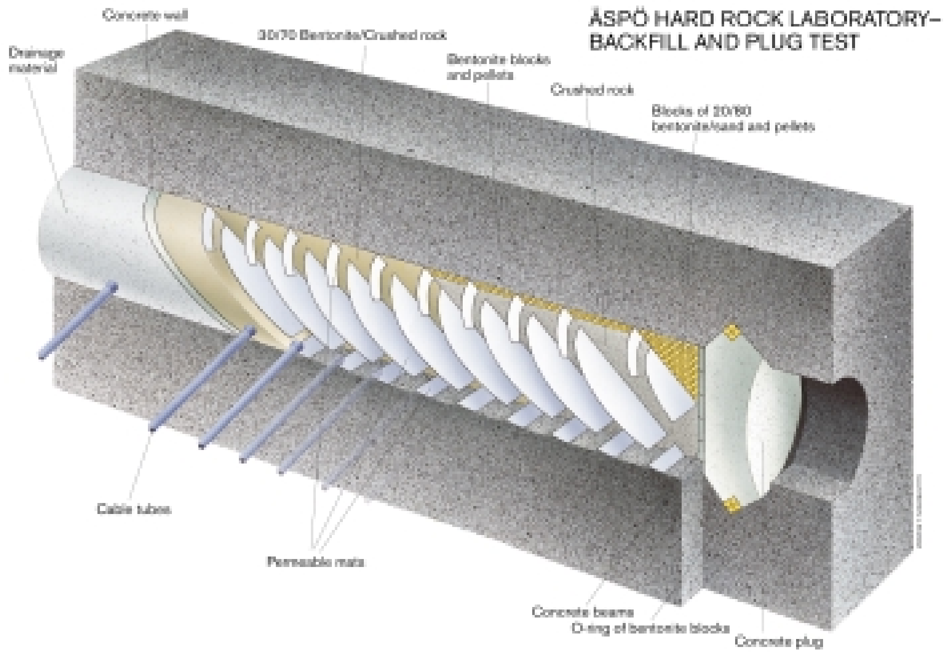


Figure 4-13. *Illustration of the experimental setup of the Backfill and Plug Test.*

4.5 Canister Retrieval Test

4.5.1 Background

SKB's strategy for the disposal of canisters with the spent nuclear fuel is based on an initial emplacement of about 10% of the number of canisters followed by an evaluation of the result before any decision is made on how to proceed. One outcome can be that the result is not accepted and that the canisters have to be recovered. In such case some, if not all, canisters can be surrounded by a saturated and swollen buffer, which holds the canister in such a grip that the canister can not just be pulled up. First the bentonite grip has to be released, for which two alternative principles can be applied; remove or shrink the bentonite. Then the canister is free to be lifted up to the tunnel and placed in a radiation shield. A concern is any type of radioactive contamination that the bentonite has been exposed to.

The retrieval test is aiming at demonstrating the readiness for recovering of emplaced canisters also after the time when the bentonite has swollen. The process covers the retrieval up to the point when the canister is safely emplaced in a radiation shield and ready for transport to the ground surface. The test is separated into two phases; Design and Set-up, and the actual Retrieval Test.

4.5.2 Objectives

The overall aim of the Canister Retrieval Test is to demonstrate to specialists and to the public that retrieval of canisters is technically feasible during any phase of operation, especially after the initial operation. In order to provide the test conditions necessary for actual retrieval tests the test set-up has to achieve the following objectives:

- Two vertically bored test holes in full repository scale, which fulfil the quality requirements deemed necessary for the real repository.

- Careful and documented characterisation of the properties of these holes including the boring disturbed zone.
- Emplacement of bentonite blocks, bentonite pellets and canisters with heaters, and artificial addition of water in accordance to conditions planned for the real repository.
- Saturation and swelling of the buffer under controlled conditions, which are monitored.
- Preparations for testing of canister retrieval.

Boring of full-scale deposition holes and geometrical/geotechnical characterisation of holes as well as emplacement of bentonite and canisters with heaters are made within subprojects that concern also other tests in the ÄHRL.

4.5.3 Experimental concept

The deposition tunnel for the experiment is located on the 420-meter level in the extension of the D-tunnel, and is excavated by conventional drill and blast. The tunnel is 6 meters wide and as well, 6 meters high, and the centre distance between the two deposition holes is 6 meters, which is in agreement with the distance considered for the deep repository. In the Canister Retrieval Test, however, the temperature influence from surrounding canisters is less than in the deep repository, which has the effect that a higher thermal power is needed in the canister in order to obtain a temperature of about 90°C on the surface of the canisters.

The buffer will be installed in the form of blocks of highly compacted Na-bentonite, which will have full diameter, 1.65 m, and a height of 0.5 m. When the stack of blocks is 6 m high the canister equipped with electrical heaters is lowered down in the centre, cables to heaters, thermocouples and strain gauges are connected, and further blocks are emplaced until the hole is filled up to one m from the tunnel floor. On top the hole is sealed with a plug made of concrete and a steel plate as cover. The plug is secured against heave caused by the swelling clay with cable anchored to the rock. The tunnel will be left open for access and inspections of the plug support.

Artificial addition of water is provided regularly around the bentonite blocks by means of permeable mats attached to the rock wall. The design of the mats is done so that they are not disturbing the future test of retrieval.

Saturation time for the test is about two-three years in the 350 mm thick buffer along the canister and about 5 years in the buffer below and above the canister. Decision on when to start the retrieval tests is dependent on information of the degree of saturation, and instruments will be installed to monitor the process in different parts of the buffer. This instrumentation will be similar to the instrumentation in the Prototype Repository and yield comparable information during the saturation period. The intention to minimise disturbance during retrieval tests, however, restricts the number and locations of instruments.

4.5.4 Results

The boring of the two full scale holes was carried through successfully in May. In the inner hole the bore head was equipped with the disc cutters, which were found during boring of the first hole in the Assembly Hall to provide the most efficient cutting of the rock. In the outer hole, however, the pre-prepared bit cutters were used, one in the centre and one at the periphery, so that the planned study on registration of forces on the rock wall caused by the bore head was carried through as planned. The reporting of these mechanical results is in progress.

Prior to boring a similar configuration of holes for acoustic emission and ray paths for ultrasonic surveys, and stress metres was created as in the Prototype Repository. Measurement of acoustic events took place during natural pauses in the boring, preferably when a new casing was added. The registered events are thus those, which occurred up to an hour after the borehead had passed the elevation. The drop in ultrasonic velocity closer to the rock wall than 20–30 mm showed the same tendency as is shown in Figure 4-5, with a drop when the borehead passed the ray elevation. Also stress measurements were made at a distance of about 300 mm from the hole wall. The results from the acoustic emission measurement and changes in rock stresses around the holes have been evaluated and presented in draft reports. One paper on the rock stress monitoring was presented at the EUROCK 2000 in Aachen, Germany. In this paper the interpretation of the stress data reveals an increase of the maximum stress after boring in a direction that is parallel to the direction of the global principal stress in five out of eight investigations. In the other three the direction is perpendicular to the direction of the global principal stress, thus indicating the complex nature of rock stresses and complex impact of tunnel, bored hole and maybe cutters on the boring head. The evaluation continues.

The design work came to the conclusion that artificial water should be added in porous mats attached to the rock wall. They will not cause harm to the later test with freeing and retrieval of the canister. The plan for instrumentation was adopted to the basic plan for the Prototype Repository, and to the same type of instruments. An advantage with this copying is that a first test of installation of the instruments is made before the work starts in the Prototype Repository.

As the tunnel will not be backfilled a support above the hole is necessary to prevent the bentonite from swelling upward. Different designs were considered and the alternative with plugs submerged in the deposition hole selected. The plug is anchored to the rock by cable bolts directed in an angle to the vertical, outward from the hole. The cables have to be designed for the swelling pressure (5 MPa) but not the groundwater pressure, as the permeable mats can neutralise this pressure.

During the second half of 1999 the main activity was preparations for the installation of bentonite blocks and canister by planning for testing of the deposition sequences using the machines manufactured for the installation (Figures 4-9 and 4-10).

4.6 Long term test of buffer material

4.6.1 Background

Bentonite clay has been proposed as buffer material in several concepts for HLW repositories. In the Swedish KBS-3 concept the demands on the bentonite buffer are to serve as a mechanical support for the canister, reduce the effects on the canister of a possible rock displacement, and minimize water flow over the deposition holes.

The decaying power from the spent fuel in the HLW canisters will give rise to a thermal gradient over the bentonite buffer by which original water will be redistributed parallel to an uptake of water from the surrounding rock. A number of laboratory test series, made by different research groups, have resulted in various buffer alteration models. According to these models no significant alteration of the buffer is expected to take place at the prevailing physico-chemical conditions in a KBS-3 repository neither during nor after water saturation. The models may to a certain degree be validated in long term field tests. Former large scale field tests in Sweden, Canada, Switzerland and Japan have in some respects deviated from possible KBS-3 repository conditions and the testing periods have generally been dominated by initial processes, i.e. water uptake and temperature increase.

4.6.2 Objectives

The present test series aims at validating models and hypotheses concerning physical properties in a bentonite buffer material and of related processes regarding microbiology, radionuclide transport, copper corrosion and gas transport under conditions similar to those in a KBS-3 repository. The expression "long term" refers to a time span long enough to study the buffer performance at full water saturation, but obviously not "long term" compared to the lifetime of a repository. The objectives may be summarized in the following items:

- Data for validation of models concerning buffer performance under quasi-steady state conditions after water saturation, e.g. swelling pressure, cation exchange capacity and hydraulic conductivity.
- Check of existing models on buffer-degrading processes, e.g. illitization and salt enrichment.
- Information concerning survival, activity and migration of bacteria in the buffer.
- Check of calculation data concerning copper corrosion, and information regarding type of corrosion.
- Data concerning gas penetration pressure and gas transport capacity.
- Information which may facilitate the realization of the full scale test series with respect to clay preparation, instrumentation, data handling and evaluation.

4.6.3 Experimental concept

The test series (Table 4-1) concern realistic repository conditions except for the scale and the controlled adverse conditions in three tests. The testing principle for all planned tests is to emplace "parcels" containing heater, central tube, precompacted clay buffer, instruments, and parameter controlling equipment in vertical boreholes with a diameter of 300 mm and a depth of around 4 m (Figure 4-14).

Adverse conditions in this context refer to high temperatures, high temperature gradients over the buffer, and additional accessory minerals leading to i.a. high pH and high potassium concentration in clay pore water. The central copper tubes are equipped with heaters in order to simulate the decay power from spent nuclear fuel. The heater effect are regulated or kept constant at values calculated to give a maximum clay temperature of 90°C in the standard tests and in the range of 120 to 150°C in the adverse condition tests.

Table 4-1. Layout of the Long Term Test series.

Type	No.	max T, °C	Controlled parameter	Time, years	Remark
A	1	130	T, $[K^+]$, pH, am	1	pilot test
A	0	120–150	T, $[K^+]$, pH, am	1	main test
A	2	120–150	T, $[K^+]$, pH, am	5	main test
A	3	120–150	T	5	main test
S	1	90	T	1	pilot test
S	2	90	T	5	main test
S	3	90	T	>>5	main test

A = adverse conditions
S = standard conditions
T = temperature
$[K^+]$ = potassium concentration
pH = high pH from cement
am = accessory minerals added

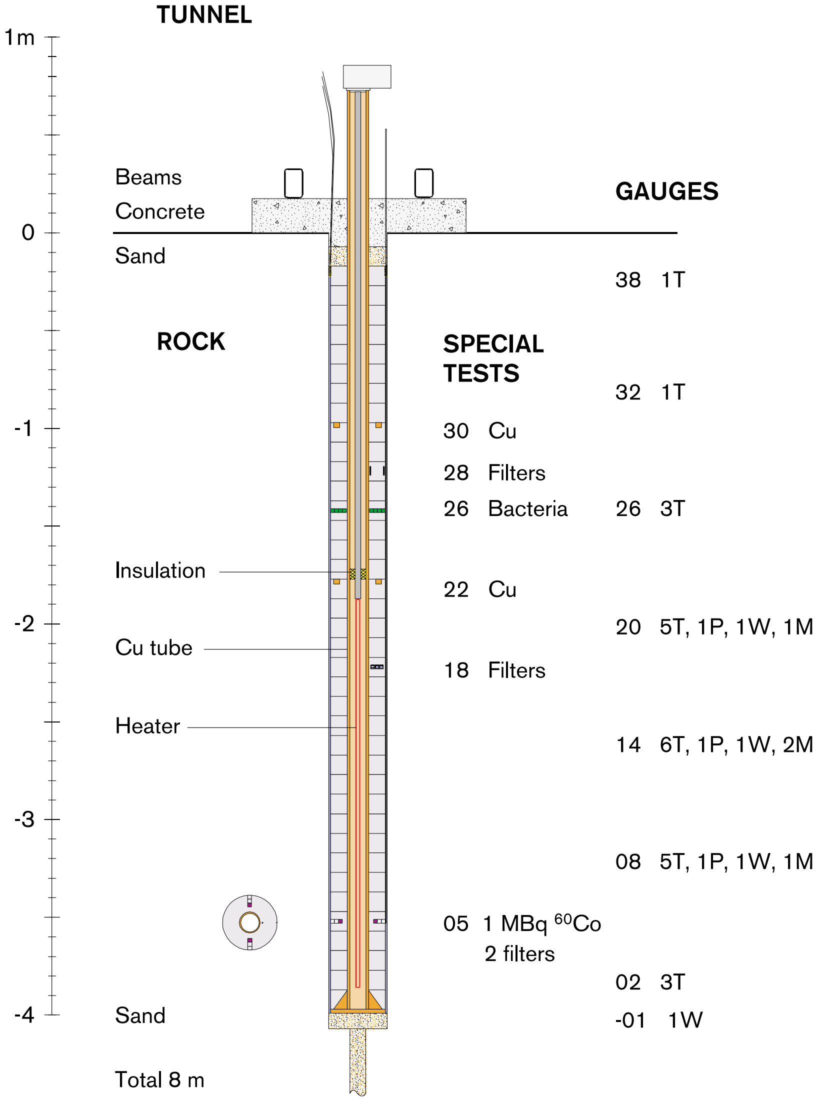


Figure 4-14. *Cross-section view of an S-type parcel. The first figures in column denote block number and second figures denote the number of sensors. T denotes thermocouple, P total pressure sensor, W water pressure sensor, and M moisture sensor.*

Temperature, total pressure, water pressure and water content, are measured during the heating period. At termination of the tests, the parcels are extracted by overlapping core-drilling outside the original borehole. The water distribution in the clay are determined and subsequent well-defined chemical, mineralogical and physical testing are performed.

4.6.4 Results

The one year pilot tests A1 and S1 have been completed. Reference material and material from defined positions in the A1 and S1 parcels material have been tested and analyzed (total number of tests within brackets):

- water ratio of parcel material (210),
- density of parcel material (75),
- hydraulic conductivity of reference (10) and parcel material (20),

- swelling pressure of reference (10) and parcel material (20),
- bending strength of reference (10) and parcel material (19),
- shear strength of reference (1) and parcel material (3),

and the following chemical and mineralogical analyses (total number within brackets):

- ICP-AES element analyses of total and clay fraction, reference (20) and parcel material (50),
- Cu-trien analyses of cation exchange capacity of reference (10) and parcel material (20),
- XRD analyses of total and clay fraction, reference (20) and parcel material (50),
- SEM microstructure and element analyses (spot and mapping).

Supporting tests and analyses have been completed and reporting is in progress.

The analyses concerning physical and mineralogical conditions in reference and exposed bentonite material may be summarised in the following way:

- No significant difference was found with respect to clay mineral structure according to CEC, XRD analyses.
- Minor mineralogical differences were found with respect to exchangeable cations and reduced silica content according to ICP/AES element analyses.
- Indications of redistribution of accessory minerals were noticed in the exposed material according to SEM analyses.
- No significant changes in physical properties were found, see Figure 4-15.

An overarching conclusion is that no unpredicted changes were found as a result of the exposure to 90 and 130 C° for 1 year.

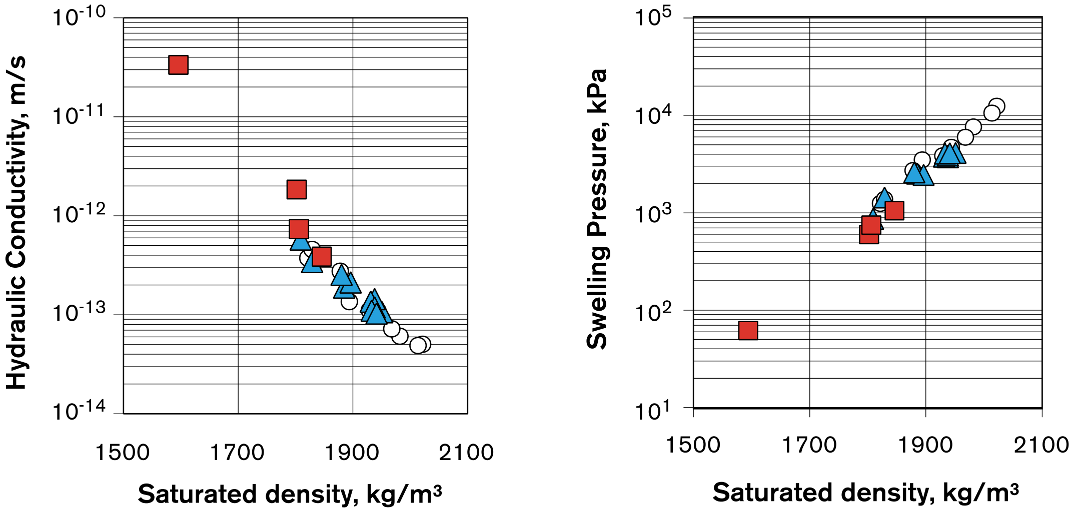


Figure 4-15. *Measured hydraulic conductivity and swelling pressure as a function of clay sample density at full saturation. Squares represent A1 parcel material and triangles S1parcel material. Open circles represent reference material.*

Long Term Test series

The 4 long term test parcels and the additional 1-year parcel have been installed. Each parcel is composed of exchangeable heater, central copper-tube, approximately 40 highly compacted bentonite (Volclay MX-80) cylinder rings, gauges, and various additives (Figure 4-14). The parcels were placed in percussion drilled bore-holes with a diameter of 300 mm and a depth of 4 m in diorite rock at a depth of 450 m below ground. Temperature, total pressure, water pressure and water content are now being measured. Each parcel contains 25 thermocouples, 3 total pressure gauges, 3 water pressure gauges, 4 relative humidity sensors, 7 titanium filters, and 12 water sampling containers. The thermocouples are jacketed by cupro-nickel alloy and all other equipment is made of titanium. All sensors are connected to a standard computer and registrations are made every hour.

4.6.5 Planned work

The physical properties of the 5 installed parcels will be closely followed up during the year. Minor laboratory work concerning development of test and analyse technique will be made. The termination of the A0-parcel is planned to start in March 2001.

4.7 Mechanical modelling of cracks caused by mechanical excavation

4.7.1 Background

The deep repository for spent fuel consists of galleries of horizontal tunnels with vertical large holes in the floor for emplacement of canisters and surrounding bentonite clay. The vertical holes are planned to be bored by means of rotating crushing boring. The tunnels can be excavated by conventional drill-and-blast or by TBM-technique. In order to be able to predict the saturation process for the buffer and the tunnel backfill the geohydraulic regime in the rock, which is in contact with the buffer and backfill, has to be sufficiently well known. This hydraulic regime is a result of the structure of the crack network that is created during excavation.

Laboratory tests have shown that the propagation and shape of cracks can be systematically related to the properties of the rock and the machine parameters. Based on earlier work with penetration of indenters into different types of rock a conceptual model for crack propagation for single tools have been proposed. This model has been further developed with respect to propagation into hard rock and mathematical expressions for the different relationships have been proposed in an Identation Crack Model. This model has been compared with some laboratory tests by means of numerical and analytical as well as by neural network fitting.

4.7.2 Objectives

The goal is to determine the degree of fraturing in the rock wall caused by the mechanical tools during excavation as a function of the force acting on the cutter head in contact with the rock wall.

4.7.3 Experimental concept

The modelling work is made on a theoretical basis, and utilises results from laboratory tests carried out by Luleå Technical University as well as reported results from laboratory tests in the literature.

Field tests have been conducted in one of the full scale holes in the Canister Retrieval Test area by installation of two instrumented cutters in the bore head, one centre and one gauge cutter, and measurement of the forces acting on them. Fracture systems in the rock wall are examined and the results compared to the measured forces on the cutter in that particular position.

4.7.4 Results

Influence of loading rate

A parameter specifying the loading rate has been defined as the stress intensity factor divided by the corresponding loading time. By means of a wedge loading applied to a short-rod rock fracture specimen tested with the SHPB (Split Hopkinson Pressure Bar), the fracture toughness of Fangshan gabbro and Fangshan marble has been measured over a wide range of loading rates, $k = 10^{-2}$–10^{6} MPa · $m^{1/2}s^{-1}$. The objective of this work is to combine the macroscopic experiment with meso- and micro-observation; to apply an unified specimen geometry for various loading speeds. Preliminary results reveal many aspects of fracture initiation and propagation with a high loading rate; among them are that fracture toughness increases very fast (30 times) within a loading rate range of 10^4 to 10^6 $MPm^{1/2}s^{-1}$ and that there is almost no increase in fracture toughness from 10^{-2} to 10^4 $MPm^{1/2}s^{-1}$, see Figure 4-16.

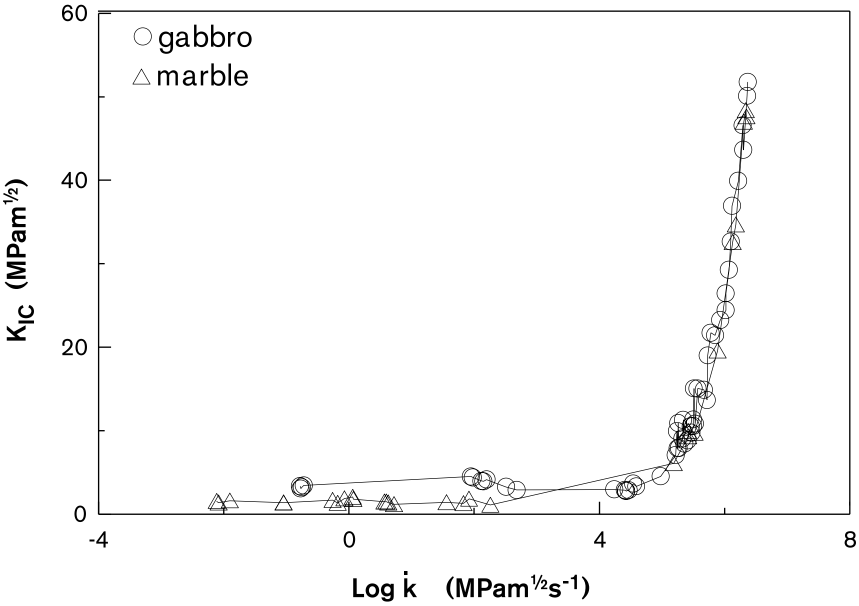


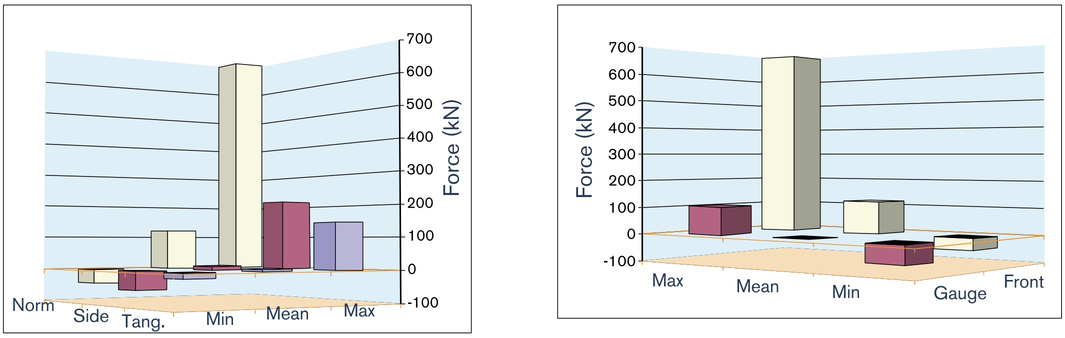
Figure 4-16. *Fracture toughness of Fangshan gabbro and Fangshan marble varies with increased loading rate. The toughness is nearly constant when* $k < 10^5 MPam^{1/2}s^{-1}$ *and increases rapidly when* $\kappa \geq 10^5 MPam^{1/2}s^{-1}$.

Preliminary results also show that fracture toughness is very sensitive to temperature variation in the low loading rate range but not sensitive in the high loading rate range. Macro-observations for fractured rock specimens indicated that, in the section (which was perpendicular to the fracture surface) of a specimen loaded by a dynamic load, there was clear crack branching or bifurcation, and the higher the loading rate was, the more branching cracks occurred. Furthermore, at very high loading rates ($k \geq 10^6$ MPa · $m^{1/2}s^{-1}$) the rock specimen was broken into several fragments rather than only two halves. However, for a statically fractured specimen there was hardly any crack branching. The experiment carried out at Äspö shows that the loading rate is approximately 10^1 to 10^2 MPa · $m^{1/2}s^{-1}$. This result indicate that the cutting speed in the Äspö deposition holes could have been increased without any increase in specific energy for cutting.

Field test at Äspö

The objective with the field study is to be able to understand the practical force magnitude in the field conditions, the practical loading rate and the cracks in the remaining rock corresponding to the forces in reality. The field test was carried through in May. The defined laboratory test concerning rock properties and the observation of the cracks in the rock core taken from Äspö are to be carried out. The data analysis and reporting is in progress.

The test results indicate that the maximum, minimum and mean normal forces of the front cutter during the first 7-minute of excavation with casing number 10 (last casing in the approx. 8.5 m deep hole) are 684, -43 and 120 kN, respectively. However, the maximum, minimum and mean normal forces of the gauge cutter in the same period are only 104, -69 and –1.2 kN, respectively. It is clear that the maximum normal force of the front cutter is much larger than that of the gauge cutter. The magnitudes of the tangential force and side force are, however, similar for both front cutter and gauge cutter. The force magnitudes of the front cutter and comparisons between the forces measured at the gauge cutter and front cutter are graphically shown in Figure 4-17.



(a) (b)

Figure 4-17. *(a) Maximum, minimum and mean values of the normal force, side force and tangential force measured at the front cutter; (b) Comparison between the forces measured at the gauge cutter and front cutter*

A mechanical model was established between indentation force and indentation depth /Kou et al, 1996/. Based on that model a linear relation ship between the penetration rate and the thrust was predicted if the rotation speed is fixed /Kou et al 1995/. This relationship has been verified by the field test results, see Figure 4-18.

In addition, since the force acting on the cutter is not constant and varies from time to time, the probability of the force magnitude has been calculated. This provided a possibility to estimate the durability of the cutters working in such a condition. Spectral analysis of the forces acting on the rock has also been carried out. The results make it possible to evaluate the loading rate of the rock during cutting process in-situ. The results indicate that quasi-static approach is valid and there is still plenty of room to increase the cutting speed without increasing the specific energy in cutting.

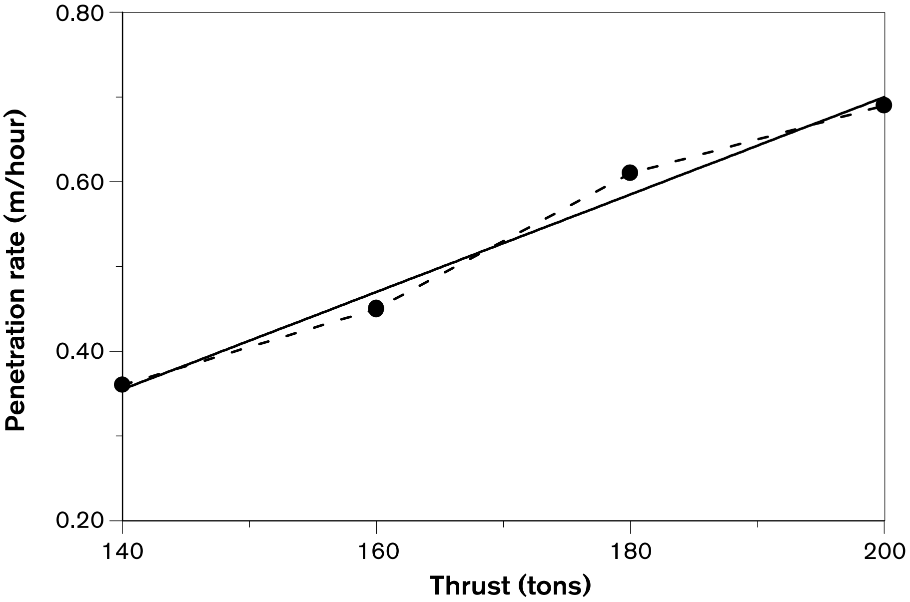


Figure 4-18. *Relationship between thrust and penetration rate of the machine obtained from the field test.*

5 Äspö facility operation

5.1 Plant operation

5.1.1 Introduction

The operation of the facility has worked smoothly. A few new projects dealing with security or reliability of the facility have been started. In accordance with the maintenance program for the facility a “five years inspection” was done. The output will result in some extra reinforcement activities, mainly in the deeper parts of the facility.

At the end of the year the responsibility for the storage of equipment and consumable supplies was taken over by the experimental service group.

5.1.2 Surface activities

A few new office rooms were built above the new chemistry laboratory. In spite of the fact that a new wing to the old office was constructed a few years ago we are already confined with space.

The electrical supply to the facility comes today from two different sources. The underground part is supplied direct from the nuclear power station, while the Äspö village gets its electricity from an airborne net on the mainland. The latter is a relatively weak net and especially during the autumn and winter there are several cuts in the delivery. A new cable from the nuclear station to Äspö is now in progress and will be in operation in spring 2000.

5.1.3 Underground activities

A new rescue chamber has been constructed at the –420 m level. The chamber is sited in an existing niche and will be equipped with a CO_2 scrubber system for cleaning of the used breathing air. The system is designed for 60 people during six hours and will considerably increase the safety at this level.

Outside the –450 m landing a new fire brigade station has been built inside a container. It is well equipped for fire fighting which also includes a four-wheel drive motorbike. An evacuation exercise was held underground in cooperation with the fire brigade. The overall result was positive, but also showed on things that must be improved.

The water supply system has been extended and includes outlets at all the experimental tunnels at levels –420 and –450 m. Both formation water and fresh water are available from the system.

A system for supervising the operation of the facility has been taken into operation. The system facilitates the operation considerably but also gives us valuable information for maintenance. Knowledge of running hours for pumps and so on will make it easier to plan the maintenance.

A project for safer registration underground has been started. The basic idea with hands free registration has been left due to lack of such systems on the market. A more simple system, but still computerised will be installed next year.

5.2 Information and public relations

5.2.1 Background

The information group's main goal is to create public acceptance for SKB in co-operation with other departments in SKB. This is achieved by giving information about SKB, the Äspö HRL and the SKB siting programme. The visitors are also given a tour of the Äspö HRL. Today there are one visitors administrator and four public relations officers stationed at the Äspö HRL.

5.2.2 Results

12,211 visitors visited the Äspö HRL during 1999. The groups have represented the general public, communities where SKB performs feasibility studies, teachers, students, politicians, journalists and visitors from foreign countries

In the spring started an education for the employees at the local nuclear power station (OKG). The tours had a special programme with focus on the process for siting the deep repository for spent nuclear fuel. After a tour in the tunnel the guests were informed about the feasibility study in Oskarshamn.

A project has been initialised to out-source parts of the booking administration. This is done as a joint venture between SKB and OKG.

A safety interaction video for visitors has been produced in order to enhance the safety for the visitors.

The Äspö nature path has been improved with further and updated information signs.

5.2.3 Urberg 500

On June 14, specially invited guests came to see "Urberg 500". After that it was opened to the general public. During the summer of 1999 we had two "Urberg 500" tours per day, in the weekends one per day. There were a lot of people interested in the tour and almost 2000 people visited us.

Two extra guides were employed over the summer for the tours.

Because of the large interest from the public, the tours continued every weekend until Christmas 1999.

The entrance building for the tours was completed during the third quarter of 1999 and was taken into use late that year. The visitors get a short presentation before going underground by bus. The tours end up in the exhibition hall on Äspö.

5.2.4 Special events

In February a media seminar was held at the Äspö HRL. The purpose of the seminar was to learn more about the way media works.

"Äspödagen" of 1999 took place on May 9. Around 300 people visited the Äspö HRL. The guests were offered information about SKB, guided tunnel tours, guided geology tours, bird watching and much more.

5.3 Data management and data systems

5.3.1 Background

The regulatory authorities are following SKB's siting work. Before each new stage, they *examine and review the available data*. A repository will never be allowed to be built and taken into service unless the authorities are convinced that the safety requirements are met. Hence, SKB is conducting *general studies* of the entire country and feasibility studies in 5–10 municipalities. *Site investigations* will then be conducted on a couple of specific sites. With the result of the studies as supporting material, SKB will then apply for permission to carry out *detailed characterisation* of one of the sites. The licence application for detailed characterisation will include a *safety assessment* and the results will be reviewed under the Act on Nuclear Activities and the Act concerning the Management of Natural Resources by the regulatory authorities, the municipality and the Government.

Management of investigation data is a highly demanding and critical task in the presented licensing process. The safety assessment must be based on correct and relevant data sets. Hence, the data management routines need to be focused on the following aspects in a long-term perspective:

- traceability,
- accessibility,
- data security and
- efficiency (system integration and user friendly applications).

A high quality baseline for the safety assessment will be established if the aspects specified above are met. The data needed in a typical safety assessment have been reported in Andersson et al /1998/. Figure 5-1 and 5-2 illustrates the need and input of investigation data in the safety assessment process.

5.3.2 Objectives

The different parts of SKB's Data Management System will be improved in conjunction with the ongoing and planned activities in SKB's siting work. This to fulfil the requirements expected from the regulatory authorities and the internal organisation as well.

SICADA is and will be one of SKB's most strategic database systems. The database should efficiently serve planned investigations activities at the future candidate sites as well as the experiments at Äspö HRL. The database should be user friendly and always guarantee a high degree of safety, quality and traceability.

The system need to be held modern and also adapted and improved in parallel with the development of new and more extensive investigation programs.

System concept

Data model

The central data table in SICADA is the activity-history table. All data rows in this table have a unique activity identifier. This identifier uniquely connects measured data with only one activity in the activity-history table. The activity identifier is located in the first column of the table. Normally the activity identifier is hidden, but it is always present in the background and is handled automatically by the system.

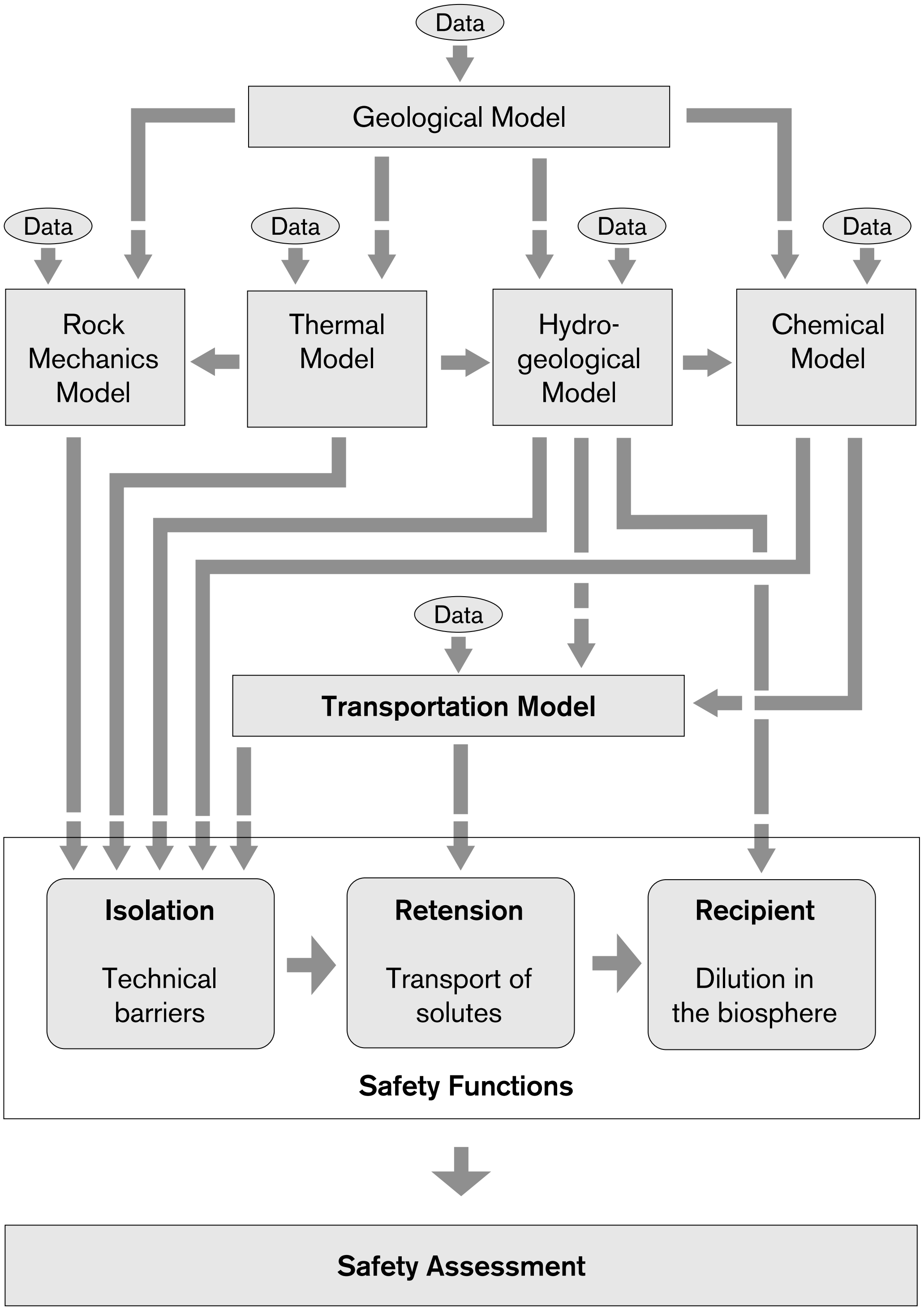


Figure 5-1. *Schematic flow chart describing how information are transferred between different geoscientific models and how these models are used in the safety assessment to be done. The need of different types of input data are shown as balloons marked Data.*

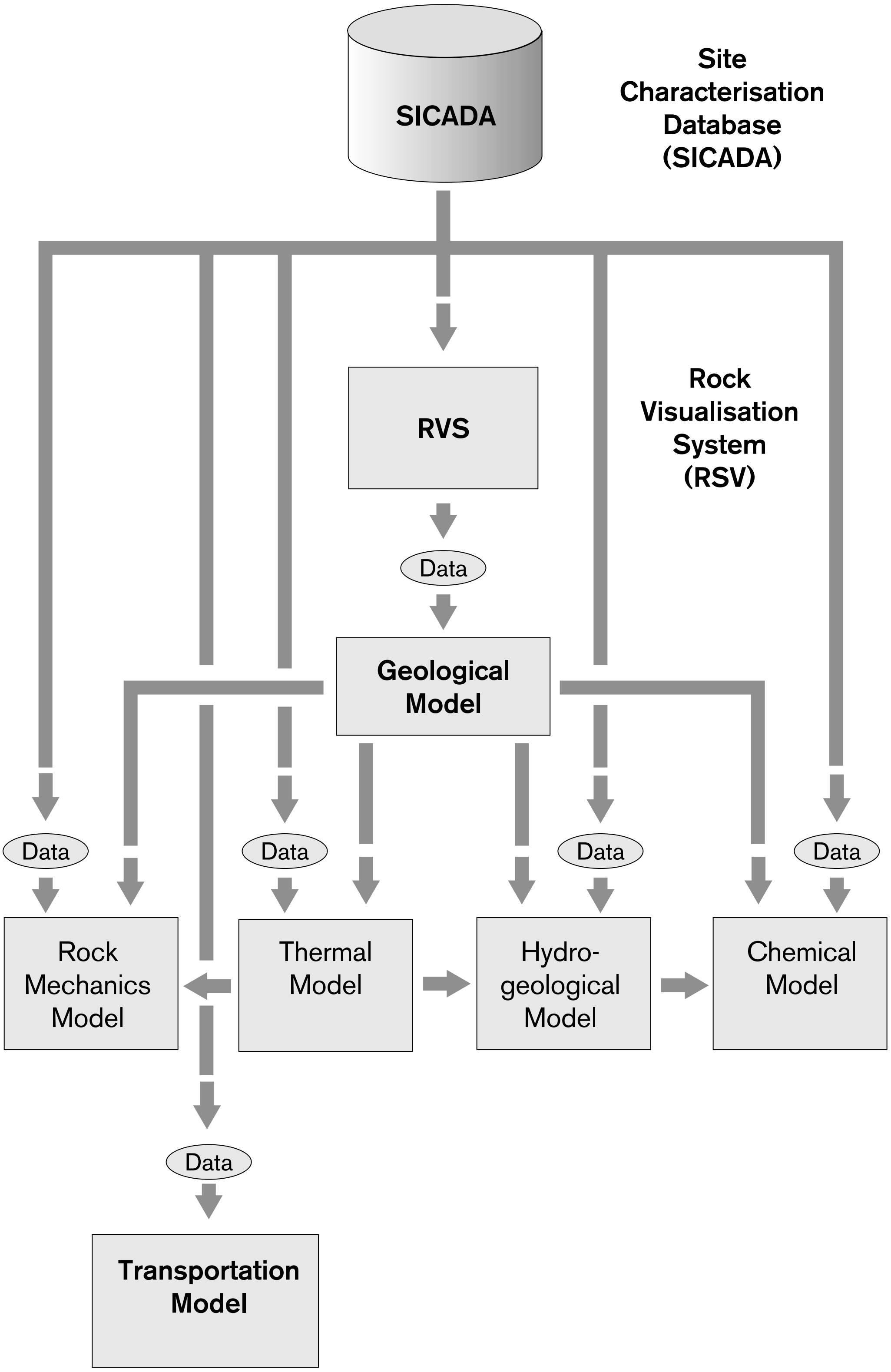


Figure 5-2. *Schematic flow chart describing where from data are taken to the different geoscientific models used as a baseline fore the safety assessment to be done. The balloons in Figure 6-1 have been complemented with the origin of data. As indicated SICADA and RVS are highly important tools on the way to convince the authorities that the safety requirements are met.*

Activity identifiers were introduced in order to make it possible to link an arbitrary number of investigation data tables to a certain activity. Hence, activity identifiers are present in all investigation data tables in the whole system.

All data rows in the activity-history table also have a time stamp and a user identification code to show and control when data was inserted into the table and who did the input.

Data structure

A hierarchical data structure was implemented in the GEOTAB system in order to make it easy to find and retrieve any investigation data. This data structure is also available in the SICADA system. The hierarchy is composed of three levels, viz.:

- Science (Level 1)
- Subject (Level 2)
- Method (Level 3)

At present the SICADA data structure contains the sciences engineering, geology, geophysics, geotechnics, groundwater chemistry, hydrology, meteorology and rock-mechanics. The principal structure with excerpt of contents of information for each hierarchical level within the seven sciences are viewed in Table 5-1. A set of activities is then associated with each method, but in general there is only one activity in each set.

Table 5-1. The hierarchical data structure of the SICADA system, with all sciences shown, but only an excerpt of subjects, methods and activities. Note, in most cases there is an *one to one* association between a certain method and an activity, but in some cases a whole group of activities are associated with only one method.

Level 1 Science	Level 2 Subject	Level 3 Method	Activity
Engineering	Tunnel excavation etc.	Drill and blast etc. D&B – Charging D&B – Round D&B – Ventilation etc.	D&B – Round drilling
Geology	Tunnel mapping etc.	Tunnel mapping etc.	Tunnel mapping with TMS
Geophysics	Borehole logging etc.	Resistance etc.	Single point resistance logging
G.W. Chemistry	Analyses etc.	Water etc. Water sampling, class 2 Water sampling, class 3 Water sampling, class 4 Water sampling, class 5 etc.	Water sampling, class 1
Hydrology	Disturbance tests etc.	Pressure build up etc.	Pressure build up test
Meteorology	Temperature etc.	Temperature etc.	Temperature from SMHI
Rock Mechanics	Insitu stress etc.	Overcoring etc.	Overcoring

Every set of investigation data in SICADA has been collected from boreholes, tunnels or other objects. Simple name conventions have been set up and used for objects. For objects in the Äspö tunnel seven to nine characters are used, like for the cored borehole KA2511A. The naming of surface boreholes is somewhat different, where only five characters are used. An example is the cored borehole KAS02 and the percussion borehole HAS05. The capitals K and H is used for cored and percussion drilled holes, AS is the area code for Äspö and finally 02 is a sequence number. As an example KAS02 was drilled before KAS03 and HAS05 was drilled before HAS06. The object codes (sometimes called idcodes) and the hierarchical data structure are the key information when searching for data in the SICADA system.

All investigation data sets or parts of data sets are not possible to store in data tables in SICADA, but as least stored as *file references*. Some examples of this type of data sets are borehole radar images and geophysical profiles. The file reference is an optional *activity tag* available during data registration. Actually there is an on-line file archive managed by the SICADA system. This on-line archive is called *SICADA File Archive*. A registered file reference is actually an on-line reference to the file in the SICADA File Archive.

The *activity tag* mentioned above is only one example of one of many useful tags in the SICADA system. There are currently about 60 different tags available in the system.

Applications

The following SICADA user applications/programs are used to handle the information in the database.

SICADA/**Diary**	This application is used to *insert or update* data in the database.
SICADA/**Finder**	This application is used to *retrieve* data from the database.
SICADA/**Retriever**	This application is used to *retrieve* data from the database. (Look like the former GEOTAB-application)
SICADA/**Project**	This application is used to *check* the progress of the data entry work for a specified project/experiment.

5.3.3 Results

SICADA is improved in parallel with the planning of future site investigations. During 1999 two development stages (99:01 and 99:02) have been completed with some minor exceptions. This implies that about forty new functions or modified existing functions have been implemented.

A new database server, Sun Microsystem ULTRA Enterprise 450, has been installed and configured to be used as a dedicated SICADA server. On this server the latest version of the relation database system Ingres, called CA/Ingres II, has been installed as a basis for SICADA. SICADA it self was copied to the new server just in time before the new millennium was entered. It has been controlled and verified that the whole system is not affected by any problems associated with year 2000.

A new software connection between HMS (Hydro Monitoring System) and SICADA has been implemented. All measured data in HMS are now available in SICADA. This will serve RVS with measured data for visualisation of pressure transients in instrumented borehole sections during drilling of new boreholes. This should increase the understanding of the hydraulic connections between different open discontinuities in the investigated rock mass.

A specification for incorporation of the HMS instrument database into SICADA has been written and the set of data in this database has been moved to SICADA.

5.4 Monitoring of groundwater head and flow

5.4.1 Background

The Äspö HRL operates a network for the monitoring of groundwater head, flow in the tunnel and electrical conductivity, as the core parameters. This system goes under the acronym of HMS (Hydro Monitoring System). Water levels and pressure head are collected from surface and tunnel boreholes. Additionally, the electrical conductivity of the water in some borehole sections and in the tunnel water is measured. The network includes boreholes on the islands of Äspö, Ävrö, Mjälen, Bockholmen and some boreholes on the mainland at Laxemar.

The monitoring of waterlevels started in 1987 while the computerized HMS was introduced in 1992. The number of boreholes included in the network has gradually increased. The tunnel construction started in October 1990 and the first pressure measurements from tunnel drilled boreholes were included in the HMS in March 1992. To date (31 December 1999) the monitoring network comprise a total of 62 boreholes most of which are equipped with inflatable packers, measuring the pressure by means of pressure transducers. The measured data is relayed to a central computer situated at Äspö village through cables and radiowave transmitters. Once a year the data is transferred to SKB's site characterization database, SICADA. Manual leveling are also obtained from the surface boreholes on a regular basis. Water seeping through the tunnel walls is diverted to trenches and further to 21 weirs where the flow is measured.

Construction of the hard rock laboratory began in October 1990 and was completed during 1995. However, the tunnel excavation began to impact on the groundwater head during the spring 1991.

5.4.2 Objectives

The scope of maintaining such a monitoring network has scientific as well as legal grounds:

- firstly it is a necessary requirement in the scientific work to establish a baseline of the groundwater head and flow situation as part of the site characterisation exercise. That is, a spatial and temporal distribution of groundwater head prevailing under natural conditions (i.e. prior to excavation),
- secondly it is indispensable to have a such a baseline for the various model validation exercises which are implemented for the Construction Phase and the Operational Phase including the comparison of predicted head (prior to excavation) actual head (post excavation),

- thirdly it was conditioned by the water rights court when granting the permission to execute the construction works for the tunnel that a monitoring program should be put in place and that the groundwater head conditions should continue to be monitored until the year 2004 at the above mentioned areas.

5.4.3 Results

The hydro monitoring system continued to support the different experiments undertaken at Äspö HRL. It provides basic information on the influence of the tunnel drainage on the surrounding environment by recording the evolution of head, flow and salinity of the groundwater.

Support of experiments

HMS data was put to use in different ways, in addition to complying with the water rights court it provided the means to continuously control the groundwater head in a rock volume where tracer experiments are conducted. The head distribution in the block should remain constant throughout the experiment since it forms an initial condition to the problem. Alteration in head gradients during the experiment might complicate the analysis. It is always supporting, and indeed is a necessary requirement during the rock characterisation stage preceding the experiments.

Seismic events

It has been possible to correlate changes in head to seismic events. During the course of operating the HMS, fluctuation of groundwater head were observed which correlate with the seismic events that caused the earthquake in Kocaeli, Turkey on 17 August 1999 at 00:01:39 UTC /Morosini, 1999/. The event was recorded at Äspö on the same day at 00:09 local time. The earthquake had a magnitude of Mw 7.4 occurred on the North Anatolian Fault Zone with a macroseismic epicenter near the town of Gölcük in the western part of Turkey. From this earthquake the induced fluctuations in pressure head was as much as 25 kPa (= 2.5 mH_2O). The observed amplitude in pressure head for all borehole sections where it was observed is shown in Figure 5-3. The Figure also include an example if the observed pressure head fluctuation, for borehole KA2511A, section 239–293 m.

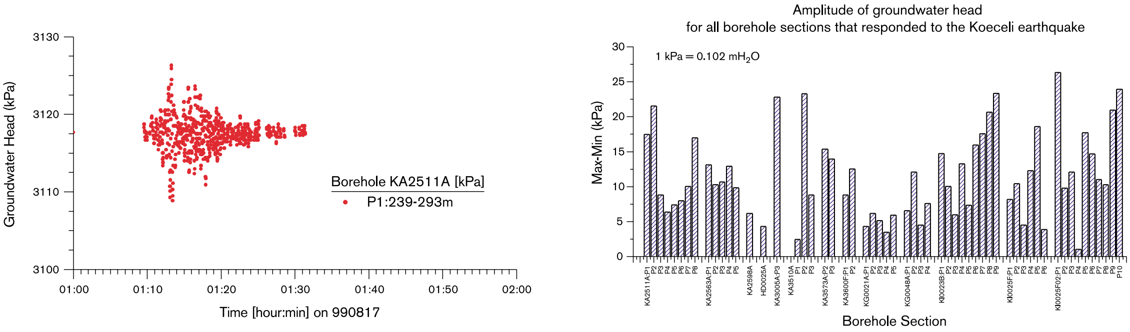


Figure 5-3. *Pressure head fluctuations and amplitude observed in Äspö groundwater caused by the August 1999 Kocaeli, Turkey earthquake.*

5.5 Monitoring of groundwater chemistry

5.5.1 Background

The groundwater chemical sampling and analyses started within the pre-construction investigations at Äspö in 1987. The hydrochemical model was developed on the basis of data from the shallow and deep boreholes at Äspö. The model was also integrated with the geological and hydrological models, which were developed simultaneously. At the end of the pre-construction investigations, 1990, these models were used to predict conditions during tunnel construction.

During the tunnel construction groundwater was sampled systematically from probing holes drilled into the tunnel front. On the basis of the first sampling in all holes with a water inflow above 0.5 l/min, some were selected for further sampling. Thus time series were obtained for these locations.

After completion of the construction work a few of the boreholes with time series sampling were selected for a more continuous monitoring together with a few surface drilled boreholes. Some of the boreholes drilled within the programme of selecting experimental sites were also selected to be monitored.

During the pre-construction investigations ten shallow percussion drilled boreholes and thirteen deep core drilled boreholes were sampled, a few of them more carefully than others. During the tunnel construction phase 68 boreholes were sampled out of which 16 have been sampled more than twice.

5.5.2 Objectives

At the beginning of the operational phase, sampling was replaced by a groundwater chemistry program, aiming to cover the hydrochemical conditions with respect to time and space within the Äspö HRL. This program should provide information for determining where, within the rock mass, the hydrochemical changes are taking place and at what time stationary conditions are or have been established.

The monitoring program should provide the data necessary to check that the pre-investigation and the construction phase models are valid, as well as it should provide new data for further development of the hydrogeochemical model of Äspö.

5.5.3 Results

The analytical results from the monitoring program undertaken between 1995 and 1998-05-01 have been presented in report IPR-99-13. The results from the sampling period in October-98 have been presented in TD-99-22 and from the sampling period in April in TD-00-10. Generally, no major trends can be recognised. The only boreholes that show defined changes in water composition are KR0012B, KR0013B, KR0015B and KXTT3:R2. Continuous pumping in KXTT3 and the fact that KR0013B has been left open for several years may have caused these changes.

Groundwater sampling was undertaken on two occasions, in April and in September 1999. Many project specific samples were taken in addition to the “monitoring samples”. The two major projects which have ordered extra water sampling are the TRUE Block Scale- and the Prototype Experiments. Within and in connection to the monitoring program 43 sections in 35 boreholes, see Table 5-2, are sampled. Sampling and analyses are performed according to SKB´s routines, Chemistry Class no. 4 and 5.

Table 5-2. Boreholes and sections sampled within the Program for Monitoring Groundwater Chemistry

Idcode	Secup	Seclow	Class No	Project	Comment
HD0025A	0	ca 200	4	GWCM	
KA1061A	0	208.5	4	GWCM	
KA1131B	0	203.1	4	GWCM	
KA1755A	88	160	4	GWCM	
KA2050A	155	211.57	4	GWCM	
KA2162B	201.5	288.1	4	GWCM	
KA2511A	Several	sections	4	GWCM	
KA2563A	Several	sections	5	TRUE Block Scale	
KA2862A	7.37	15.98	4	GWCM	
KA3110A	20	29	4	GWCM	
KA3385A	7	31	4	GWCM	
KA3566G01	Several	sections	4	PROTOTYPE	Only in April
KA3566G02	Several	sections	5	PROTOTYPE	Only in April
KA3572G01	1.3	5.3	5	PROTOTYPE	Only in April
KA3573A	Several	sections	4	GWCM	
KA3590G02	Several	sections	4	PROTOTYPE	Only in April
KA3593G	1.3	7.3	4	PROTOTYPE	Only in April
KA3600F	Several	sections	4	GWCM	
KAS03	107	252	4	GWCM	
KAS03	533	626	4	GWCM	
KAS09	116	150	4	GWCM	
KI0023B	Several	sections	4	TRUE Block Scale	
KI0025F	Several	sections	4	TRUE Block Scale	
KI0025F02	Several	sections	4	TRUE Block Scale	
KR0012B	5	10.57	5	GWCM	
KR0013B	7.05	16.94	5	GWCM	
KR0015B	19.82	30.31	5	GWCM	
KXTT3	12.42	14.42	4	GWCM	
SA0813B	5.6	19.5	4	GWCM	
SA1009B	6	19.5	4	GWCM	
SA1229A	6	20.5	4	GWCM	
SA1420A	6	50	4	GWCM	
SA1730A	5.6	20	4	GWCM	
SA2074A	6	38.7	4	GWCM	
SA2273A	5.8	20	4	GWCM	
SA2600A	5.8	19.4	4	GWCM	
SA2783A	5.8	19.9	4	GWCM	
SA2880A	11.92	13.92	4	GWCM	
SA3045A	0	20.7	4	GWCM	

5.5.4 Planned work for 2000

The analytical results from the monitoring program undertaken in September 1999 will be presented in a Technical Document in March 2000. The program for monitoring groundwater chemistry has been reduced to one sampling occasion a year and this will be performed in September/October 2000.

5.6 Technical systems

5.6.1 Background

The monitoring of groundwater changes (hydraulic and chemical) during the construction of the laboratory is an essential part of the documentation work aiming at verifying pre-investigation metods. The great amount of data calls for efficient data collection system and data management procedures. Hence, the Hydro Monitoring System (HMS) for on-line recording of these data have been developed and installed in the tunnel and at the surface.

5.6.2 Results

The weirs in the tunnel have been calibrated.

The section limits of the boreholes KA 2511A and KA 2563A have been changed.

The installation of the presentation system has started. It will be in full operation in summer 2000.

REX Experiment has been finished and disconnected from HMS.

The boreholes KG 0021A and KG 0048A have been connected to HMS.

The borehole KI0023F03 has been connected to HMS.

The last six pressure transducers in weirs have been replaced with Ultra sonic transducers.

5.7 Quality assurance

5.7.1 Background

Quality assurance means to ensure that activities are undertaken with due quality of high efficiency. In order to achieve this goal it is required that a smoothly running systems are in place to manage projects, personnel, purchasing economy, quality, safety and environment.

The structure of a quality assurance system is based on procedures, handbooks, instructions, identification and traceability quality audits etc.

The overall guiding document for issues relating to management, quality and environment is SKB-HLK (SKB:s Handbook for Management and Quality Assurance).

Employees and contractors related to the SKB organisation are responsible that works will be performed in order to achieve SKB quality goals and guidelines.

5.7.2 Objectives

A project is in progress to implement a common management system for SKB to break down all requirements from legislator, authorities and from other interested parties and also internal requirements of our own organisation. The aim of the project is to certify SKB according to the Environmental Management System ISO 14001 and also to the Quality Management Standard ISO 9001.

The present SKB Management System compares with the requirements from the ISO-standards. Realised GAP-analysis results in suggestions to actions.

Great efforts are required to produce documents and document routines, instructions with the purpose to reach the goal in being ISO-certified.

5.7.3 Results

A new updated Purchasing Handbook is almost completed.

A revision of the Äspö Handbook (The Handbook cover issues of decision-making, procedural instructions, manuals etc to guide the works pertaining to quality assurance and environmental issues at the Äspö HRL) is undertaken and will be finished in May 2000. Co-ordination is done with the department of Safety and Technology.

Goals have been identified and important environmental aspects which influence the environment negatively have been specified in order to get through an Environmental Management System. This goals are to be followed up and includes also to improve the working environment accordance to safety and health requirements.

SKB started up an inventory of prerequisites for a common identification- and archival system. Important documents from activities shall be recorded and archived in an integrated and traceable manner. Will be completed during year 2000.

A project started up to develop a better structure for managing time and resources, by means of a software application called Äspö Plan Right which is running under MS Project. In addition to improve a more efficient planning system, the project management system is revised within the SKB organisation.

6 International cooperation

6.1 Current international participation in the Äspö Hard Rock Laboratory

Nine organisations from eight countries have during 1999 been participating in the Äspö Hard Rock Laboratory in addition to SKB. They are:

- Agence Nationale pour la Gestion des Déchets Radioactifs, **ANDRA**, France
- Bundesministerium für Wirtschaft und Technologie, **BMWi**, Germany
- Empresa Nacional de Residuos Radiactivos, **ENRESA**, Spain
- Japan Nuclear Cycle Development Institute, **JNC**, Japan and The Central Research Institute of the Electric Power Industry, **CRIEPI**, Japan
- Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle, **NAGRA**, Switzerland
- United Kingdom Nirex Limited, **NIREX**, Great Britain
- **POSIVA OY**, Finland
- Sandia National Laboratories, **SANDIA**, USA

In each case the cooperation is based on a separate agreement between SKB and the organisation in question. The cooperation with the Japanese organisations is performed under one agreement. JNC is the official representative within the cooperation. The work performed within the agreements and the contributions from the participants are described under 6.2.

Multilateral projects are established on specific subjects within the Äspö HRL programme. These projects are governed by specific agreements under the bilateral agreements between SKB and each participating organisation. The TRUE Block Scale Experiment (see 3.3.2) is an example of such a project.

Specific technical groups so called Task Forces is another form of organising the international work. A Task Force on groundwater flow and solute transport in fractured rock is ongoing (see 3.9).

A new Task Force on Engineered Barrier Systems is being discussed between a number of the participants. A decision will be taken during the IJC-meeting in May 2000.

A joint committee, the Äspö International Joint Committee, IJC, with members from all participating organisations, except from Japan which is represented by JNC only (see above), is responsible for the coordination of the work arising from the international participation. The committee meets once every year. In conjunction to each IJC meeting a Technical Evaluation Forum, TEF, is held. TEF consists of scientific experts appointed by each organisation.

6.2 Summary of work by participating organisations

6.2.1 POSIVA

Introduction

The Project Agreement between SKB and POSIVA covers the co-operation in the Äspö HRL. The work within the Joint Project comprises three main areas:

- Detailed investigation methods and their application for modelling the repository sites.
- Test of models describing the barrier function of the bedrock.
- Demonstration of technology for and function of important parts of the repository system.

An agreement regarding the LOT–project was attached to the Project Agreement between SKB and Posiva in August 1999. Posiva will participate in the LOT-project during the period 1999–2001.

According to a specific agreement Posiva participated in TRUE Block Scale (TBS) experiment together with Nirex, ANDRA, SKB, ENRESA and PNC.

The following text comprises the work done during 1999 according to the Joint Project and the TBS agreement:

Detailed investigation methods and their application for modelling the repository sites

Applicability of different investigation methods for assessment of repository sites

Posiva conducts an investigation programme in the Laxemar KLXO2 borehole by the technology used in the site characterisation programme in Finland. Details of this study are presented in the description of the Hydrochemical Stability project.

Test of models describing the barrier functions of the bedrock

Task Force on Modelling of groundwater flow and transport of solutes

Tracer Retention and Understanding Experiment (TRUE-1), Task 4

Background

Between 1995 and 1999 nearly 20 different tracer tests have been performed. Task Force modelling groups modelled eight of the tracer tests as blind modelling predictions before the experimental results were made public. Posiva provides Task Force with a modelling team from VTT.

Objectives

From Posiva's point of view this project is useful to learn more about water flow and tracer transport in a heterogeneous single fracture as a basis for flow and transport conceptualisation for performance assessment. Especially a carefully conducted set of tracer tests in a hydraulically well characterised fracture with accurately measured source terms and varied pumping conditions was expected to reveal essential features of flow and transport processes.

Experimental Concept

Tracer experiments are performed in a very detailed scale. Transport distance in most of the experiments has been in order of 5 m. It is intended that no fracture network is activated in the tracer experiments. Tracer tests are performed in a single fracture using simple flow geometry and both conservative and sorbing tracers.

Results

At early 1999 the last sorbing tracer test STT–2 was accomplished. The modelling of the STT–2 test was performed and blind predictions for the breakthrough curves of the tracer test were presented in the 13th Task Force meeting in Sweden. Reporting of the Task 4E and 4F and evaluation of the tracer tests STT–1, STT–1b and STT–2 were started in 1999. Reporting will be finalised during year 2000.

Impact of the tunnel construction on the groundwater system at Äspö - a hydrological-hydrochemical model assessment exercise, Task 5

Background

Task 5 (Impact of the tunnel construction on the groundwater system at Äspö, a hydrological-hydrochemical model assessment exercise) aims at the comparison and ultimate integration of hydrochemistry and hydrogeology. The simulation of reactive transport on the aerial scale to the Äspö HRL is beyond present scope for several reasons. Therefore, the task "modelling of groundwater flow and transport of solutes" was broken down into two sub-tasks: to studies of groundwater chemistry (VTT/Community & Infrastructure), and to hydrogeological simulations (VTT/Energy).

Task 5 is also part of the Hydrochemical Stability project. The detailed scope for modelling during 1999 is described below.

Objectives

The groundwater flow modelling on the basis of the M3 chemical modelling formed the first part of Task 5. Mixing calculations were performed using the reference water types that have been identified based on the analyses of geochemical data and on the interpretations of the Quaternary history of the Äspö HRL. In the hydrological simulations the mixing fractions of the reference water types can be transported like conservative parameters. The groundwater flow modelling aims at the determination of the mixing proportions, which result the sample composition studied.

The mixing ratios calculated at the control points and at certain cut planes are compared with those from the chemical modelling. Detailed performance measures are used for the presentation of the results.

The study of the groundwater chemistry aims at determination of the dominating geochemical reactions, quantification of the extent of reactions, and mixing calculations, which give the sample composition studied. Mixing calculations are extended to reference water-types that have been identified based on the analyses of geochemical data, and on the interpretations of the Quaternary history of the Äspö HRL. In the hydrological simulations mixing fractions of the reference water-types can be transported like conservative parameters, and the geochemical reactions can be coupled indirectly to hydrological transport.

Experimental concept

The flow model was constructed by including the hydrologic connections recognised during the tunnel construction. The observed properties of water and bedrock were included in the simulation model. The groundwater table applied over the Äspö island was replaced by a flow rate boundary condition in the first updating of the tunnel. The hydraulic data gained from boreholes was utilised to confirm the residual pressure and flow rate boundary conditions in the tunnel and the shaft(s).

In essence, the simultaneous modelling of flow and transport is a coupled process. The initial salinity or chloride boundary was fixed in accordance with the observations of the groundwater composition. The FEFTRA code, which is based on the porous medium concept and the finite element method, was used to solve both the coupled equations of residual pressure and concentration and the transport equations of the different water types.

The simulation time steps covered the period from the natural conditions until the completion of the tunnel and the shafts. The dual porosity transport model was applied to the equations of the different groundwater types, which were solved using the previously simulated residual pressure and concentration fields. The initial concentration boundary condition for the transport equations of the different water types was given in the basis of the M3 modelling and the inverse modelling.

The method used in geochemical studies aims at solving step by step reference water mixing fractions in groundwater samples collected from the Äspö HRL. Simultaneously the net geochemical reactions required for reaching the sample composition are solved. The approach implements the inverse-modelling method (PHREEQC-2) and calculations are carried out both samples taken before the excavation of the HRL tunnels (undisturbed conditions) and samples taken during and after excavations (disturbed conditions).

Results

The mixing ratios calculated at the control points and at certain cut planes were compared with those from the M3 mixing model. As regards the mixing ratios in the control points, the future condition of the brine water seems steady, except in the prediction section (tunnel length >3,000 m), where it is mildly increasing. The glacial water decreases, because it is a relic component in the present-day groundwater conditions. The meteoric water generally increases. The overall future condition of the Baltic water seems quite steady. These results are fairly well in line with the M3 modelling. The tunnel construction caused the upconing of the brine water, the decrease of the relic glacial water and the increase of the mixing ratios of the meteoric and Baltic waters in the tunnel area. This piece of work showed the essential role of the dispersion lengths as regards to the calculated mixing ratios at the control points. Also, the infiltration from the sea had to be restricted.

In the geochemical modelling the calculation results for the undisturbed conditions form the basis for disturbed sample calculations. Furthermore, the detected depth distributions of mixing fractions in undisturbed samples form geochemical boundaries necessary in hydrological simulations. An example of results of disturbed condition calculations is given in Figure 6-1 that illustrates how mixing fractions evolve in time in a control point, and how large CaX_2 mole-transfers has to be taken into account as a function of fresh Baltic Sea fraction intruding into a control point. At the moment, the project is in the final draft-reporting phase.

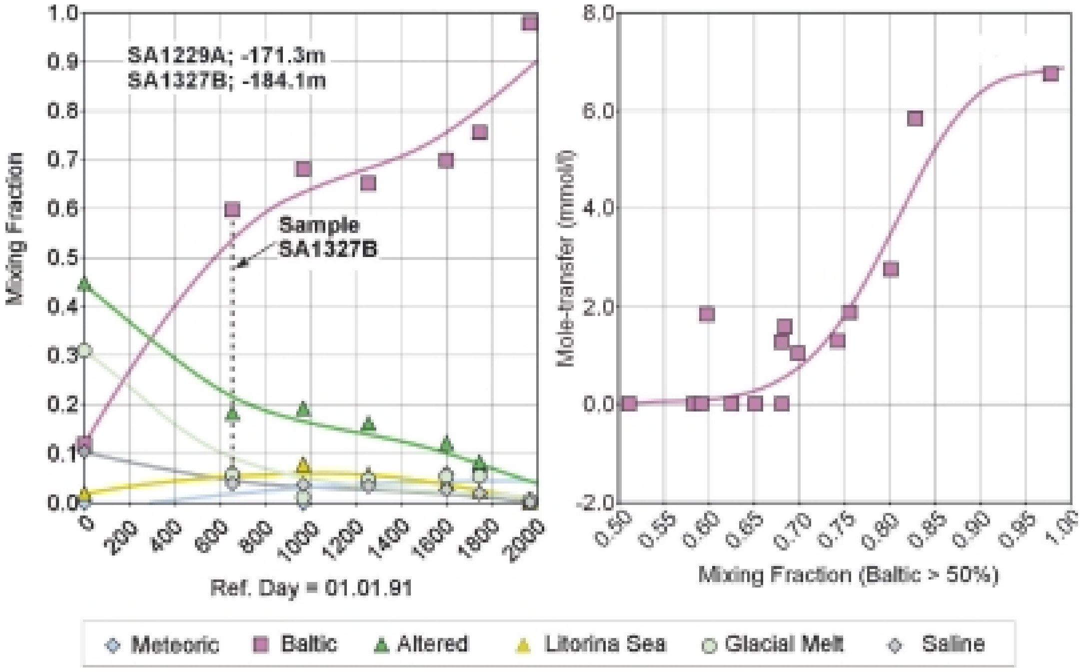


Figure 6-1. *Reference water-type mixing fractions in control points SA1229A and SA1327B as a function of time, and CaX2 mole-transfer as a function of fresh Baltic Sea fraction. Drawn regressions are visual approximations.*

Tracer Retention Understanding Experiments (TRUE) - Block Scale

Background

The TRUE Block Scale project is an international project funded by ANDRA, ENRESA, Nirex, Posiva, PNC and SKB. It is part of Tracer Retention Understanding Experiments (TRUE). First part of the TRUE project has been conducted in a detailed scale (~5 m) and in a single feature. TRUE Block Scale experiment will be performed in network of fractures with expected transport length of 10–50 m.

Objectives

From Posiva's point of view this project is useful to learn more about water flow and tracer transport in a network of fractures. This provides a basis for flow and transport conceptualisation for performance assessment.

Experimental concept

The experiment is designed to study transport of tracers in a network fractures. The intended target volume is a cube with size about 50 m. The experimental volume has been investigated by six boreholes. Based on the structural model suitable fractures in the experimental volume have been isolated by packers. Tracer experiments will be performed between the intersected fractures so that a couple of different fractures can be expected to be active in the tracer test.

Results

In the modelling workshop of the TRUE Block Scale project in September scoping calculations were presented on the possible importance of the two fracture intersection line for the transport. Scoping calculations indicated that it might be very difficult to test the fracture intersection line as a transport path in the in-situ tracer test.

During year 2000 the TRUE Block Scale Experiment reaches tracer test phase. Posiva's approach is to predict the breakthrough of the tracer using flow rate information from tracer tests and dilution tests.

Hydrochemical stability project

Background

Posiva and SKB initiated in 1997 a joint project with the aim to investigate the hydrochemical stability of deep groundwater in crystalline bedrock. This project has been carried out within the Äspö agreement between SKB and Posiva. It also covers the technical parts of the participation in the EC EQUIP (Evidences from Quaternary Infillings for Palaeohydrology) project and the modelling Task 5 within the framework of the Äspö Task Force for modelling of groundwater flow and transport of solutes.

Objectives

The project aims at clarifying the general hydrochemical stability of importance for the site performance. Important questions concern the understanding of the critical groundwater parameters, such as redox parameters and salinity, and processes influencing and controlling them. The processes affecting them presently form the basis for evaluation of future evolution and stability. The aim is to form a "conceptual model" for hydrochemical evolution at Äspö over the next 100 000 years, which will form a basis for a methodology to describe the hydrochemical evolution at any candidate site in Sweden and Finland, e.g. Olkiluoto.

Subprojects conducted within the frame of the project are:

- modelling groundwater evolution,
- re-sampling and analysis of groundwater from KLX02,
- chemical characterisation of groundwater in very low conductivity rock (Matrix Fluid Chemistry project).

Experimental concept

The modelling strategy is based on the process identification for Swedish and Finnish sites, geochemical mixing modelling for Äspö and Olkiluoto, site intercomparison with PCA analysis, including also M3 and NETPATH modelling for Olkiluoto. Task 5 is also included as a test case (PHREEQC–2). The impacts of different geological periods are assessed according to the modelling results of several investigation sites in Sweden and Finland, namely Äspö, Olkiluoto, Hästholmen, Kivetty and Romuvaara.

The aim of the joint SKB/POSIVA measurements of the deep borehole **KLX02** at Laxemar was to demonstrate Posiva´s new flow measurement and sampling techniques and to compare the results with earlier measurements from this borehole. The overall goal was to increase the information from deep saline groundwater in Sweden and Finland.

The equipment used were the Difference flowmeter for hydrogeological determination of the flow situation including also the EC-electrode (to be used for the estimation of TDS), and the PAVE equipment for groundwater sampling illustrated in Figure 6-2.

The Matrix Fluid Chemistry experiment has been designed to sample matrix fluids from predetermined, isolated borehole sections in the borehole KF0051A located in the F-tunnel at depth of 450 m at the Äspö HRL. The detailed studies of the drillcore material (fluid inclusions, interstitial and intragranular fluids) form an essential part of the project. Posiva's participation of the project consisted of the follow-up of the progress, as well as commenting the test plans for the principal investigator by Fintact Oy and planning of the fluid inclusion studies by Kivitieto Oy. Kivitieto will study the fluid inclusions of the samples with heating-freezing experiments and LA–ICP–MS in co-operation with the universities of Stockholm and Bern. The aim of Posiva's participation is to get practical information and experience for planning and performing similar tests at Olkiluoto, as well as to gain experience and confidence of fluid inclusion studies.

The partly EC-funded, three year project **EQUIP** started in 1997 after British Geological Survey (BGS) had observed that zoning of calcite fracture minerals may reflect effects of ancient climatic changes on hydrogeochemical conditions. BGS had especially developed cathodoluminescene and micro analytical techniques to detect growth zones and to analyse their chemical composition by studying calcite samples from the Sellafield site. The Olkiluoto calcite samples were studied by stereo microscopy, polarization microscopy, photography, electron microscope analysis, SEM, cathodoluminescence, X-ray, qualitative line analysis, EPMA, LA-ICP-MS, freezing-heating (H/F) technique and MS. The usage of the LA-ICP-MS technique, although associated with difficulties, gave data specific for the late calcite zone, not for a bulk sample with mixed growth layers. Backscattered electron images, toned for clarity, proved to be the most useful for visualisation of the different calcite generations.

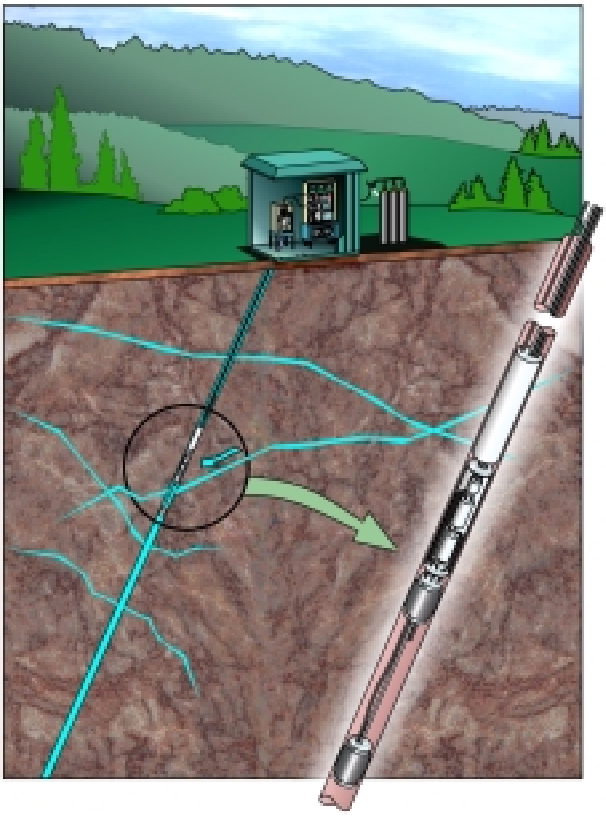


Figure 6-2. *The pressurized groundwater sampling equipment (PAVE) developed by Posiva OY.*

Results

The Modelling Tasks were carried out in accordance with the modelling plan by comparing of the results of different modelling methods during 1999. The final report is scheduled for March 2000. VTT has been actively involved in the project. The reporting includes evaluation of sites, similarities and differences, consideration of climatic changes and their effects on hydrodynamics and hydrogeochemistry and approaches to model these changes. The expected outcome is evaluation and implications for repository performance and assessing of the hydrochemical stability in candidate sites.

The program for the difference flow measurements with Posiva Flowmeter at **KLX02** was partly run in 1999. The work began with pressure measurements in natural condition and the result was that borehole is fresh water filled down to the depth of 1,200 m and there are two relatively homogenous saline layers below 1,200 m. The work continued with the difference flow measurements. The result was that the flow direction is from the borehole to the fractures above 1,100 m depth. As a result of development of the Posiva Flowmeter the single point resistance was measured simultaneously with the flow. In the year 2000 two campaigns has been planned, including also measurements in detailed mode in order to test possibility of studying individual fractures and detailed flow logging and EC–measurements in the entire borehole.

Groundwater sampling from **KLX02** with the PAVE equipment was successfully accomplished during July–December 1999 from the following depths:

1. 1,090–1,097 m
2. 1,155–1,165 m
3. 1,345–1,355 m
4. 1,385–1,392 m.

Posiva was responsible for the field measurements and PAVE samplings. The reporting of the field measurements, gas and microbe analyses is scheduled for the spring 2000.

The exercise showed that the PAVE sampler due to it's design and low weight is easy to operate and is robust in it's function and samples of good quality for dissolved gases and microbes could be obtained from three sections. The low flow caused sometimes difficulties for the on-line Eh-measurements. The field EC measurements (from the automatic and manual logging) indicate same salinity levels (chloride contents) as obtained during previous sampling campaigns such as SKB packer sampling 93, Tube samplings 93 and 97.

A final report for **the Matrix Fluid experiment** is scheduled for January 2001. Kivitieto from Finland participates in the intercomparative study on characterisation of fluid inclusions. The actual performance of these studies will be during 2000 and they will be reported by the end of 2000. The present plan is to continue the investigations up to the end of 2000.

During 1999 the main emphasis of the Finnish part of **EQUIP** has been on characterisation and classification of the most recent calcite generation, interpretation of the results and writing reports. There is a rather limited amount of observations of the latest calcites, but according to their habit and chemical composition they have been classified to indicte the probability of calcite crystallisation in hydrologically open conditions. The late calcite generations are very thin, 10–50 µm, and either scaly or with idiomorphic features, typically with relatively high iron and manganese contents compared to the other calcites. The late calcites have no or only extremely small fluid inclusions.

Though the $\delta^{18}O$ values of the calcites suggest equilibrium between calcite and modern groundwaters, this study did not find any clear indication of deep penetration of glacial meltwaters. The results for the ^{13}C isotopes did not indicate equilibrium between fracture calcites and the $\delta^{13}C$(DIC) values of presently observed groundwater types. Two of the $\delta^{13}C$ values were peculiarly high, suggesting effects of microbiological processes. Methanogenetic or acethogenetic conditions may have prevailed earlier at depth levels closer to the ground level compared to the present situation. The $^{87}Sr/^{86}Sr$ data of the calcites refer to dissolved strontium, apparently ultimately originating from plagioclase dissolution. The study with the Sr-isotopes also pointed clearly out how demanding it is to sample the extremely thin layers of the latest calcite.

The work will continue in the beginning of 2000 with the compiling of the final report of the whole project.

Demonstration of technology for and function of important parts of the repository system

Prototype Repository

Background

Posiva is a participant in SKB's group proposing a project called "Prototype Repository" for EU's 5th framework programme. The Prototype Repository is an experiment to test and demonstrate SKB's final disposal concept, which has several common features with Posiva's concept.

Long Term Test of Buffer Material (LOT)

Background

Posiva's task is to study groundwater and bentonite porewater chemistry within the LOT-project. The task will be carried out by VTT Chemical Technology.

Objectives

The aim of the work to be carried out by VTT Chemical Technology is to obtain data of the chemical conditions to be developed in bentonite considering the effect of the temperature, additives and rock fractures. The study gives information about the chemical processes occuring in bentonite, but also supports the other planned studies in respect of the chemical conditions.

Results

The development work of the measurement and analysing methods for bentonite and bentonite porewater has been underway in the year 1999. The work will be completed and the results reported during the first quarter of the year 2000.

Excavation of the parcel A0 is scheduled for the beginning of the year 2001. Detailed planning and preparative work will be carried out during 2000.

Characterisation of excavation disturbance around full-scale experimental deposition holes

Background

In the deep repository, bedrock in the excavation-damaged zone adjacent to the walls of deposition holes for waste canisters may provide a potential pathway for the transport of groundwater and radionuclides. Rock characteristics in the excavation-damaged zone may play a role in saturation of the bentonite buffer and in gas release.

Experimental concept

The excavation disturbance caused by boring of the experimental full-scale deposition holes was characterised in the Research Tunnel at Olkiluoto. Characterisation was carried out by using two novel methods: the ^{14}C-PMMA and He-gas methods. Both of the measurement methods have been in continuous use in 1999 and the work has included development of both the measuring and interpretation techniques in order to study disturbance caused by boring with mini discs, a technique used in the Äspö Hard Rock Laboratory.

Results

New applications of measuring techniques were developed and tested to measure the hydraulic conductivity of the damaged zone and verify the earlier results obtained by using the He-gas method. The microfracturing in the damaged zone and dependence on mineralogy was analysed quantitatively in 1999 by using image analysis and different microscopical techniques including polarising, fluorescence, confocal laser scanning and scanning electron microscopy. The parameters analysed were the orientation, specific surface, aperture and volume of microfractures. The results verified the earlier results, which showed that most of the disturbance is located at a depth of few millimeters from the surface.

According to the study the porosity of disturbed rock samples is clearly higher than that of the undisturbed ones. The permeabilities and diffusion coefficients obtained for the disturbed rock samples are also clearly higher than those obtained for the undisturbed ones. Both permeabilities and diffusion coefficients are clearly oriented, being larger in the direction of the schistosity of the rock than at an angle of 458 to the schistocity. Studies of the microstructure of the rock carried out using SEM, fluorescent microscopy and 14C-PMMA method have shown that porous zones in the undisturbed rock follow the oriented clusters of biotite. Close to the disturbed surface there is prominent connected microfracturing in all directions, which overrides the natural anisotropy of the rock. The final summary reporting of the work is in progress.

In situ failure test

Background

The stability of the deep repository is of great importance from the point of view of both safety and constructability. For the rock to be failed, fracturing must occur and result in an unstable situation. A significant component of progressive failure is the fracture propagation. The development of computers and associated modelling programs has made it possible to model the process of fracture propagation.

Objectives

The general objective of the in situ failure test is to assess the applicability of numerical modelling codes and methods to the study of rock failure and associated crack propagation in larger than laboratory scale.

Experimental concept

In the in situ failure experiment, a hole cored in one of the full-scale deposition holes will be broken by using an artificial stress field large enough to cause failure. After the failure test the observed patterns of failure and the results obtained from the computer model will be compared and evaluated.

Results

One of the major tasks carried out in 1999 was the modelling of rock failure by using both a conventional method of modelling without fracture propagation and a more sophisticated method capable of modelling the process of fracture propagation (Figure 6-3). As part of this work, the compressive strength of the rock with respect to orientation (Figure 6-4) was determined and the state of in-situ stress was measured in order to provide correct input data for the actual modelling. The study is in progress and the final in-situ failure test shall be carried out in 2000.

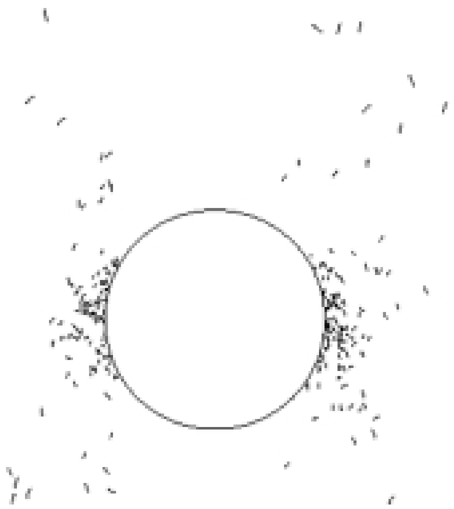


Figure 6-3. *Simulation of fracture propagation around the test hole using Particle Flow Code (PFC).*

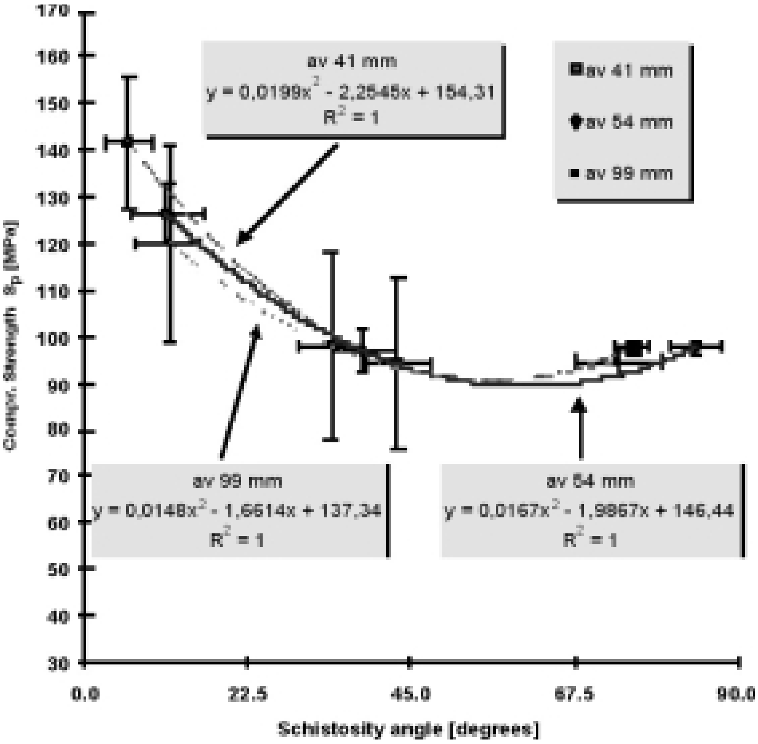


Figure 6-4. *Compressive strength of different diameter samples for three different schistocity orientations (0° is parallel to the sample axis).*

Study of blast damaged samples from ZEDEX tunnel

Background

When excavating using drill and blast technique a zone of damaged bedrock will appear adjacent to the surfaces of the deposition tunnels. The zone of damaged bedrock is a possible pathway for water flow and the consequent migration of radionuclides from the deposition holes. Both the structure and the properties of this zone are of interest.

Experimental concept

Samples have been taken from the ZEDEX tunnel and studied by using the ^{14}C–PMMA technique.

Results

Studies of the fracturing around blast holes and the increased porosity of the damageded zone using the ^{14}C-PMMA technique have shown that the zone of increased porosity penetrates to a depth of some centimetres, while the penetration of the radial fractures is an order of magnitude deeper (Figure 6-5). The final reporting of the work is in progress.

6.2.2 ANDRA

Background

L' Agence Nationale pour la Gestions des Dechets Radioactifs (ANDRA) provides experimental and modelling support to the HRL with emphasis on site characterisation to complete research activities in France.

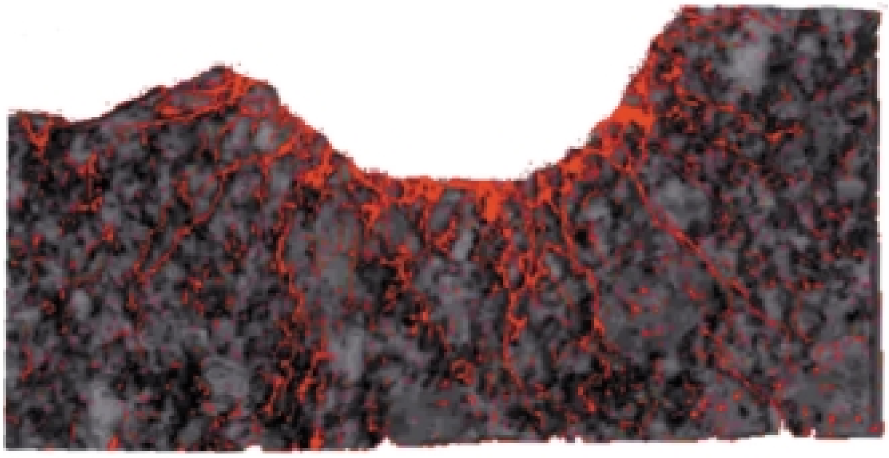


Figure 6-5. *Superposition of high porosity zones (red) on a photoimage of a half-barrel of a blast hole taken from the walls of the Zedex-tunnel in a section perpendicular to the blast hole.*

The contributions of ANDRA and its contractors to the *TRUE Block Scale experiment* focused in the past on:

- participation in the Steering Committee and the Technical Committee to guide the project with the Project Manager and other participants,
- design, performance and interpretation of single-hole and cross-hole hydraulic tests,
- development and installation of multi-packer systems,
- participation in the design of the tracer test stage,
- modelling for the optimal orientation of an additional borehole,
- modelling studies on the correlation of flow and transport data as a means for predictions.

The contributions of ANDRA and CEA to the *REX experiment* focused on laboratory work on the removed part of the experimental fracture.

In 1999, ANDRA started with three modelling teams on *Task 5 of the Äspö Task Force* (Hydrological-hydrochemical modelling of the perturbations of the initial conditions due to construction of the HRL).

Objectives

The main objectives are to increase the understanding of flow and transport in fractured rock, and to evaluate experimental and modelling approaches in view of the site characterisation of granites in France.

Experimental concept

TRUE Block Scale Experiment

During 1999 ANDRA participated in the design of the tracer test stage and focused on an in-situ evaluation of non-sorbing tracers at the TRUE-1 site. The primary purpose was the evaluation of potential tracers and tracer detection techniques for future transport experiments at the True Block Site. Helium, Deuterium and a cocktail of 7 dyes (uranine, eosin, sulforhodmine G, pyranine, dimethylfluorescein, naphthionate, UV1**)** were used in the same tracer run. The Helium technique has not yet been used at the HRL and has the potential to easily identify diffusion processes due to the high diffusion coefficients of ^{3}He in comparison to other conservative tracers such as uranine.

A tracer test technique utilizing dissolved He (^{3}He and ^{4}He) as tracer and a commercial He leak tester for on-line He concentration detection was developed in the framework of the radio-nuclide migration experiment at the Grimsel Test Site, Switzerland. The concept of the on-line He detection is based on a flow-through cell with two chambers separated by a highly gas-permeable membrane. The fluid passes through one chamber. In the second chamber, the He leak tester creates a vacuum. The dissolved gases in the fluid are extracted through the gas-permeable membrane into the vacuum chamber, which is connected to the mass spectrometer of the He leak tester. The He concentration in the fluid is proportional to the leak rate through the membrane as long as fluid flow rate and pressure are constant. The transfer of the He tracer equipment to the Äspö rock laboratory required a few equipment modifications. The two most critical items for feasibility of the planned He tracer tests at the Äspö test site are the high static heads and the loss of He in polyamide flow lines.

The feasibility tests were performed at the TRUE-1 site in a 4-m long flow field established between borehole KXPP3, interval R3 and borehole KXPP4, interval R4. To maximise tracer recovery, the dipole flow field was kept narrow by a high (=13) ratio of extraction to injection flow rate. Helium and uranine were detected using on-line detection devices. For sample analysis of fluorescent tracers advanced measuring procedures as HPLC technique were successfully applied.

The breakthrough curves of Helium-3 and uranine are presented in the Figure 6-6. The peak arrival time and the tailing are longer for Helium than uranine. This indicates diffusion from the mobile water into stagnant zones. The tests showed that the Helium technique is feasible at the True Block Experiment.

Sampling of the dyes and the HPLC tracer analysis technique worked well. All tracers except Sulforhodamine G that shown an non-conservative behaviour, are possible candidates for future tracer experiments. Therefore, it is possible to run tracer tests with a large number of fluorescence tracers.

Task Force on Modelling Groundwater Flow and Transport : Task 5

ANDRA is participating together with three French modelling teams (ANTEA, CEA and ITASCA) to the Task Force on Modelling Groundwater Flow and Transport (Task 5).

The objective of the Task 5 is to estimate by the mean of numerical models the effect of Äspö Hard Rock Laboratory tunnel and shaft construction on the groundwater and solute transport behaviour and the impact on the mixing of four types of waters (brine, glacial fossil, Baltic sea and meteoric waters) in order to gain experience on modelling a real granite site. According to ANDRA's modelling approaches and strategy three modelling teams were involved in the Task 5 for performing the work by the use of different numerical techniques and approaches with the aim of comparing the final results. As the modelling work is still on the development phase, a summary of the modelling approaches and techniques is given.

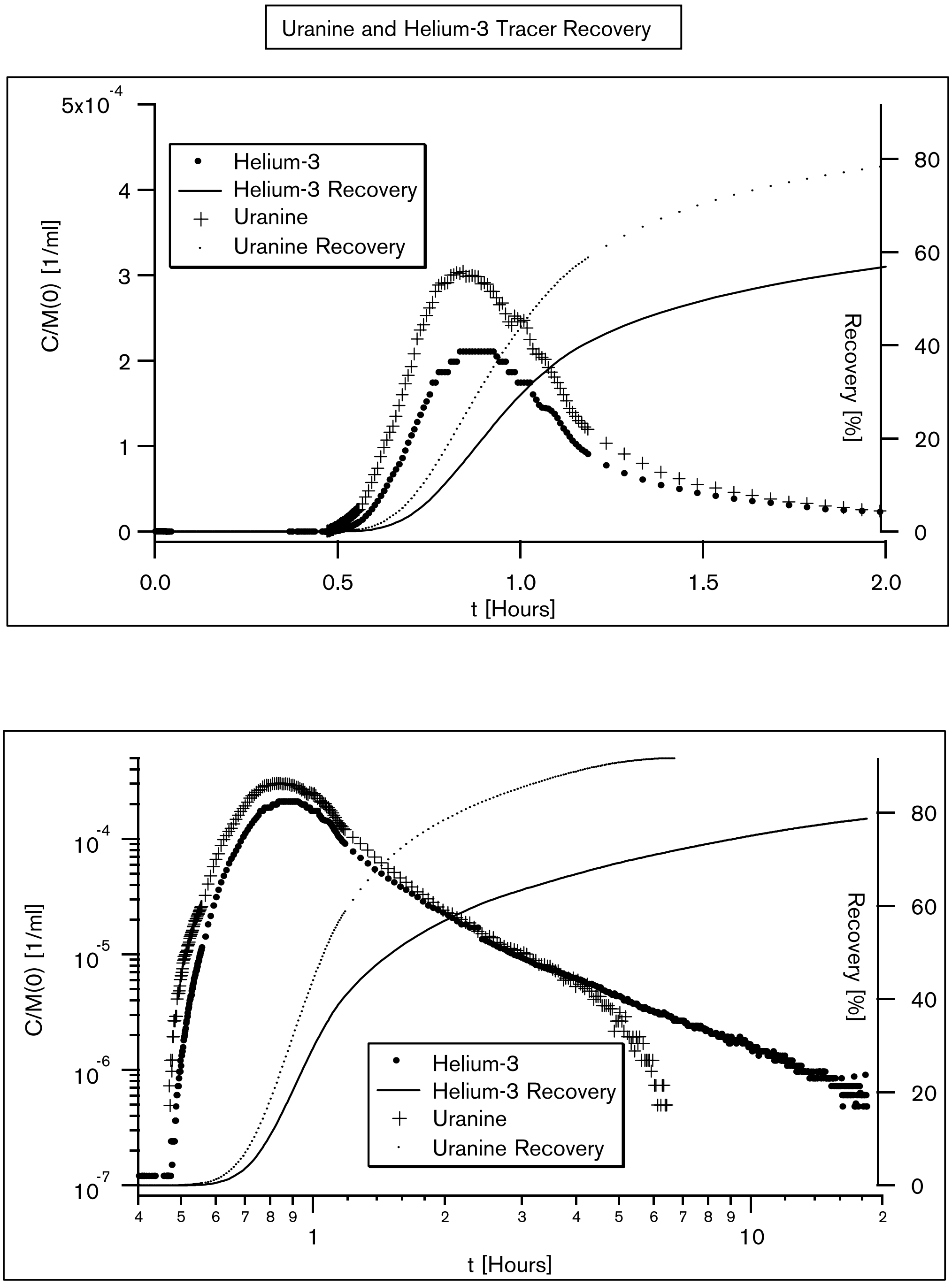


Figure 6-6. *Breakthrough curves of He-3 and Uranine for a feasibility test at the TRUE-1 site.*

ANTEA

Based on series of site characterisation data and measured parameters as pressure, head, flow into the tunnel and hydrodynamic values derived from insitu hydraulic tests acquired from SKB, a conceptual model of the Äspö Hard Rock Laboratory was constructed. The present conceptual model incorporates the fracture network, the tunnel and the shaft. The granite rock matrix acts as porous media who is connected to the fracture network. The hydraulic continuity is prescribed through the head and the flow through the interface rock matrix/fracture. The rock matrix and fracture are discretized into 3D finite elements mesh. The modelling tool called "TAFFETAS" is a 3D dual porosity computer code based on Mixed and Hybrid Finite Element Method developed by BRGM for computing the flow and solute transport in the fractured porous media. The simulations results of the hydrodynamic and hydrochemical disturbances induced by the tunnel construction progress, compared to observed and measured data will improve the characterisation of the site.

The preliminary simulation results show that NE-2 fractures zone has higher computed hydraulic conductivity compared to the measured. This may be explained by the existence of others hydraulic conductors in the vicinity of NE-2.

CEA

The CEA conceptual model incorporates the fracture network, the tunnel and the shaft. The rock matrix is considered as no flow domain, which means that the flow and transport occur only in the fracture network. The fracture intersection space is not discretized. The computer program imposes the continuity in terms of mass. As the rock matrix is omitted in this modelling, 16 (EW1S, EW3, EW7, NE1, NE2, NE3, NE4N, NE4S, NNW1, NNW2, NNW3, NNW4, NNW5, NNW6, NNW7, SFZ11) connected fractures to fractures crossing the tunnel were extracted from the 21 fractures data base delivered by SKB. In the next phase, the rock matrix will be connected to the fracture network in order to perform a stochastic dual porosity modelling. CASTEM2000 computer code is full 3D Mixed and Hybrid Finite Element Method (MHFEM) based code developed at the CEA Department of Mechanic and Technology. The geometry of the hydrogeological features of the Äspö HRL to be modelled is the fractures, the fracture zones and the bedrock matrix. The discretization into 3D Finite Element Mesh is performed using the pre-processor code IDEAS. CASTEM2000 is density dependant flow and advective, dispersive and diffusive transport model that has the ability to simulate a particle tracking procedure and/or the coupling of geochemical reactions and transport.

The flow boundary conditions are taken from the regional modelling performed by Svensson /Svensson, 1997/. No flow occurs from the bottom limit while meteoric water is infiltrated through the soil surface which represent the upper boundary. The transport boundary and initial conditions are mainly represented by the salinity of four types of water prior to the tunnel excavation.

The models were calibrated against: Svensson modelling of the flow results prior to tunnel excavation, the measured inflow to the tunnel during the excavation and the measured drawdown of the monitoring boreholes (KAS02, KAS04 to KAS09, KAS13 and KAS14). The computed and the measured drawdown profiles of the pressure in the monitoring boreholes match fairly well.

ITASCA

Itasca task is to model Äspö site during the tunnel construction by the use of a first limited approach to coupling of transport and geochemistry. A discrete fracture model including 21 fractures zones whith channelized flow was developed. Transmissivity, with and storage coefficient are constant for each feature, except at the bottom of the Baltic Sea where a skin factor is applied.

The boundary conditions are:

- constant flux under land,
- constant head (with skin factor) on the sea bottom,
- constant head on vertical faces,
- no flux on the bottom face.

Finite element transient flow (3FLO) model developed by Itasca is performed to compute the drawdown histories in the boreholes by imposing the inflowrates during the tunnel front progress. Conservative transport is modelled by advective/dispersive particle transport, with spreading due to both longitudinal dispersion in channels and the mixing in the channels intersections. Mixing ratios at the control points are used to calibrate the skin factor (100) at the bottom of the Baltic Sea. The calibration parameters values are fairly close to the measured ones with the exception to the fracture NE2 where the calibration transmissivity is two degree of magnitude higher than the experimental one. This may mean there is another unknown hydraulic conductor in its vicinity.

Itasca is developing geochemical module to be added to 3FLO computer code to compute chemical equilibrium before and during the transport phase. Reactive transport simulation results will be presented in the near future. From the preliminary results produced by the modelling teams as part of ANDRA's contribution to the Task 5, one conclusion may be drawn, the existence of unknown hydraulic conductors in the vicinity of NE-2 fracture zone. Further results of the on going modelling work will be presented on the next Äspö Modelling Task Force meeting.

Scope for 2000

ANDRA's contribution to the TRUE Block Scale experiment will focus on the design of the tracer test stage, the use of Helium at the block scale and a continuation of the modelling studies concerning predicting arrival times of tracer breakthrough based on hydraulic data

The modelling work started last year will be completed on 2000. The evaluation of the results produced by the modelling teams will allow making a decision on the participation in the Task 6.

6.2.3 JNC

Tracer Retention Understanding Experiment

Japan Nuclear Cycle Development Institute (JNC) actively participated in the Äspö Task Force on Modelling Groundwater Flow and Transport and in the TRUE-Block Scale experiment during 1999. The Task Force work involved analysis of sorbing tracer transport at the single fracture scale for Task 4F /Winberg, 1998/, and hydrogeochemical pathways analysis for Task 5 /Wikberg, 1998/.

JNC activities for the TRUE-Block Scale experiment included support for experimental design and interpretation, development of the rock block structural model, tracer and hydraulic test simulation, statistical fracture studies, and sensitivity studies of fracture intersection zone (FIZ) effects.

Äspö Task Force on Modeling Groundwater Flow and Transport, Task 4F

Background

Task 4F of the Äspö Task Force consisted of flow and transport predictions for the STT-2 sorbing tracer transport experiment carried out on "Feature A" of the "TRUE-1" rock block /Winberg, 1999/. SST-2 included both conservative tracers, HTO, Uranine, and Br-82, and sorbing tracers, Na-22, Ca-47, Sr-85, Ba-131, Ba-133, Rb-134, and Cs-134. Several of these radioisotopes (Ca-47, Br-82, Sr-85, Ba-131, and Rb-134) have half lives short enough that decay must also be modeled.

JNC participated in Task 4F by carrying of discrete fracture network (DFN) transport pathway simulations to predict the results of the SST-2 experiment. This effort required calibration to previous transport experiments using the borehole array of STT-2 with non-sorbing tracers, and derivation of effective sorbing tracer parameters by calibration to previous sorbing tracer experiment (STT-1) in the same discrete feature.

Approach

Throughout the TRUE-1 experiment the JNC/GOLDER modeling group has used stochastic discrete feature network (DFN) models to make predictions. Initially, for PDT-3 and STT-1, the DFN models were based upon multiple stochastic DFN realizations of a Feature A geologic conceptual model. This DFN model included three deterministic features, Feature A, Feature A', and Feature NW, and background fractures. Flow simulations of the DFN models provided simulated drawdowns and, via particle tracking, simulated non-sorbing tracer breakthrough curves. Acceptable models were chosen by comparing the measured drawdowns and breakthrough curves of PDT-3 to the model results. Accepted models were then used to predict STT-1 by calculating a retardation factor for each sorbing tracer.

JNC used the FracMan/PAWorks code for these simulations. This approach considered processes of:

- advection,
- dispersion,
- diffusion to immobile zones (fracture infillings, rock matrix, stagnant zones),
- sorption on fracture surface,
- sorption within immobile zones.

These processes are illustrated in Figure 6-7. The JNC discrete feature network model for this simulation is illustrated in Figures 6-8.

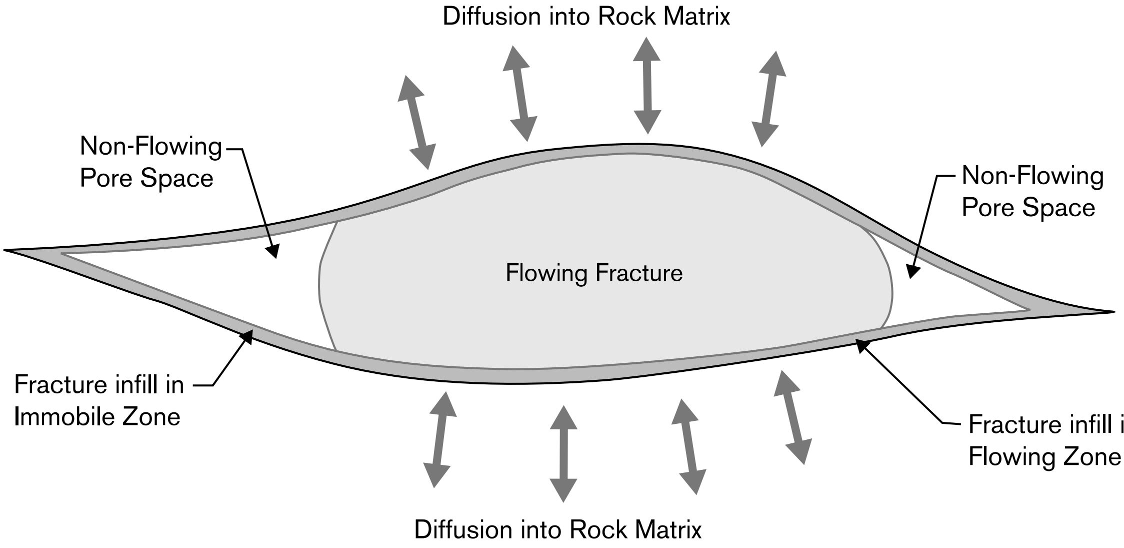


Figure 6-7. *FracMan/PAWorks Solute Transport Processes.*

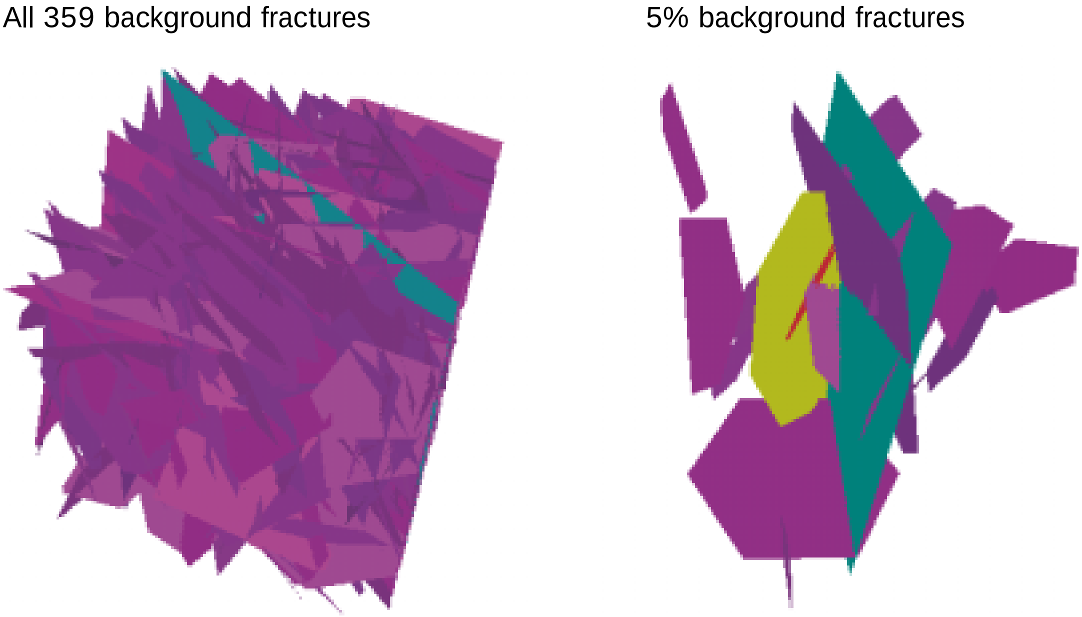


Figure 6-8. *FracMan/PAWorks Fracture Conceptual Model of Feature A.*

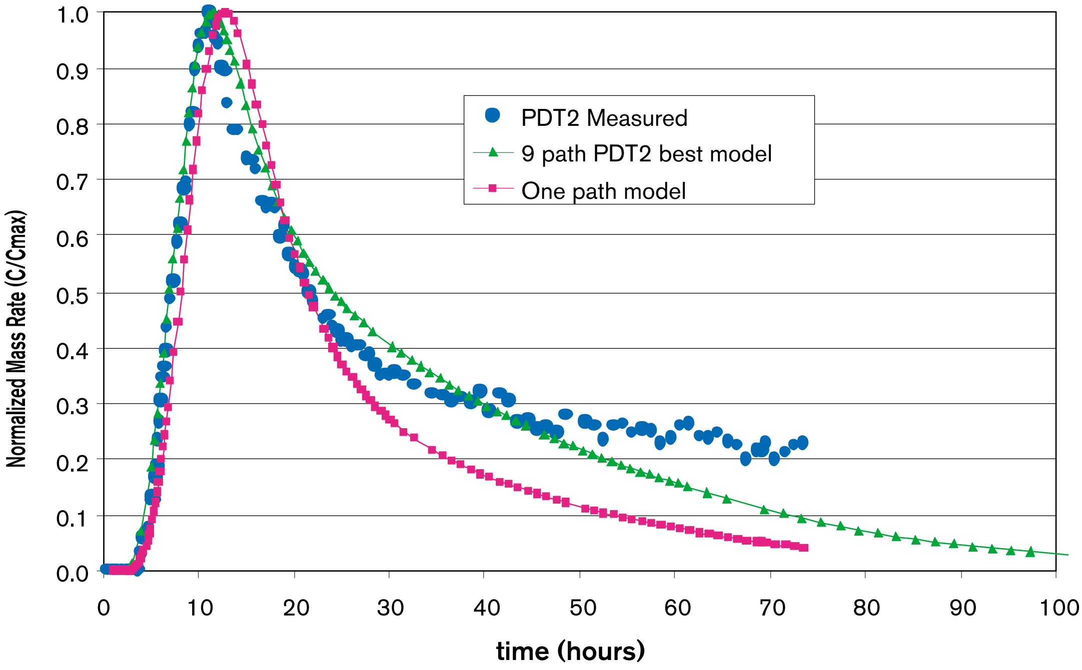


Figure 6-9. *PDT-2 Calibration of FracMan/PAWorks Model.*

Figure 6-9 illustrates an example calibration simulation used to derive pathway parameters for the STT-2 prediction. This calibration compares results for a simple single pathway through the fracture network with a more complex pathway based on 9 pathway segments. The 9 pathway segment model was used for the STT-2 prediction.

Results

The results of JNC simulations are illustrated in Table 6-1 and Figure 6-10.

JNC's predictions for STT-2 were presented at the Äspö Modeling Task Force meeting in April, 1999. The results provided a very good match both in terms of percentage recovery and breakthrough times t_5,t_{50}, and t_{95}. Example comparisons of predicted and measured breakthroughs for conservative Uranine and Sorbing Cesium are provided in Figures 6-11 and 6-12. The observed breakthough showes indications of multiple pathways, indicating that the multiple path model adopted in JNC's modelling may be appropriate for the STT-2 experimental layout used.

Table 6-1. STT-2 Transport Predictions.

Tracer	T5 (h)	T50 (h)	T95 (h)	T100 (h)	Recovery
Uranine	9.7	65.3	247.9	886	100.0%
HTO	11.3	61.3	229.5	641	100.0%
Na-22	16.3	105.3	650.0	3078	100.0%
Ca-47	18.7	414.5	-	458	50.7%
Br-82	9.4	135.3	-	234	57.1%
Sr-85	22.7	170.6	-	3078	89.6%
Ba-131	162.7	1130.7	-	1130	18.3%
Ba-133	180.1	1106.6	-	3078	76.1%
Rb-134	533.5	-	-	1322	8.3%
Cs-134	1233.4	-	-	3078	16.8%

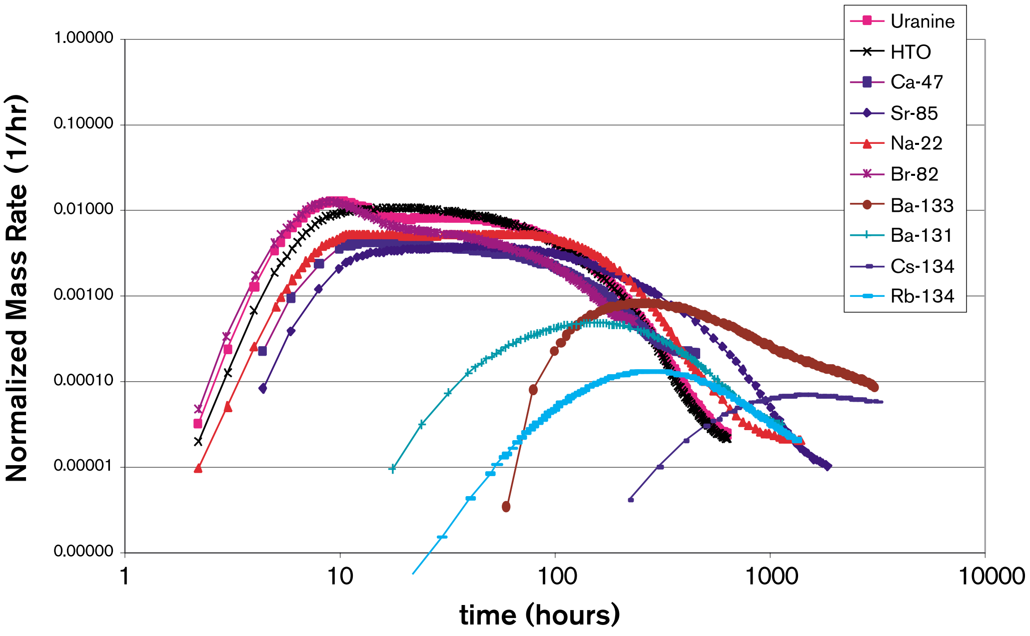


Figure 6-10. *STT-2 Transport predictions.*

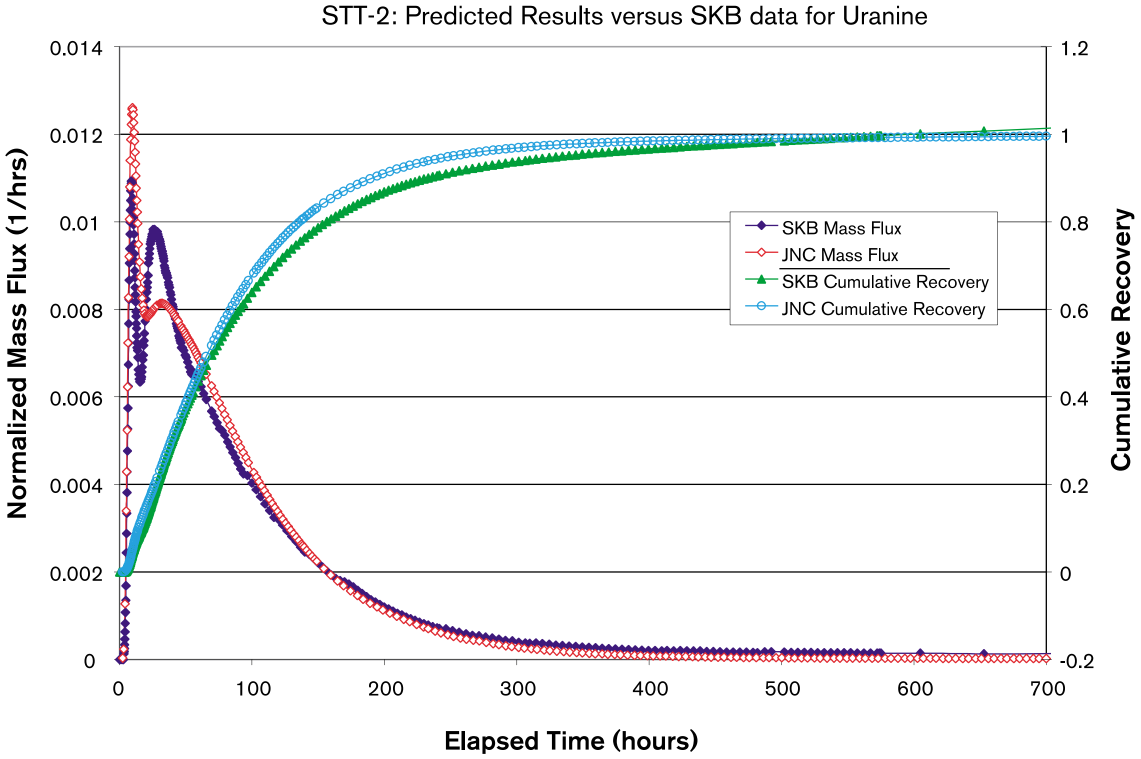


Figure 6-11. *Uranine breakthrough comparison of JNC predictions to SKB measurements.*

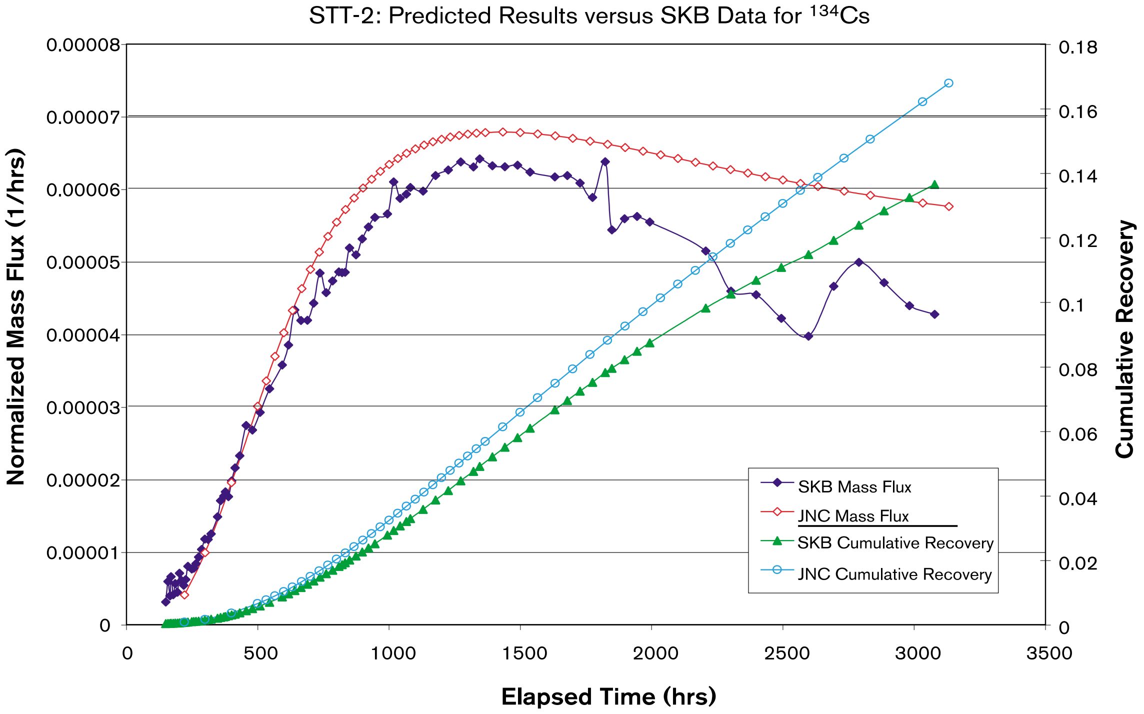


Figure 6-12. *Cesium breakthrough, comparison of JNC prediction to SKB measurement.*

Äspö Task Force on Modeling Groundwater Flow and Transport, Task 5

Background

Task 5 is a unique task for combined hydrological and geochemical modelling at the Äspö site scale. During 1999, JNC participated in Task 5 by carrying out coupled hydrogeological/geochemical pathway modelling of the construction of the Äspö Hard Rock Laboratory during the period 1990 through 1996. Modelling was carried out to the specifications of the Äspö Task Force on Modeling of Groundwater Flow and Transport of Solutes, Task 5. In order to demonstrate the value of geochemical data in hydrogeological modelling, models were calibrated separately to hydrogeological data and geochemical data. Both of these calibrated models were then used in predictive simulations.

Objectives

JNC's objectives for Task 5 included the following:

- to determine the value of geochemical data in hydrogeological modelling, models,
- to demonstrate the use of geochemical data in hydrogeological model development and validation, and
- to assess e the applicability of DFN pathways analysis at the 2 km scale.

These objectives were met through JNC's iterative DFN/Channel network modelling approach which provided separate analyses based on hydrogeological and hydrogeological/geochemical calibrations.

Approach

JNC implemented two models for the Task 5 predictions. The first model "H" was based solely on geological and hydrogeological data. The second model "G" was further conditioned and calibrated based on geochemical data. Both model "H" and model "G" were then used in predictive simulations, and were evaluated by comparison to head and geochemical responses not included in the predictive simulations.

JNC/Golder modelling was carried out using the discrete feature network/channel network approach. In this approach, both major deterministic fracture zones and background fracturing was modeled explicitly as two dimensional discrete features using FracMan/FracWorks. Deterministic fracture zones were based on the zone specifications of Rhen (1999), with the addition of a northwest trending feature to explain the step drawdown responses observed during shaft construction.

Flow and transport were modeled by transforming the fracture network to a topologically equivalent pipe network using FracMan/PAWorks. Flow velocities were adjusted to account for the effect of salinity on density and flow.

Hydrological and geochemical initial conditions for the model were provided by SKB. All transport calculations were made using transport pathways defined by graph theory searches through the channel network model. Transport was expressed in terms of travel times and proportions of four geochemical end members: meteoric, glacial, marine, and brine. Oxygen-18 and Chloride were back calculated from the geochemical end members. The modeled period was from 1990 through 1996.

Head Predictions

Model predictions were prepared for drawdown (head) and geochemical end-members at control points. Figures 6-13 through 10 present comparisons of typical head predictions against measurements. Figure 7 shows an example interval in which the predictive model (G4) provided an excellent prediction, even out to two years following the calibration stage. In contrast, the hydrogeologically based model had significantly more error during the calibration stage, and increasing error during the predictive stage.

Figure 6-14 shows an example prediction in which the model correctly predicts constant head at the control point during the predictive period. As a result, the level of error for the geochemical prediction at this control point remains constant throughout the predictive period. This implies that the model is adequate for pathways connected to this control point, since it is not effected by activities during the predictive period.

In contrast, Figure 6-15 show a control point at which 25 meters of drawdown during the prediction period, even though tunnel advance has stopped. This cannot be explained by any of the boundary conditions in our model, and therefore it is a good thing that our model does not predict this occurrence. Thus, for our model to predict the observed behaviors at the control point, our model would require a different boundary condition.

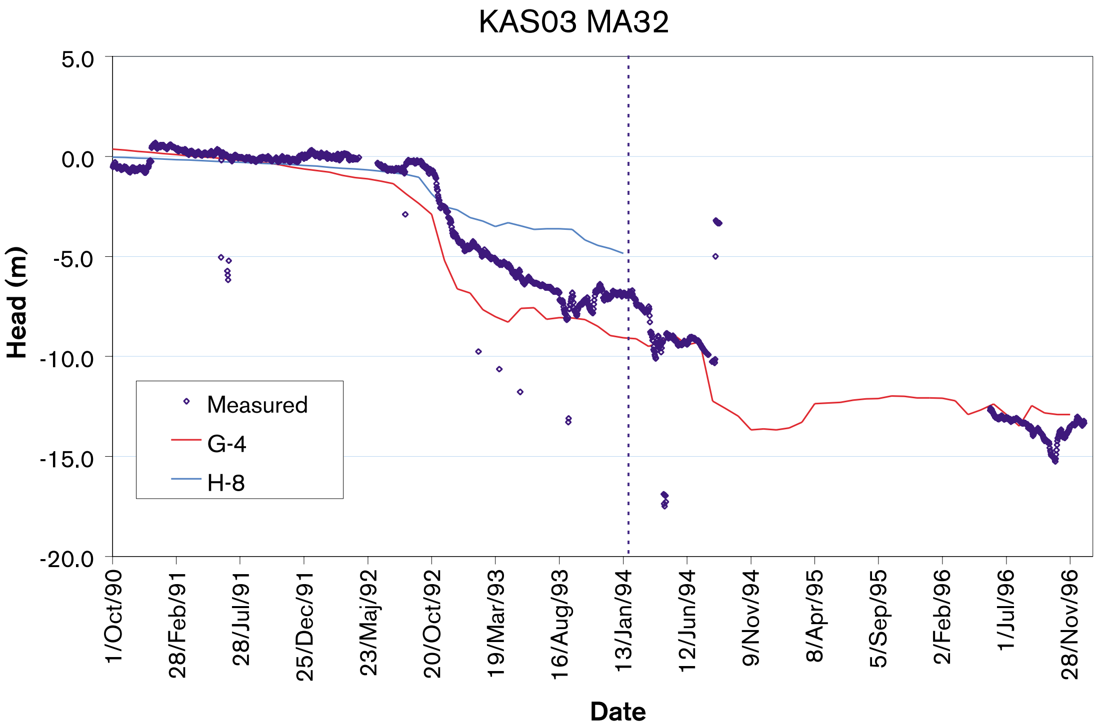


Figure 6-13. *Head prediction and measurement for KAS03/MA32***.**

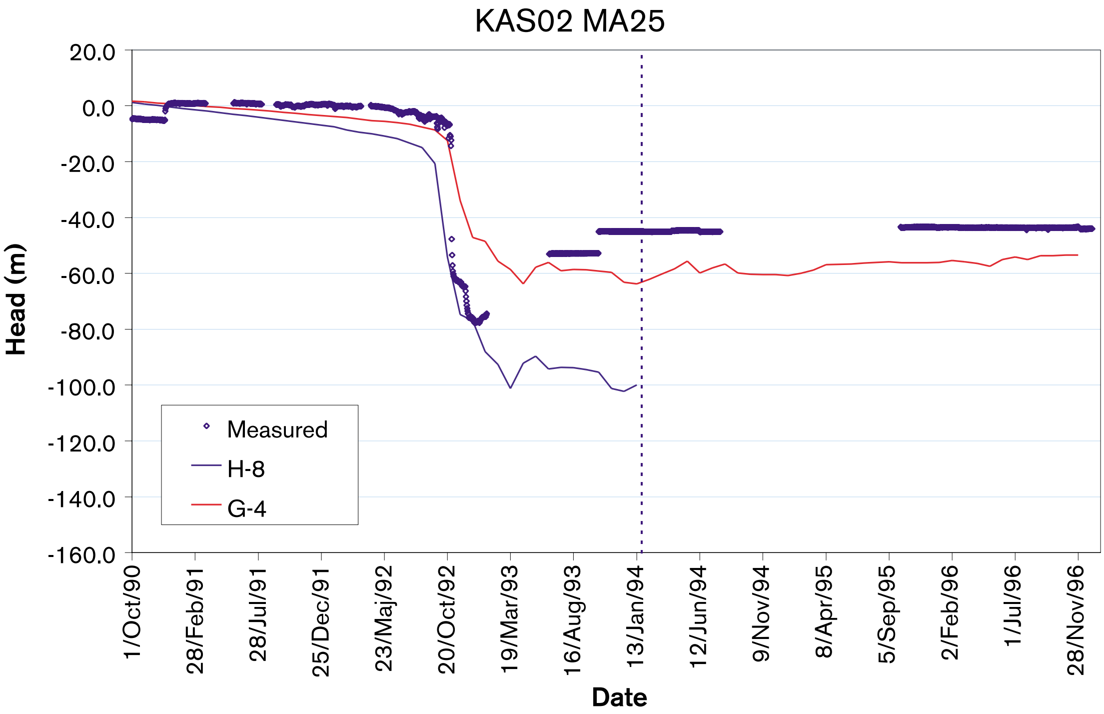


Figure 6-14. *Head prediction and measurement for KAS02/MA25.*

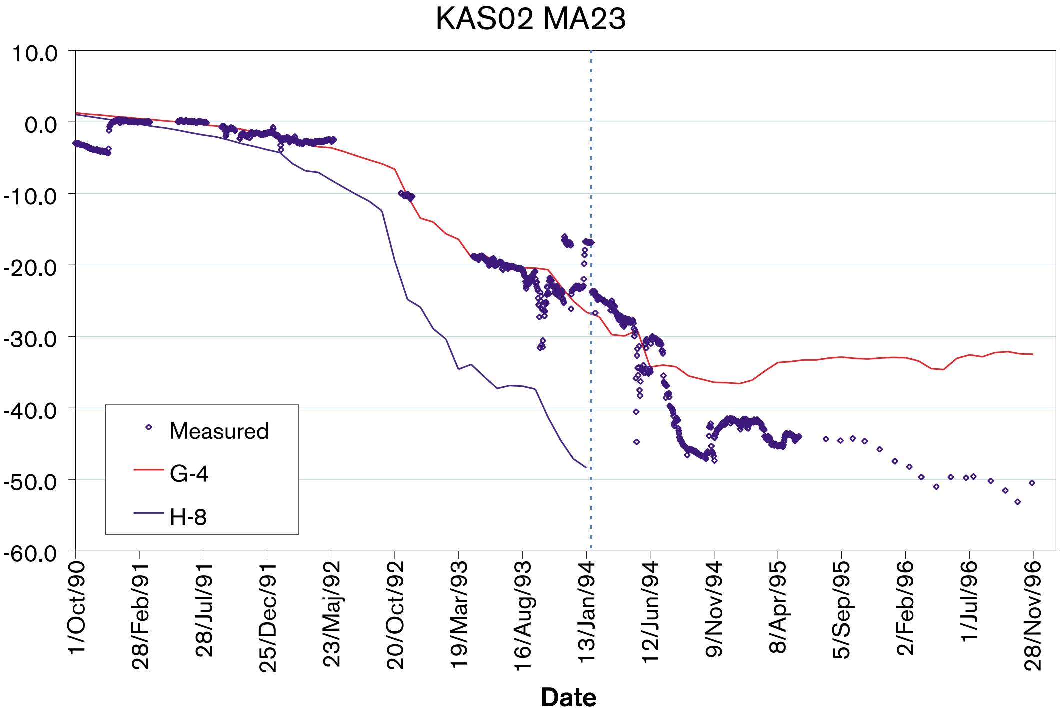


Figure 6-15. *Head prediction and measurement for KAS02/MA23.*

Figure 6-16 presents error measures dh and DH for the accuracy of the geochemical model predictions. The average error dh remains constant at approximately ±2 m for the first six months of the predictive period. Then, following the completion of tunnel construction, the average error gradually increases to approximately 5 meters. The systematic nature of this increase in error implies that activities being carried out during this period are not being captured in the model. Most activities carried out in the HRL should be captured by the model boundary conditions, which use measured tunnel inflow. As a

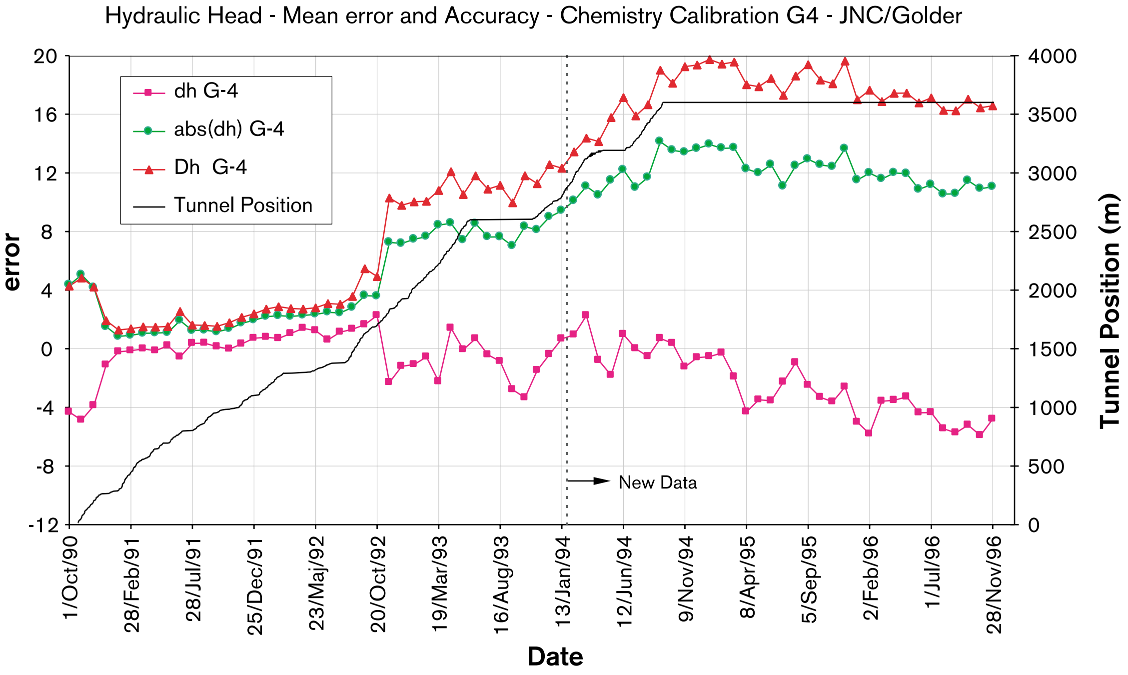


Figure 6-16. *Average predictive error dh and dH.*

result, the predictive error should not increase due to activities such as grouting and borehole installation unless they significantly change the flow pathways to the tunnels. An example of this type of activity might be for example installation of a borehole which provides depressurizes a local region but does not produce sufficient flow to produce a noticeable change to the tunnel inflow boundary condition.

The fact that the model error remained fairly constant for the first six months of the predictive period implies that more accurate prediction would have needed to include additional processes to describe activities in the tunnel during the period June 1994 to December 1996. However, this systematic increase in error for a time period during which no tunnel contraction is taking place does not imply issues regarding the model pathways.

Geochemical Predictions

As in the case of geochemical predictions, there are cases in which the model predictions provided a good match, and other cases in which the match was less than inspiring. These latter cases fall into three basic categories:

a) Cases where the model predicts no change, yet change does occur,

b) Cases where the model predicts change, yet the geochemistry remains stable, and

c) Cases where the model calibration was poor, and remains poor during the prediction stage.

The comparison of our "H" series predictions to measurements based solely on hydrogeological data generally fall into category c) as shown in Figure 6-17. Figure 6-18 shows an example "H" prediction in which our model predicted a significant breakthrough of marine (Baltic) water through a strong pathway to the Baltic. This breakthrough did not occur at the control point, which remained essentially unchanged during the prediction time period.

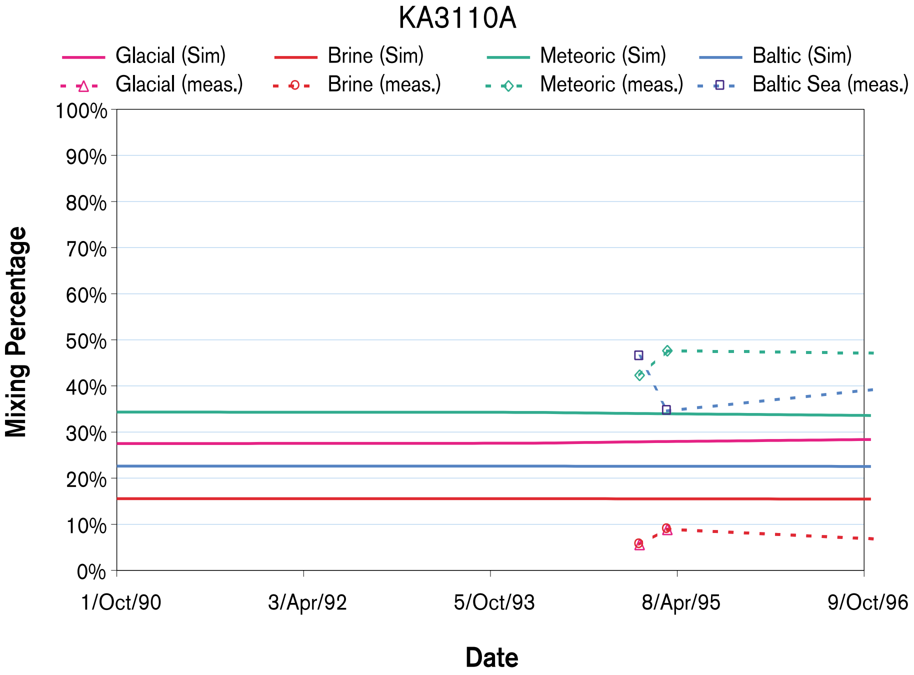


Figure 6-17. *Comparison of geochemical predictions and measurements, H8 Model.*

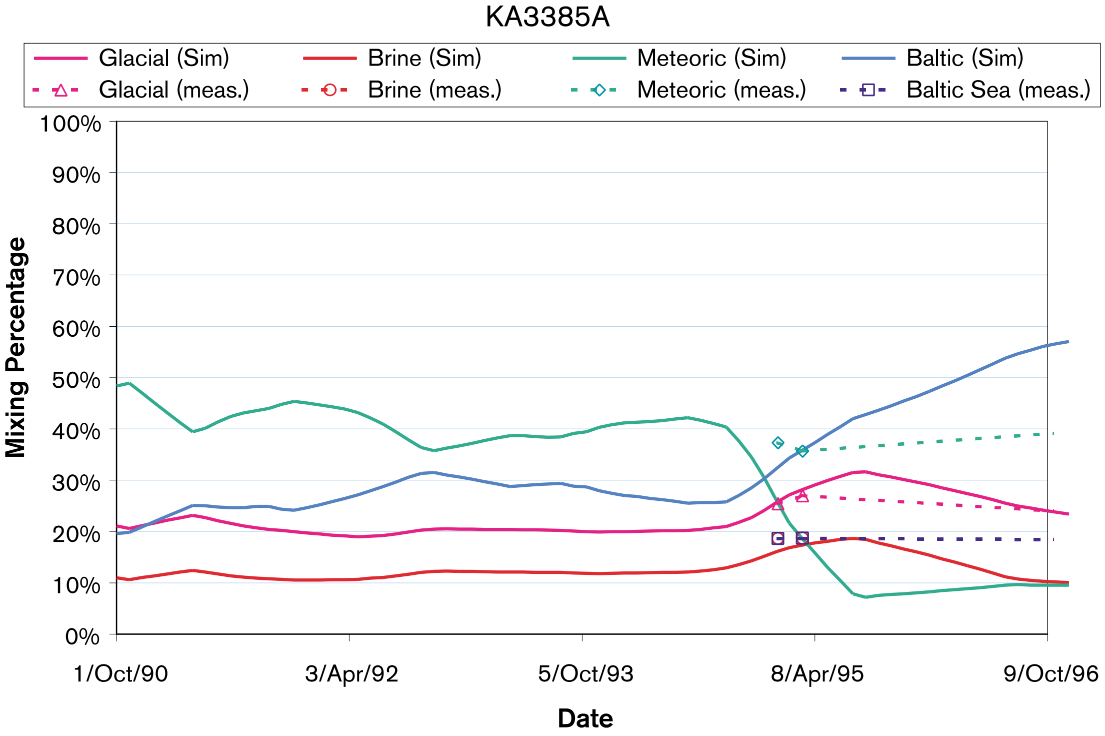


Figure 6-18. *Comparison of geochemical predictions and measurements, H8 Model.*

Figure 6-19 illustrates a prediction from our geochemical model "G4" in which our model predicted (successfully) that geochemistry would remain essentially constant during the prediction period. Unfortunately, for this case the calibration was not very good, such that the geochemical end member mixture at the end of the calibration period did not provide a good match. Figure 6-20 presents an example in which our "G4" model did provide a good match for measurements in the predictive period. However, since little dramatic occurs geochemically during the prediction period, it is hard to discern the effect of pathways connecting to model boundaries and other pathway properties.

Redox experiment in detailed scale

Objective

The main objective of the REX projects is to investigate dissolved molecular oxygen consumption by creating a controlled oxidizing perturbation to the deep rock environment at the Äspö Hard Rock Laboratory which is representative of a deep repository environment /Puigdomenech et al, 1998/.

The specific objectives are:

1. assess the capacity of the host rock system to buffer against an oxidising disturbance,
2. determine the kinetics (half-life) of oxygen consumption,
3. apply quantitative descriptions of these processes that can be used in performance assessment of the repository redox stability for the post-closure phase.

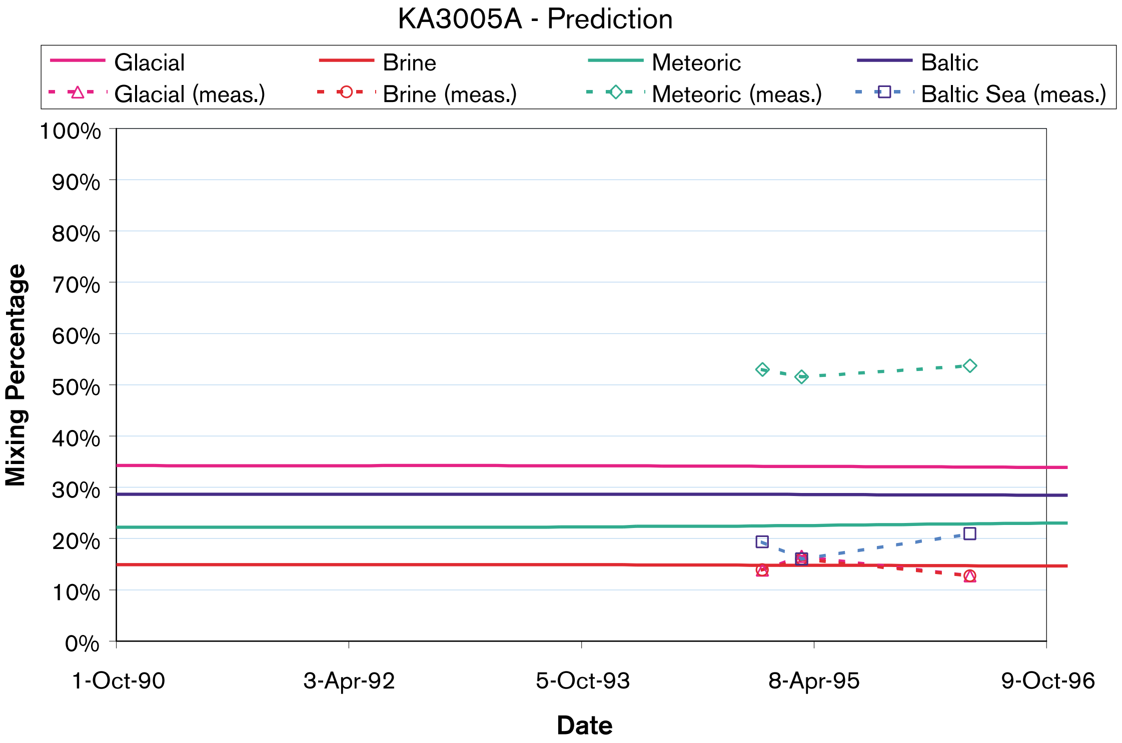


Figure 6-19. *Comparison of geochemical predictions and measurements, G4 Model.*

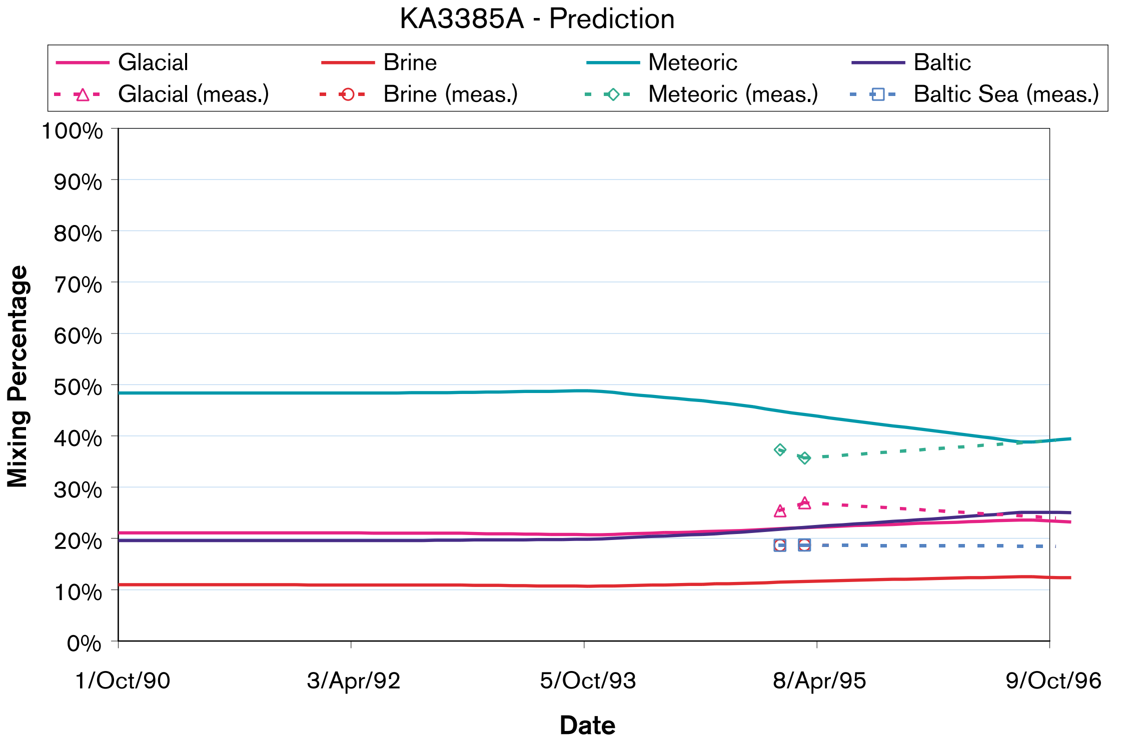


Figure 6-20. *Comparison of geochemical predictions and measurements, G4 Model.*

Experimental

JNC-BGS team has carried out a complementary laboratory study to the REX programme. It examines the interaction of microbes with mineralogical surfaces involved with groundwater flow.

The experiments were started in Year1 (1996) using batch systems and a complete interpretation of the results was given in West et al (1997). Results showed the microbes potentially have complicated effects on the geochemistry of the system. At the end of Year 2, a series of flow through columns were set up under anaerobic conditions. However, problems were encountered with blocking of the columns shortly after the experiments started. Consequently, a series of continuously flowing cells were set up in Year 3 which ran under both anaerobic and aerobic conditions.

Conclusions

The residues from the different types of experiment undertaken all show only very limited evidence of mineralogical alteration relative to the starting material. In most cases, it is the very fine grained (<2 µm) comminuted material, produced by crushing of the Äspö Diorite starting material, which has reacted preferentially. A significant amount of this fine material remained adhered to the coarser grain surfaces of the experimental charge material, despite attempts to remove it by washing and ultrasonic treatment. XRD showed that this fine material is mineralogically similar to the bulk of the starting material. Its reactivity is attributed to its high surface area.

There is petrographic (SEM) evidence for the formation of very minor amounts of secondary smectite- or chlorite-smectite-like clay nucleation on grain surfaces. Mineralogical changes, detected by XRD analysis of the fine fraction also provide evidence of mineral reaction during the course of the experiments. Minor alteration of chlorite and chloritised biotite fines present within the crushed diorite has resulted in the production of smectite and smectite interlayers in the 'primary' phyllosilicates. Although the fluid phase was saturated with respect to smectite solubility in all of the experiment, the amount of smectite formed appears to be very significantly enhanced by the presence of the Äspö bacteria. Possibly, the bacteria catalyse the growth of smectite, perhaps by acting as favourable sites for nucleation. The local site chemistry of bacterial cell surfaces or associated biofilm may create a microchemical environment that speeds the kinetics of clay nucleation, or may present suitable template surface for clay nucleation. Additional research is required to confirm whether the hypothesis of bacterially enhanced smectite formation is correct. If bacterial action is indeed shown to be responsible for the enhanced rate of smectite formation, then the mechanism needs to be established by further work.

6.2.4 CRIEPI

Background

CRIEPI has joined the Äspo HRL project along with JNC and participated in the Task to demonstrate the modeling and analytical methods on groundwater flow and radionuclide migration. Furthermore, CRIEPI was conducted groundwater sampling at the Aspo site for demonstration of groundwater dating methods.

Objectives

CRIEPI has been joined the following two international cooperation tasks and the voluntary task to develop methods to perform exactly the natural barrier:

A. Task Force on Modeling Groundwater Flow and Transport of Solutes, Task 4,

B. Task Force on Modeling Groundwater Flow and Transport, Task 5,

C. Voluntary Project on the Groundwater Dating Method.

A. Task Force on Modeling Groundwater Flow and Transport of Solute, Task 4

CRIEPI performed numerical analyses for Task 4F and Task 5. Our developed numerical codes for groundwater flow and solute transport in rock formations, i.e. FEGM and FERM, were used in the analyses.

In Task 4F, we analyzed results of tracer test STT-2 which was conducted using absorbing solution in the TRUE-1 experiments using three-dimensional model. In the model, feature A was represented as a single flat square of constant aperture of which the length of the side was 30 meters and the surrounding rock matrix was represented as porous media block of 10-cm thickness on each side of feature A. Before analyzing STT-2, we calibrated our model of feature A using the data set of another tracer tests which had already been analyzed. The calibrated parameters were distribution of transmissivity in feature A, hydraulic boundary conditions, aperture of feature A, dispersivity in feature A and rock matrix, surface conditions controlling the magnitude of the absorption coefficients and the matrix diffusion coefficients. According to the result of calibration, transmissivity is very large around KXTT3 R2 in feature A. The calibrated values of absorption coefficients for most radionuclides are 5–10 times as large as those obtained in the batch tests except a few radionuclides. We think that it is a very important how to reduce great differences in values of absorption coefficients between the field test and the batch experiment in the future.

The following Figure 6-21 shows comparison of our calculated breakthrough curves with the observation at the pumping section, KXTT3 R2, during STT-2 test. Our calculated results are in line with the measured ones, although peaks of radionuclides concentration in the calculated breakthrough curves are larger and emerge faster than the measured ones. The following two factors are considered to cause the slight difference between the calculated results and the experimental ones. The first is the change of the natural hydraulic gradient. We determined the hydraulic boundary condition on basis of the natural hydraulic head prior to start of PDT-3. But the natural hydraulic gradients during STT-1a and STT-2 are obviously different from the one prior to start of PDT-3. The other is the redistribution of transmissivity in feature A through all the tracer tests. For example, the pumping ratio during STT-2 is the same as PDT-2, whereas the hydraulic head difference between KXTT3 R2 and KXTT4 R3 during STT-2 is almost twice as large as during PDT-2.

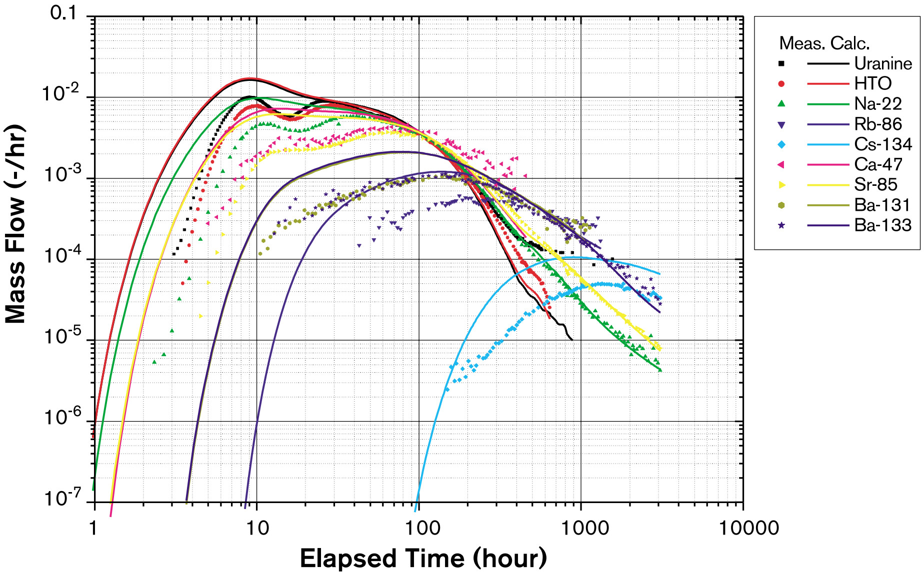


Figure 6-21. *Breakthrough curves at pumping section, KXTT3 R2, during STT-2.*

B. Task Force on Modeling Groundwater Flow and Transport, Task 5

Objectives of Task#5 are to evaluate the changes of groundwater flow and solute transport caused by tunnel construction. The predicting calculation has been done using the data before tunnel reaching the position at 2,900 m.

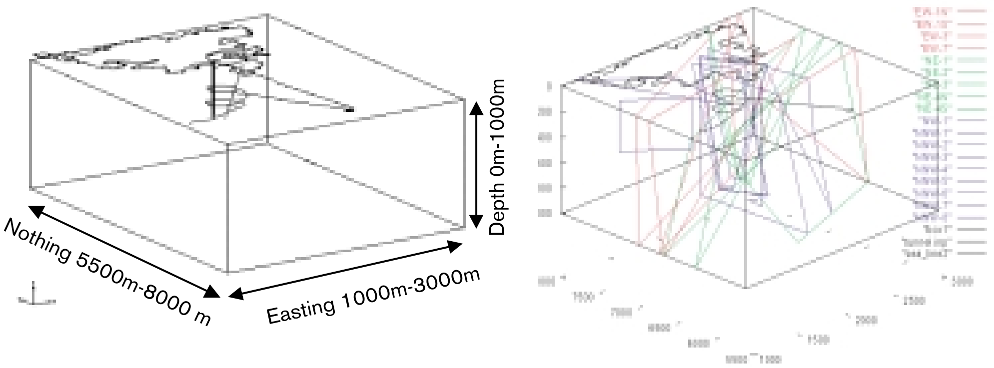
We verify:

1. to enhance the applicability of FEGM/FERM developed by CRIEPI on site scale groundwater flow and solute transport, and
2. to understand site scale groundwater flow and solute transport.

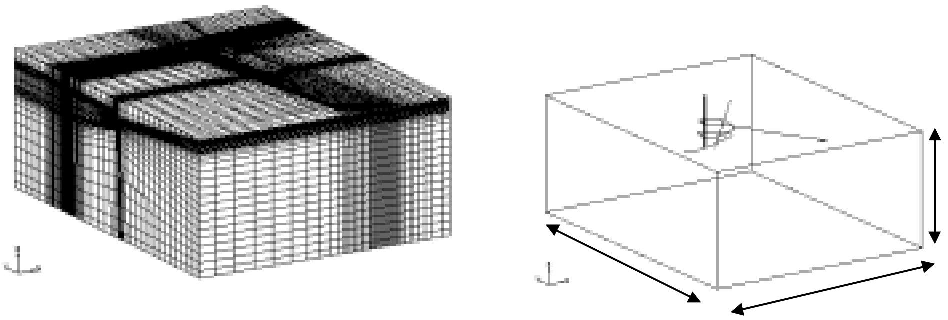
Outline of the model

FEGM/FERM are numerical codes of groundwater flow and solute transport based on the finite element method. In this calculation, it has been done to evaluate the change in the draw down of groundwater table, concentrations of conservative tracers (i.e. Cl^-, ^{18}O) and mixing among four end-members (Meteoric water, Baltic seawater, brine water and glacial-water) with time.

The modeling area composed by 17 fracture-zones and 1 rock mass, however the analyzed results displayed in Figure 6-22 and Figure 6-23 are consistent with not only the trend of entire variation but also patterns of sensitive local changes in these.



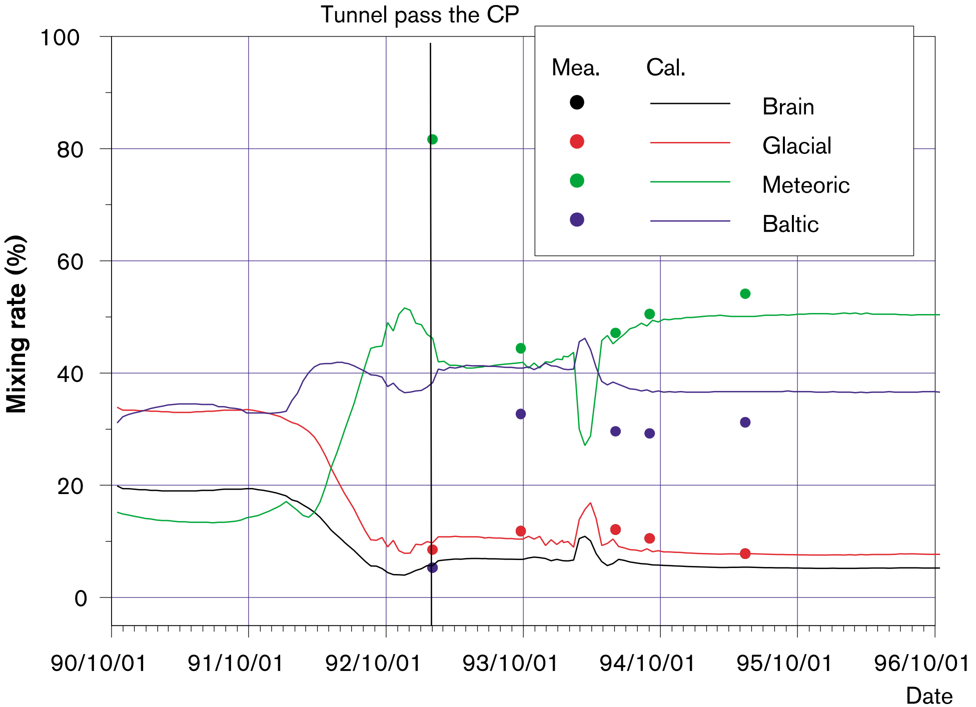
(1) Modeling area (2) Considered Fracture zones in our modeling



(a) Hexahedral element (b) Line element

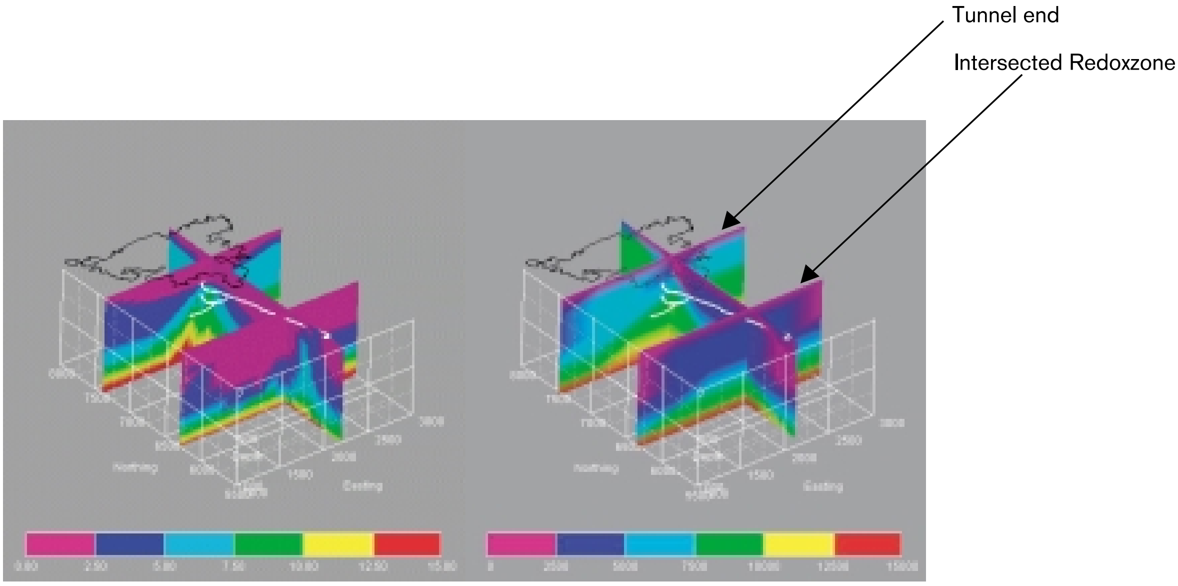
(3) Finite element mesh (159,214 hexahedral elements and 349 line elements.)

Figure 6-22. *Concept of our modeling on Task#5.*



(4) SA2074A

Figure 6-23. *Mixing rate changing during tunnel construction.*



Calculated by M3 model

Calculated by FEGM/FERM

Figure 6-24. *The distribution of CI concentration at disturbed condition.*

C. Voluntary Project on the Groundwater Dating

Introduction

CRIEPI conducted groundwater surveys at Äspö HRL in 1995 and 1997, for the purpose of investigating the origin and residence-time of groundwater and estimating changes and stability in groundwater environments during tunnel excavation. Groundwater was investigated in noble gas hydrology, isotope hydrology and chemical hydrology by collecting groundwater samples at 21 points in the tunnel and one deep borehole outside the tunnel. Dissolved noble gas contents and isotope ratios, stable isotopes, ^{36}Cl/Cl ratios, tritium concentration and chloride concentration were measured to collect palaeohydrological information.

Results

Distributions of dissolved He content and chloride concentration were heterogeneous in the entire tunnel. The highest content of He and chloride were located surrounding KA2862, which is 380 m below the ground surface and is not the deepest location in the tunnel. There was little change in the content of He and chloride at KA2862 in the past two years. The area surrounding KA2862 is estimated to be isolated from groundwater disturbed by tunneling. This zone is defined in the undisturbed zone. On the other hand, the areas including KA3105 and KA3110 have already lost the primary geohydrological conditions because of the intrusion of much Baltic seawater via fractures. The He content in samples collected here is 50 times less than that measured in the undisturbed zone. There were no changes in stable isotopes, chloride concentration and He content in this zone, which was defined as the disturbed zone. Dissolved He content at KR0013, KA3010 and KA3067(g) changed drastically in the past two years because of the tunneling. However, other indicators (stable isotopes and chloride concentration) remained little changed. Furthermore, the He content is mid-level compared with that of samples collected at the same depth in the undisturbed zone and the disturbed zone. This area is called the mixing zone where it has gradually been mixing with Baltic seawater intruding through micro fractures or fissures.

The changes in the stable isotopes changes for two years indicate that groundwater in the tunnel has consisted of a mixing between groundwater which has not lost the primary geohydrological conditions in the undisturbed zone and Baltic seawater intruding by tunnel excavation. The mixing line was expressed in eq. $\delta D = 6.38\delta^{18}O – 9.97$ having high saline water and Baltic seawater as both end-members. KA3358 moved greatly to a direction of Baltic seawater on this mixing line for two years. On the other hand, KA2862 and KA3010 also moved greatly to a direction of Laxemar Deep groundwater on a different eq. $\delta D = 11.3\delta^{18}O + 56.2$. This suggests that deep high-saline water at Äspö has not completely been isolated from groundwater flow but has gradually circulated in a regional groundwater flow including the Laxemar region.

^{36}Cl content and He content were measured to estimate groundwater residence time. However, since the in-situ ^{36}Cl production is not negligible, groundwater residence time can not be estimated from a decrease in ^{36}Cl atoms produced by cosmic irradiation. This result is supported by Louvat et al (1999). The residence times were predicted from dissolved He content and He dispersion effects in stratum. The oldest groundwater with a high salinity of more than 14,000 ppm of Cl^- is estimated to be more than $1.8 \cdot 10^6$ years old. The groundwater residence time ranges from 900 to $9 \cdot 10^5$ years in the gradually mixing-zone. Groundwater in the disturbed zone where a intrusion of Baltic seawater occurred is too young to date reliably and the primary paleohydrological characteristics have already been lost.

Conclusions

On Äspö island, very old groundwater of which the residence time is over one million years has partially been remained and it might have kept palaeohydrological conditions such as stagnant water see Figure 6-25. However, this is still open for discussion. On the other hand, some parts of the tunnel have been losing primary conditions of groundwater by the intrusion of Baltic seawater via fractures from the tunneling. The investigation for the past two years indicates that the groundwater flow is very complex in crystalline rocks and depends on the characteristics of fractures. The in-situ production rate of ^{36}Cl in the granite rocks is not negligible for that of the cosmogenic ^{36}Cl.

A bird's-eye view of the Aspo Site

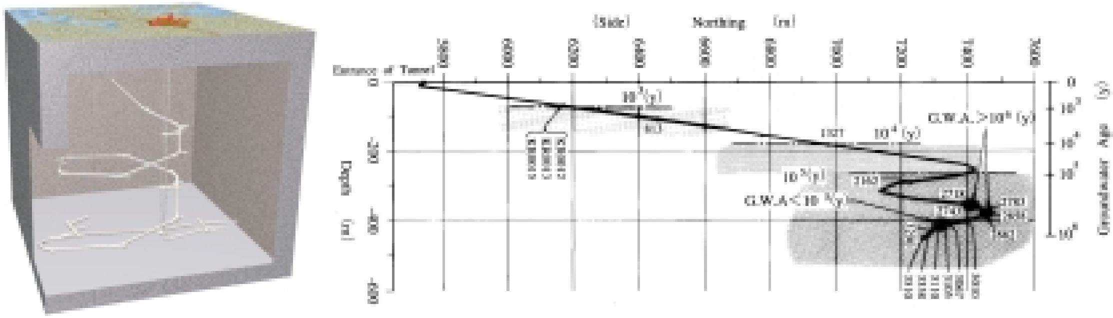


Figure 6-25. *Groundwater dating results at the Äspö site in Sweden (using the He accumulation method).*

6.2.5 UK Nirex

Background

United Kingdom Nirex Limited (Nirex) has been supported by AEA Technology plc to provide modelling for the TRUE Block Scale Project.

Objectives

The TRUE Block Scale Project is an international project designed to:

- increase understanding and the ability to predict tracer transport in a fracture network,
- assess the importance of tracer retention mechanisms in a fracture network,
- assess the link between flow and transport data as a means for predicting transport phenomena.

Experimental Concept

The TRUE Block Scale Project is in its final phase. The project is entering the so-called "Predictive Stage of Tracer Testing". This phase consists of a progressive campaign of hydraulic interference testing, point dilution measurements and finally tracer testing of progressively more reactive tracers, culminating in a series of sorbing radioactive tracers. The three phases of this stage have been defined as Phase A, Phase B and finally Phase C. The activities this year supported by Nirex have been principally focussed on the predictive modelling of the Phase A testing. Phase A consists of five tests. The first three tests consist principally of dilution tests with different sink (abstraction) configurations. The final two consist of tracer testing.

There have been various modelling concepts used by the partners in the project. Nirex (supported by AEA Technology) is using the discrete fracture network (DFN) approach to predict the outcome of the various phases of the project.

Nirex's modelling support has been used to develop a:

- site-model, that includes the influence of the HRL, tunnel system and Äspö island to capture the overall water balance, establish the distribution of salinity and to provide appropriate boundary conditions for sub-models,
- local scale model of the TRUE Block on a 100-500m scale to capture the features of the March' 99 structural model (this model encompasses the current knowledge of the structures in the TRUE Block); and
- detailed subscale model to describe variability of the components (structures) of the structural model.

Site-scale model

A site-scale model has been established that includes both the discrete features of the site (fracture zones) and the distribution of salinity. The purpose of this model is to study the influence of the larger scale flows on the local scale model of the TRUE Block and provide self-consistent boundary conditions for the local-scale models.

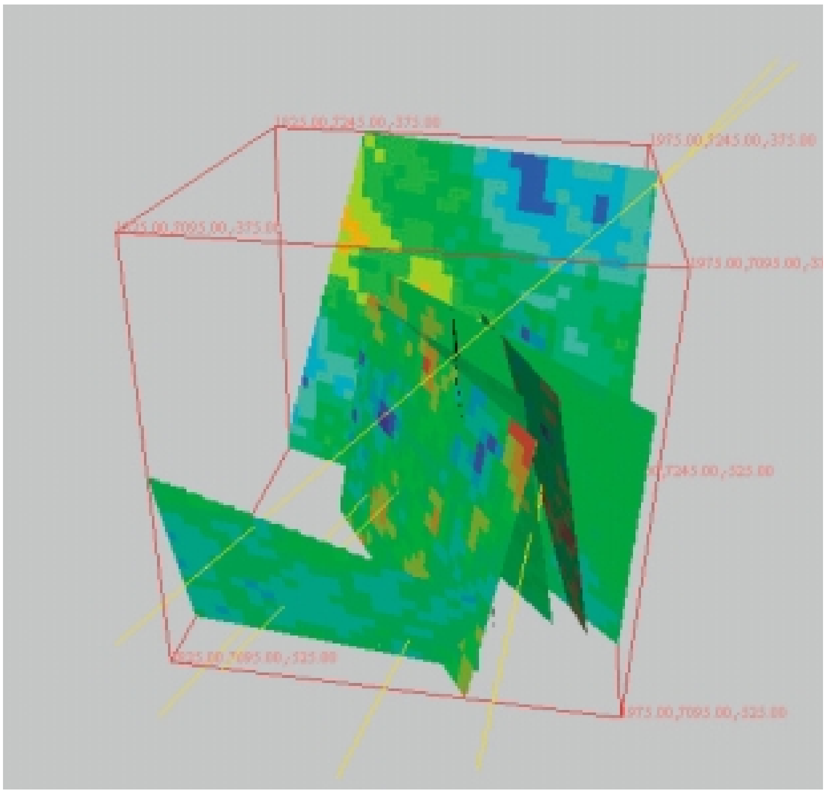


Figure 6-26. *Basic March '99 structural model with heterogeneity in transmissivity, T on a 20 m scale. The colour shading indicates the scale of variability in T.*

Local-scale model

A basic local model of the TRUE Block site has been constructed based on the so-called March'99 model. This includes a parameterised structural model (primarily based on transmissivity measurements arising from the pretesting of the key structures) of the basic geometrical model. This has been implemented using the DFN software NAPSAC. Figure 6-26 shows the March '99 model with transmissivity correlation length on a 10–100 m scale.

Detailed subscale model

The discrete fracture network software NAPSAC has been used to include variability on a sub-scale to enable small-scale variability, potentially down to a scale commensurate with the dimensions of a borehole diameter, to be included. Figure 6-27 shows the results of a NAPSAC groundwater flow calculation (showing pressure contours). The underlying model has variability on the 1m length-scale with borehole KI0025F03:P5 used as a sink. Figure 6-28 shows a release of tracer travelling towards the sink, the flow channels have been removed to more easily show the dispersion of the flow paths. This has demonstrated that it is possible to perform detailed scale calculations. Work is progressing on calibration approaches and the integration of data on various length-scales.

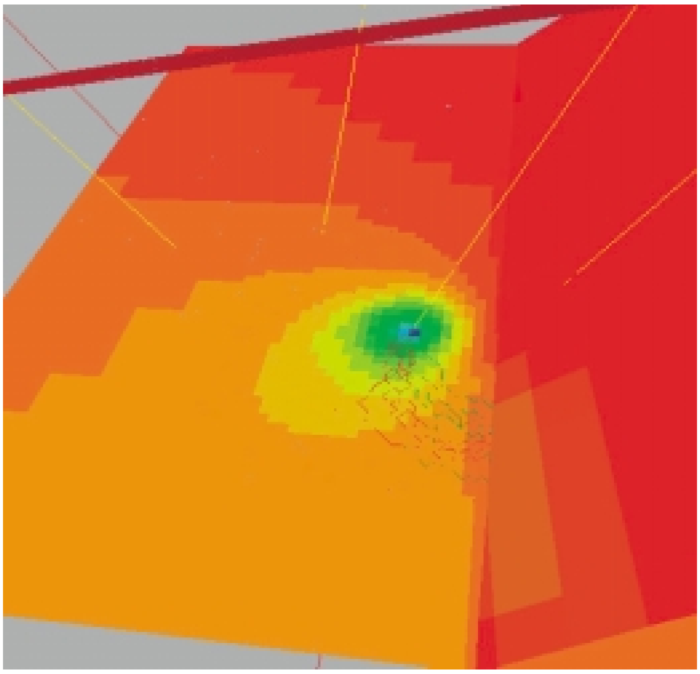


Figure 6-27. *Pressure contours showing drawdown as a result of pumping borehole section KI0025F03:P5 with pathlines visible from a release in a neighbouring borehole. This is a result of the simulation of tracer test A-5.*

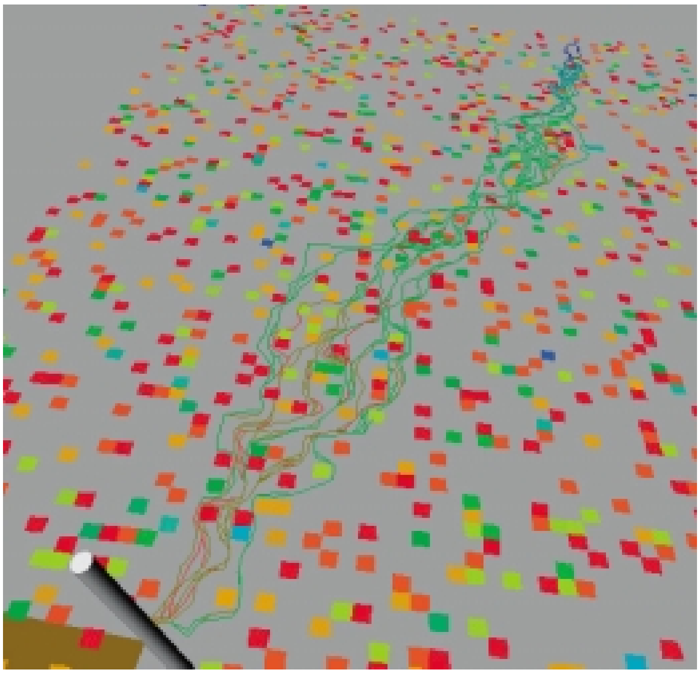


Figure 6-28. *This figure shows pathlines of particles (coloured according to time) released from a point in the feature and being received by the abstraction borehole. The flow channels (higher T>1.0 · 10^{-8} m^2s^{-1}) have been removed (in the visualisation) to more easily visualise the flow in the channels. The small-scale variability is on a 10 cm scale.*

Scope for 2000

Future modelling work in 2000 will concentrate on the understanding and prediction of tracer experiments performed in the TRUE Block. In particular, this will cover:

- the prediction and subsequent calibration as part of a structured testing programme,
- Phase B predictions,
- Phase C predictions.

The modelling activities will be undertaken on behalf of the TRUE Block Scale Project.

6.2.6 NAGRA

Introduction

Migration experiments on the field scale with typical length scales of several meters are performed to increase the fundamental understanding of various phenomena of importance for radionuclide migration through the geosphere. In addition, such experiments are the basis for the evaluation of the adequacy and accuracy of different models. Results from laboratory and field experiments as well as observations on the natural system are compared with (blind) predictions of competing models followed by a careful analysis of the discrepancies between predictions and observations which constitute the principal basis for, either, suitable model refinements or – in a strict sense – for a model rejection.

In 1997 the PSI modelling team joined the Äspö Task Force to participate in the international modelling effort of Task 4e comprehensive tracer transport experiments. Our specific objectives were:

1. To apply our simple model for flow and contaminant transport, which was already successfully applied to the modelling of the former field migration experiments performed at the Finnsjön and Grimsel (Switzerland) test sites, to another type of fractured rock with different transport properties.
2. To explore how information obtained from structural geology could be considered in our flow and transport model.
3. To examine whether values for the transport parameters obtained in small-scale laboratory experiments could be used for modelling the field tracer tests on a much larger spatial scale. If this would be feasible, how would these parameter values scale up?
4. To obtain information regarding the advantages and disadvantages of competing models, especially for those with more sophisticated descriptions of the hydrology.
5. To test and further develop our model for groundwater flow and nuclide transport.

Modelling approach

The experiments were performed in Feature A on the "detailed scale" with typical length scales of about five meters. Hence, these tracer tests allowed, in principle, to fully address different retention processes such as sorption and matrix diffusion.

Due to the special experimental conditions at the TRUE-1 site at Äspö which resulted in extreme narrow and fast flow fields for all tracer tests within Tasks 4e and 4f, our model for flow and transport is conceptually quite simple.

The hydrological part of the model is based on a 2D-streamline/streamtube formalism with an underlying homogeneous and isotropic transmissivity field. In this part of the model, water flow through fractures occurs in an equivalent porous medium with a homogeneous and averaged flow porosity. In addition, an averaged and uniform steady-state natural background flow-field is taken into account. Furthermore, constant injection and pumping flow-rates are assumed.

Tracer transport modelling is performed in the frame of the 1D-dual porosity medium approach. Hence, it is a continuum and deterministic description with averaged values for the transport parameters which are – in addition – constant in space and time. Matrix diffusion occurs in the model into a limited porous zone adjacent to the fractures, and sorption processes are described by linear isotherms. Both, the flow and transport parts of the model are linked to each other by the flow width[1], only, hence one single number.

Blind predictions for the STT1 tracer test and subsequent model refinement

The following figure illustrates the very limited domain of interest for the STT1 tracer test due to the rigid pumping at the extraction borehole in order to guarantee full tracer recovery.

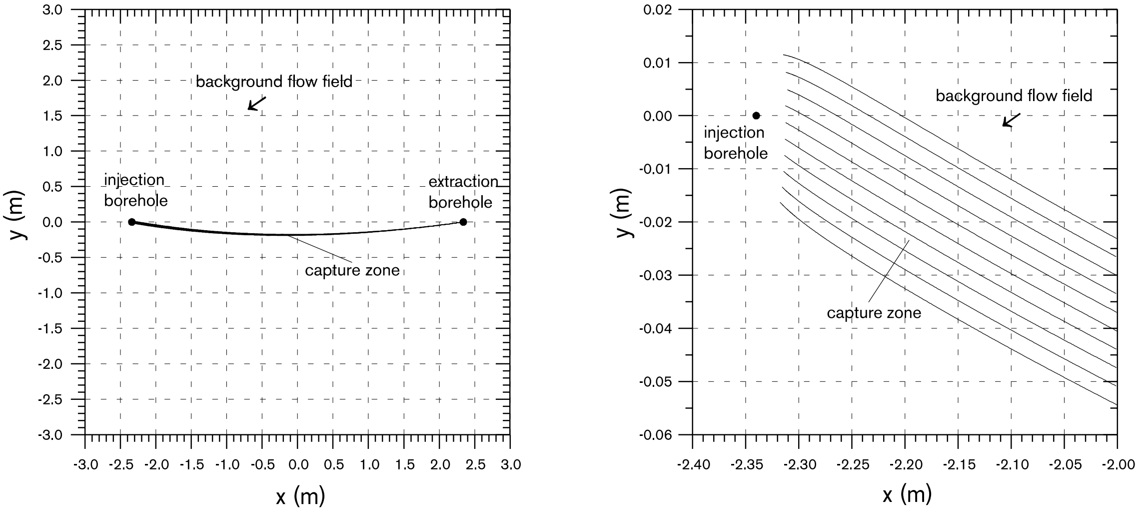


Figure 6-29. *Flow domain for the Task 4e – STT1 tracer test. Drawn are ten 1D-streamlines of the considered capture zone[2]. Due to a weak natural background flow-field the capture zone is slightly deformed. As a consequence of the high pumping rate at the extraction borehole, all the injected tracer migrates within the capture zone. In the right sub-figure a magnification of a part of the flow domain close to the injection borehole is drawn. Shown are again ten 1D-streamlines which start at the borehole/rock interface. Due to the strong pumping at the downstream boundary and nearly passive injection the capture zone is very narrow and has a width of only a few centimetres. (Note the different scales on both axes.)*

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[1] The flow width is the product of flow porosity and aquifer thickness.

[2] Regions of interflow between a recharge and a pumping well within a flow domain are denoted as "capture zone".

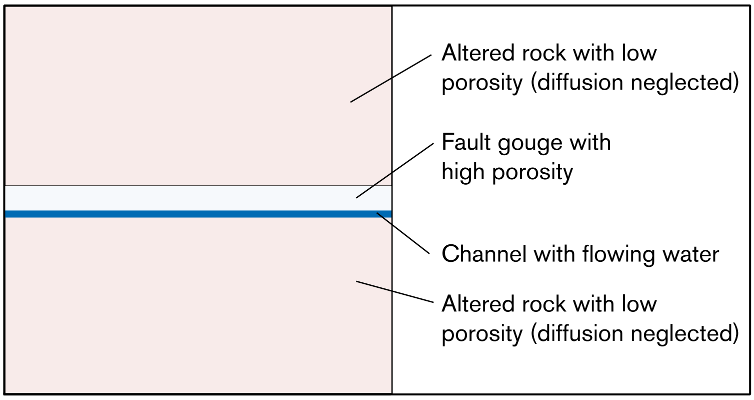

Figure 6-30. *Schematic diagram of the geometrical aspects of the transport model used as a basis for the blind predictions of the STT1 tracer test.*

According to the results of geological investigations, water mainly flows in a network of connected major faults and is not only in contact with fault gouge[3], characterised by a relatively large porosity, but also with cataclasite[4], mylonite[5] and altered rock[6] of (much) lower porosity.

The model was calibrated by fitting one single uranine breakthrough curve performed in the same flow field as used in the subsequent STT1 tracer test. The best-fit yielded an excellent representation of the measured data, and the shape of the trailing edge indicated a surprisingly large effect of matrix diffusion. This result was later confirmed by observations of fault gouge material in the neighbourhood of Feature A. Therefore, we assumed one-sided[7] limited matrix diffusion into fault gouge for the blind predictions of the STT1 tracer test.

Due to the nature of the uranine injection distribution – a more or less square pulse injection followed by a long injection tail at lower concentrations – it was not possible to identify any tail-end perturbation at the trailing edge of the breakthrough curve indicative of a limitation of diffusion in the extent of the fault gouge. Hence, a value for the width had to be guessed, and the value assumed (1 mm) represents a relatively small (averaged) thickness of the diffusion-accessible zone. Finally, applying interpreted[8] values for the transport parameters determined in laboratory experiments we achieved surprisingly good predictions when compared with measurements except for the more strongly sorbing rubidium and caesium. For illustration purposes, in the following figure, three out of a total of eight predictions are compared with measurements.

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[3] "Fault gouge" is a geologic term for the crushed and ground-up rock produced by friction between the two sides when a fault moves.

[4] "Cataclasite" or fault breccias form in brittle fault zones and consist of larger angular rock fragments dispersed in a fine-grained matrix.

[5] Mylonite indicates any foliated (and usually lineated) fine-grained metamorphic rock which shows evidence of strong ductile deformation. The term is purely structural and conveys no indication of the mineralogy of the rock. Thus, a mylonite can be of any rock type.

[6] "Alteration" is the partial chemical transformation of a rock or mineral through aqueous solutions.

[7] This assumption was based on results from structural geological investigations of a fracture system in the neighbourhood of Feature A.

[8] Mass specific sorption coefficients K_d were re-scaled to account for crushing in the batch sorption experiments and to extrapolate to (crushed) mylonite which was considered as the laboratory rock sample closest to fault gouge. The values for the pore diffusion coefficients were extrapolated from that for uranine and we were using Swedish nuclide-dependent values for the diffusion coefficient D_w in free water.

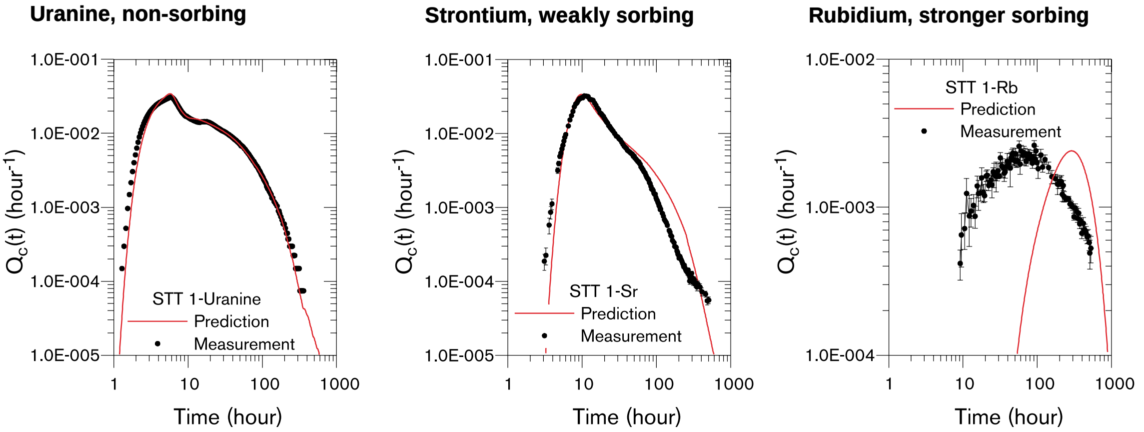

Figure 6-31. *Comparison of blind predictions and measurement for three out of eight tracers of STT1. With increasing sorption capacity the predictions become less accurate.*

In the subsequent analysis using all eight tracer breakthrough curves, it turned out that the assumed value for the thickness of the fault gouge material was too small and had to be adjusted to 5 mm. However, especially for the stronger sorbing tracers, an early tracer breakthrough could not be obtained by the model, even when the values for the (longitudinal) dispersion were increased to unrealistic large values. Only by using a refined model in which a second flow path family was included, an improved representation of the rising edge could be achieved. Applying the refined model to caesium indicated irreversible sorption or sorption with a very slow desorption rate for about 50% of the tracer.

Our methodology for the analysis of the tracer breakthrough curves was as follows: In a first step all nuclide-independent parameters were fixed using data from the conservative tracer uranine, only. In a second step, keeping these parameters fixed, only nuclide-dependent parameters were adjusted. Here, only small variations for the (pore-)diffusion coefficient were allowed. Hence, in fact the only free fit-parameters were the bulk sorption coefficients K_d.

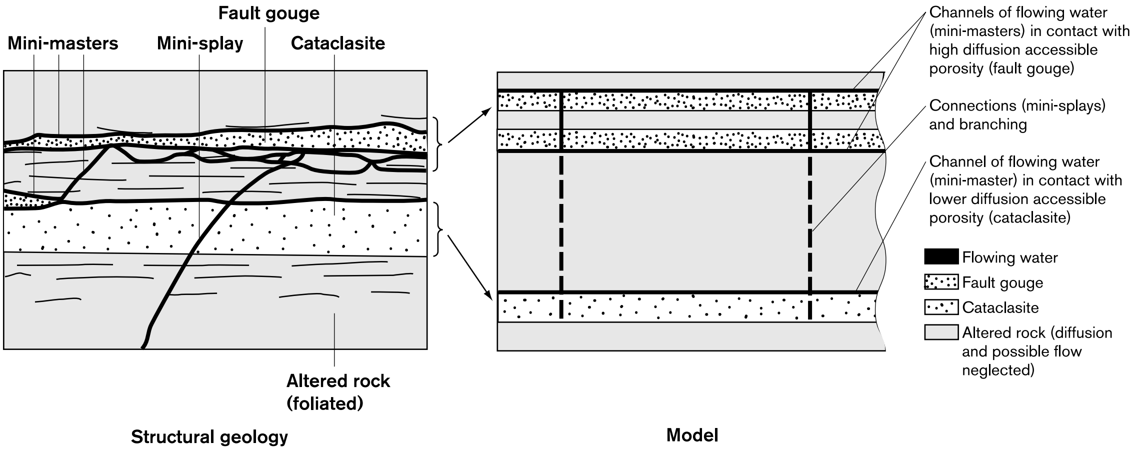

Figure 6-32. *Sketch of the refined geometry for flow and transport after the analysis of the STT1 tracer breakthrough curves. The sketch on the left illustrates some important aspects of Feature A as they were identified in structural geological investigations. In the right part the transformations into a relatively simple model geometry are shown. This was the basis for the subsequent blind predictions of the STT1b tracer test performed again in the frame of the dual porosity medium approach.*

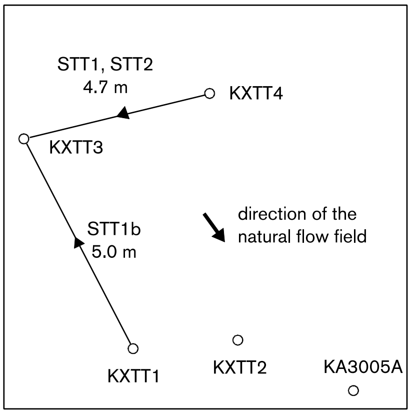

Figure 6-33. *Configuration of the borehole intersections with a hypothetical plane representing Feature A. The general trend of the direction of the natural background flow field is indicated by the arrow. A near passive injection of the tracer took place in borehole KXTT4 for the STT1 and STT2 tracer tests and in borehole KXTT1 for the STT1b migration experiment. Pumping was always in borehole KXTT3.*

Blind predictions for and subsequent analysis of the STT1b tracer test

Based on the best-fit parameter values obtained by inverse modelling of all eight tracers of the STT1 tracer test, a further single uranine breakthrough (PDT4) in the new flow field for the STT1b tracer test was calculated. The comparison with measured data, which were released again for calibration purposes only, lead to adjusted values for the flow width and, hence, to a changed water velocity and specific interface area between flowing water and fault gouge and cataclasite, respectively.

With this updated model and using these best-fit parameter values, which differ from laboratory data obtained on generic Äspö diorite in maximum by a factor of five, only, blind predictions were made for the STT1b tracer test. For potassium and cobalt, there were no sorption measurements known at all. Hence, rough estimations on their sorption distribution were made implying large uncertainties.

Again, as for STT1, no significant discrepancies between predictions and measurements could be observed. This is shown in the following figure.

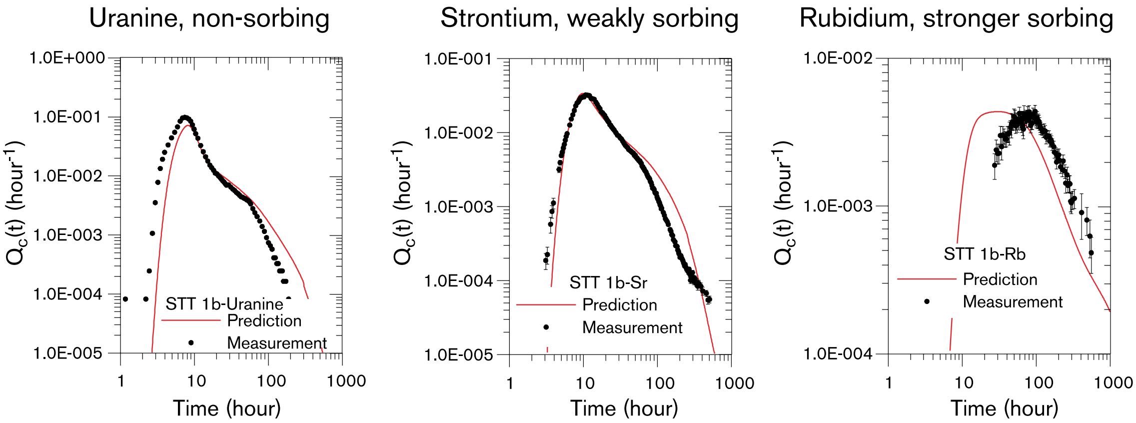

Figure 6-34. *Comparison of blind predictions and measurement for three out of seven tracers of STT1b.*

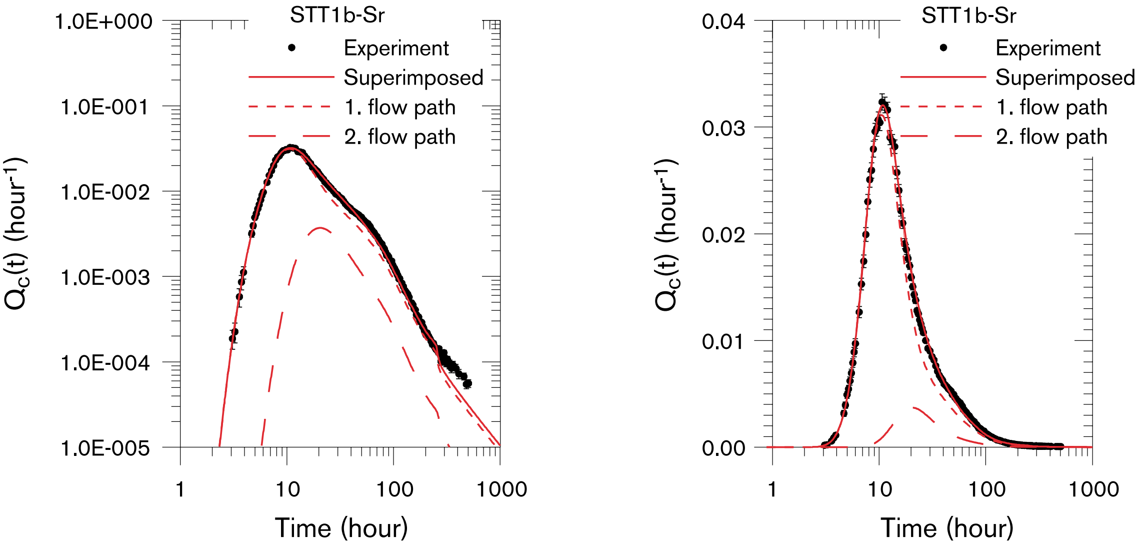

Figure 6-35. *Best-fit for strontium of the STT1b tracer test in the frame of a two-fracture family model. In a log/log and in a lin/log representation the contributions of each of the two flow paths and their superposition as indicated in the legends are shown. Considering the first fracture family, only, would yield nearly the same results. Fit parameters were* D_p *and* K_d *only. All the other parameter were kept fixed to the best-fit values from modelling the conservative tracer uranine. For the pore diffusion coefficient only slight variations up to a factor of 1.5 were accepted and had to be identical for both fracture types. The values for* D_p *had to be identical for both fracture types.*

Inspecting the breakthrough curves of all seven tracers of STT1b, it turned out that the slope of the trailing edge for the conservative and weakly sorbing tracers does not follow the well-known $t^{-3/2}$-dependency indicative of matrix diffusion but is somewhat steeper. In the subsequent analysis we could show that this is just an effect due to the shape of the second part of the injection distribution. In addition, for these tracers – in principle – the first flow path family bounded by fault gouge would be sufficient to reproduce the measurements with high quality.

However, for the more sorbing tracers, such as rubidium, taking into account the second fracture family slightly increased the quality of the fits at the expense of more freely adjustable parameters. Thus, it is a matter of taste which one of the two options is preferred.

Best-fit values for K_d were larger by roughly an order of magnitude when compared to laboratory measurements, but – as already mentioned – these laboratory values were obtained on Äspö diorite instead of on fault gouge material.

Blind predictions for the STT2 tracer test and analysis of the measured breakthrough curves

In 1999 all modelling teams of the Äspö Task Force were asked for blind predictions for a third tracer test, called STT2. The new migration experiment was performed between the same borehole combination already applied for the first tracer test STT1 (see also Figure 6-33 for details) but with a smaller extraction flow rate (by a factor of two). Hence, the dipole flow field was widened, and it was expected that the influence of the natural background flow field could be slightly stronger.

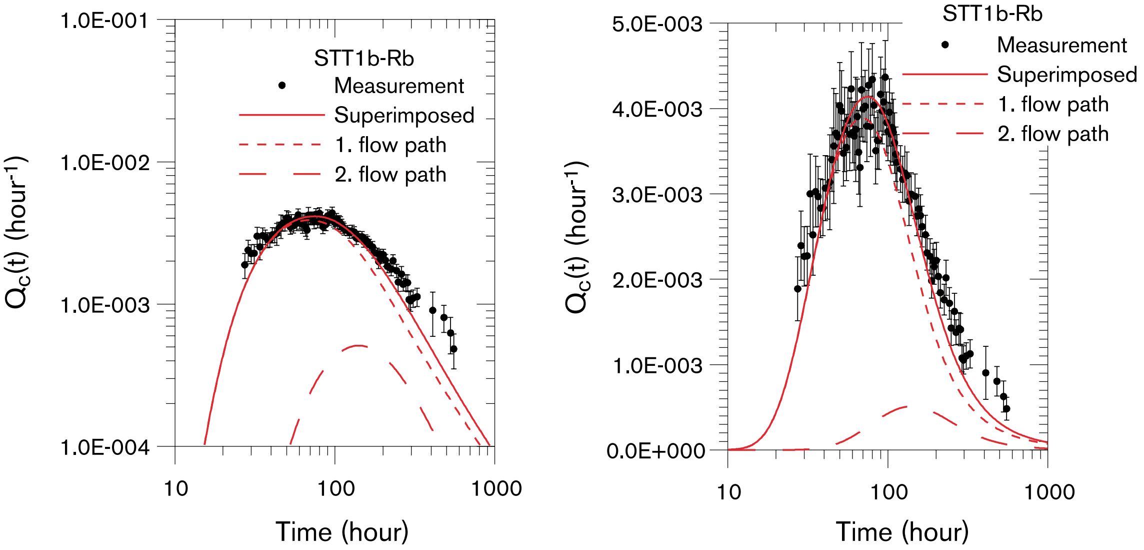

Figure 6-36. *Best-fit for rubidium of the STT1b tracer test in the frame of a two fracture family model. In a log/log and in a lin/log representation the contributions of each of the two flow paths and their super-position as indicated in the legends are shown. Considering the first fracture family, only, would result in a worse representation of the trailing edge. Fit parameters were the pore diffusion coefficient* D_p*,* K_d*, and, in addition, the longitudinal dispersion length* a_L*. The last parameter was fitted only for a certain fine-tuning of the rising edge of the breakthrough curve. All the other parameter were kept fixed to the best-fit values from modelling the conservative tracer uranine. For* D_p *only slight variations up to a factor of 1.5 were allowed since this parameter is a – more or less – nuclide independent quantity. The values for* D_p *had to be identical for both fracture types.*

Blind predictions were made in the frame of the two-fracture family model using best-fit values extracted from inverse modelling of the STT1 tracer test. All our predictions only yielded one single peak; however, the measurements clearly showed double-humped breakthrough curves for all non-sorbing and weakly sorbing tracers. For the stronger sorbing tracers barium, rubidium and caesium one single maximum could be seen, only, due to the smoothing effects of matrix diffusion and sorption.

In the subsequent analysis, first the values for the mean water velocity and the weights of the two fracture families had to be adjusted using only the breakthrough curves of the conservative tracers. With a simple fine-tuning of the remaining transport parameters an excellent agreement between measured and calculated breakthrough curves could be obtained, even for the sorbing tracers. Caesium was an exception because – as for STT1 – a marked "tracer loss"[9] of roughly 30% had to be taken into account. This is illustrated with the help of the following figure where, as examples, the best-fit curves for uranine, strontium and barium are shown.

The best-fit values for the sorption equilibrium distribution coefficient, K_d, for the weakly sorbing tracers (sodium, strontium and calcium) are by a factor of 10–70 larger than the values measured in the laboratory. For the stronger sorbing tracers barium, rubidium and caesium the differences between in-situ and laboratory values are smaller. There are hints that fault gouge has an unspecified clay mineral content which could cause higher K_d values than those measured in the laboratory on Äspö diorite[10].

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[9] Based on the available data we cannot decide whether, indeed, tracer was lost by irreversible sorption or whether caesium shows a very slow desorption rate.

[10] For all tracers differences in the CEC (cation exchange capacity) and the water chemistry between field tracer tests and batch sorption experiments might be of importance.

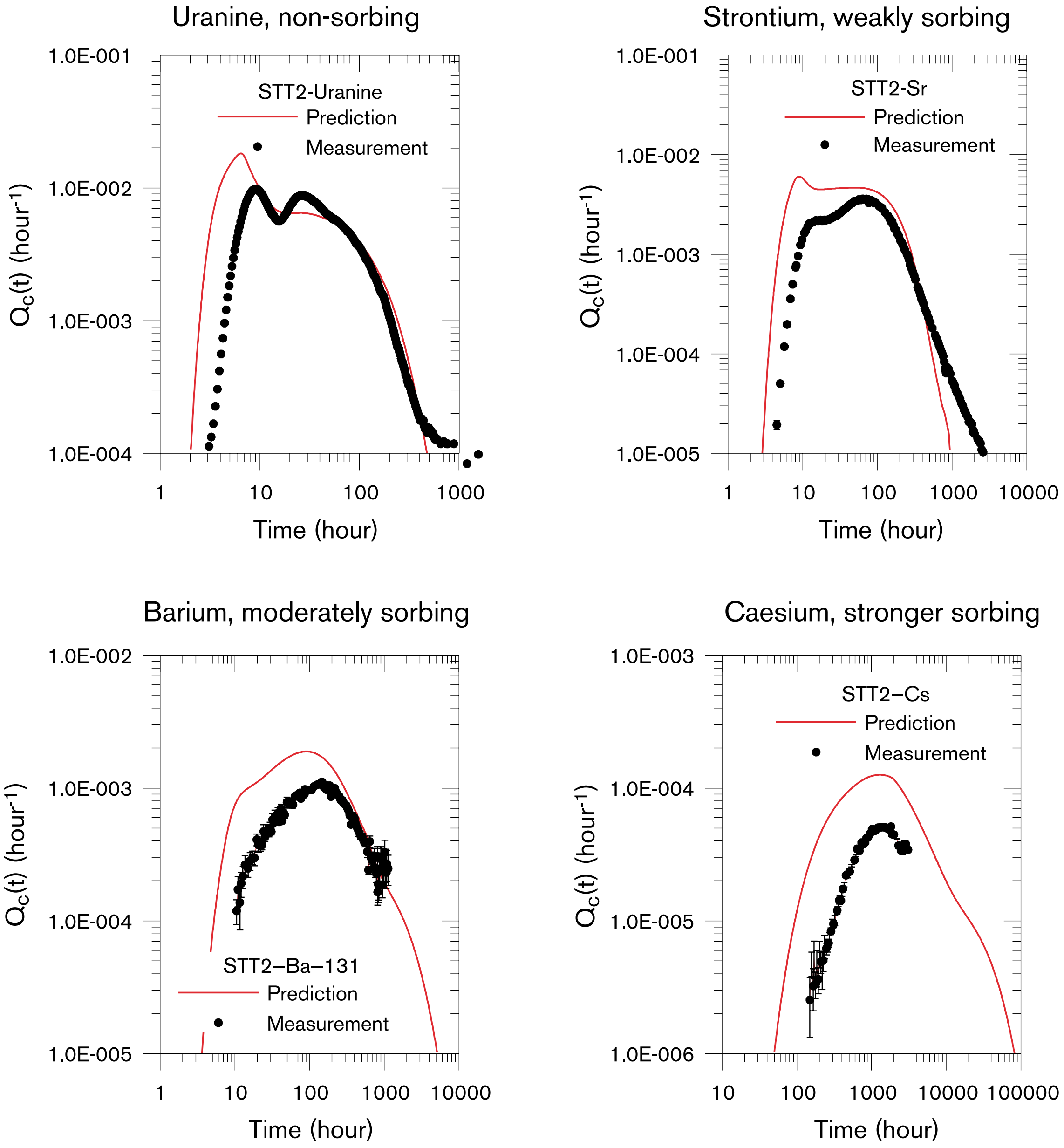
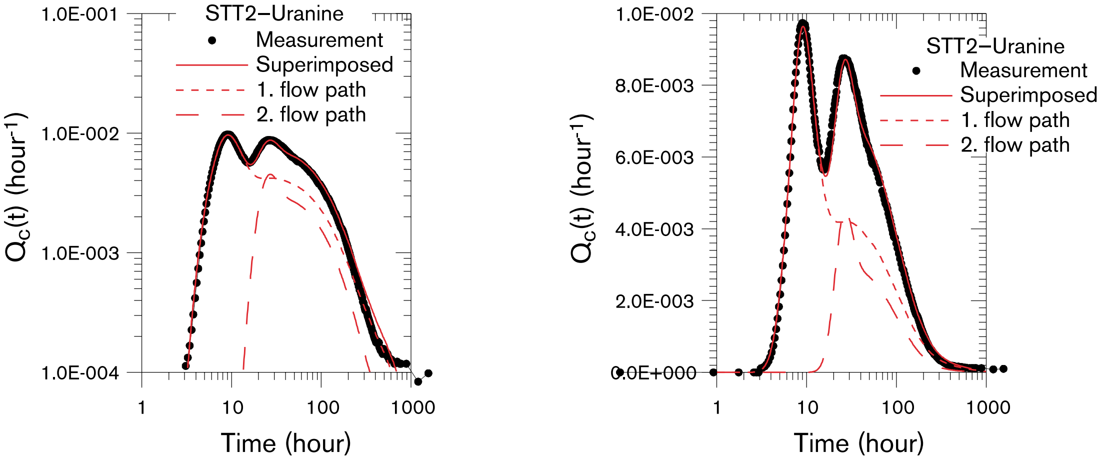


__Figure 6-37.__ Comparison of blind predictions for and measurements of four out of ten tracers of the STT2 migration experiment.

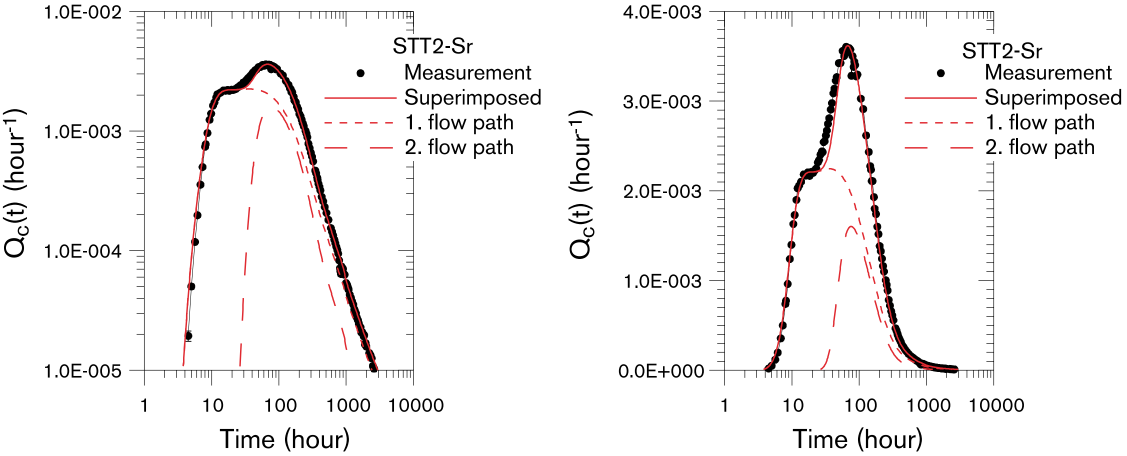
Best-fit values for the pore-diffusion coefficient are, in maximum, an order of magnitude smaller than values measured in the laboratory on pieces of bore-cores of Äspö diorite. However, larger values for the pore diffusion coefficient measured in the laboratory may result from decompression effects of the bore-cores, and, as emphasised above, the diffusion zone in the field experiments is fault gouge and not diorite.

An intercomparison of all the extracted best-fit values for the transport parameters for all three tracer tests does not yield any obvious inconsistency in the data. Of course, best-fit values for the transport parameters may scatter but the differences are smaller or comparable to the size of the systematic errors of the experiments which are estimated to be at least 30%.

Uranine, non-sorbing (conservative)



Strontium, weakly sorbing



Barium, stronger sorbing

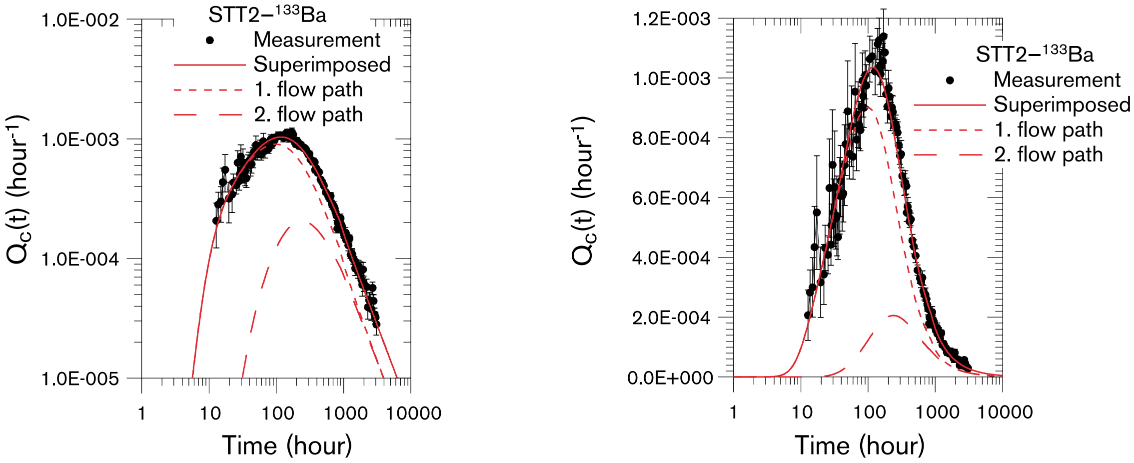


Figure 6-38. *Best-fit for non-sorbing uranine, weakly sorbing strontium and stronger sorbing barium of the STT2 tracer test in the frame of a two-fracture family model. In a log/log and in a lin/log representation, the contributions of each of the two flow paths and their superposition as indicated in the legends are shown. Fit parameters were the pore diffusion coefficient D_p and the sorption distribution coefficient K_d. All other parameters were kept fixed to the best-fit values from modelling the conservative tracer uranine. For D_p only slight variations up to a factor of 1.5 were allowed since this parameter is a – more or less – nuclide independent quantity.*

Conclusions

- The analysis clearly showed that matrix diffusion into a zone of fault gouge of limited extent and with a relatively high porosity had to be taken into account; otherwise the trailing edge of the breakthrough curves could not be modelled satisfactorily.
- For all tree experiments there was a strong indication that – in the frame of the double porous medium approach – at least two independent fracture families had to be included in the model.
- The extracted best-fit values for K_d may be larger by a factor of 3–70 than data obtained in laboratory experiments. With regard to the best-fit values for the pore diffusion coefficient such differences are much smaller, and the values are always smaller than the laboratory data. An intercomparison of the in-situ data does not reveal any inconsistency between the different best-fit values, although they may scatter in a certain range.
- From the inverse modelling of all three tracer tests no serious limitation of the model could be detected and no effect of a transport mechanism not already included in the model could be observed.
- For caesium, a significant "tracer loss" had to be considered in the modelling for the STT1 and the STT2 tracer tests, but further information about this loss could not be deduced from the available data.
- Unfortunately, important information on the nuclide/rock interaction was obscured by the second part of the injection distribution requiring unnecessary assumptions for the blind predictions.

One may ask for the reasons why such a simple model for flow and transport was able to produce reliable blind predictions and to reproduce the measured breakthrough curves with high precision.

- Due to the very narrow flow field caused by strong pumping at the extraction bore hole heterogeneities on the decimetre scale played only a minor role and transport dominated hydrology effects to a large extent. Even when taking into account only one single streamline/streamtube and even when neglecting velocity variations along the migration path, reliable predictions and excellent fit-results were obtained.
- Impact from geologists – and other scientists – was needed to set up an appropriate model structure. Calibrating our model with the help of one single uranine breakthrough curve, we could get strong indication of a marked effect of matrix diffusion. Such a conclusion was corroborated by results from structural geological investigations. In addition, from the geologists we got helpful information concerning fracture mineralogy and the fact that matrix diffusion might act on one side of the fracture only. Furthermore, maximum values for the penetration depth of matrix diffusion were addressed, and also values for the porosity of the different materials of importance were roughly estimated. We are convinced: without the help of such "soft data" or "indicators" we would have failed in designing an appropriate model structure for these migration experiments.
- Laboratory data for the transport parameters obtained with the help of small-scale laboratory experiments on generic Äspö diorite were applied for the first predictions. The subsequent analysis, however, demonstrated that especially the K_d values for sodium and strontium had to be increased by at least an order of magnitude. These refined data – together with an updated model structure (the inclusion of a second preferential flow path) – were then used for further blind predictions and adjusted

again after the release of the new experimental data. Hence, in every successive modelling step the whole information known so far was put into the model and applied for new predictions.

- It turned out that our methodology for the analysis of the tracer tests was a feasible way of achieving convincing results: In a first step all the nuclide-independent parameter values were determined using only data from the conservative tracers. For all sorbing tracers these parameter values were then kept fixed and only the nuclide-dependent parameters – K_d and D_p – were adjusted. Because the pore diffusion coefficient D_p is more or less nuclide-independent, only small variations for this parameter were allowed during the fitting procedure for the reactive tracers.
- Finally, the double porous medium model accounts for the most important transport mechanisms; it is a simple and transparent model because its underlying physics and chemistry are easy to understand. There are only a few lumped parameters, and no fudge-factor was needed to reproduce the data.

Outlook

Working on the Äspö migration experiments of Task 4e and 4f, the PSI modelling team has learnt a lot. Our results have increased the confidence in both our methodology and our models, and this is why these experiments, although they are very expensive, are highly appreciated. We believe that such tasks, where models and the principal understanding of the modellers, too, are tested in a crucial manner, are an important step to gain the necessary scientific as well as the indispensable public acceptance.

How to proceed in the future?

1. An important item is the up-scaling procedure. It is still an open question how values for the transport parameters from laboratory and field experiments have to be re-scaled to performance assessment conditions. In addition, on the one side for performance assessment purposes, great simplifications are normally inevitable due to the lack of comprehensive site-specific data, the number and complexity of processes being present and their interplay. On the other side, in field tracer tests a small number of mechanisms and processes were addressed only and the underlying geometry of the experiments, e.g. the flow field, is much less complex than that on the much larger scale under natural conditions. Hence, simplifications of the natural system are made by both sides, by the performance assessment side as well as by the modelling and investigation side in field experiments; and accordingly, the nature of these simplifications may be different for both of them. For example, in Tasks 4e and 4f it turned out that matrix diffusion into a limited zone of highly porous fault gouge had to be considered in the model, but such a zone will definitely play a negligible role in a performance assessment study. There, e.g., other porous rock zones could become the main sink for released and migrating nuclides which was not addressed at all in the experiments. Therefore, and based on our modelling results, defensible up-scaled values for the transport parameters will have to be examined. Geometrical considerations and relevant transport mechanisms at the spatial and temporal scales of performance assessments will have to be addressed. The initial work will mainly focus on the sensitivity of these parameters and mechanisms that matter to performance assessments results.
2. We have quite successfully modelled three different series of field migration experiments performed in Finnsjön, Grimsel and Äspö in different crystalline rocks with underlying different chemical conditions on the, roughly, 2 to 30 m scale. Therefore, we believe that, now, it would be of advantage to carefully look at slightly more com-

plex systems, where the interaction between hydrology and transport is more pronounced. In such experiments one should successively increase the travel distances and weaken the artificial flow field in order to more and more address the small-scale heterogeneities (on the decimetre scale), which so far have only played a very minor role, and even if one runs the risk of a certain tracer loss. Of course, such tracer tests should be performed using radioactive tracers again, for two reasons: first, to address ranges for the nuclide concentration which are comparable to those under repository conditions and, second, to allow measurements over many orders of magnitude of the concentration range.

6.2.7 BMWi

Background

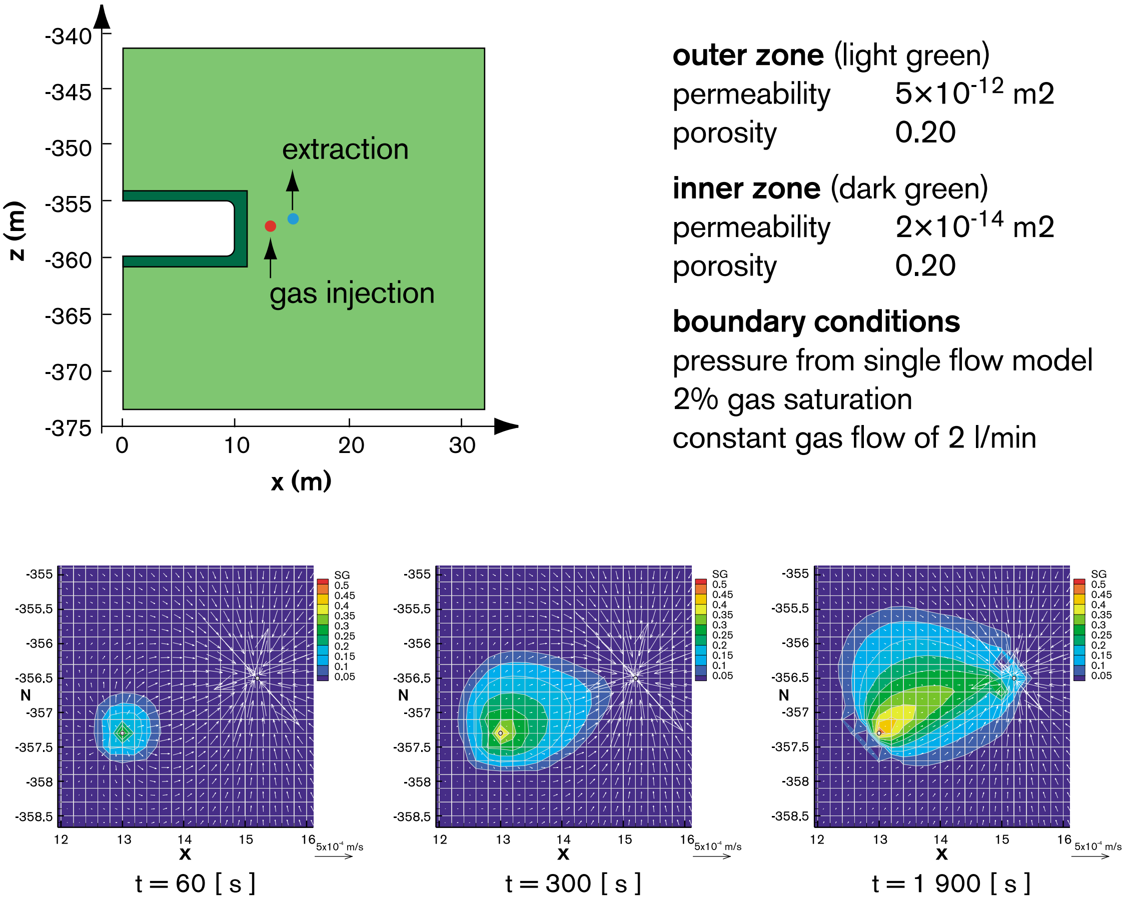
In addition to the German research activities related to final disposal of radioactive waste in rock salt, the objective of the cooperation in the Äspö HRL program is to complete the knowledge on other potential host rock formations for radioactive waste repositories. The work comprises investigations on two-phase flow, groundwater flow and solute transport, geochemistry, and on developing and testing of instrumentation and methods for underground rock characterization. Five research institutions are performing the work on behalf of BMWi: BGR, FZK/INE, GRS, TU Braunschweig and TU Clausthal.

Two-phase flow investigations

The activities related to the two-phase flow experiment carried out by GRS and BGR were continued. Hydraulic investigations with gas and water were performed to characterize the flow conditions in the tunnel near field. The geological structures around the new drilled boreholes in the niche at 2715 m and the relevant tunnel section were mapped and interpreted. Hydraulic index experiments were performed and evaluated. The code ROCKFLOW was used to model the flow conditions of a system consisting of a water saturated continuous fracture and the adjacent rock matrix. The code MUFTE-UG was developed further to be used in 3-dimensional simulations of a multiphase-multi-component system, and the computer code "GMTM Tracer Transport by Gas Flow" was tested. Figure 6-39 shows the calculated gas saturation over time in a dipole test. According to the calculation, steady state is reached after 1,900 seconds.

Task Force on modelling of groundwater flow and transport of solutes

BGR continued its activities in the Task Force on Modelling of Groundwater Flow and Transports of Solutes by modelling and interpreting the behaviour of radioactive and sorbing tracers in the TRUE test field (Task #4). In Task #5, Hydrogeological and Hydrochemical Modelling, a 2 ½ – dimensional flow and transport model including ten fracture systems was developed and used to calculate the alterations caused by the tunnel construction. Figure 6-40 shows the distribution of meteoric water before and ten years after tunnel construction.



outer zone (light green)
permeability 5×10^{-12} m2
porosity 0.20

inner zone (dark green)
permeability 2×10^{-14} m2
porosity 0.20

boundary conditions
pressure from single flow model
2% gas saturation
constant gas flow of 2 l/min

t = 60 [s] t = 300 [s] t = 1 900 [s]

Figure 6-39. *Dipole test: Modelled region (top) and calculated gas saturation over time (bottom).*

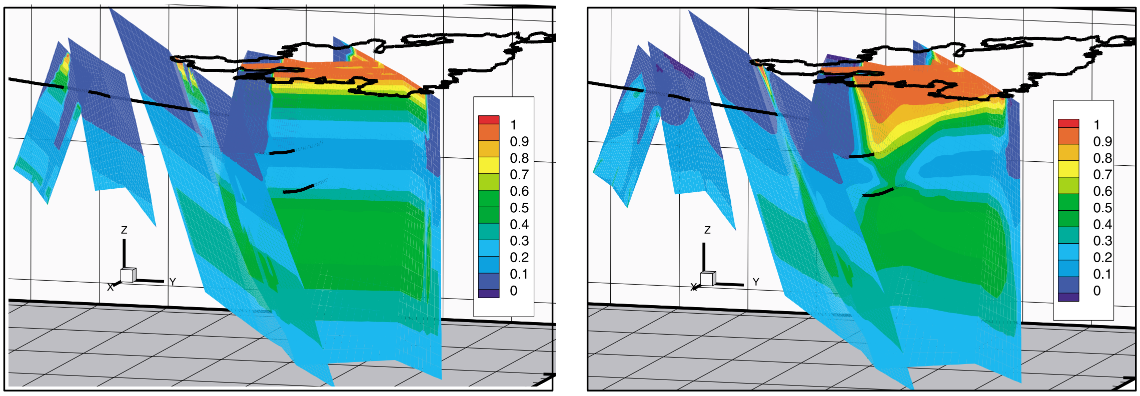


Figure 6-40. *Distribution of meteoric water in the HRL-Äspö region, initial conditions (left), 10 years after tunnel construction (right).*

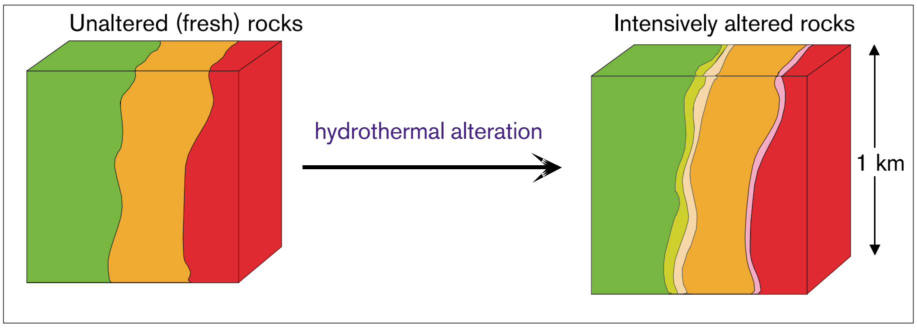
Geochemistry

TUC's work addresses the mobility of radionuclides in crystalline rocks. The investigations deal with 1) mobilization and immobilization of selected trace elements in different granitic rocks and fluids and 2) mobilization behaviour of Uranium and Thorium as a natural analogue for the mobility of actinides in granitic rocks.

In order to assess the potential immobilizing capacity for radionuclides, the distribution of main- and trace-elements in altered granitoids from the Äspö region was investigated. Reaction products formed by hydrothermal alteration of granits serve as indicators for reactions that might occure after radionuclide release from repository boreholes. Figure 6-41 illustrates the results for a 1 km^3 granite block. Based on these studies it can be concluded that altered granitoids have a significant immobilization capacity for radionuclides.

The mobility of Uranium and Thorium in granite in the past may serve as a key for understanding and predicting actinide migration in the future. U-238 is fixed in some million years old secondary carbonates occurring as fracture fillings and it is assumed to have been in secular equilibrium with its short-lived daughters U-234 and Th-230. Upon reaction of these carbonates with migrating solutions, U-238 and U-234 can specifically be taken up by secondary calcites or, alternatively, may be extracted from the carbonates by the solutions. In this case, due to the insolubility of Thorium in migrating solutions, the activity ratios U-234/U-238 and Th-230/U-234 are expected to attain disequilibrium ratios. These disequilibrium ratios bear the information on the time of the last carbonate/solution reaction.

In carbonate samples taken from drillcores from the HRL, U- and Th-concentrations vary between 0.5 and 5 ppm. The U / Th activity ratios of 20 samples show disequilibria from which the time of the last rock-water-interaction was calculated to have occurred between 60 thousand and 400 thousand years ago. The activity ratios of one third of these samples show that these samples have experienced more than one water-rock-interaction.



Gain and loss of chemical elements caused by hydrothermal alteration within a 1 km^3 reference block of Äspö-granitoids

+ 0.35% K_2O	+ 0.5 µg/g Li	- 0.75% SiO_2
+ 47.7 µg/g Ba	+ 1.1 µg/g Co	- 0.50% CaO
+ 30.5 µg/g Rb	+ 1.3 µg/g Ce	- 0.1 µg/g Cs
+ 13.6 µg/g Sr	+ 0.5 µg/g Nd	
	+ 1.1 µg/g Sm	
	+ 0.1 µg/g Gd	

Figure 6-41. *Gain and loss of chemical elements in a 1 km^3 granite block.*

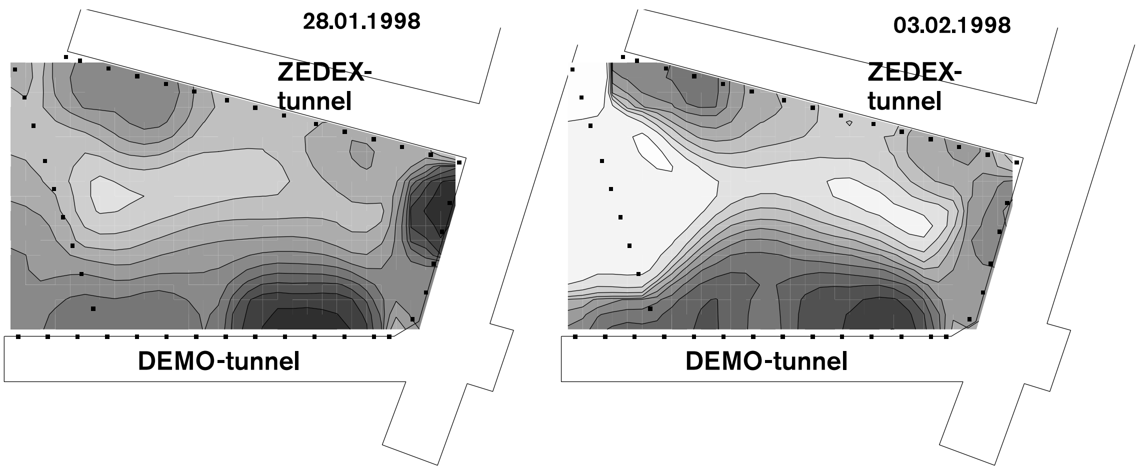


Figure 6-42. *Change in geoelectrical resistivity distribution between ZEDEX- and DEMO-tunnel (dark: low resistivities, high saturation; light: high resistivities, low saturation).*

The FZK/INE investigations are focusing on the behaviour of natural colloids and the transport of radionuclides, esp. actinides, in fractured rock. In 1999, the work concentrated on developing and testing special cells for encapsulating drill cores to be used in the CHEMLAB - II probe. The hydraulic properties of the cores were studied by tracer experiments. Sorption properties of granite and fracture filling material for the selected actinide ions were determined from results of batch and column experiments. The technical development work for field and parallel laboratory experiments has been finished.

Underground measurements methods and instruments

The geoelectrical measurements along the walls of the ZEDEX-drift and the DEMO-tunnel as well as the tomography in the rock between both galleries were continued. Tomography measurements in the deeper part of the backfilled ZEDEX-drift were started. The results show that usually the EDZ has an extension of no more than several decimeters and that saturation of the EDZ changes due to grouting of the walls. Because of the rather large electrode spacing the resolution of the tomographic measurements is limited. However, the results show clearly short time resistivity changes which could be related to saturation changes resulting from drilling activities in this area see Figure 6-42.

6.2.8 ENRESA

The purpose of ENRESA's contribution is:

- To develop and test a dynamic pore water pressure sensor based on the piezocone principle, for the direct measurement of local saturated permeability in the backfill.
- To model a particular section of the backfill, including the hydration process and the hydraulic tests to be performed.

The dynamic pore pressure sensors and the measurement system required to control the sensors and to perform the pulse tests, were installed in 1999. The sensors were installed in section A4 of the backfill, and preferably in the areas where a higher density gradient may be expected (i.e. rock proximity), in order to measure hydraulic conductivity when saturated. In this way, a map of local permeability values will be obtained and will be compared with the global value estimated by backanalysis from the flow test in saturated conditions.

Once saturation is reached, a pulse pore water pressure will be applied, and the corresponding dissipation time will be measured. There is a relation between soil permeability and the shape of this dissipation curve. The details of this relationship are presented in the next section.

Regarding the modelling work, an effort has been made to incorporate the effect of salt concentrations of Äspö water in the simulation of the hydration process. So far, only a preliminary approach has been adopted, as additional laboratory tests are going to be performed in order to understand the coupling between hydraulic properties and salt concentration of water in the backfill. The effect of this coupling has been considered as important, after realising that in Äspö, water with different salt concentrations can be mixed in the backfill and therefore, influence on the hydraulic process.

Local permeability measurements in a selected zone of the Backfill

The dynamic pore pressure sensors

A dynamic pore pressure (DPP) sensor is a specially constructed hydraulic piezometer, with a cylindrical ceramic filter of 60 microns pore size, and including a miniature pressure sensor inside. Figure 6-43 shows the DPP sensor configuration. Each piezometer has two metallic capillary tubes for water input and output, and an electrical cable for the pressure transducer signal.

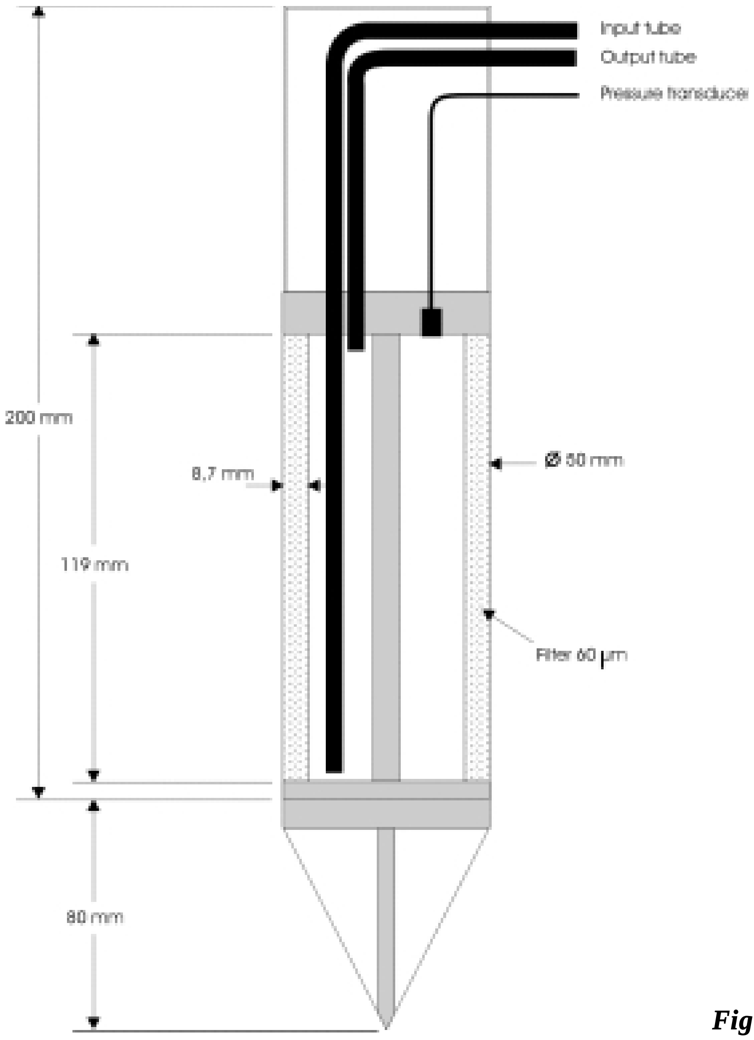


Figure 6-43. *DPP sensor description.*

The DPP sensors work in the same way as the "piezocone" testing method: A controlled positive pressure pulse will be applied to the sensors, and the evolution of the pressure drop in the sensor body, which is controlled by the local permeability of the surrounding material, will be analysed.

According to the initial calculations made by UPC, the compressibility of the water existing in the measuring circuit is a very sensible parameter, provided that the mechanical components (tanks, pipes, ...) are sufficiently rigid. As the expected range of the permeability to be measured may be very wide (from 10^{-8} to 10^{-11} m/s), the system has been designed so that the internal volume of the measuring circuit may be easily modified. Also the possibility of measuring the volume (flow) of water transfer to the backfill during the pulse test has been included in the system design, for the case of very permeable media.

Additional equipment and system description

The complete system comprises a number of DPP sensors (13 units), and a common measuring system, which is located outside the backfill area.

The measuring and control system performs the following three basic functions:

- Flushing and de-airing of the hydraulic circuit of each DPP sensor.
- Pressure pulse generation and control.
- Recording of the pressure variation at the DPP sensors.

The hydraulic/electric control system scheme is shown in Figure 6-44. The two hydraulic tubes of all the DPP sensors are connected to electric valves in a circuit-switching panel, so that only one sensor circuit is connected to the measuring system at any one time.

The data acquisition and control unit (DAC) controls the switching panel, which actuate the appropriate valves in the system, according to manually input commands. Electrical signals from all the DPP sensors are permanently connected to the DAC unit for data recording and storage.

The measuring system includes two basic hydraulic circuits:

1. The **primary** circuit, using de-aired Äspö water, which is the one to be actually circulated through the sensor circuit.
2. A **secondary** circuit, which uses compressed Nitrogen gas, used for pressure transmission and flow control purposes. This circuit does not mix with the primary.

The component of the measuring system called **transfer**, is a tank with a balloon inside, which is used as a pressure exchanger to apply a constant pressure pulse into the (primary) sensor circuit.

Other components of the system are:

- **Return tank** used for the storage of the water recirculated from the sensors.
- A vacuum pump for de-airing the Äspö salt water to be used in the primary circuits and to remove air from the primary circuits if necessary.
- A bottle of compressed Nitrogen, to generate the positive pressure.
- Auxiliary high speed solenoid valves, to control pulse generation.
- Three auxiliary tanks, one of 10 dm^3 and two of 50 dm^3 for changing the internal volume of the DPP sensor hydraulic circuit, as required by the test conditions.

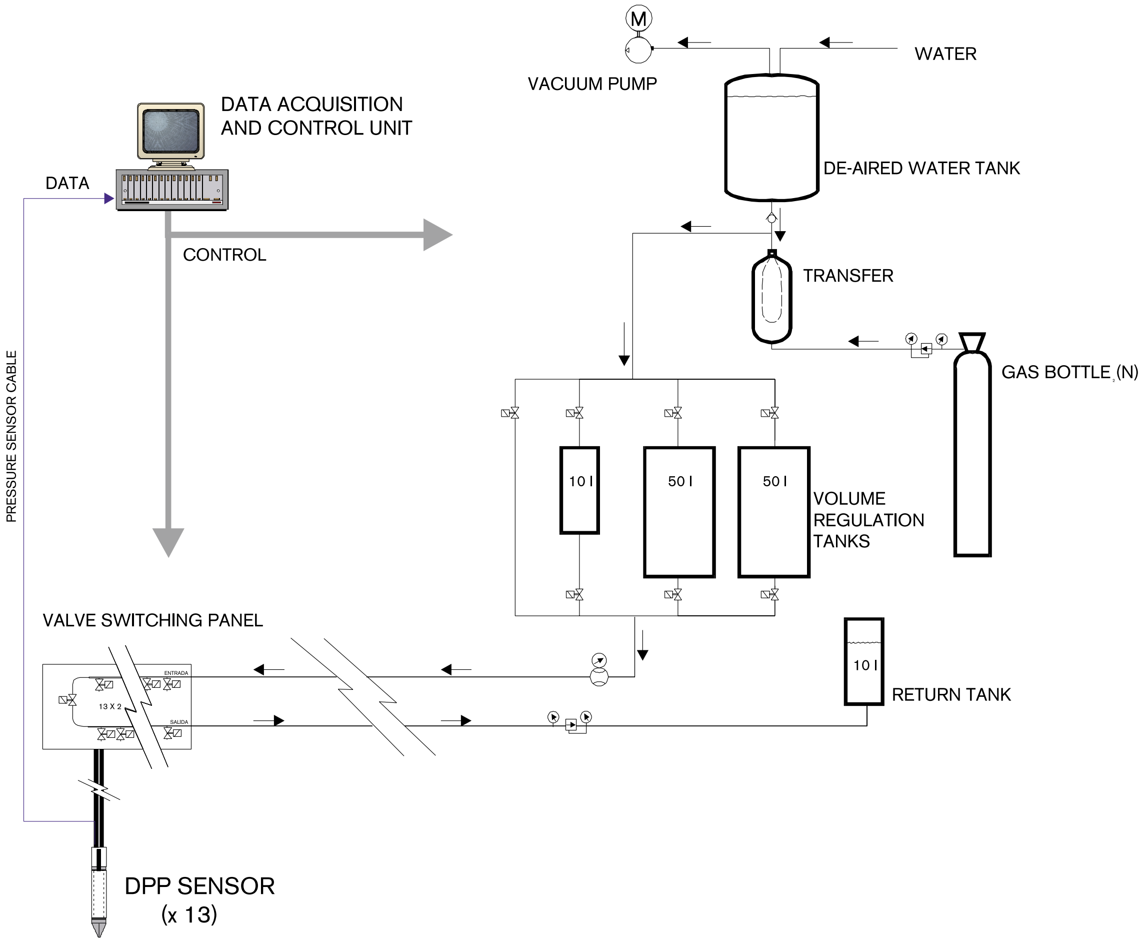


Figure 6-44. *Control system scheme.*

The compressibility of the water in the measuring circuit is a relevant parameter for this type of test, and therefore the volume of water in this circuit must be reduced to the minimum required by the test. The volume of water estimated for the circuit (with 60 m long conduits) is about 1 l. As the range of permeability, which may be expected during the test, is very extensive (from about 10^{-8} to 10^{-11} m/s), it becomes necessary to increase the internal volume of the measuring circuit for the higher range of permeability. This will be accomplished by introducing in the primary circuit an auxiliary tank (designated as **volume control tanks** in Figure 6-44). The volume relations of these tanks are equivalent to the expected changes in permeability (2 orders of magnitude, 1/10/100).

However, the possibility exists that the permeability in the backfill would still be too high to be measured by a system such as the pulse test proposed. In this case, the measurement could be carried out by controlling the total water inflow into the backfill during the test. To enable this option, the system is equipped with a high accuracy flow meter.

Test procedure

The initial situation for the operation of the system is the following:

- The **return tank** is almost empty of water.
- The **transfer** is full of de-aired salt water.

The test procedure for each DPP sensor is as follows:

1. **Flushing of DPP sensor hydraulic circuit**. The purpose of this operation is to completely fill the hydraulic circuit of the sensor (primary circuit), removing all the air that may exist in it. For this, the valve connecting the transfer and the circuit is opened and the input and output valves of the corresponding DPP sensor are opened. Sufficient pressure is applied to the transfer's balloon by means of the bottle of compressed Nitrogen and a manual pressure regulator. Then this pressure is transmitted to the water inside the transfer, thus flushing salt water through the sensor circuit up to the return tank. The flush flow should be low enough to see the air bubbles in the circulated water in the return tank, which is made of transparent plastic. Salt-water circulation is stopped (closing the input and output valves of the DPP sensor) when no bubbles are observed at the return tank. It is estimated that a volume of water of about 6–7 times the circuit volume has to be circulated to remove all the air entrapped in the conduits, tanks, and sensor.
2. **Pressure pulse generation**. A pressure equal to the static pore pressure observed at the DPP sensor plus around 2-3 bars will be applied to the balloon by means of the compressed Nitrogen regulator, and this pressure will also be transmitted to the water inside the transfer. The input valve of the corresponding DPP sensor is then opened, the output valve being kept closed. A high-speed valve placed between the transfer and the DPP sensor input valve is opened and closed very quickly, in order to transmit a controlled pressure pulse to the DPP sensor. The evolution of the pressure at the piezometer during and after the pulse is measured by the pressure sensor installed in the DPP sensor and recorded by the data acquisition and control system (DACS).

In principle, the entire measurement sequence is carried out manually, although some of the operations are automated (specially valves control) to simplify the process, making it more accurate and repetitive, and avoid disoperation. Data is recorded automatically.

System layout

The system layout is shown in Figure 6-45.

All cables and tubing from DPP sensors have been taken from the ZEDEX to the Demonstration drift through a dedicated pipe inside a borehole drilled for this purpose. The hydraulic isolation between backfill and the pipe is performed by cable and tubing glands installed on a metallic flange at the ZEDEX drift end of the pipe.

Tubing from DPP are connected to circuit switch valves box at Demonstration drift, from where only two tubings connect with the measuring and control system, which is placed some 40 m away at the control room. The valve switch system makes that only one sensor circuit is connected to the measuring system at any one time.

All cables from DPP are connected to the measuring and control system by a multiwire cable using an electrical junction box placed also at the Demonstration drift.

The measuring and control system is composed by all the hydraulic components necessary for the DPP operation (tanks, transfer, vacuum pump, auxiliary valves, flow meter, etc.), which have been integrated inside a cabinet called "hydraulic panel", and all the electric components (computer, data acquisition boards and interfaces,...) integrated inside a cabinet called "data acquisition system".

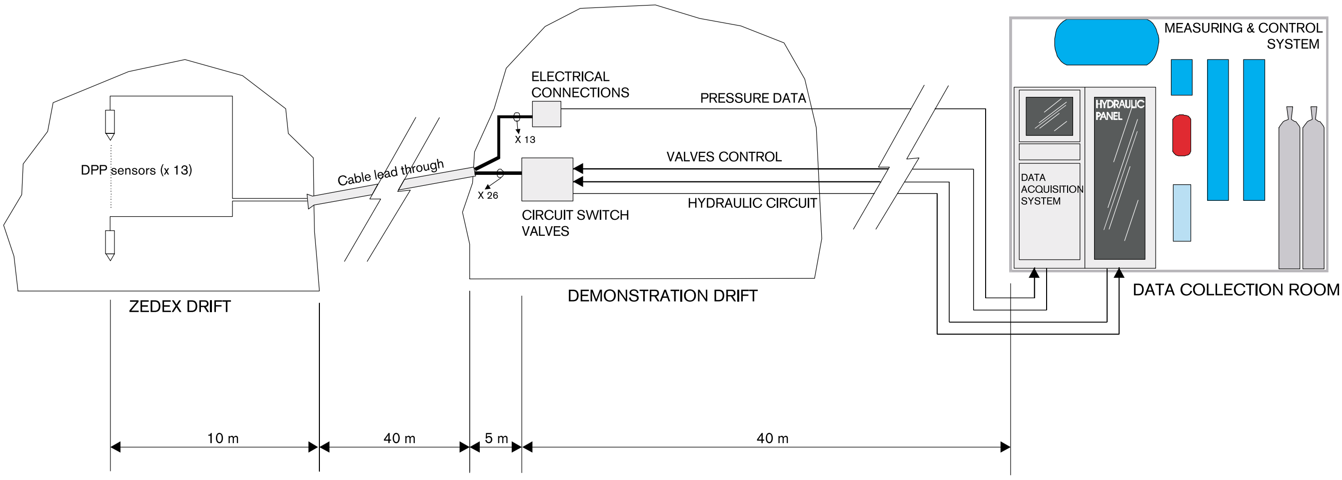


Figure 6-45. *System layout.*

Field installation

The sensors, as well as, the whole system were finally installed during March 1999.

The total number of sensors installed in A4 section of the 30/70 backfill is thirteen, and the final measuring points as well as their tubes and cables situation are shown in Figure 6-46. The location of some of the initial measuring points were changed during the installation due to:

- the risk of damaging other sensors installed in the previous compacted layer,
- the impossibility of drilling more that one compacted layer.

To reduce mechanical damage to the DPP sensors, these were installed in their positions after the corresponding 20 cm thick layer had been compacted, manually drilling or excavating a well-formed hole for DPP sensor insertion. Special precautions were taken to keep the walls of these excavations as uniform as possible, to avoid a low-density space around the DPPs.

Sensors horizontally installed in the layer were covered with a metallic perforated steel tube to protect them from any damage when compacting the next layer on top. For the same reason and once the sensors of one layer were installed, a channel for cables and tubes was dug from each sensor to the cable pass-through flange, see Figures 6-47 and 6-48.

The circuit switch valves box and the electrical junction box were located in the Demonstration drift near the pass-through pipe that connects this drift with the ZEDEX drift, see Figure 6-49.

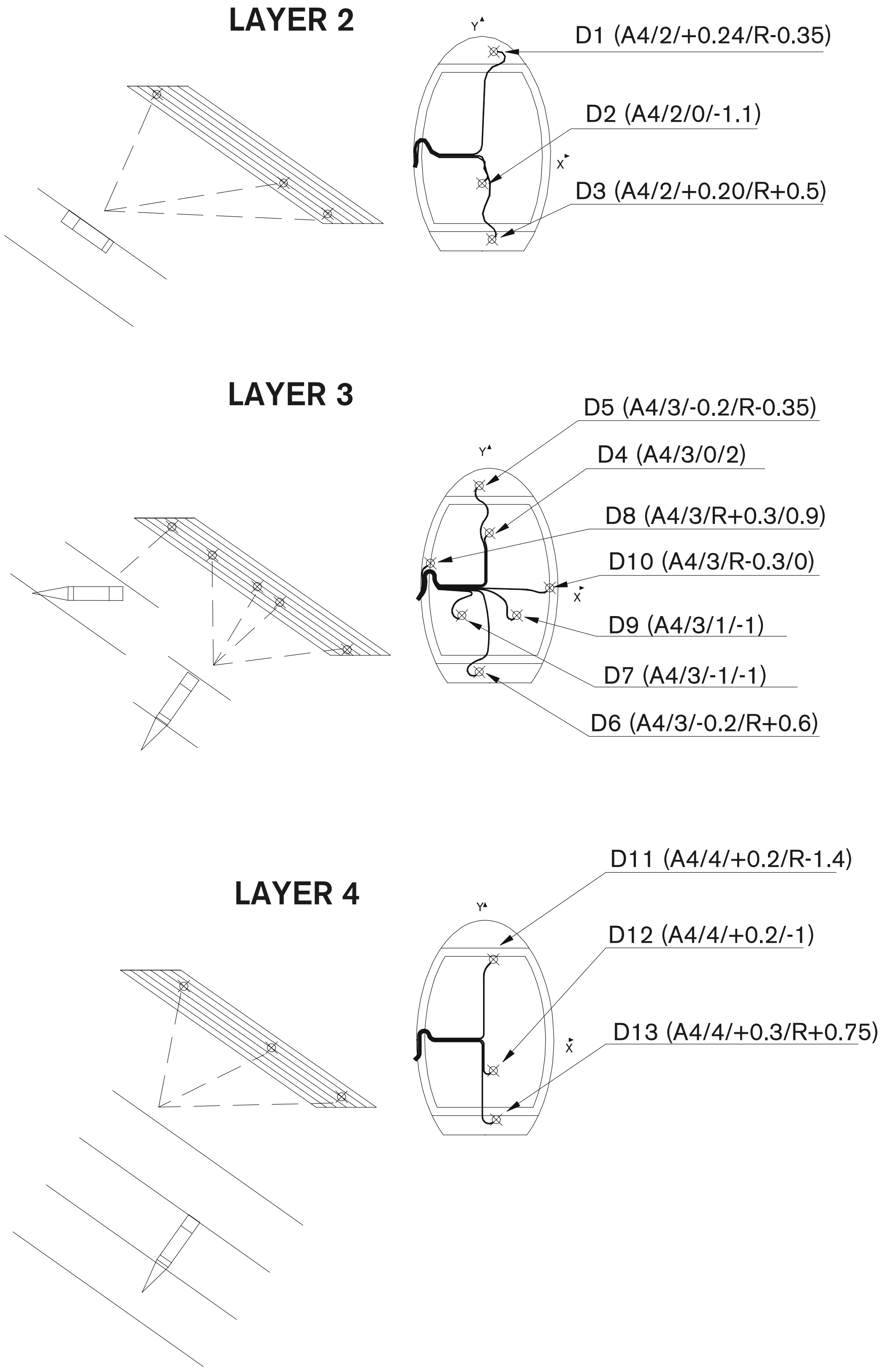


Figure 6-46. *Sensors location in A4 section.*

Figure 6-47. *DPP sensor installed perpendicular to layer.*

Figure 6-48. *DPP sensor installed parallel to layer.*

Figure 6-49. *Valves box (left) and junction box at Demonstration drift***.**

Figure 6-50. Measuring and control system (metallic structure outside control room).

The measuring and control system was situated in the control niche, in front of the Demonstration drift in the main gallery see Figure 6-50. Part of the system was located inside the control room:

- The cabinets called "hydraulic panel" and "data acquisition system"
- The return tank.
- The compressed nitrogen bottle.
- The electrical distribution box.

The rest of the system is fixed to the metallic structure and located out of the control room see Figure 6-50.

The measuring and control system was started and adjusted to comply with all the system requirements. The acquisition and control software was developed under Windows 95 and it is based on commercial SCADA software called FIX DMACS from Intellution Inc. (USA).

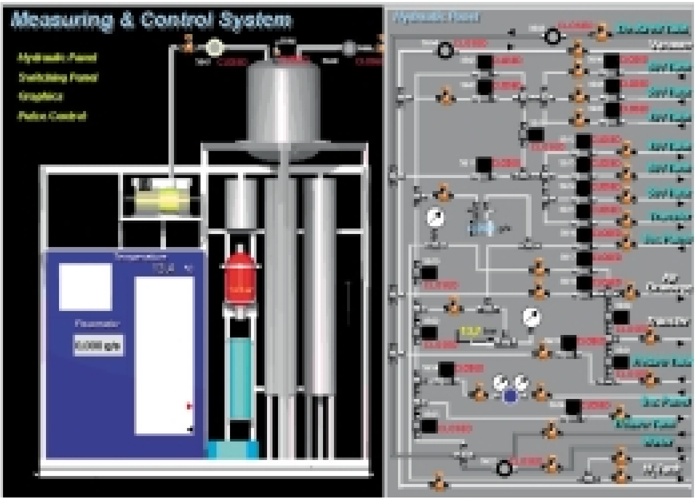


Figure 6-51. *Example of control screen.*

The application includes a database where sensors readings are being stored. This software enables to precisely monitor and control the test, as well as to collect, deliver, and display data in graphical formats. As an example, a control screen is shown in Figure 6-51. Measurements from all sensors are being stored in the database every 10 minutes, except when a test pulse will be performed, in which case readings will be stored every second.

Nowadays, the system is working properly and sensors data are recorded to see the evolution of the pressure in the backfill.

The system is linked with AITEMIN´s office in Madrid by a standard telephone line. Data transmission between the system located in the Äspö laboratory and the AITEMIN´s office (Madrid), sensors measurements checking and control system are carried out through the telephone network, using modems see Figure 6-52.

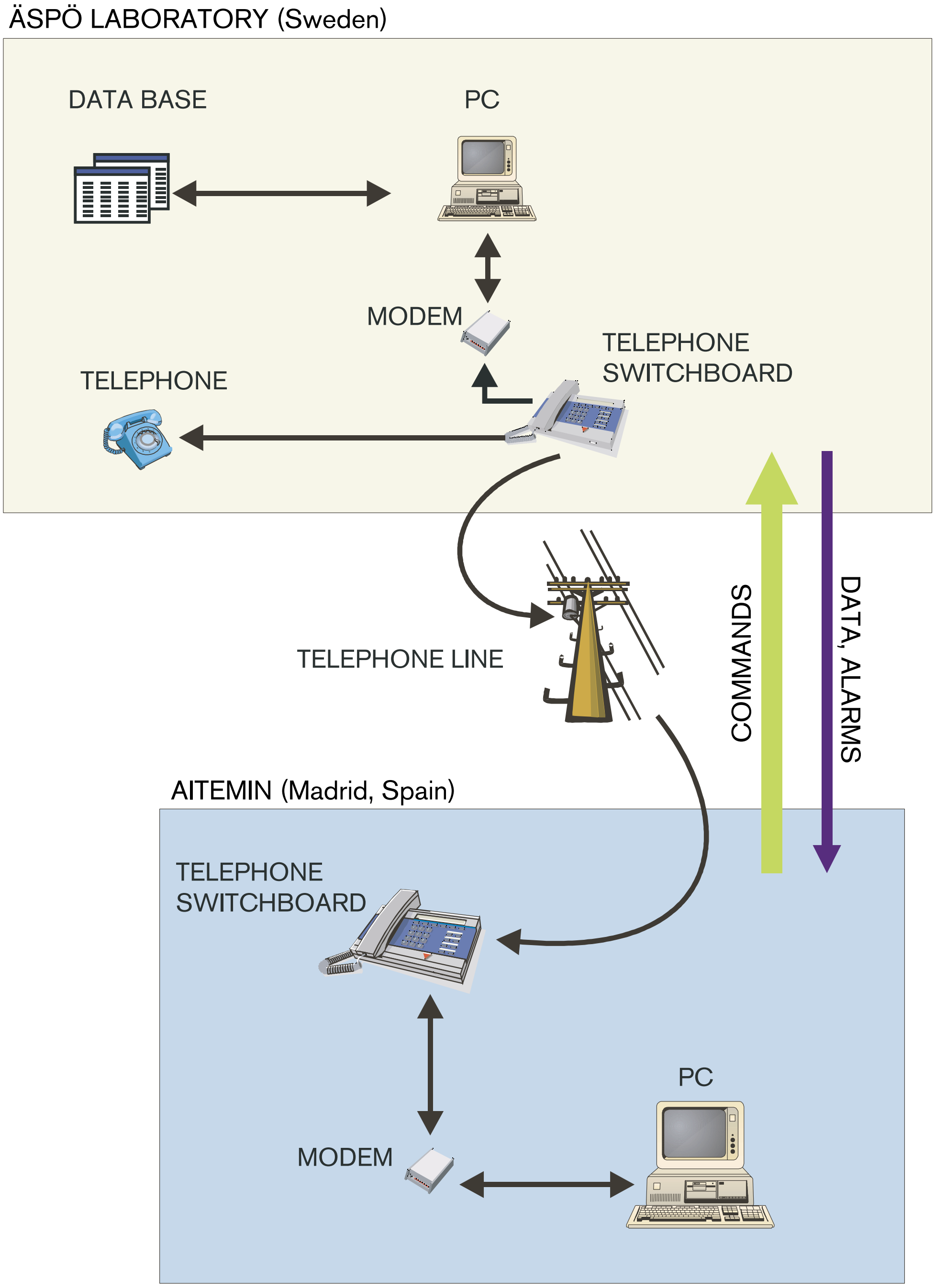


Figure 6-52. *Communication system.*

DPP laboratory calibration - Pulse tests

Regarding the calibration process of the DPP (Dynamic Pore Pressure system) (AITEMIN, 1999), some pulse tests were made in a specially designed cell in the UPC laboratory. The scheme of the pulse test is shown in Figure 6-53. The DPP is installed into the cell with the compacted backfill. Then the backfill is saturated and the pulse can be made. A pressure system, a high-speed valve and a control and acquisition system are needed. A computer manages the test. When the pulse is done, the pressure-time curve obtained is analysed using parameter estimation techniques.

The sensor was designed taking into account the analytical solutions provided by /Gibson, 1963/. The solved problem is the variable head test in an infinite medium (Figure 6-54), within an elastic, homogenous and isotropic soil. Mathematically this problem is governed by the next set of equations in spherical symmetry:

$$C\left\{\frac{\partial^2 u}{\partial r^2}+\frac{2}{r}\frac{\partial u}{\partial r}\right\}=\frac{\partial u}{\partial t} \tag{6-1}$$

$$u(r,0)=u_0 \qquad (r>a) \tag{6-1a}$$

$$u(\infty,t)=u_0 \tag{6-1b}$$

$$u(a,t)=\gamma_w h(t) \qquad (t>0) \tag{6-1c}$$

$$4\pi a^2 \frac{k}{\gamma_w}\left(\frac{\partial u}{\partial r}\right)_{r=a}=A\frac{dh}{dt} \tag{6-1d}$$

where $u(r;t)$ is the pore water pressure (not the excess), u_0 is the initial water pressure in the medium, k is the hydraulic conductivity, $h(t)$ is the head level in the standpipe, A is the cross section of the standpipe, a is the radius of the spherical shaped piezometer, and C is the consolidation coefficient.

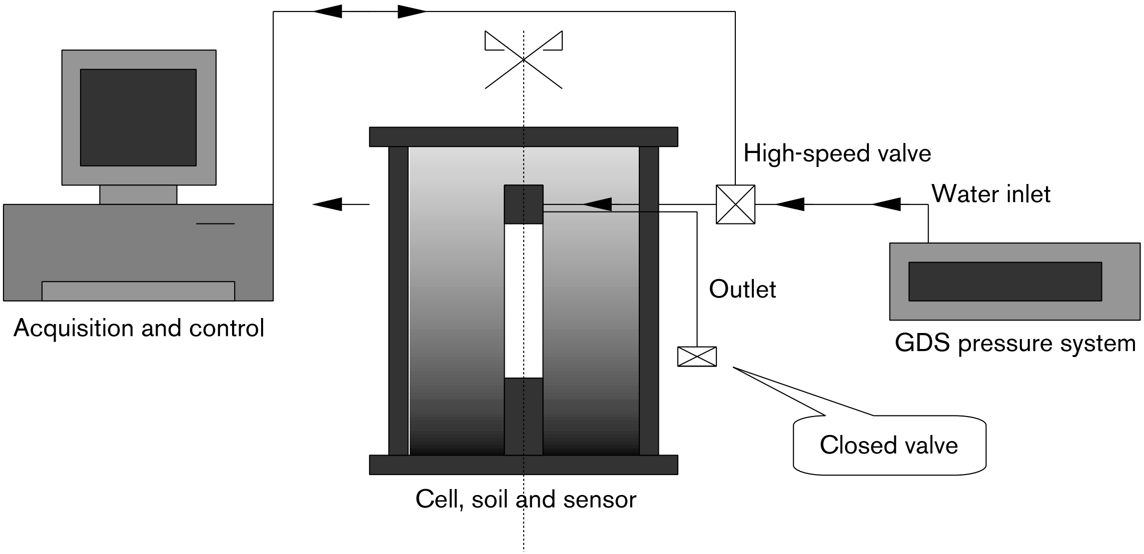


Figure 6-53. *Scheme of the laboratory pulse test.*

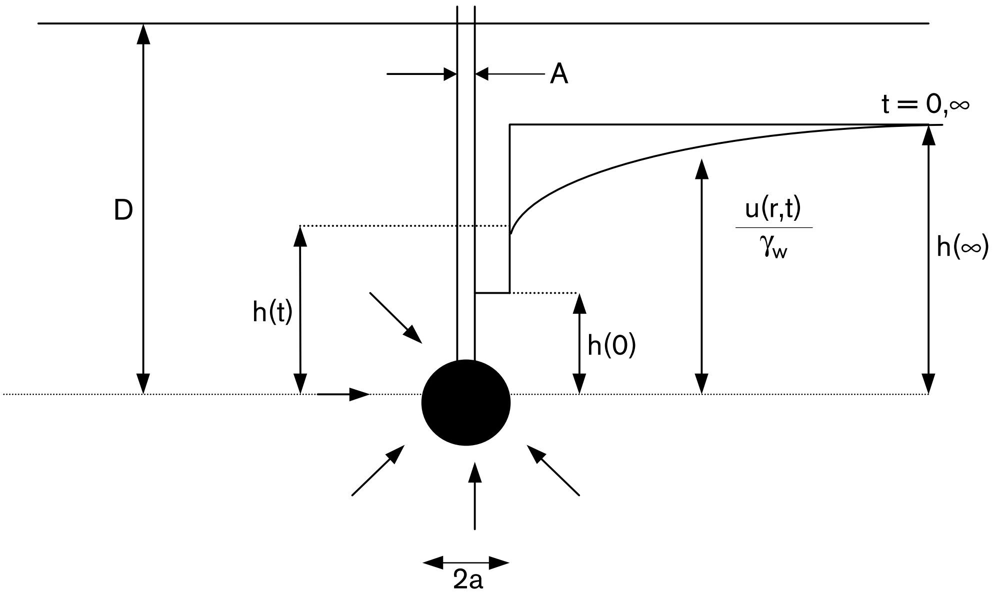


Figure 6-54. *Water pressure distribution at the surroundings of a spherical piezometer.*

However, the problem considered in the cell has two main differences with respect to the problem solved by Gibson: Condition (6-1b) is different, as a Neumann condition is applied at radius R (the cell radius), instead of a Dirichlet condition at the infinite. Condition (6-1d) also changes: *A* must be transformed to take into account the system flexibility (water compressibility, the tubes deformability and the sensor flexibility). By doing this, the condition (6-1d) transforms into:

$$4\pi a^2 \frac{k}{\gamma_w}\frac{\partial u}{\partial r}(a,t) = \lim_{\Delta t\to 0}\frac{\Delta V}{\Delta t}\bigg|_{r=a} = \lim_{\Delta t\to 0} f_{total}\frac{\Delta P}{\Delta t}\bigg|_{r=a} = \gamma_w f_{total}\frac{dh}{dt} \tag{6-2}$$

where f_{total} is the total flexibility of the system, that was measured in the laboratory. This parameter includes the water compressibility, the measuring system flexibility and the deformability of the tubes. Figure 6-55 presents a curve "pressure-volume" of the system that allows the estimation of that parameter. The total flexibility value estimated is f_{total} » $4.e^{-12}$ $m^3/N/m^2$.

Figures 6-56 and 6-57 show two pulses performed in the laboratory, compared with the pulses generated using the Gibson's theory, without modifying condition (6-1b). These pulses were analysed with parameter estimation techniques used in identification of parameters in geotechnical problems /Ledesma et al, 1996/. A Levenberg-Marquardt method /Marquardt, 1963/ to optimise real functions was programmed to estimate the consolidation coefficient and an adimensional stiffness of the system given by (6-3):

$$\mu = \frac{F^3 m}{16\pi^2 \cdot f_{total}} \tag{3}$$

where *m* is the soil compressibility and *F* is the intake factor of the DPP. This optimisation method evaluates the "objective function" which depends on the differences between measurements and computed pressures using Gibson theory. That function depends on the parameters used in the model, and thus its minimum gives the best set of parameters reproducing the experiment.

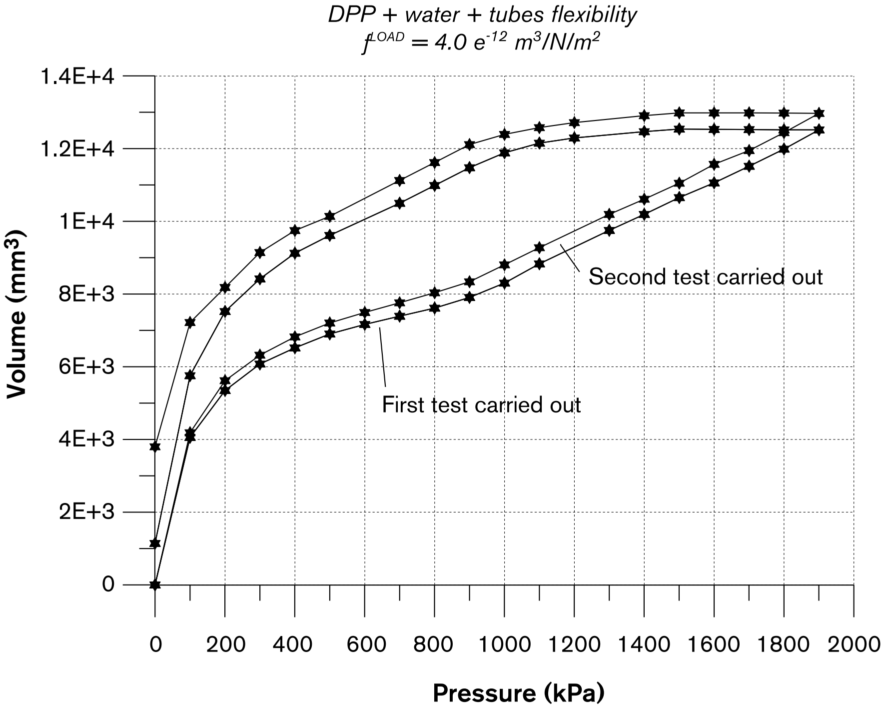


Figure 6-55. *Volume-pressure curve obtained in laboratory measuring the system flexibility.*

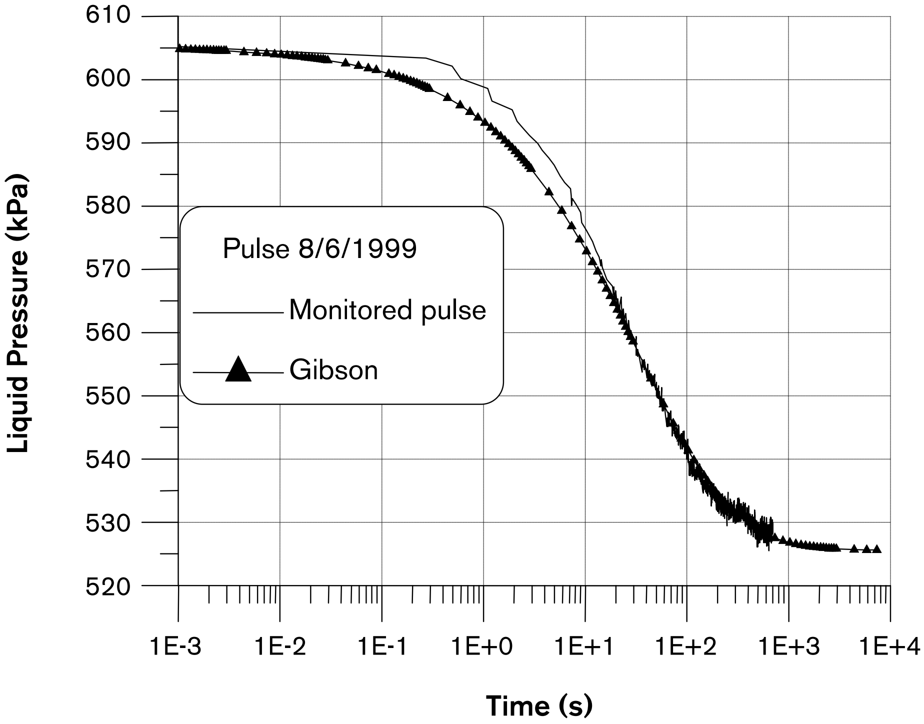


Figure 6-56. *Pulse test made in laboratory (8/June/1999), and its fit with the Gibson´s theory.*

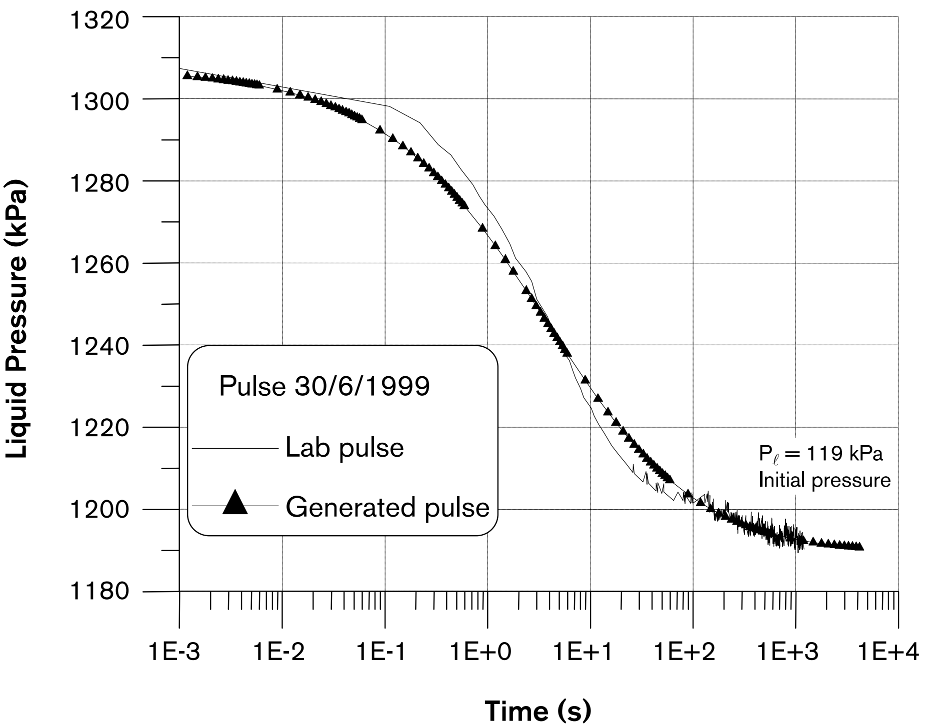


Figure 6-57. *Pulse test made in laboratory (30/June/1999) and its fit with the Gibson's theory.*

Table 6-2 presents the results of the identification procedure. A wide range of m is observed. This is because this parameter depends on mechanical properties (m and f_{total}) and the information provided by the test is mainly hydraulic. The objective functions obtained for these two test pulses are shown in Figures 6-58 and 6-59. The paths followed by the iterative optimisation procedure have also been included. A valley is observed in the m-direction, which makes very difficult its estimation and is consistent with the range of m indicated in Table 6-2.

The hydraulic conductivities obtained in the tests are in agreement with the values found by Clay Technology /Johannesson et al, 1998/. More pulse tests are going to be made in 2000 and will be compared with an independent flow test into the cell.

Table 6-2. Results obtained in the identification process from the pulse tests carried out in the laboratory. P_{l0} is the initial water pressure into the cell, Δp is the water pressure increment during the pulse test, and J_{min} the value of the objective function at the minimum

Test	P_{l0} (kPa)	DP (kPa)	C_{min} (m^2/s)	m_{min}	J_{min} (kPa^2)	k (m/s)
8/June/99	525	80.2	$3.12 \cdot 10^{-6}$	2.87	833.1	$6.720 \cdot 10^{-10}$
30/June/99	1190	117.4	$2.01 \cdot 10^{-7}$	32.78	2823.3	$4.948 \cdot 10^{-10}$

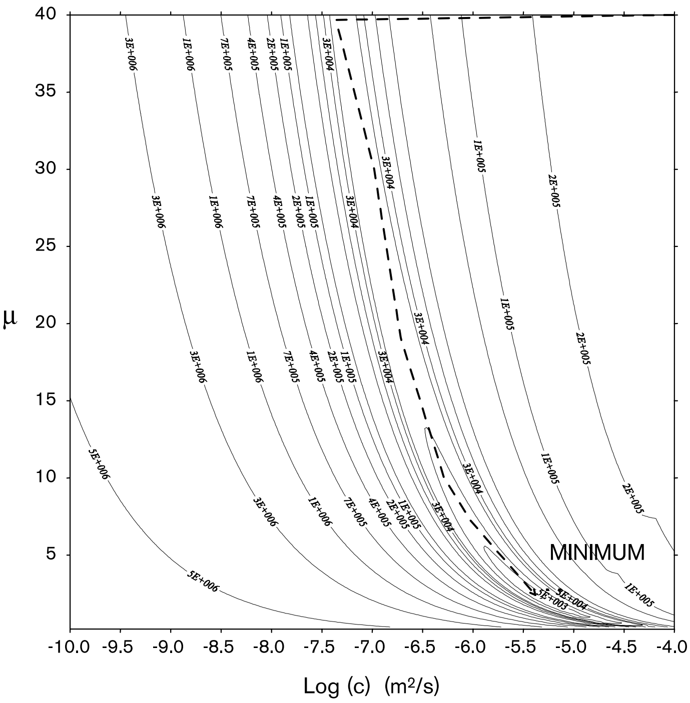


Figure 6-58. Objective function obtained for the first pulse (8/June/1999) and the trajectories followed by the estimating process.

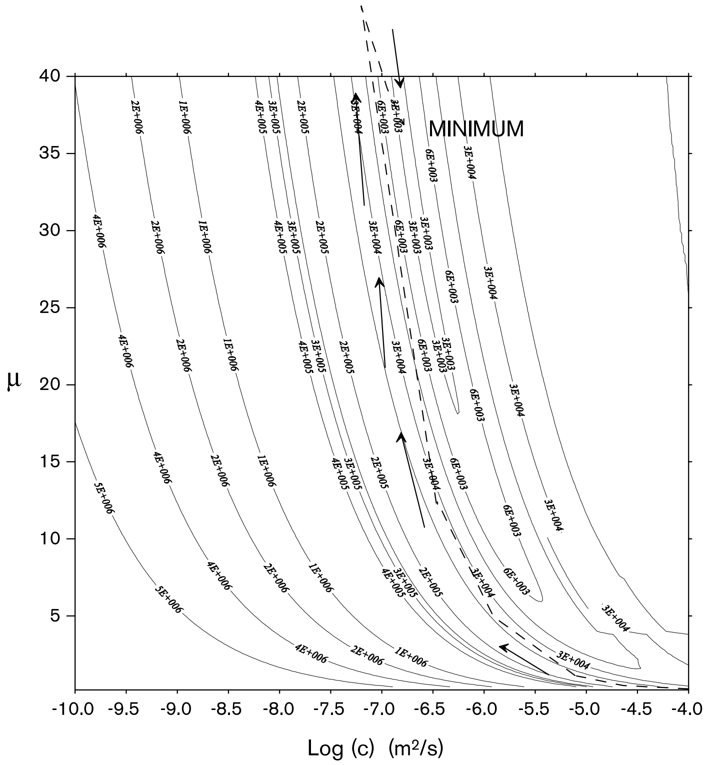


Figure 6-59. Objective function obtained for the second pulse (30/June/1999) and the trajectories followed by the estimating process.

The DPP has been installed fifteen months in the cell. Figures 6-60 and 6-61 show the DPP into the cell and the backfill after the DPP extraction. The DPP has proven to be a sturdy system and a powerful measuring new device estimating the hydraulic conductivity of the backfill. Now the influence of the change of the boundary condition in the laboratory test with respect to the general equation (6-1) is being studied, and that will improve the interpretation of the pulse tests performed in the laboratory.

Figure 6-60. *Detail of the sensor surrounded by the backfill after 15 months into the cell.*

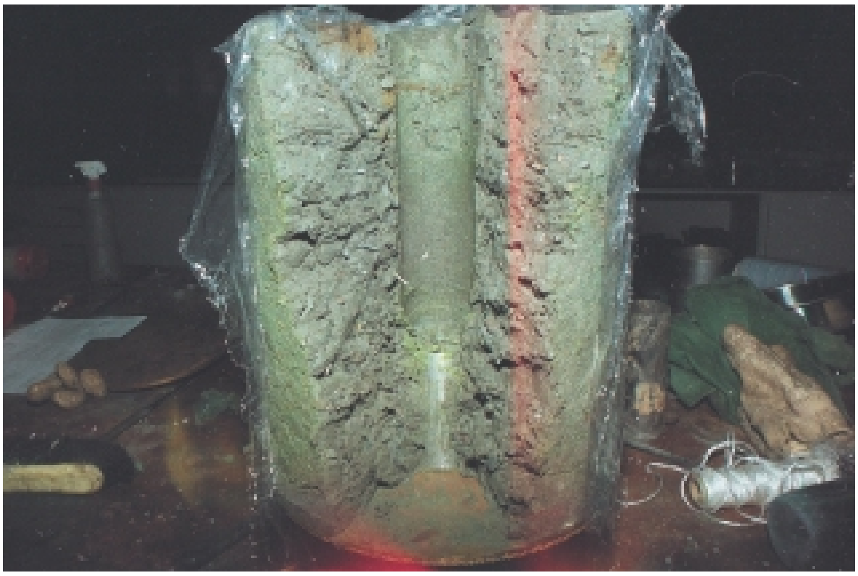


Figure 6-61. *Detail of the backfill after the extraction of the DPP.*

Effects of salt on flow parameters: Historical review

Introduction

During the evolution of the project (since it started in 1997) one unexpected aspect has become very important in the hydration process of the backfill: the different concentrations of salt found in the Äspö water. Here, we have to distinguish between the water used in the mixing process of the bentonite and the crushed granitic rock (30/70 in weight), and the water used in the hydration process.

Different concentrations of salt in water have produced important changes in the expected hydraulic parameters of the backfill. Therefore, a brief historical review of the concentration of salt present in the water used is needed to make clear the evolution of the numerical simulations of the hydration process of the backfill studied during last two years.

Salt content in water used in the mixing and hydration process

First, the laboratory tests carried out in the backfill were made with 12 g/l of salt (about 50% of NaCl and 50% of $CaCl_2$ in weight) in both waters (mixing water and hydration water). Then the salt content was always the same. That explains why the salt effect was not taken into account initially, as gradients of salt concentrations were not expected. It was well known that changes in salt concentration would affect the hydraulic conductivity. Unfortunately, in Äspö, depending on the origin and the age of water, the salt content can vary in a significant manner. This fact was missed out and it produced important changes in the flow parameters obtained by numerical simulations of the uptake tests carried out by Clay Technology.

Because of that, during the last two years, three families of hydraulic parameters have been calculated simulating different uptake tests. These three families are shown in Table 6-3, in a chronological order.

Two parameters were estimated from the uptake tests carried out by Clay Technology: the intrinsic permeability (k_{int}) and the liquid relative permeability coefficient (k_{rl}).

$$k_{nosat} = k_{\text{int}} \cdot \frac{\gamma_w}{\mu_w} \cdot k_{rl} \tag{6-4}$$

where γ_w is the water specific weight and μ_w is the dynamic viscosity. The liquid relative permeability law was assumed as potential, that is: $k_{rel} = (Sr)^n$, where “Sr” is the degree of saturation.

Table 6-3. Parameter families calculated from uptake tests performed by Clay Technology. The main parameters studied were the intrinsic permeability, k_{int}, and the exponent, n, of the relative permeability law.

First test series (late 1997)		Second test series (middle 1998)		Third test series (middle 1999)	
Salt content		Salt content		Salt content	
Mixing water 12 g/l	Hydration water 12 g/l	Mixing water 6.2 g/l	Hydration water 12 g/l	Mixing water 6.2 g/l	Hydration water 18 g/l
$k_{int} = 4 \cdot e^{-18}$ m^2 n = 11		$k_{int} = 4.5 \cdot e^{-19}$ m^2 n = 3.4		$k_{int} = 8.5e^{-19}$ m^2 n = 6	

Table 6-4. Actual salt content in the backfill (in 100 grams of sample) in all uptake tests carried out by Clay Technology

First test series g_d = 1.75 g/cm^3 (late 1997)	Mass of water (gr)	Salt water content (% in weight)	Mass of salt (gr)
Bentonite (w_0 = 10%) (30 gr)	3.00	0	0
Granitic rock (w_0 = 0%) (70 gr)	0	0	0
Mixing water (w_{design} = 12%)	8.64	1.20	0.1036
Hydration water (1.2% salt content)	8.91	1.20	0.1069
At saturation	20.55		0.2105
Second test series γ_d = 1.7 g/cm^3 (middle 1998)			
Bentonite (w_0 = 10%) (30 gr)	3.00	0	0
Granitic rock (w_0 = 4.5%) (70 gr)	3.15	0	0
Mixing water (w_{design} = 12%)	5.11	0.62	0.0316
Hydration water (1.2% salt content)	8.62	1.20	0.1035
At saturation	19.88		0.1351
Third test series γ_d = 1.7 g/cm^3 (middle 1999)			
Bentonite (w_0 = 10%) (30 gr)	3.00	0	0
Granitic rock (w_0 = 4.5%) (70 gr)	3.15	0	0
Mixing water (w_{design} = 12%)	5.11	0.62	0.0316
Hydration water (1.8% salt content)	8.62	1.80	0.1551
At saturation	19.88		0.1867

Table 6-4 summarises the conditions and the different salt contents in the mixing water and the hydration water used in the three different uptake tests series. Clay Technology provided with this information. They changed the salt content in each test group as a consequence of the actual situation in Äspö.

Using a water in the mixing process with a lower salt content (0.62% in weight instead of 1.2%) produces important changes in the hydraulic conductivity and the exponent of the potential law employed in the liquid relative permeability, as indicated in Table 6-2. These changes have an important practical consequence: hydration process can be longer or shorter depending on the salt concentration of the water used in the mixing process (0.62%) and the water used in the hydration process (1.6% nowadays).

After the last uptake test carried out by Clay Technology (family number 3, Table 6-3) new numerical simulations of the hydration process of a section of backfill have been developed. In next section a summary of these results is presented.

Modelling hydration and flow processes in the Backfill

Following the notation used in previous annual reports, a new hydration case of a typical section was simulated ("case D") by means of the CODE_BRIGHT simulator /Olivella et al, 1996/. The geometry employed is shown in Figure 6-62. There are two sections of backfill with nine mats. Rock is considered but it never becomes unsaturated (high air entry value is assumed in the water retention curve). Gas phase was not considered because there is not information available about it.

The retention curve employed is shown in Figure 6-63, where the law corresponding to the FEBEX bentonite has been included for comparison. The hydraulic parameters corresponded to family number three (Table 6-3, middle 1999). Figure 6-64 presents the pressure applied in the mats in the simulation. The temporal evolution was decided considering the experiments of Clay Technology regarding hydraulic fracture. This curve

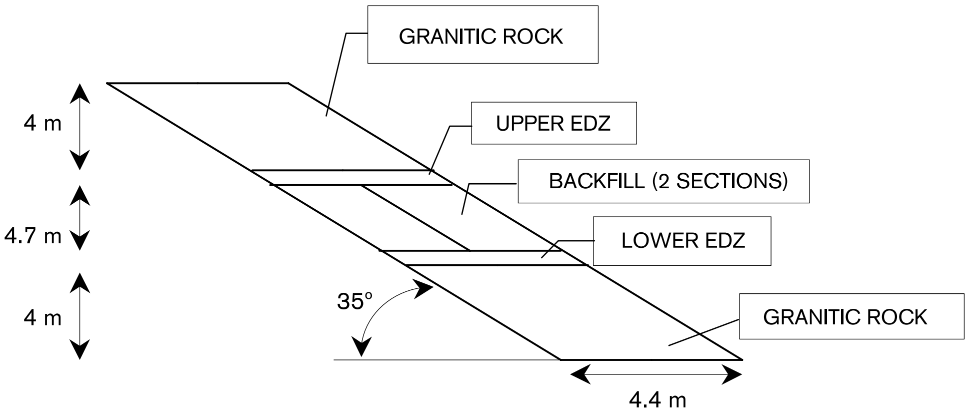


Figure 6-62. *Geometry employed in case D.*

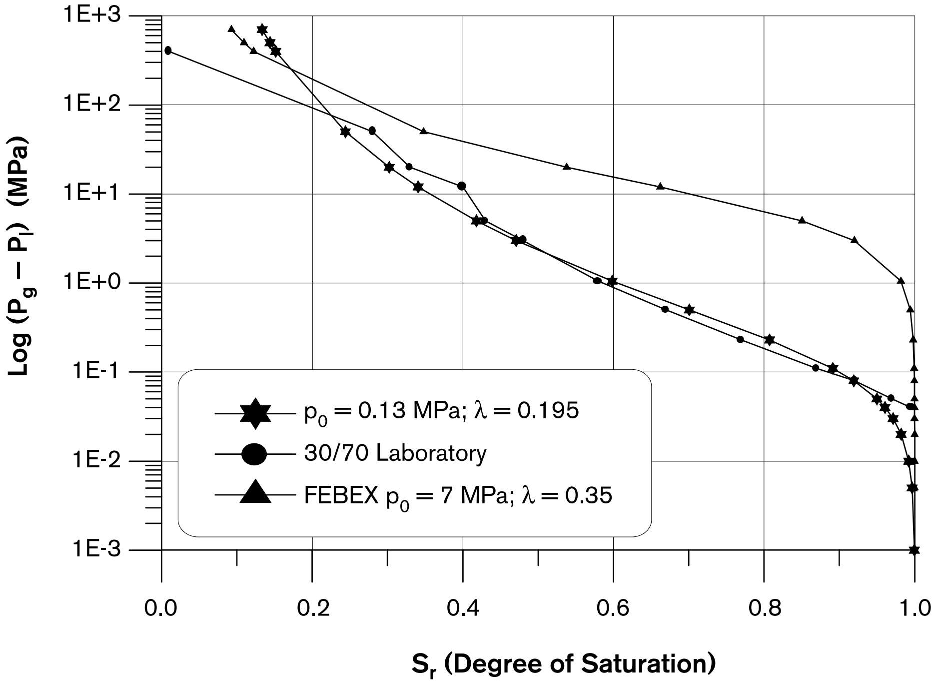


Figure 6-63. *Backfill retention curve used in the calculations.*

consisted on an initial injection of water at 50 kPa during three months. After first three months, pressure was increased until 2 MPa in two months. This curve was applied in 6 mats (case D1) or in all 9 mats (case D2). In case D1, the three inner mats were considered impervious boundaries (no differences were appreciated if considered as seepage surfaces). In Figures 6-65 and 6-66 the evolution of the degree of saturation in case D1 has been depicted. Figures 6-67 and 6-68 are similar, but they correspond to case D2.

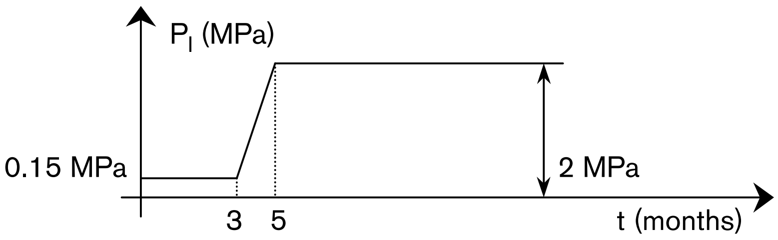


Figure 6-64. *Pressure law applied in mats in case D.*

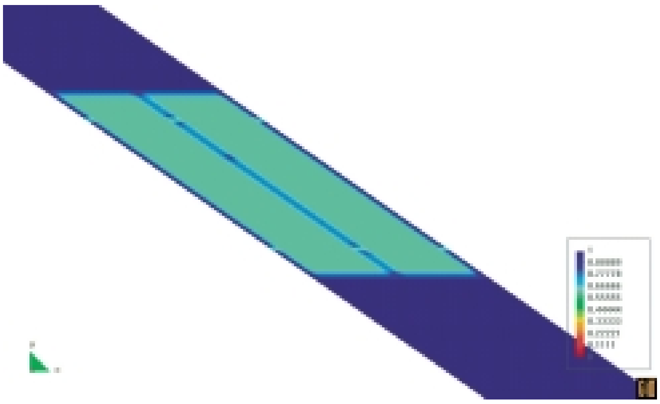


Figure 6-65. *Degree of saturation at 0 days in case D1.*

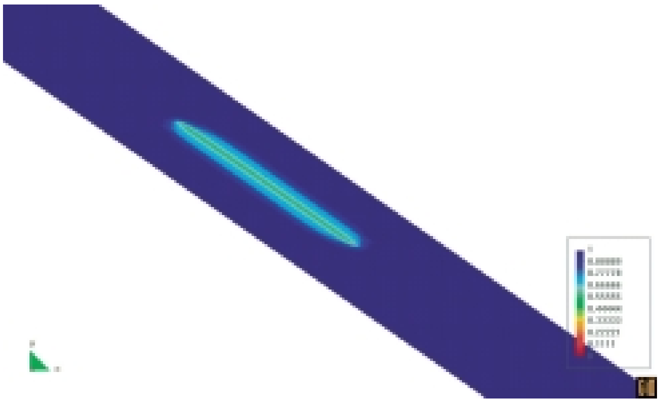


Figure 6-66. *Degree of saturation at 566 days in case D1.*

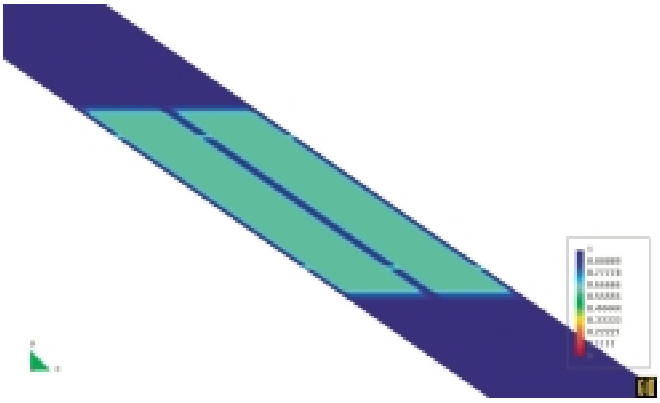


Figure 6-67. *Degree of saturation at 0 days in case D2.*

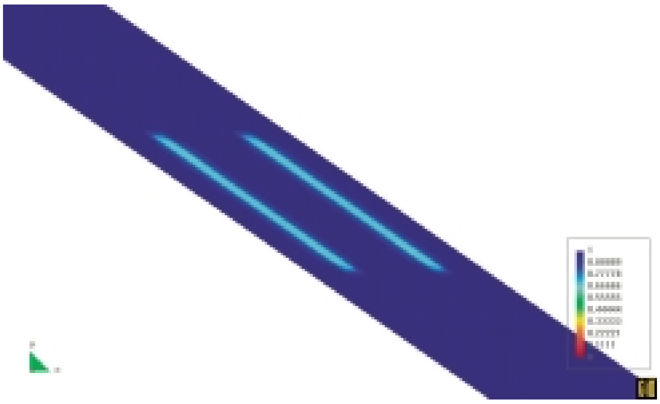


Figure 6-68. *Degree of saturation at 250 days in case D2.*

In this situation, time needed to reach 95% of the saturation in all the backfill (t_0) and time to get 99% of saturation in the backfill (t_1) were calculated. Results of these calculations are presented in Table 6-5.

Table 6-5. Results obtained in the numerical simulation of the hydration process using the parameters estimated in the third test series (0.62% salt content in the mixing water, and 1.8% of salt content in the hydration water).

Case	Number of mats with applied pressure	Backfill retention curve parameters		Hydraulic parameters		Time (years)	
		p_0 (MPa)	λ	k_{int} (m^2)	n	t_0	t_1
D1	6	0.13	0.195	$8.5 \cdot 10^{-19}$	6	2.08	2.25
D2	9	0.13	0.195	$8.5 \cdot 10^{-19}$	6	0.81	0.84

The retention curve is assumed independent of the water salt content. The transport phenomena and coupling between hydraulic conductivity and salt content have not been taken into account in these calculations. Those processes should be considered in the future to improve the simulation of the hydration and flow problem in the backfill placed in the ZEDEX tunnel.

The hydration time is very sensitive to the use of 6 or 9 mats injecting water. However, injecting from 9 mats may produce gas accumulations near the contact between the rock and the backfill (this fact was checked in some calculations made in 1998). Another problem is the possibility of hydraulic fracture in the backfill. It can appear if water is injected at high pressures. No information is available of this phenomenon, but during the hydration process of the backfill in the tunnel (it started in September 1999), hydraulic fracture has been observed in section A4 injecting at 100 kPa, as reported by Clay Technology. The hydration process of the backfill in the tunnel is being carried out with 1.6% water salt content.

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