Technical Report

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Äspö Hard Rock Laboratory

Annual Report 1998

Svensk Kärnbränslehantering AB

May 1999

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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. Experiments with sorbing radioactive tracers have been completed in a single fracture over a distance of about 5 m. These tests have been subject to blind predictions by the Äspö Task Force on groundwater flow and transports of solutes. Breakthrough of sorbing tracers in the TRUE-1 tests is retarded more strongly than would be expected based on laboratory data alone. Results are consistent for all tracers and tracer tests.

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

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.

The project Degassing of groundwater and two phase flow was initiated to improve our understanding of observations of hydraulic conditions made in drifts and interpretation of experiments performed close to drifts. The analysis performed so far shows that the experimentally observed flow reductions indeed are consistent with the degassing hypothesis.

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 in progress.

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 will be instrumented with about 230 transducers for measuring the thermo-hydro-mechanical processes. The Retrieval Test is aiming at demonstrating the readiness for recovering of emplaced canisters also after the time when the bentonite has swollen. Planning and preparations for these experiments has continued during 1998.

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. Two test holes were instrumented late 1996 and the temperature was raised to 90 and 130°C, respectively. The test parcels have now been retrieved and analysed. All tests and analyses except those concerning microstructure have been completed. No unexpected results have been obtained.

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

Sammanfattning

Äspölaboratoriet har anlagts som en förberedelse för djupförvaret för det svenska använda kärnbränslet. Årsrapporten för 1997 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. Dessa försök har använts för prediktiv modellering av Äspös arbetsgrupp för modellering av grundvattenflöde och transport. Genombrottskurvorna visar att de sorberande ämnena retarderas mer än vad som kunde förväntas med utgångspunkt från laboratoriedata. Resultaten är konsistenta för alla spårämnen och genomförda försök.

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. Projektet genomförs under en period av 4,5 år och beräknas vara avslutat vid utgången av år 2000.

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.

Projektet om avgasning av grundvatten och tvåfasflöde syftar till att utreda om de trycksänkningar som sker i närheten av dränerade tunnlar leder till förändringar i de hydrauliska egenskaperna. Analysen av genomförda fält- och laboratorieförsök visar att de observerade minskningarna i flöde är konsistenta med hypotesen om minskad hydraulisk konduktivitet på grund av avgasning.

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 på gång.

Backfill and Plug Test innefattar prov av olika återfyllnadsmaterial och packningsmetoder samt prov av en tunnelplugg i full skala. Ungefär 230 mätgivare kommer att placeras i återfyllnadsmaterialet och berget för att mäta termiska, hydrauliska och mekaniska egenskaper under försöket. Projektet Prov av återtag syftar till att demonstrera förmågan att återta kapslar från deponeringshål efter det att bentoniten vattenmättats och svällt. Planering och förberedelser för dessa experiment har fortsatt under 1998.

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. Två försökshål fylldes med bentonit och instrumenterades i slutet av 1996. Temperaturen i hålen höjdes till 90 respektive 130°C. De två hålen har nu överborrats och bentoniten tagits om hand för provtagning och analys. I stort sett alla prover och analyser är slutförda och inga oväntade resultat har erhållits.

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

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Executive summary

The Äspö Hard Rock Laboratory constitutes an important component of SKB:s work to design and construct 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. 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 1 – Verification of pre-investigation methods

The main aim of this stage goal is to demonstrate that investigations on the ground surface and in boreholes provide sufficient data on essential safety-related properties of the rock at repository level.

Geoscientific investigations on Äspö and nearby islands began in 1986. Since then, bedrock conditions have been investigated by several deep boreholes, the Äspö Research Village has been built and extensive underground construction work has been undertaken in parallel with comprehensive research. This has resulted in a thorough test of methods for investigation and evaluation of bedrock conditions for construction of a deep repository. The final reports for this Stage Goal were published in 1997. A summary of the results were presented at the 3rd Äspö International Seminar, June 10-12 1998, which was focussed on "Characterisation and evaluation of sites for deep geological disposal of radioactive waste in fractured rocks". The seminar was attended by 72 persons from 10 countries. Results are also submitted to scientific journals for publication.

A relatively high number of events with a high inflow rate during drilling have been observed both during the construction and operating phases of the Äspö HRL. A study has been initiated to analyse data on the occurrence of such High Permeable Features (HPF) and investigate the possible correlation between HPFs and other observed features. It was found that somewhat less than half of the HPFs can be explained by what was classified as fracture zones during the mapping of the cores and the rest by one or a few natural joints. About half of the HPFs can be associated with deterministically defined fracture zones with a large extent. HPFs are most frequent in fine-grained granite, taking the amount of different rock types at Äspö HRL into account. The arithmetic mean distance between HPFs, defined as features having a transmissivity $T \geq 10^{-5}$ m^2/s, is ≈ 75–105 m.

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 realisation phase of the project started in March 96 and was completed during autumn 1997. During 1998 three new versions have been released. Currently RVS version 1.3 is used within several of the projects undertaken at Äspö HRL.

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.

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.

During 1998 the experimental activities within the TRUE-1 tracer test programme has comprised two main activities. The study of the breakthrough of tracers injected as part of STT-1b, including continued monitoring of ^{137}Cs injected as part of STT-1 was continued until March 1998. Pumping continued and was decreased from 0.4 l/min to 0.2 l/min in late May without interruption of the pumping. Injection for the ensuing test with radioactive sorbing tracers, STT-2, was made early June. The official in-situ sampling for STT-2 was discontinued early December. All tests have been performed as radially converging tests with extraction from the same borehole. Injection has been made from two different holes.

Breakthrough of sorbing tracers in the TRUE-1 tests are featured by significant kinetic effects, and are retarded more strongly than would be expected based on laboratory data alone. The results show that laboratory data are insufficient to fully explain the breakthrough. By increasing the matrix diffusion with a factor of about 30 a good correspondence between simulated and measured breakthrough is obtained. It should be noted that the evaluation/interpretation is consistent for all tracers and tracer tests performed as part of TRUE-1, i.e. the results can be explained without contradictions. In the modelling and evaluation a Lagrangian stochastic advection-reaction framework (LSAR) has been adopted.

The Pilot Resin Experiment is performed with the objective to develop a technology for verification of transport paths in tracer experiments. The concept is to obtain data on the aperture distribution and the distribution of sorbed tracers in a fracture where tracer experiments have been performed through injection of resin followed by excavation. Large diameter (146–200 mm) core drilling has been undertaken to sample a fracture injected with resin. This has been followed by analysis of resin distribution and thickness. During the past year evaluation work has been completed and reporting is underway. The average aperture is varying in the sampled fracture between about 240–270 microns.

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. Late 1997 in total three boreholes, KA2563A, KI0025F and KI0023B, 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, KI0025F02, 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 KI0025F02. 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. The POSIVA flow meter has been employed in a detailed mode for the first time in borehole KI0025F02. 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. At the same time the modelling has become more focused on the experimental work. 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.

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. Work is presently underway to produce a test plan for the experiment.

The REX project focuses on the reduction of oxygen in a repository after closure due to reactions with rock minerals and microbial activity. 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 2,861 m. Rock and fracture filling mineral samples that had been collected from the Äspö tunnel are being used for the laboratory experiments. The results obtained so far show that the rate of O_2 consumption depends both on the particle size of the samples, and on their origin in the Äspö tunnel. The values of the first-order rate constant obtained are in the range: 1 to 140×10^{-3} ℓ g^{-1} day^{-1}. Rates of microbial oxygen consumption ranged from 0.32 to 4.5 μ mole ℓ^{-1} day^{-1}. Several O_2 injection pulses have been performed in the REX field and replica experiments. The results show that concentrations of O_2 in the range 1 to 8 mg ℓ^{-1} are 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. No new results have been obtained during 1998 from the diffusion experiments, because of problems in the CHEMLAB system. After completion of the diffusion experiments a new site for the CHEMLAB experiments will be selected and the equipment installed there. A simplified version of the CHEMLAB probe will be manufactured in order to speed up the entire experimental sequence.

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. During 1998, a series of laboratory degassing experiments was completed. Through these experiments, the impact of both groundwater degassing and changes in the flow regime on the fracture transmissivity was investigated. Furthermore, as a part of the preparation for writing a summarising technical report on groundwater degassing, data from different laboratory, field and model studies addressing groundwater degassing were summarised and interpreted. The analysis performed so far shows that the observed flow reductions indeed are consistent with the degassing hypothesis. Turbulence may be ruled out as a plausible factor contributing to the observed flow reductions.

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.

Task #5 of the Modelling Task Force 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. The first groundwater flow modelling sequence of Task #5 is completed. New hydrochemical boundary and initial conditions were provided to the modelling groups soon after the 11th Task Force Meeting at Äspö 1–3 September, 1998.

EQUIP is an EC project including several of the organisations participating in the Äspö project. The project started in 1997 and is planned to continue for three years. A compilation has been made of the Late Pleistocene and Holocene (the last 130,000 years) climate and hydrology with focus on the conditions at Äspö. Since Äspö is situated on the Baltic east-coast, not only climatic variations but also eustatic (changes in sea-level) and glacio-isostatic movements have changed the hydrogeological and hydrochemical conditions significantly.

The Matrix Fluid Chemistry project aims at determining the origin and age of matrix fluids. 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. The expected flow is in the order of ml:s per day. During the first 6 months no extractable groundwater was obtained.

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. The modelling groups were initially given data from the site characterisation and data on the experimental set-up of the tracer tests. Based on this information, model predictions were performed of drawdown, tracer mass recovery and tracer breakthrough. The performed predictions shows that the concept of Feature A as a singular well-connected feature with limited connectivity to its surroundings is quite adequate for predictions of drawdown in boreholes and conservative tracer breakthrough. Reasonable estimates were obtained using relatively simple models. The general flow and transport processes are well understood, but the methodology to derive the necessary parameters for predictions needs development.

Tasks 4E and 4F concerns blind predictions of the tests with sorbing tracers. Predictions of the STT-2 test will be presented at the 12th Task Force meeting in April 1999.

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 will be mechanically excavated by full face boring, diameter 1.75 m and to a depth of 8 m. The distance between the holes will be 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.

General planning of the project has been completed. The field activities fpr characterisation of the rock mass around the Prototype Repository have continuously been going on. During the year, planned field activities according to characterisation stage 2, have been completed and analyses and reporting work is in progress. The dominant rock type at the Prototype Repository site is Äspö diorite. Minor parts of greenstone and fine grained granite occur as inclusion bands or veins. The main joint set trends WNW with steep dips. These joints are also the main water bearing structures, which is indicated from tunnel mapping and confirmed by the coring. Manufacturing of canisters is proceeding as planned. The design of the electrical heaters and other details needed for power output is in progress. At present the boring of the deposition holes is planned to start in June 1999. The design of the road bed and the equipment for emplacement of the buffer and canisters has been decided and manufacturing is proceeding.

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 drift was excavated by drill and blast. The program for geological characterisation and locating of places for simulated deposition holes has been completed. During 1998 installations have been made in the drift to prepare for the drilling of the deposition holes and the arrival of the deposition machine.

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 will be made in the old part of the ZEDEX tunnel that has been excavated by normal blasting. Half the test part will be filled with a mixture of 30% bentonite and crushed granite rock. The other half will be filled with crushed rock without addition of bentonite, except for the upper 10–20 cm, where a slot will be left and filled with blocks of highly compacted bentonite/crushed rock mixture and bentonite pellets. The backfill will be 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 part will be divided into five sections parted by drainage layers of permeable mats. Outside the backfill an approximately 3 meter thick plug will be placed with the required function of both being a mechanical support and a hydraulic seal. The backfill and rock will be instrumented with about 230 transducers for measuring the thermo-hydro-mechanical processes.

Characterisation of the test site has been completed. Instruments have been placed in the boreholes for monitoring the behaviour of the rock during the experiment. The cables and tubes for the instruments are lead to the data collection system outside the test area through 12 holes drilled from the left wall of the test tunnel to the neighboring Demonstration Tunnel. All preparations are completed and backfilling of the drift was begun in January 1999. Scoping calculations with preliminary modelling of the hydrology of the rock around the test site, the water saturation phase, and the flow testing after saturation have been made using the finite element code ABAQUS. The compaction technique has been further developed and tested. Two vibrators will be used. One with a large vibrating plate for inclined compaction of the 30 cm thick layers and one smaller vibrating plate especially designed and built for compaction close to the roof.

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 project on full-scale retrieval tests was initiated during 1997 and the decision was taken that two deposition holes will be bored and equipped with buffer and copper/steel canister. The tunnel for the test, which is an extension of the D-tunnel on 420 m level with about 15 m, has been completed. Geological mapping of the tunnel has shown that the location of the two full-scale deposition holes for the test can very well be placed in accordance with the most suitable geometrical layout for the equipment, that is planned to be used for the retrieval of the canisters. The geological characterisation indicates very dry conditions, so dry that artificial addition of water is deemed necessary in order to saturate the buffer within a reasonable time period. Preparations have been made for the actual boring, which at the moment is planned to start in May 1999.

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. The first test parcel, S1, designed to simulate normal repository conditions, was put in the test hole in October 1996 and its temperature has successively been increased to 90°C. The second test parcel, A1, was inserted into its borehole in mid November 1996. The temperature in this borehole was increased to 130°C in order to test the buffer under adverse conditions, e.g. super-saline groundwater, high temperatures, high pH, and high potassium concentration in clay pore water.

The 15 month pilot tests A1 and S1 have been completed. The test series have been extended, compared to the original test plan, by the A0 parcel in order to replace the part which was lost during the uptake of the A1 parcel. All tests and analyses except those concerning microstructure have been completed and compilation of the final report is in progress. No unexpected results have been observed. Supporting laboratory tests concerning CEC determination techniques have been made in order improve the determinations with respect to time and accuracy. Minor mineralogical changes have been observed regarding i.a. exchangeable cations and reduced silica content. No significant changes in physical properties have been observed. The copper analyses have been completed and the results indicate a corrosion rate in the range of what was expected for oxidising conditions.

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. 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 for mechanical (e.g. TBM) excavation. 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. The modelling work has continued with analysis of dynamic fracturing and the influence of heterogeneity on rock fragmentation. Preparations of the field work has continued with planning of the instrumentation of cutters for installation of strain gauges and with scoping calculations of expected deformations and strains in the shafts and saddles of the instrumented cutters. The two cutters that are going to be used have been sent to Luleå Technical University for calibration before being installed on the bore head in the ÄHRL.

Facility operation

The office building has got a new wing, providing new office space, conference rooms, and an exhibition hall. Also the storage facility has been enlarged. The Äspö HRL now has office space for 50 persons. The operation of the facility has worked smoothly. A fire alarm system has been installed underground.

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.

Groundwater sampling is performed twice every year, in May and in October, 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

Ten organisations from nine countries participated during 1998 in the Äspö Hard Rock Laboratory research in addition to SKB. They are:

- Atomic Energy of Canada Limited, AECL, Canada.
- Posiva Oy, Finland.
- Agence Nationale pour la Gestion des Déchets Radioactifs, ANDRA, France.
- The Power Reactor and Nuclear Fuel Development Co, PNC, 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 Bildung, Wissenschaft, Forschung und Technologie, BMBF, Germany.
- Empresa Nacional de Residuos Radiactivos, ENRESA, Spain.
- 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.

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 (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.

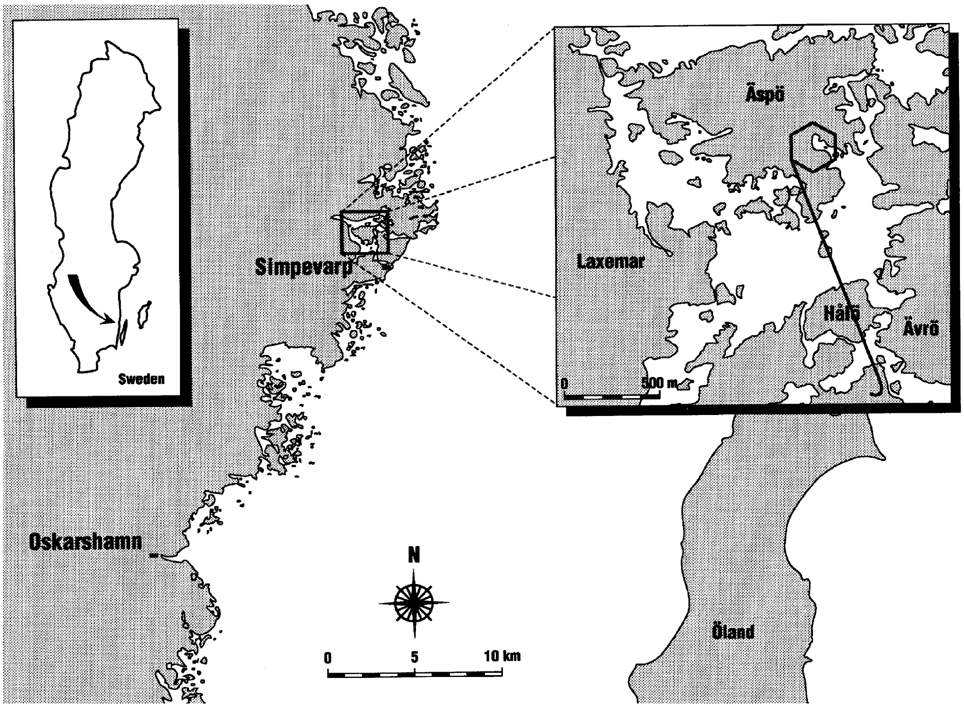


Figure 1-1. Location of the Äspö HRL.

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 (Figure 1-2). The total length of the tunnel is 3,600 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 (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.

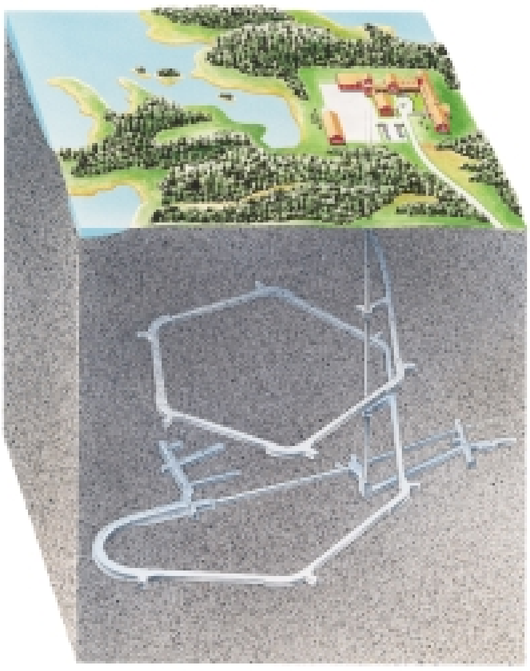


Figure 1-2. *Overview of the Äspö Hard Rock Laboratory Facilities.*

***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 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 SKB:s organisation

A reorganisation has been made of SKB that became effective on July 1st 1998. The reorganisation has been made in order to provide a better focus of activities and use of resources to meet SKB:s main near term goal, which is to get acceptance for performing site investigations at two sites in 2001. Investigations, including drilling, should commence in 2002. The strategy to reach this goal is described in the latest Research, Development and Demonstration Program 98, which SKB delivered to the Swedish government at the end of September.

SKB has been organised into four divisions corresponding to SKB:s main tasks. These are Siting, Safety and Technology, Facility Operations, and Consulting services. There are four support units for Communications Technology, Information policies, Quality systems and planning, and Administration (Figure 1-4).

All research, technical development, and safety assessment work has been organised into one department, Safety and Technology, in order to improve co-ordination between the different activities. The Safety and Technology department has been organised into four units:

- Safety and Science with responsibility for research, safety assessments, and systems analysis.
- Repository Technology with responsibility for development of site investigation programs and methods, development and testing of deep repository technology, and in-situ research on the natural barrier. The unit is also responsible for the operation of the Äspö Hard Rock Laboratory and the co-ordination of the research performed in international cooperation there.
- Encapsulation technology is responsible for development and testing of the copper canister and the design of the Encapsulation Plant. This unit is also responsible for the operation of the Encapsulation Laboratory located in Oskarshamn.
- Large construction projects have been organised in a separate unit. The main future task of this unit is the construction of CLAB 2, the expansion of CLAB to a total storage capacity of 8,000 tons of spent nuclear fuel.

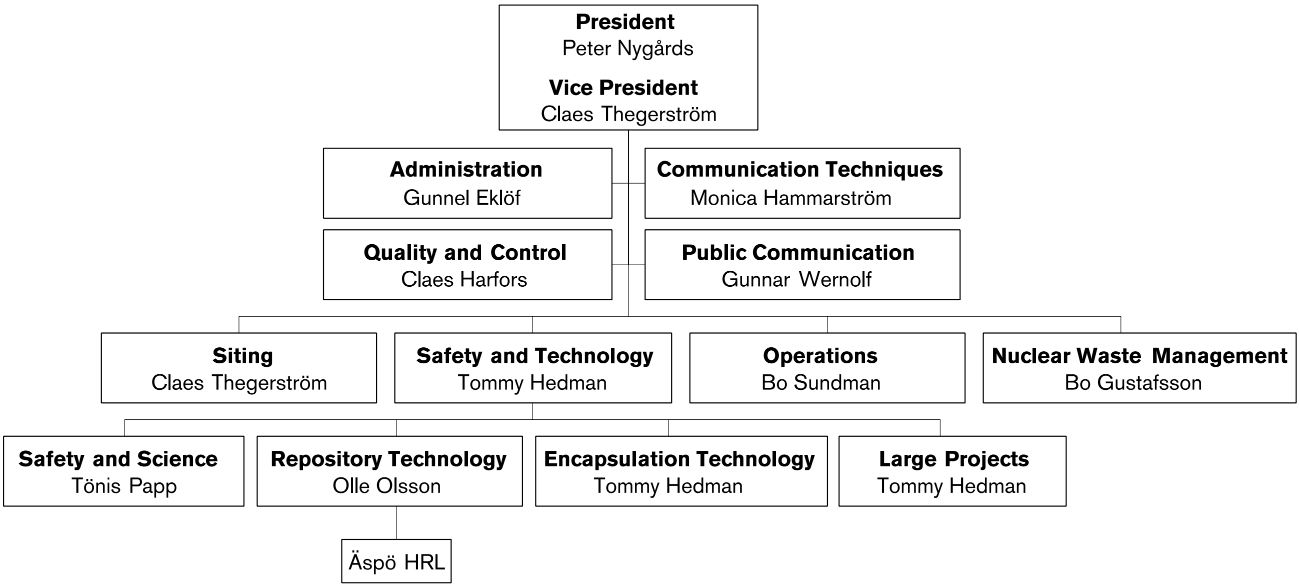


Figure 1-4. *Organisation at SKB valid from July 1st 1998.*

1.3.2 Repository Technology and the Äspö Hard Rock Laboratory

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.

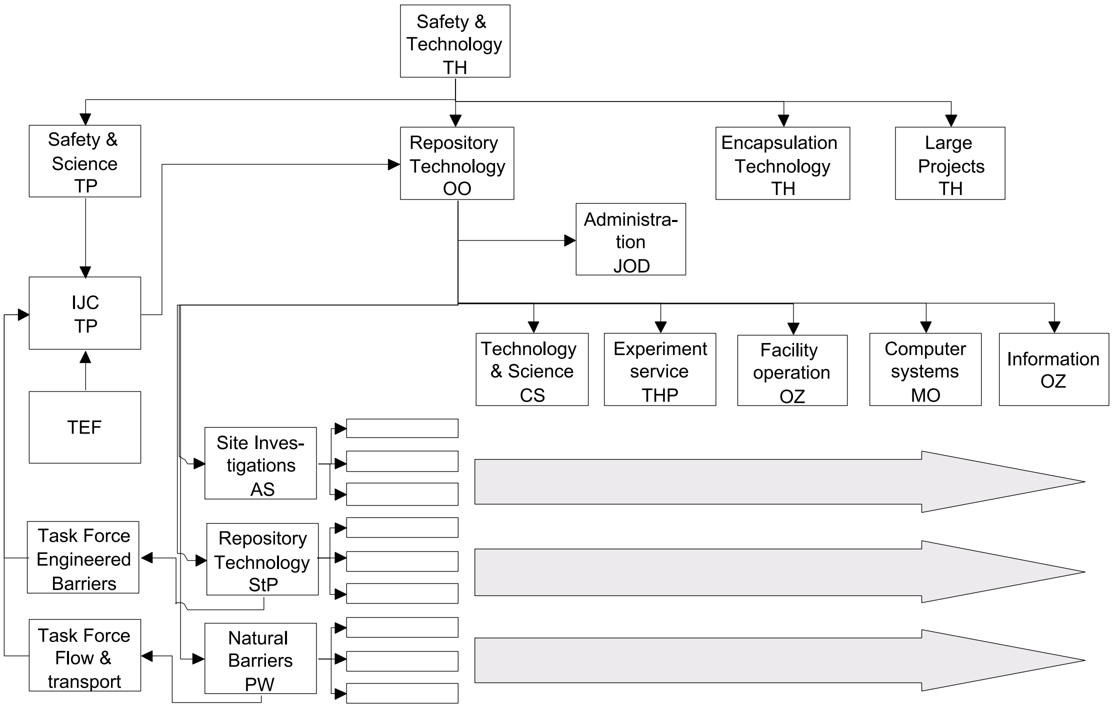


Figure 1-5. *Organisation of Repository Technology.*

- 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.
- 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.

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.

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 Site Office 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.

1.3.3 International participation in Äspö HRL

The Äspö Hard Rock Laboratory has so far attracted considerable international interest. As of February 1999 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 pour la Gestion des Déchets Radioactifs (ANDRA), France; Posiva Oy, Finland; UK Nirex, United Kingdom; Nationale Genossenschaft für die Lagerung 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).

1.3.4 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 (November 1998).

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.

1.3.5 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 (November 1998) is Gunnar Gustafson, CTH and secretary is Mansueto Morosini, SKB.

1.4 Formulation of experimental programme

The experiments to be performed in the Operating Phase will be described in a series of Test Plans, one for each major experiment. The Test Plans should give a detailed description of the experimental concept, scope, and organisation of each project. The Test Plans are structured according to a common outline. In cases where experiments are planned to extend over long time periods (up to 10 years) it is not appropriate or even possible to plan the experiment in detail in advance. In such cases, Test Programmes will be prepared outlining the objectives and overall scope of the programmes, which will be divided into stages with duration of 2–3 years. Detailed Test Plans will then be prepared for each stage, following an evaluation of results obtained to date. These evaluations may result in programme revisions.

Initially, draft Test Plans will be prepared which will be submitted for review by the Task Force and other bodies. After review, as well as scoping or design calculations, the Test Plans will be updated, detailed where appropriate, and published as Progress Reports or International Cooperation Reports. The general strategy is to begin preparation of the Draft Test Plans approximately one year before field work or some other significant preparation work is planned to start. The intention is also to actively engage the Task Force on modelling of groundwater flow and transport of solutes in the planning, design, and evaluation of the flow and transport experiments.

1.5 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.

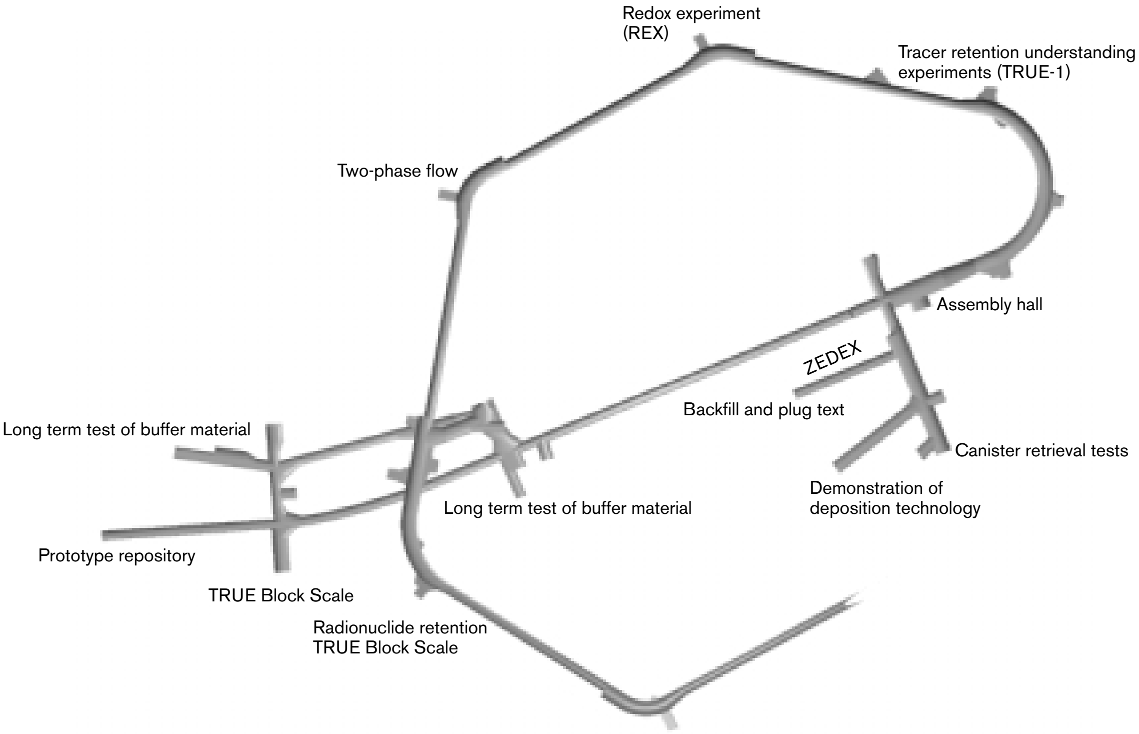


Figure 1-6. *Underground excavations at the 300–450 m levels and current allocation of experimental sites.*

2 Verification of pre-investigation methods

2.1 General

The purpose of pre-investigations or site investigations is to:

- show whether a site has suitable geological properties,
- provide data and knowledge concerning the bedrock on the site so that a preliminary emplacement of the repository in a suitable rock volume can be done as a basis for constructability analysis,
- provide the necessary data for a preliminary safety assessment, which shall serve as support for an application under NRL (the Act Concerning the Management of Natural Resources) to carry out detailed site characterisation, and
- provide data for planning of detailed site characterisation.

This was the first stage goal of the Äspö projected and the results of characterisation, evaluation and modelling were presented in five technical reports, Rhén et al /1997a, b, c/ and in Stanfors et al /1997a and b/. During 1998 the figures in Rhén et al /1997a, b, c/ and Stanfors et al /1997a, b/ have been transferred mainly to TIF format with 300 dpi, which is expected to give good reproducing quality. Some of the figures made in Micro station will also be delivered in Postscript format.

Some of the results were presented at the 3rd Äspö International Seminar, June 10–12 1998, which was focussed on "Characterisation and evaluation of sites for deep geological disposal of radioactive waste in fractured rocks". Results are also submitted to scientific journals for publication.

2.2 Code development and modelling

Numerical groundwater flow modelling for different purposes has been done during the pre-investigation phase and the construction phase. The code used has mainly been PHOENICS. Early during the pre-investigation generic studies were done of the drawdown around Äspö HRL and the salinity distribution around the Äspö island. Later the code was used for prediction of e.g. the drawdown during construction of Äspö HRL. The code has during the years been developed and documented in order to improve the numerical modelling and the visualisation of the results.

Tests of embedded grids have been made. The purpose is to see if it is 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 Coordinates) 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. The test indicated that embedded grids might be a feasible approach.

However, it may not be a problem with the spatial assignment method in the BFC grid, with a limited aspect ratio, with the method for generating the hydraulic conductivity field mentioned below that start. It has however not been tested.

2.3 High-Permeability Features (HPF)

2.3.1 Background

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 a number of times and these features were in several cases not a part of the deterministically defined major discontinuities. This has also been observed in drillings during the operation phase of the Äspö HRL.

It was therefore considered important to assess the possibility to predict fractures or features with high transmissivities from data collected during the pre-investigation phase.

With the term High Permeable Feature (HPF) in this report is understood a fracture, system of fractures or 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.

The objective with the current study is to:

- compile information that can be coupled to High Permeable Features at southern Äspö,

- analyse these data statistically and investigating possible correlation's between HPF and other observed features.

2.3.2 New results

It is of interest to make a first attempt at setting the occurrence of HPFs in a structural geological context. Of special interest in this study is shown if HPFs occurs in the vicinity of:

- any special rock type,
- any special rock contact,
- rock veins,
- crush zones/natural joints,
- areas where RQD is high/low.

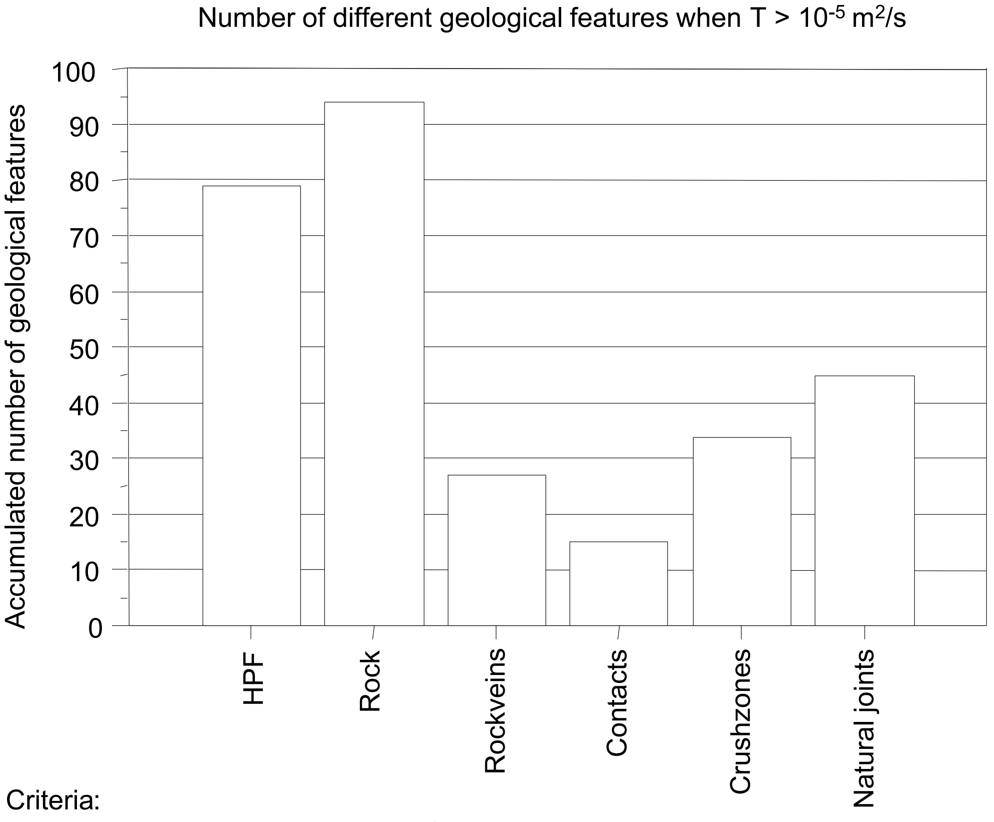
The evaluation of HPFs for the surface bore holes are based on the injection tests with a packer spacing of 3 meters and accordingly the geological data for the same packer interval.

The evaluation of HPFs in the tunnel core holes is based on positions of flows into the boreholes. If these are based on drilling records it is judged that there exist an uncertainty of ±1 meter from the given position. If flow logging is the base of position it is judged as more certain. However, in this evaluation ±1 meter from the observed HPF has been the base for the bore hole section to be used for the evaluation.

In the bore holes mentioned above the total number of HPFs, based on T ≥ 10^{-5} m^2/s are 79, and the correlation study is based on those data.

The results of the correlation study are presented in Figure 2-1. The figure shows not the total number of features occurring within a bore hole interval but the number of intervals with the feature registered. This applies to the bars Rock, Rockveins and Contacts. This gives that the number of HPFs + Contacts equals the number of Rock.

The definition of the HPFs (High-Permeability Features) as having a transmissivity T ≥ 10^{-5} m^2/s or a flow rate Q ≥ 100 l/min into a bore hole with pressure close to atmospheric was more or less arbitrary chosen for this study. However, it was known from the previous studies at Äspö HRL that features, with properties around these values mentioned above, were not uncommon and not all of them could be explained by fracture zones with large extent defined deterministically using geological, geophysical, hydrogeological and hydrochemistry data. This study has shown this in a more clear way and the main conclusions are:



Criteria:
Tunnel boreholes – HPF position +/- 1 meter
Surface boreholes – within packer interval (3 m)

Figure 2-1. *The total number of HPFs and the number of changes of the geological features within an interval associated to the HPF. For surface boreholes the interval was the packer interval (3 m) and for tunnel boreholes +/- from the position of the HPF.*

Somewhat less than half of the HPFs can be explained by what was classified as fracture zones during the mapping of the cores and the rest by one or a few natural joints. It clearly shows that high permeability features in the sparsely fractured rock mass exist.

About 48% of the HPFs can be connected to the deterministically defined fracture zones with a large extent, which existence, extension and properties were based on evaluation of geological, geophysical hydrogeological and hydrochemistry data.

HPFs are most frequent in fine-grained granite, taking the amount of different rock types at Äspö HRL into account.

The arithmetic mean distance between HPFs, defined as features having a transmissivity $T \geq 10^{-5}$ m^2/s, is ≈ 75–105 m.

2.3.3 Planned work

A draft of the report has been made and is now reviewed. The report is planned to be printed during 1999. Late 1999 it is planned to re-analyse the old data and new data in order to give a more detailed description of conductive features in a similar manner as shown in the HPF study.

3 Methodology for detailed characterisation of rock underground

3.1 General

Detailed characterisation includes construction of access tunnel to a potential repository and investigations made from the tunnels and boreholes drilled from the tunnels.

The purpose of detailed characterisation of a repository site is:

- to confirm the existence of a sufficiently large rock volume suitable for use as a repository at a selected site,
- to provide the data needed for the safety assessment required for obtaining the permit to construct the deep repository, and
- to provide data on bedrock conditions in order to optimise repository design with respect to engineered barriers and repository layout.

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.

Projects performed to meet this Stage Goal include detailed characterisation of the disturbed zone around blasted and bored tunnels (ZEDEX), development of interactive computer systems for interpretation of data and design of the repository (Rock Visualization System) and further development and testing of instruments and methods for characterisation from underground tunnels and boreholes.

3.2 Underground measurement methods and methodology

3.2.1 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.

3.2.2 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.

3.2.3 Results

Work on a report on underground investigation methods used during the construction phase of the Äspö HRL has been performed and the report will be published during 1999. 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.

Radar and seismic

Areas of potential interest for further studies are the geophysical methods seismic and radar. Those methods are regarded as remote characterisation methods for location of discontinuities in prospective repository rock volumes, in particular during detailed investigation and repository construction stage. While the seismic method covers relatively large volumes the radar is foreseen to give more detailed information in the near field. These methods have been used at Äspö during 1998, and several data sets from different measurement configurations exist.

Tunnel and large hole documentation

A method test of overview documentation with the BIPS image video recording system was made in the TBM tunnel when the BIPS borehole system was delivered. This method has a potential to be used not only for TBM mapping but also for large hole documentation like the deposition holes. Laser scanning has been tested as a method for documentation of tunnels, both with respect to their geometric dimensions and as a basis for geological mapping (Nilsson, 1997). The technique may also be tested for mapping the deposition holes to be drilled as part of the Prototype repository project.

Other studies

Some methods have been tried out within the framework of other projects in the Äspö HRL. For example, the reliability of rock stress measurements performed with the overcoring method has been checked (Myrvang, 1997).

3.3 Rock Visualisation System

3.3.1 Background

A 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.

The experiences obtained from the investigations 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 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 has developed the Rock Visualization 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.

SKB:s Rock Visualization System is based on the CAD-system MicroStation 95 including MicroStation Modeler and MicroStation QuickVision. RVS version 1.0 is designed as a single-user system, and the data exchange link between RVS and SKB:s Site Characterization Database System (SICADA) is based on a client/server technique. There is also a database engine (MS/Access) 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 if another database engine is needed in the future.

3.3.2 Results

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 3-1. By using the object selector, an unique feature in the system, objects can be turned on (visible) or off (not visible).

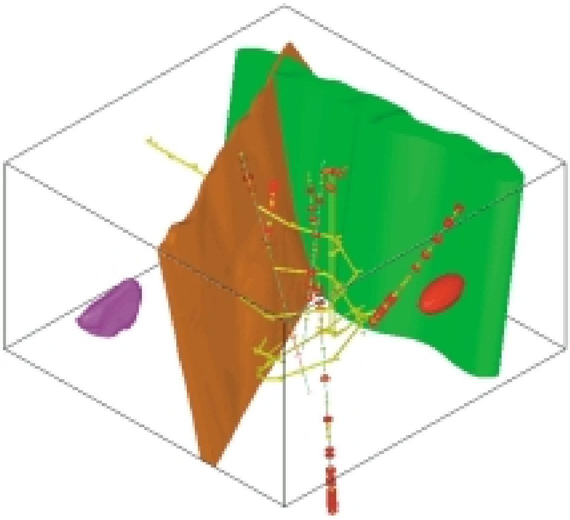


Figure 3-1. *Objects can be turned on (visible) or off (not visible), by using the* ***object selector****. The rock mass visualised in this case includes visible objects of several types including borehole data, modelled objects (a fracture zone in brown, a lens in red and two arbitrary rock bodies in purple and green) and construction objects (tunnels in yellow).*

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

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

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

During 1998 three new versions have been released. Currently RVS version 1.3 is used. Some of the many new functions to be highlighted here are:

- Arbitrary orientation of the model boundary. The position is defined by giving the global coordinates of the origin of the model boundary, and the rotation is defined by giving the bearing and the inclination of the local Y-axis of the model boundary in relation to the global Y-axis (Norting). It is also possible to shift (dx, dy, dz) the model boundary relative the local coordinate axes. (In the previous version it was only possible to work with an model boundary that was in parallel with the axis of the global coordinate system.)
- Improved import of MicroStation drawing files. The contents in each MicroStation drawing level is now stored as separate objects. This means that the user can turn on or off different drawing levels by using the RVS Object Selector. (In the previous version the whole drawing was stored as one single object.)
- Backup and Restore of a project (model). A backup procedure is always activated when the user decides to exit from the system, but the user could cancel the procedure if not meaningful.

- Copy project is used to make a total or partial copy of an existing project.
- Move project is used to remove a project from the local RVS database. The project is packaged into an archive file. This archive file is possible to import on another RVS workstation.
- Compress project at export. A ZIP-file is generated when projects are exported.
- Hierarchical search in the Object Quick Selector has been implemented.
- Import of borehole coordinates from ASCII-file.
- Preview/Inspection of data in the local database.
- Plot of legends. This feature is available when the system is working in drawing mode.
- Modelling of mapped discontinuities along tunnels.

An educational programme was planned and completed during 1998. Totally 18 users have been educated within this programme and some of them are now working with visualisation and modelling tasks within the different underground research sites at Äspö Hard Rock Laboratory.

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

4.1 General

The Natural Barriers for a deep geological repository for radioactive wastes are the bedrock, its properties and the on-going processes in the rock. 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 function of the natural barriers as part of the integrated disposal system can be presented as *isolation*, *retention* and *dilution*.

Isolation

Isolation is the prime function of the repository. It is obtained through the co-function of the engineered and the natural barriers. For deep geological disposal, 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 good isolation it is thus necessary to minimise the groundwater flow to the waste containment. Additional conditions, which affect the isolation, are the chemistry of the groundwater and the mechanical stability of the rock.

To date conceptual and numerical groundwater flow models have been developed within the entire Äspö project. The numerical groundwater flow model of the Äspö site and region has been further developed during 1998, see section 2: Verification of pre-investigation methods.

Hydrochemical stability and potential variability is assessed within several on-going projects. These aim at explaining possible chemical conditions in a repository host rock based on the assumption of different scenarios for future conditions. The REX project deals with redox conditions and microbial activity at the time of closure of the repository. TASK #5, within the Task Force on modelling of groundwater flow and transport of solutes, integrates the models of hydrology and hydrochemistry and checks their consistency on data from the tunnel construction phase. EQUIP is an EC supported project which aims at testing the potential in using fracture fill minerals to reveal the previous hydrochemical regimes. Matrix Fluid Chemistry is focussed on the groundwater chemical composition in the rock matrix.

Retention

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, which 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 that occur in the near-field and far-field.

Some radionuclides are strongly retarded while others are escaping with the flowing groundwater. The major emphasis in the safety assessment calculations has therefore been put on the weakly retarded nuclides, even if they do not represent the dominant waste hazard.

Strontium and all negatively charged elements will be transported through the bentonite buffer by diffusion. They will then be retarded by interaction with the fracture minerals along the flow paths of the rock and by 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 migration. The chemical composition of the groundwater is important for the magnitude of sorption for some of the nuclides. Negatively charged nuclides are not sorbed on the mineral surfaces. They are retarded from the groundwater flow only through the diffusion into the stagnant pores of the rock matrix.

To estimate the nuclide retention in-situ, tracer test experiments are carried out within the TRUE-project. 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. The first set of experiments, TRUE-1 in the 5 m scale, has been completed during 1998. Characterisation of the 50 m test site, TRUE Block Scale, has started and planning for the Long Term Diffusion Experiment has also started.

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

CHEMLAB experiments are to be conducted using moderately and highly sorbing nuclides. Experiments will be carried out in simulated near-field conditions e.g. bentonite and also in tiny rock fractures.

Degassing and Two Phase Flow deals with gas phase transport. Laboratory and modelling studies have been completed during 1998. An on-going experiment is conducted by BGR on behalf of BMBF in the tunnel.

Dilution

Dilution is the third important barrier function and will take place in the rock volume surrounding the repository. The magnitude of dilution will very much depend on the site specific conditions, and the nature of the performance assessment calculations to conceptualise the flow. In the geosphere the dilution is caused by the dispersion in the groundwater flow and by mixing.

4.2 Tracer Retention Understanding Experiments

4.2.1 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 characterization 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 a 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 characterization 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 TRUE Stage Tracer test cycle. Early 1997 preparatory work at the site commenced 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 1997. The first of the tests with radioactive sorbing tracers (STT-1) was started up mid July 1997 and comprised injection of ^{22}Na, ^{47}Ca, ^{85}Sr, ^{86}Rb, ^{133}Ba and ^{137}Cs in the flow path KXTT4→KXTT3. The results showed a strong retardation of ^{137}Cs and a relative retardation of the radioactive sorbing tracers compatible with what has been measured in the laboratory. Late 1997 it was decided to prolong the study of Cs breakthrough.

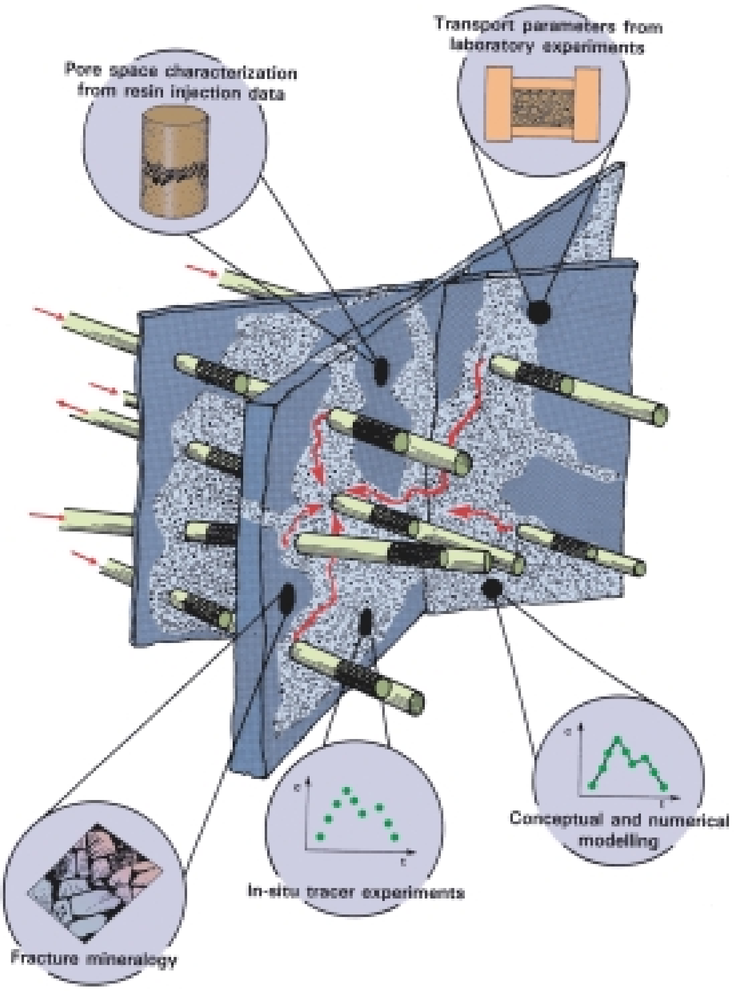


Figure 4-1. *Principal outline and components of the TRUE-1 experiment.*

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 ^{137}Cs and ^{133}Br were not included, and with the addition of the two radioactive conservative tracers, ^{131}I and ^{82}Br, the sorbing tracer ^{58}Co and the redox-sensitive tracer ^{99m}Tc. The latter test is denoted STT-1b.

Results

TRUE-1 structural and conceptual modelling

Development of a conceptual structural description of the TRUE-1 site has partly been made as a collaborative work with the FCC project /Äspö Annual 97/. The resulting conceptual structural model of the TRUE-1 rock block is shown in Figure 4-2. In addition detailed conceptualisations of the Feature A intercepts have been produced which have been used in the construction of a conceptual representation of Feature A.

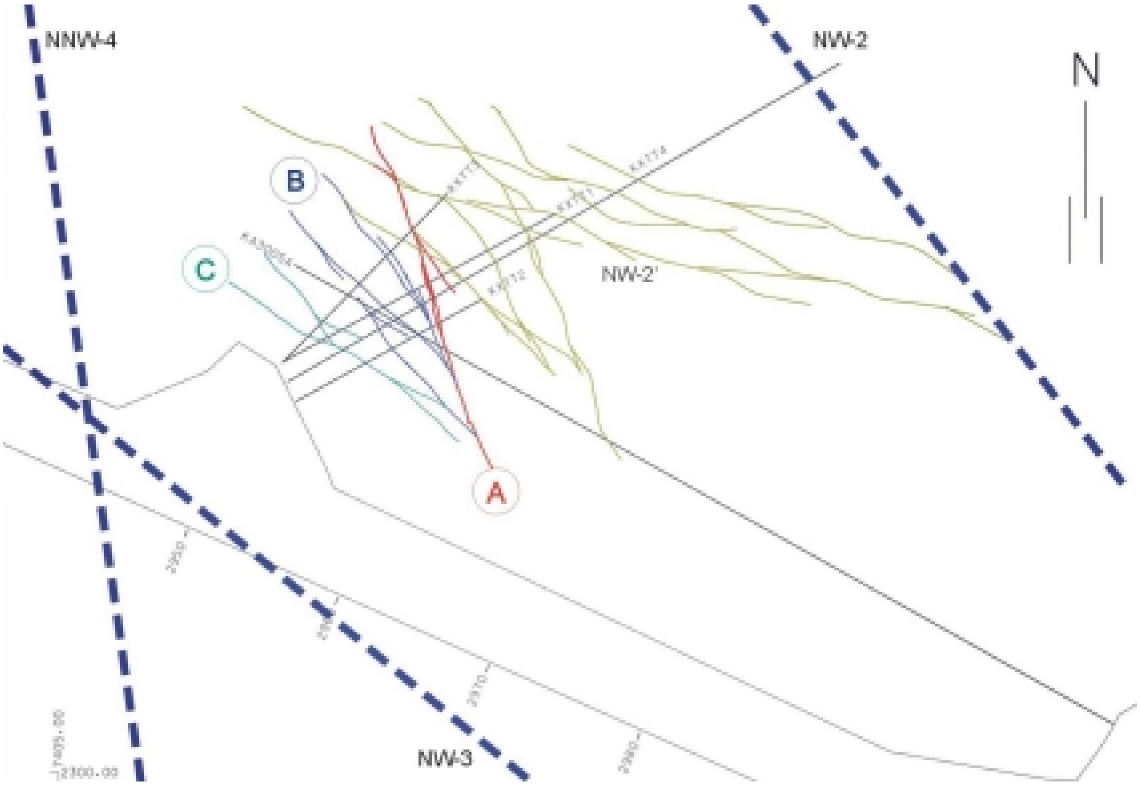


Figure 4-2. *Structural model of the TRUE-1 rock block.*

TRUE-1 tracer test programme

The activities within the TRUE-1 tracer test programme has comprised two main activities. The study of the breakthrough of tracers injected as part of STT-1b, including continued monitoring of ^{137}Cs injected as part of STT-1 was continued until March 1998. Pumping continued and was decreased from 0.4 l/min to 0.2 l/min in late May without interruption of the pumping. Injection for the ensuing test with radioactive sorbing tracers, STT-2, was made early June 1998.

STT-1b

Breakthrough was observed for all tracers but the redox-sensitive tracer ^{99m}Tc. The breakthrough curves for the tracers are shown in Figure 4-3. The figure shows the relative retardation of the sorbing tracers, indicating the strongest retardation for ^{58}Co.

The tailing of the breakthrough curve for ^{137}Cs from the injection in the previous sorbing tracer test STT-1 (KXTT4→KXTT3) was also followed during STT-1b. The recovered mass for ^{137}Cs at the end of STT-1b monitoring test period was 33%.

The evaluation of tracer mass recovery showed some inconsistencies. Calculated mass recoveries based on integrated mass fluxes were found to be more than 100% and differ considerably to values calculated based on weighing and concentration measurements of tracer mass from the exchange procedure. Based on earlier tests and uncertainties in the weighing and concentration measurements, the values determined by integration of the injection and breakthrough curves, corrected by assigning a larger (28%) volume to the injection section, were considered to be the most appropriate to use.

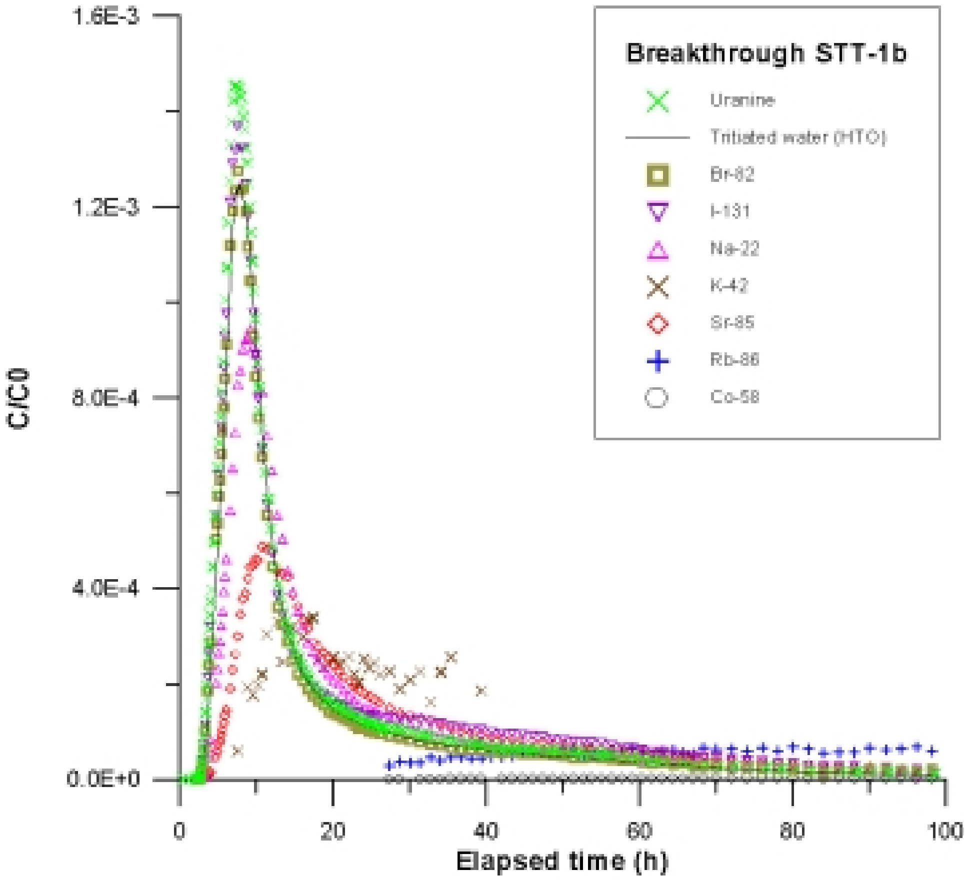


Figure 4-3. *STT-1b – Tracer breakthrough after 100 hours of pumping in section KXTT3:R2. Tracer concentrations are normalised to injection concentrations at t=2 hours.*

STT-2

The flow path used for this test is the same used for STT-1, i.e. KXTT4→KXTT3. The injected tracers included the same used in the case of STT-1, with the exception that ^{137}Cs was not used, and with the addition of ^{42}K, ^{134}Cs (t_2=2.1 years) and the redox-sensitive short-lived nuclide, ^{99m}Tc. The reference conservative tracers used include Uranine, ^{82}Br and tritiated water (HTO). In order to obtain a well defined injection pulse shape, two exchanges of the tracer-spiked water in the injection loop were performed after a four hour circulation. The resulting injection function for the reference conservative tracer Uranine is shown in Figure 4-4.

The resulting family of breakthrough curves for the tracers is shown in Figure 4-5. Breakthrough was observed for all tracers but ^{42}K and the redox-sensitive species ^{99m}Tc. Significant retardation is observed for ^{134}Cs. The breakthrough curves, unlike the ones obtained from STT-1 (see Äspö HRL Annual report for 1997), show signs of dual peaks, most distinctively in the breakthrough of the conservative tracers, cf. Figure 4-5. This is interpreted as a manifestation of transport taking place in two flow paths. A subparallel structure to the interpreted Feature A has indeed been interpreted in the injection section in 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 in combination with the

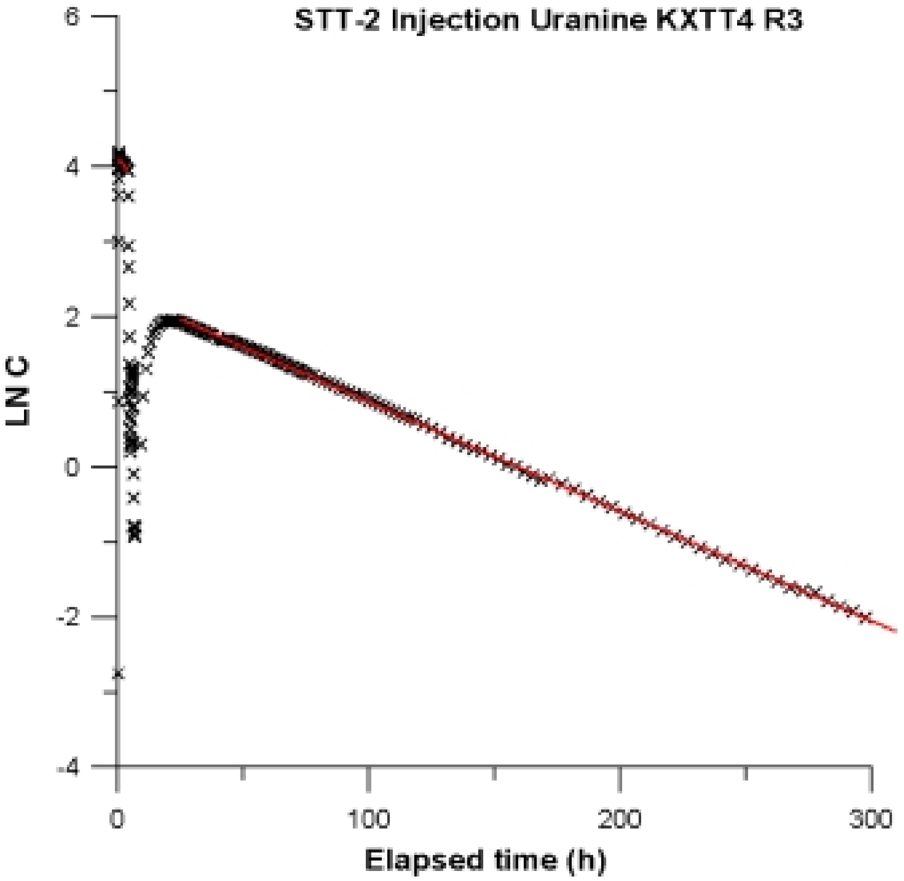


Figure 4-4. Tracer injection mass flux vs. time in borehole section KXTT4:R3 for the conservative tracer Uranine.

acting boundary conditions. The reduction appears to be sufficient to activate the subordinate flow path, which did not stand out in the STT-1 experiment. It should however be mentioned that an anomalous high dispersivity value has been interpreted for the flow path in question from RC-1 and onwards. This high dispersivity has been attributed to multiple flow paths.

Mass recovery calculated for Uranine based on integration of injection and breakthrough curves is in the order of 98%. Using this technique, the mass recovery of the sorbing tracers range from 11% (Cs-134) to 83% (Na-22).

The official in-situ sampling for STT-2 was discontinued early December.

Modelling

Breakthrough of sorbing tracers in the TRUE-1 tests with sorbing tracers are featured by significant kinetic effects, and are retarded more strongly than would be expected based on laboratory data alone. The objective of the performed evaluation modelling has been to provide a consistent interpretation of the measured breakthrough curves for all tracers using a minimum of filed-scale parameters. A comprehensive description of the theory, evaluation procedure and results is given in Cvetkovic et al (in prep).

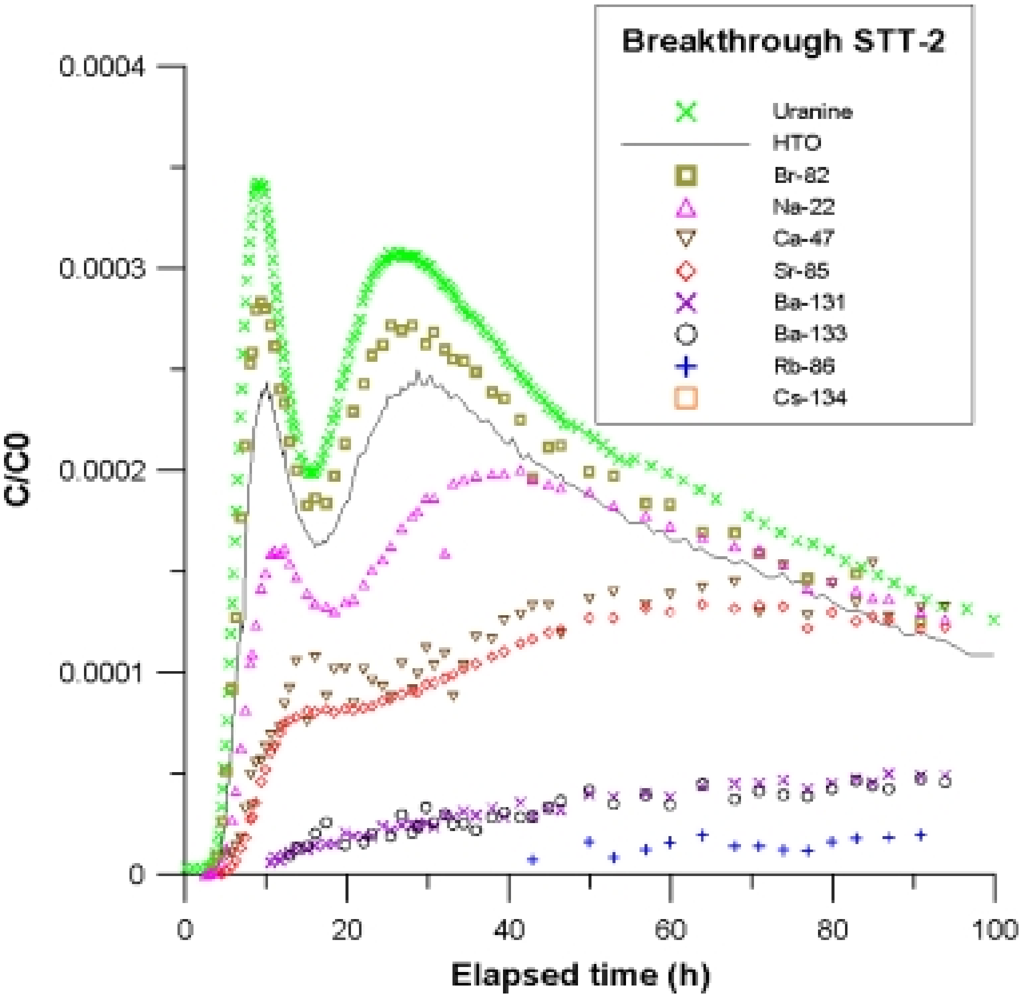


Figure 4-5. *STT-2 – tracer breakthrough after 100 hours of pumping in section KXTT3:R2. Tracer concentrations are normalised to injection concentrations at t=2 hours.*

The key hypotheses adopted are:

- Dominant effects are due to diffusion/sorption in the rock matrix which are linear processes.
- The relationship between the two flow-dependent parameters that influence diffusive mass transfer, τ and β, can be approximated as being deterministic and linear.
- The parameter values for mass transfer reactions (sorption and/or diffusion) determined in the laboratory may differ from corresponding parameters applicable in the field.

Kinetic effects other than those due to diffusion and sorption in the rock matrix are attributed to sorption in gouge material. These kinetic effects are likely to be due to diffusional resistance in the fracture (e.g. in the gouge material). It should be noted that no significant kinetics was observed in laboratory experiments on Äspö material (Byegård et al, 1998).

The conceptual model adopted is one of an open heterogeneous fracture where diffusive mass transfer takes place across the flow path boundary, especially across its contact with the rock matrix. In the modelling a Lagrangian stochastic advection-reaction framework (LSAR) has been adopted (Cvetkovic et al, 1999). When solving the system of coupled transport equations for a single trajectory, a new parameter β was derived, which is a random quantity, which integrates the velocity-weighted variable aperture along the flow path. The parameter β controls surface sorption and diffusion/sorption into the rock matrix, and is related to the flow field. This allows direct accounting of the effect of flow heterogeneity on mass transfer reactions. All mass transfer reactions are assumed linear and the coupled effect can be obtained by convolution. To account for dispersive effects, the convoluted result for a single flow path is integrated over different flow paths described by distributions of τ and β. The parameters τ and β have been shown to be significantly correlated for generic conditions and for the flow conditions in Feature A. Based on this result an approximate linear (deterministic) relationship between τ and β has been obtained using Monte Carlo simulations. The coefficient of proportionality k ($\tau = k \cdot \beta$) corresponds to the "flow-wetted surface".

Two key parameter groups which control sorption and diffusion are K_a-β for surface sorption and β-κ for diffusion/sorption. The parameters K_a and κ have been determined/estimated in the laboratory for all tracers. The parameters β and τ are dependent on the flow conditions and cannot be determined in the laboratory. Two additional parameters considered in the evaluation are the distribution coefficient for the gouge material K_d^g and the kinetic rate α. The latter parameters have to be backed out of the breakthrough curves.

The evaluation consists of two basic steps:

1. Determination of the water residence time distribution $g(\tau)$ by deconvoluting breakthrough curves and accounting for matrix diffusion.
2. Use $g(\tau)$ to model the reactive breakthrough curves by accounting for mass transfer processes, using parameters determined in the laboratory. If the modelled breakthrough curves deviate from those determined in the field, mass transfer is enhanced by increasing the diffusion factor $f(\cdot\kappa)$, and adding sorption in the gouge material.

Figure 4-6 shows a typical result of the evaluation process for ^{137}Cs. The results show that laboratory data are insufficient to fully explain the breakthrough. By increasing the matrix diffusion with a factor f=30 a good correspondence between simulated and measured breakthrough is obtained. Accounting for sorption in the gouge material has limited effect in this case. In contrast it has been shown that in modelling of the more weakly sorbing tracers, e.g. Ba and Sr, the result is more sensitive to sorption in the gouge material.

The basic results is that retention observed in the field cannot be predicted using laboratory data alone. Calibration with an enhanced diffusion factor f was required in order to attain a close correspondence between measured and modelled breakthrough. A relatively limited range of enhanced diffusion, f= 24–50, is found to be required to model the TRUE-1 breakthrough curves. For some cases sorption in the gouge material also has to be introduced. Also in the latter case the range of K_d^g is relatively narrow. The physical explanation for the enhanced diffusion is increased porosity, in part caused by enhanced micro-fracturing and alteration in a limited rim zone along the fracture surface.

The inherent heterogeneity of Feature A entail that all field scale parameters are associated with uncertainty, hence the need for a calibration procedure as an integral part of the evaluation. It should however be pointed out that; (i) the evaluation/interpretation is

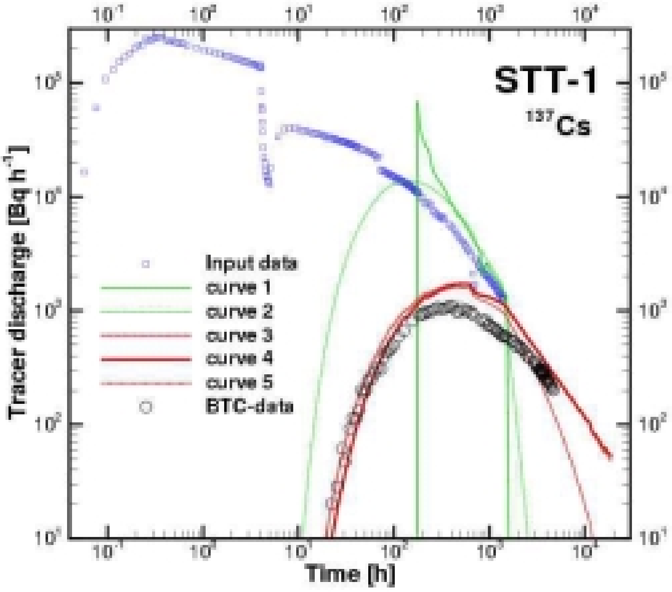


Figure 4-6. Illustration of interpretation of Cs-137 breakthrough during STT-1. Curves 1, 2, 3 and 4 are obtained using the LSAR model. Curve 1 is obtained by assuming that surface (equilibrium) sorption with constant (effective) b is the only retention mechanism, Curve 2 is obtained by assuming that surface (equilibrium) sorption with variable b is the only retention mechanism, Curve 3 is obtained by assuming that surface (equilibrium) sorption, matrix diffusion and matrix sorption with variable b are the retention mechanisms, and Curve 4 is the same as Curve 3 where in addition non-equilibrium sorption in the gauge is accounted for.

consistent for all tracers and tracer tests performed as part of TRUE-1, i.e. the results can be physically explained without contradictions, (ii) the number of parameters was kept to a minimum.

Resin technology

At the so called Pilot Resin Site in the F-tunnel, a trial resin injection followed by excavation with large diameter (146–200 mm) core drilling has been undertaken followed by analysis of resin distribution and thickness. During the past year evaluation work has been completed and reporting is underway.

Measurements on the resin impregnated cores have been conducted by Fracflow at Memorial University of New Foundland and by Itasca at KTH. The method used by Fracflow involves use of a photo-microscope and a digitizer. The method used by Itasca employs automated measurements on binary images from the microscope using an image analysis system (IBAS).

The resulting statistics from the analysis made on the two collected samples are presented in Table 4-1. The average aperture (all data) is varying between about 240–270 microns. The percentage of contact areas observed for Sample 3b is in parity with it being interpreted as a shear fracture.

Planned work

- Final Reporting of TRUE-1 (Winberg et al, in prep).

Table 4-1. Summary of results from aperture measurement of two in-situ epoxy resin impregnated samples from the Pilot Resin Injection experiment site. Results are given for individual quadrants and for the composite sample

Fracture Sample	Mean Aperture Resin [µm]	Coefficient of variation [%]	Contact Area [%]	Void area [%]	Mean Aperture All data [µm]
1bI	308	33	0.5	0	284
1bII	280	32	1.6	0	260
1bIII	240	41	2.3	0	221
1bIV	290	39	0.02	0	289
1bTotal	**281**	**37**	**1.0**	**0**	**266**
3bI	310	27	31	18	218
3bII	327	31	21	9	258
3bIII	282	39	37	17	179
3bIV	278	46	13	27	268
3bTotal	**295**	**39**	**22**	**20**	**239**

Note: Sample 1b is from borehole KXTE1, L=2.30–2.52 m.
Sample 3b is from borehole KXTE3, L=1.12–1.36 m.

4.2.2 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.
- Detailed 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-party project involving ANDRA, NIREX, POSIVA, and SKB. During 1997, also ENRESA and PNC have joined the project.

Late 1997 in total three boreholes, KA2563A, KI0025F and KI0023B, 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, KI0025F02, 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 KI0025F02. 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. The POSIVA flow meter has been employed in a detailed mode for the first time in borehole KI0025F02.

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. At the same time the modelling has become more focused on the experimental work

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 KI0025F02, is presented in a position report prepared for the 2nd TRUE Block Scale Review Meeting (Winberg, 1999).

Results of characterisation

The performed seismic work, and subsequent co-interpretation of old data, include different measurement modes including vertical seismic profiling (VSP), horizontal seismic profiling (HSP), and 3D cross-hole modes. The results of the subsequent interpretation is that three fracture systems can be identified which are almost orthogonal to each other; 1) nearly vertical structures oriented northwest, 2) a subhorizontal set, and 3) a near vertical set striking essentially NS. The average spacing between the reflectors is about 30–60 m. The northwesterly set appears to be more continuous than the other two.

The objectives of the cross-hole interference, tracer dilution and tracer tests performed in the Spring 1998 were to test the present structural model and to test the feasibility to perform tracer tests in a designated part of the investigated block. In total 19 tests were performed with varying duration, including 13 short time tests (<1 day). The change in flow rate due to pumping were determined in six selected sections during 6 of the tests using tracer dilution techniques. One test, was prolonged to observe breakthrough from three of the injection sections. The obtained pressure interference data were condensed in constructed response matrices. These matrices clearly identify families of structures with similar response patterns. This data set has been instrumental in developing the next update of the structural model (Sep'98), cf. Figure 4-7. Quantitative interpretation was performed of interpreted primary responses. The tracer dilution tests show a larger variability in the natural flow rates within the block. High natural flow rates observed in

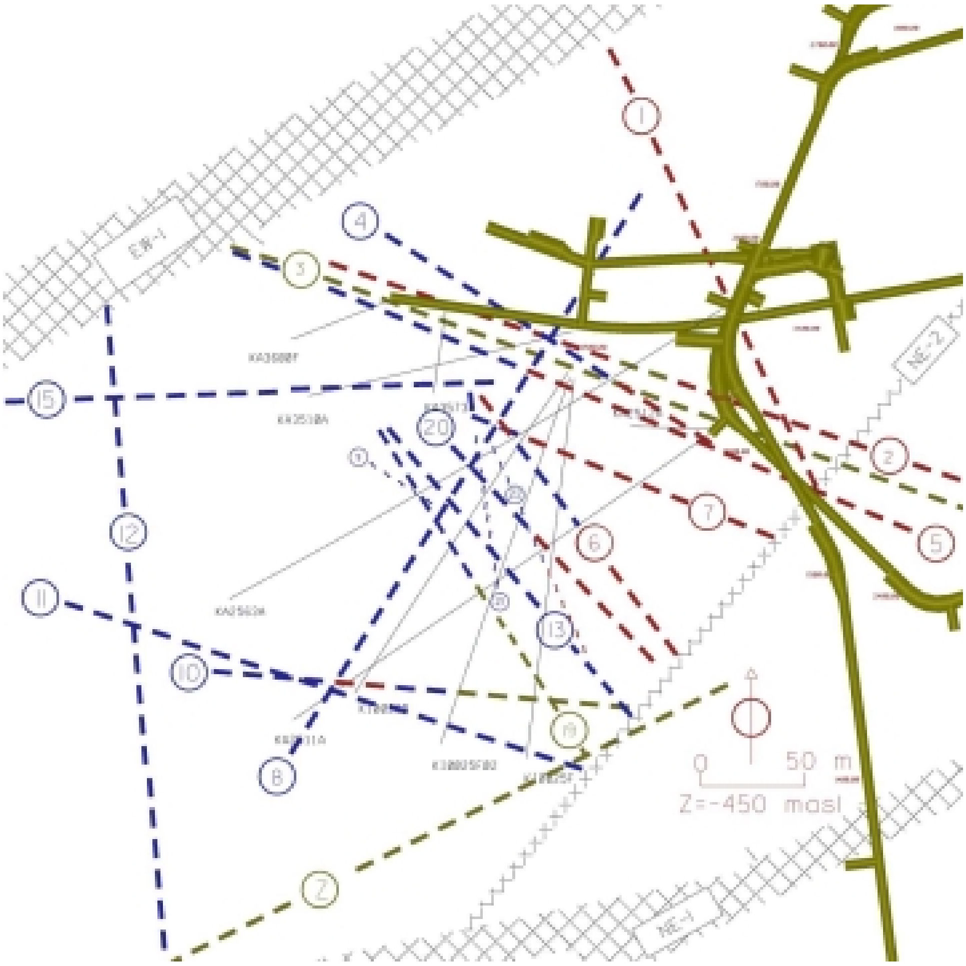


Figure 4-7. *Structural-geological conceptualisation of the TRUE Block Scale rock volume. The colours resfer to the geological classification of structure intercepts shown in Figure 4-10. Red represent fractures, blue represents faults, and yellow fracture zones. Swarms of fractures exist but are limited in extent.*

two sections are in the order 600 and 1,200 ml/hr, respectively, whereas the majority of sections show flow rates less than 10 ml/hr.

The performed tracer test showed breakthrough only for one flow path from Structure #20 in KA2563A to the interpreted Structure #9 in KI0023B over an Euclidian distance of 16 m. Although the mass recovery in this case is low (44%), the results show that tracer tests in a fracture network in the block scale are feasible.

The new 76 mm borehole, KI0025F02 was targeted between the existing KI0025F and KI0023B, cf. Figure 4-7. The characterisation in the borehole included:

- Observations during drilling (inflow between uptakes).
- Registration of pressure responses in instrumented boreholes.
- Acoustic flow logging (UCM).
- Borehole TV (BIPS).

- Core logging using the BOREMAP system which makes use of the BIPS images.
- POSIVA flow logging (1 m sections, 0.1 m increments).
- Borehole radar (RAMAC) (250 MHz high frequency and 60Mhz directional antennas).
- Initial selective cross-hole flow tests for identification of connectivity and sections (N=9).
- Single hole tests outside the principal zones of interest (N=10).
- Tracer dilution tests with pumping in 2 selected intervals.

The observation during drilling and the results from the subsequent sonic flowmeter log (UCM) identified five basic anomalies along the borehole, most of which had been well predicted on the basis of the existing structural model. The BIPS log provides the geological basis for the interpretation of these anomalies. Subsequently the POSIVA flow log was used both in a continuous diff mode and in a difference flow mode. The first measurement is conducted at open hole conditions and provides a high resolution identification of conductive fractures, both in terms of location and in terms of flow rate. The second measurement is performed at open and closed borehole conditions, which allow calculation of the hydraulic conductivity of the section and the hydraulic head. The identification of intercept is enhanced by a single point resistivity probe. The flow is measured by thermal pulse and thermal dilution with a range of 0.1–5,000 ml/min. Figure 4-8 illustrates typical results from detailed mode POSIVA flow logging.

The performed cross-hole tests performed in KI0025F02 allow a clear identification of Structures #7, #20 and #19, where Structure #20 is the dominant structure, i.e. all observation sections/structures respond faster to a disturbance in Structure #20. The single well test interpretation yields transmissivity estimates which are ranging from $1 \cdot 10^{-12}$ to $1 \cdot 10^{-6}$ m^2/s. Most cross-hole responses show influence of a constant head boundary. It is identified that the observed boundary effect may lead to an overestimation of the transmissivity when employing conventional analysis techniques. The estimates of transmissivity should therefore be regarded as rough estimates, which should be subject to further refinement through calibration using numerical models. Produced connectivity measures, and particularly the s/Q measure provide important qualitative information useful for improving the hydrostructural model. The use of storativity from conventional Jacob's method analysis as a measure of connectivity seems to be most appropriate for 2D heterogeneous media based on the existing scientific base. A comparison between specific capacities evaluated from the POSIVA difference flow measurements with that obtained from the flow and pressure build-up tests, indicate a good agreement between the two techniques. The POSIVA results in general are within a factor two lower than the performed double packer tests.

Hydraulic model

A hydraulic conceptual model has been devised on the basis of the pressure responses obtained during drilling and the Spring 1998 cross-hole interference tests. The indicated conductors shown in Figure 4-9 represent the strongest connections based on drawdown and diffusivity. The two conductors located closest to the borehole collars are well connected. The two deeper ones are more isolated from each other and the shallow two.

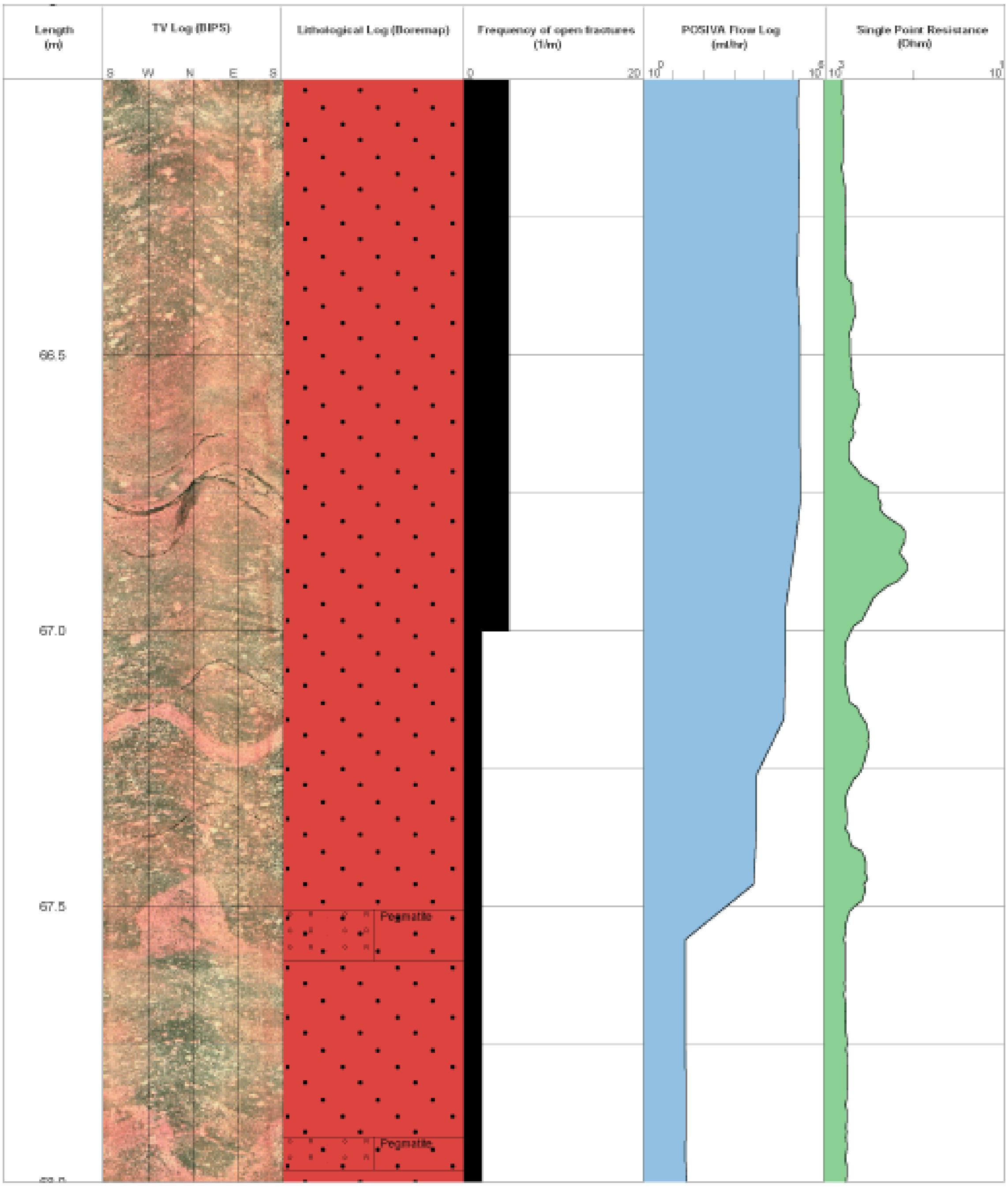


Figure 4-8. Co-plot of BIPS, POSIVA and BOREMAP logs for section 66.0–68.0 m in borehole KI0025F02.

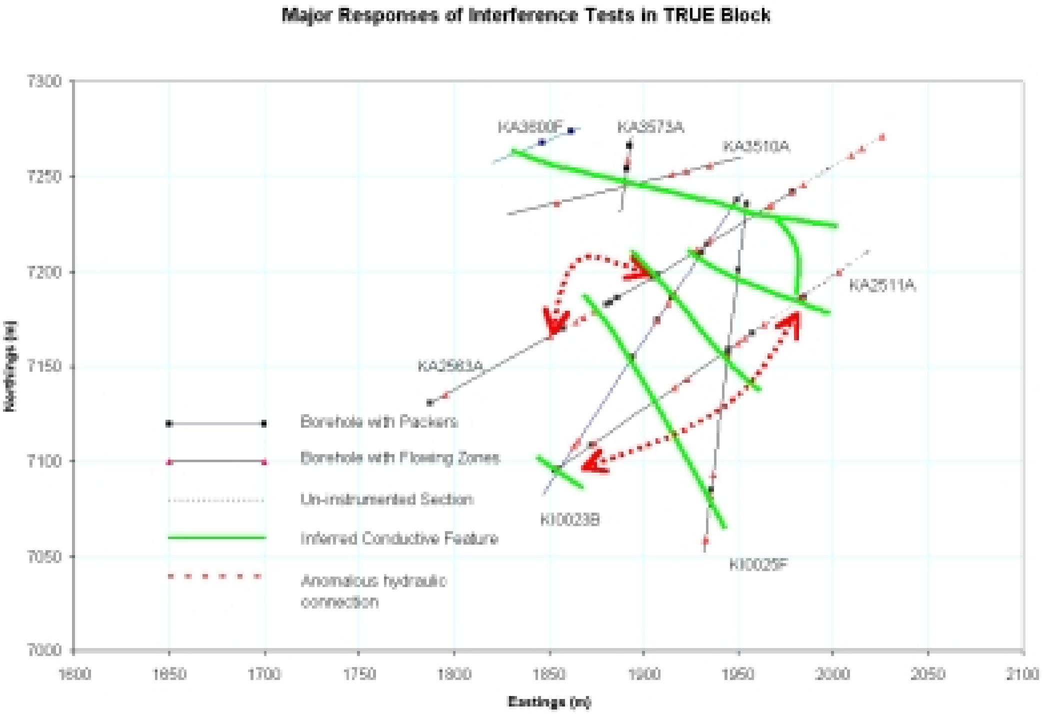


Figure 4-9. Hydraulic Conceptual Model of the TRUE Scale rock volume based on pressure interference tests. Please note that the conductor at the bottom of KI0023B is based on drilling responses, as there were no interference tests run on those intervals. Also the location of the deepest conductor in KA2563A is based on drilling responses as this interval of the borehole was not instrumented during the pressure interference tests. The solid green lines corresponds to the observed strongest hydraulic connections. The hatched red lines indicate observed anomalous hydraulic connections.

The observed major conductors seems to underscore the dominance of the northwesterly connections relative to connections along a northeasterly system or for that matter a subhorizontal set. The two indicated anomalous hydraulic connections are presently interpreted as being artefacts introduced by the instrumentation, which are subject to continued analysis.

Deterministic structural model

During the year one major update of the structural model has been performed. The main data sets used in the updating are characterisation data from KI0023B, the cross-hole seismic results, and the cross-hole interference and tracer tests from Spring 1998. The resulting model, Sep'98, is shown in Figure 4-7.

The main (structural) geological findings of the Sep'98 model are:

- None of the existing structures in the Oct'97 1997 model could be rejected on the basis of data from drilling and characterisation in KI0023B.
- Structure #9 is defined in two intercepts in KA2563A and KI0023B.
- One new structure, #13, is interpreted with intercepts in KA2563A and KI0023B.
- Structure #20 is interpreted to intersect KA2563A, KA2511A (non-conductive intercept), KI0025F and KI0023B.

- Structure #19 is interpreted to intersect KA2563A, KA2511 (non-conductive intercept), KI0025F, and KI0023B.

An important contribution of the structural model update is the definition and introduction of geological structure types, including fractures, faults, fracture swarms and fracture zones, cf. Figure 4-10 and Figure 4-7.

Modelling work

During the year modelling work has been performed using discrete feature and stochastic continuum models. In addition, work has started up using channel network models. AEAT work with a NAPSAC DFN model has been used to derive an effective hydraulic conductivity tensor K_{ij} for a TRUE Block Scale rock block using available statistical input data. The sensitivity of this effective value to the underlying parameters was also analysed. In addition the range of fluxes through a hypothesised block has been estimated using various assumptions of boundary conditions.

Results show that the components of the effective hydraulic conductivity tensor remain unchanged, both in terms of orientation and magnitude, even when shifting the cut-off to 10^{-9} m^2/s such that 80% of the fractures are eliminated. This result is also supported by similar results from FRACMAN/MAFIC results by Golder (Sweden). However, the AEAT network modelling on a 40×40×40 m block clearly show lack of transport connectivity of fractures with a cut-off transmissivity of 10^{-8} m^2/s, which is relevant for performing successful tracer experiments. The latter result is also supported by

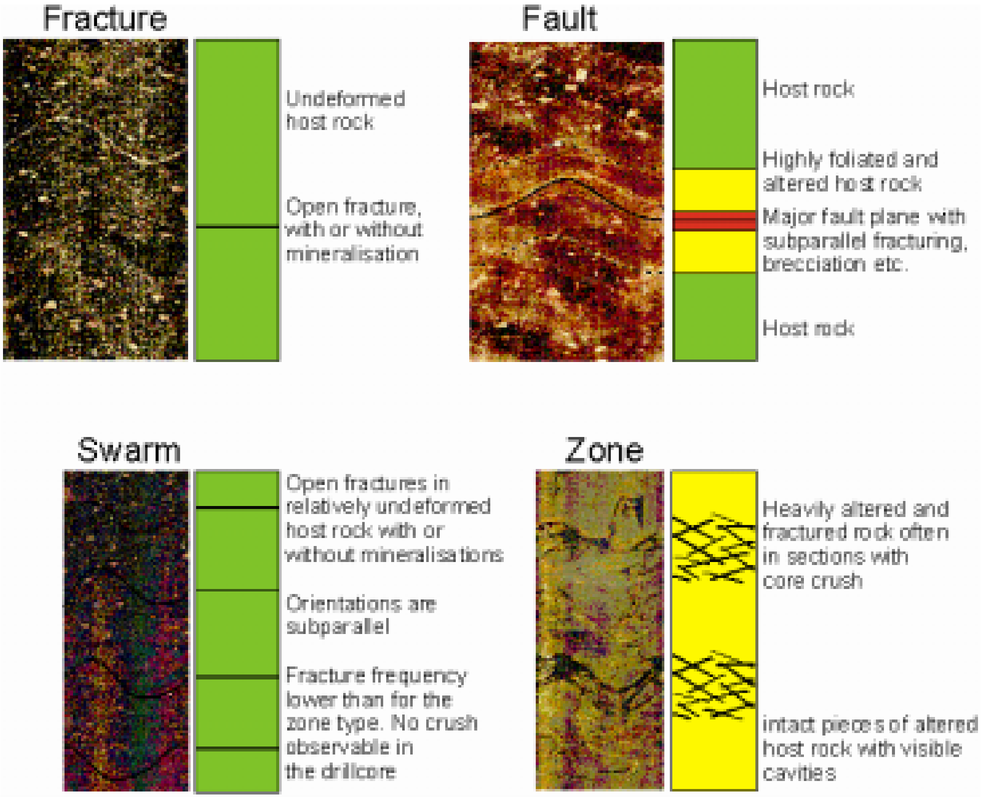


***Figure 4-10.** Examples of identified types of geological structures in the TRUE Block Scale rock volume; a) fracture, b) fault, c) fracture swarm, d) fracture zone.*

FRACMAN/MAFIC work performed by Golder (Sweden) on a 15×15×15 m block. Fluxes through the block, calculated using NAPSAC and a gradient of 10%, range from 0.02 l/min and 0.5 l/min.

Golder (Sweden) also used the October'97 structural model and performed a calibration to the head distribution prior to onset of the cross-hole tests performed in the Spring 1998. Subsequently, a prediction was made of one of the performed cross-hole interference and tracer dilution tests. In 60% of the observation sections the difference between simulated and actually measured drawdown at the end of the test was less than 1 meter. The model was found to overestimate the change in flow rate as a consequence of pumping.

UPV of Spain has implemented a stochastic continuum model, which is conditioned to available data, and where the interpreted structures are included deterministically with a statistical distribution of transmissivity other than that of the matrix rock. The model has been conditioned using steady state and transient hydraulic head data. The conditioning process i sequential (one test at the time). In total 6 cross-hole interference tests have been used in the conditioning. This allows an assessment of the evolution of the log conductivity field as more information is introduced. It has been observed that the conditioning process to transient hydraulic head is not able to match some of the experimental data. This is presently being investigated further.

It has been observed that although all modelled structures start out with the same statistics (mean and variance), some of the structures undergo a dramatic change during the conditioning process. The average log conductivity of Structure #5 e.g. increase from -6.5 to -4.6 $\log_{10}$m/s. The joint evolution of the network of structures can be used to better understand the joint behaviour of the studied fracture network.

Outcome of 2nd Review Meeting

A 2nd Review Meeting was held November 17 in Stockholm. At this meeting the basic results from the project as given by Winberg (in press) were presented. The two external reviewers are Dr. Jane Long of MacKay School of Mine, Nv, U.S.A. and Prof. Wolfgang Kinzelbach of ETH, Zurich, Switzerland. The basic recommendation of the reviewers was to:

- Go out and perform tracer test in the studied array.
- Formulate hypotheses to be tested by experiments.
- Test hypotheses in developed computer models.
- Do not add another borehole (at this time).

Plans for future tracer experiments

The work performed has resulted in putting forward a selected system of structures for further study. This network is made up of Structures #20 and #13 and structures connecting these two structures, e.g. Structure #9. Three suitable sink (pumping) sections have been selected. During a planned series of Pre-tests, combinations of source (injection) and sink intervals will be evaluated for use in future tracer experiments. As a part of the ongoing planning a strong emphasis is put on formulation hypotheses, visualisation of potential flow paths, all forming part of a comprehensive tracer test programme.

Planned work

Preliminary Characterisation Stage

- Reporting of the Preliminary Characterisation Stage is under way.

Detailed Characterisation Stage

- Optional reinstrumentation of borehole array.
- Performance of Pre-tests to complement the possible combinations of sources and sinks.
- Identification of issues and formulation of hypotheses.
- Design calculations.
- Identification of need for further optimisation of borehole array, including assessment of need of another borehole.

Tracer Tests Stage

- Start performance of tracer tests in the block scale.

4.3 Long Term Diffusion Experiment

4.3.1 Background

This 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. Work is presently underway to produce a test plan for the experiment.

4.3.2 Objectives and Experimental concept

The experimental objectives include investigation of matrix diffusion in-situ under natural mechanical, chemical and hydraulic conditions. In addition derived diffusivities will be compared with the corresponding parameters derived in the laboratory. The experimental concept put forward will include two different approaches to meet the project objectives. The two approaches include injection of tracers with subsequent sampling over a period of about 4 years followed by over-coring and sampling for tracer distribution. The second approach includes an initial tracer injection similar to the one described immediately above. The difference being that following 0.5–1 years, the tracer solution would be exchanged with a non-spiked solution. The successive back-diffusion of tracer from the matrix rock will be studied for about 3–4 years. In addition the natural back-diffusion of naturally occurring natural tracers (gases), assumed to saturate the rock, will studied.

4.3.3 Results

During the latter part of 1998 scoping calculations have been performed by Oregon State University and Chalmers University of Technology under the lead of Prof. Roy Haggerty, OSU. These scoping calculations have included use of the heterogeneous (multi-rate) diffusion concept that allows inclusion of heterogeneity in diffusivity. Preliminary results from these scopings show that:

- When using a homogeneous diffusion model, there is a danger of overestimating the diffusivity from results influenced by heterogeneous diffusion. In order to avoid use of too high diffusivities in the performance assessment, a very important task of the LTDE experiment should therefore be to address the question of heterogeneous diffusion.
- The experiments that are best suited to obtain information on heterogeneous diffusion are the natural gas tracer diffusion experiment (i.e., studies of the diffusion of tracers already abundant in the rock matrix) or back diffusion studies of synthetic tracers. The over-coring or the observation borehole options do not provide as good possibilities for studying heterogeneous diffusion.
- Calculation has shown that breakthrough (through diffusion) can be obtained within realistic time frame in an observation borehole at a distance of 0.2 from the injection borehole (continuously flushed).

The plans of the experiment will be subject to review in March 1999 and subsequent revision.

4.4 The REX Experiment

4.4.1 Background

A block scale redox experiment was carried out in a fracture zone at 70 m depth in the entrance tunnel to Äspö. 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) is planned to focus 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.

4.4.2 Objectives

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?

4.4.3 Experimental concept

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

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

4.4.4 Results

Four laboratory groups participate in the REX-experiment: Dept. 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); Dept. of General and Marine Microbiology of the Göteborg University. Additionally several consultants in Sweden participate in the project.

Rock and fracture filling mineral samples that had been collected from the Äspö tunnel are being used for the laboratory experiments at Bradford University. The results obtained so far show that the rate of O_2 consumption depends both on the particle size of the samples, and on their origin in the Äspö tunnel. The values of the first-order rate constant obtained are in the range: 1 to 140×10^{-3} ℓ g^{-1} day^{-1}.

Measurements of dissolved gases (methane, hydrogen, etc) in Äspö groundwaters have been performed. They have been combined with the measurements of bacteriological oxygen consumption in Äspö groundwater's. The experiments performed have shown that oxygen consumption depends exponentially on time. Rates of microbial oxygen consumption ranged from 0.32 to 4.5 µ mole ℓ^{-1} day^{-1}. Depending on temperature and the type of groundwater the approximate time needed for the total microbial consumption of 500 µ mole ℓ^{-1} of dissolved O_2 ranged from 0.31 to 3.99 years.

The drilling where the REX field experiment will take place was completed during 1996. A single fracture at 8.81 m from the tunnel wall was sampled in this borehole (called KA2861A), and the drillcore has been sent to CEA (Cadarache, France) where a replica of the field experiment started during 1998. The fracture surface, available for heterogeneous chemical and microbial reactions, has a diameter of 176 mm.

Several O_2 injection pulses have been performed in the REX field and replica experiments. The results show that concentrations of O_2 in the range 1 to 8 mg ℓ^{-1} are consumed in the experiments within a few days, 5 to 10 days, both for the field and replica experiments. A mechanistic interpretation of the results is under way.

4.5 Radionuclide retention

4.5.1 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 caused by the chemical character of the radionuclides themselves, 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 of 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. In many of these retention processes the sorption could well be irreversible and thus the migration of the nuclides will stop as soon as the source term is ending.

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 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. The CHEMLAB probe, see Figure 4-11 has been constructed and manufactured for validation experiments in-situ at undisturbed natural conditions.

4.5.2 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 the relevant radionuclides.

4.5.3 Experimental concept

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

The full suite of planned experiments are:

- Diffusion of radionuclides in bentonite clay.
- Migration of redox sensitive radionuclides and actinides.
- Radionuclide solubility.

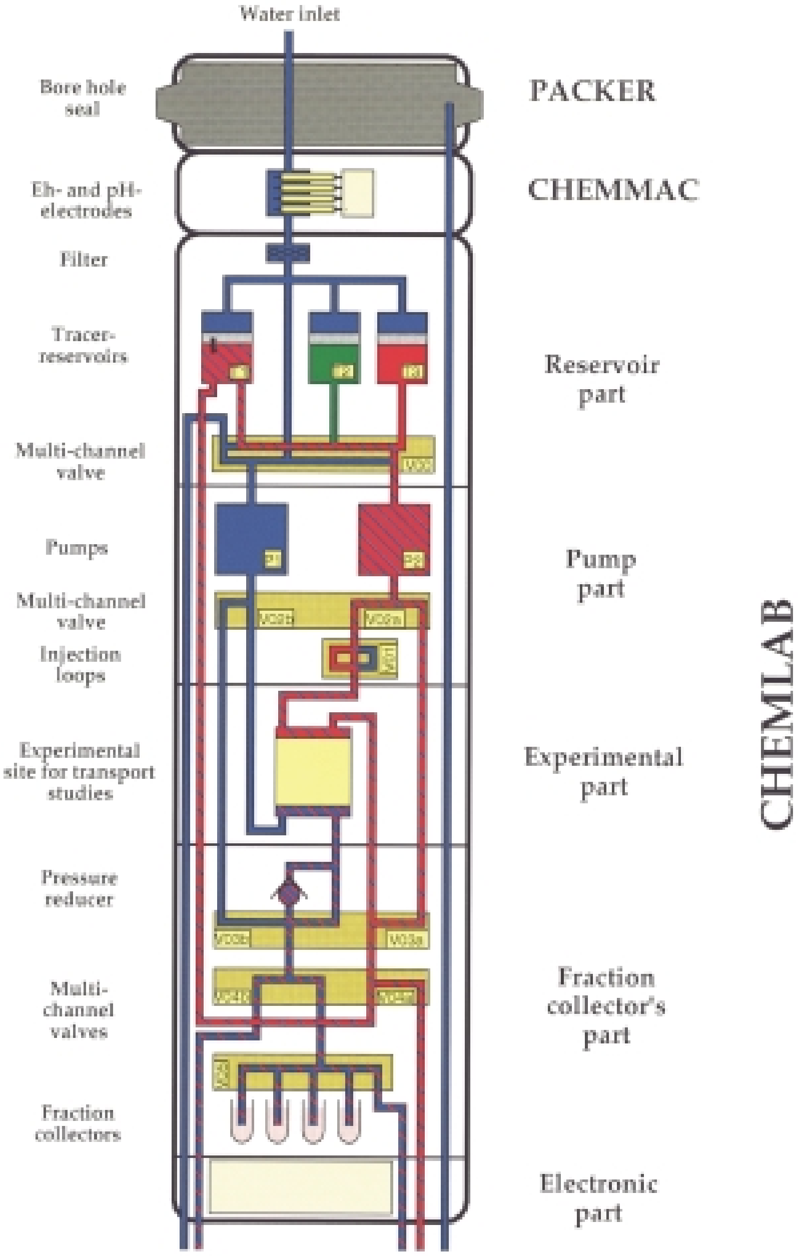


Figure 4-11. Schematic illustration of CHEMLAB.

- Desorption of radionuclides from the rock.
- Migration from buffer to rock.
- Radiolysis.
- Batch sorption experiments.
- Spent fuel leaching.

4.5.4 Results

No new results have been obtained from the diffusion experiments, because of problems in the CHEMLAB system. The last diffusion experiment with ^{99}Tc and ^{131}I was started at three different occasions, but had to be terminated for different reasons.

A simplified version of the CHEMLAB probe was planned in order to speed up the entire experimental sequence. The new probe will include only one pump and one reservoir. All sampling from the experiments will be made in the gallery and the probe will therefore not contain any fraction collectors. Planning for the CHEMLAB 2 system is completed and the contract for the construction was signed with the manufacturer of CHEMLAB 1 in competition with two other companies. The construction of CHEMLAB 2 has been delayed because of repairs to CHEMLAB 1.

The planning for redox sensitive nuclide and actinide experiments in CHEMLAB 2 is made in cooperation with reseachers from Institut für Nuklear Endsorgung in Karlsruhe (within the BMBF cooperation).

New rock fractures have been drilled from tunnel section 2195A. These will be used for the pre-experiments and for the CHEMLAB 2 redox sensitive and actinide nuclide migration experiments.

After completion of the diffusion experiments a new site for the CHEMLAB experiments will be selected and installed.

4.6 Groundwater degassing and two-phase flow

4.6.1 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 1998, a series of laboratory degassing experiments was completed. Through these experiments, the impact of both groundwater degassing and changes in the flow regime on the fracture transmissivity was investigated. Furthermore, as a part of the preparation for writing a summarising technical report on groundwater degassing, data from different laboratory, field and model studies addressing groundwater degassing were summarised and interpreted. The degassing experiments and the data interpretation are described in more detail in the two sections below.

4.6.2 Laboratory degassing experiments

These laboratory degassing experiments (Gale, 1998), which consist of three sets of experiments, were conducted to examine the impacts of gas evolving or degassing from saturated water, as the fluid pressure drops below the bubble pressure of a specific gas, on the transmissivity of discrete fracture planes. The main focus of this laboratory work was to determine the relative effects of sample size, fracture deformation, relative surface roughness, changes in flow regime, two-phase flow and degassing on the measured changes in fracture transmissivity.

In the first set of experiments, a series of two-phase flow experiments were completed on an existing large scale physical model (LSPM). In these experiments, both water and gas were injected into the fracture plane at the same time. In addition, tests were conducted where the fracture plane was filled with a gas saturated water and the fluid pressure was then decreased at a central borehole to induce the gas to evolve or degass within the fracture plane under convergent flow conditions. The LSPM provides a fracture surface area that is approximately 3.5 square meters in area. The fracture plane was created by imprinting a geotextile fabric into the high strength concrete surface, between the two halves of the physical model, producing a surface with a uniform small scale roughness. A 50 mm diameter borehole was drilled to intersect the center of the fracture plane at an angle of 42 degrees, creating an elliptical opening or sink within the fracture plane. The fracture plane was instrumented with a series of manometers to measure pressure heads during linear, divergent or convergent, flow experiments. Flatjacks, coupled to a reaction frame, were used to change the normal stress acting across the fracture plane and hence induce fracture closure.

Single phase flow experiments on this large model showed that, with increasing flowrate and increasing fluid velocity, additional head losses were measured and it is assumed that this was due to either a change in flow regime, from laminar to turbulent – some degree of turbulence, or changes in effective stress. When the measured head losses were used with the measured flowrates to compute fracture transmissivities, major changes in the fracture transmissivity were computed. The addition of gas to the injection water introduced additional head losses and hence additional changes in fracture transmissivity. Figure 4-12 shows that the drop in hydraulic head (expressed as Delta P: the change in hydraulic head between the outside boundary and the borehole for convergent flow) versus flowrate curve is non-linear for both single and two phase flow. At the lower flowrates, the two phase flow data show larger drops in hydraulic head than was measured for the corresponding single phase flowrates. However, at the higher flowrates there is very little difference between the transmissivities computed from the single and the two phase flow data. It is clear, that with increasing flowrates, the two-phase flow impacts can be masked by the changes induced by the changes in the flow regime or by coupled stress-flow effects.

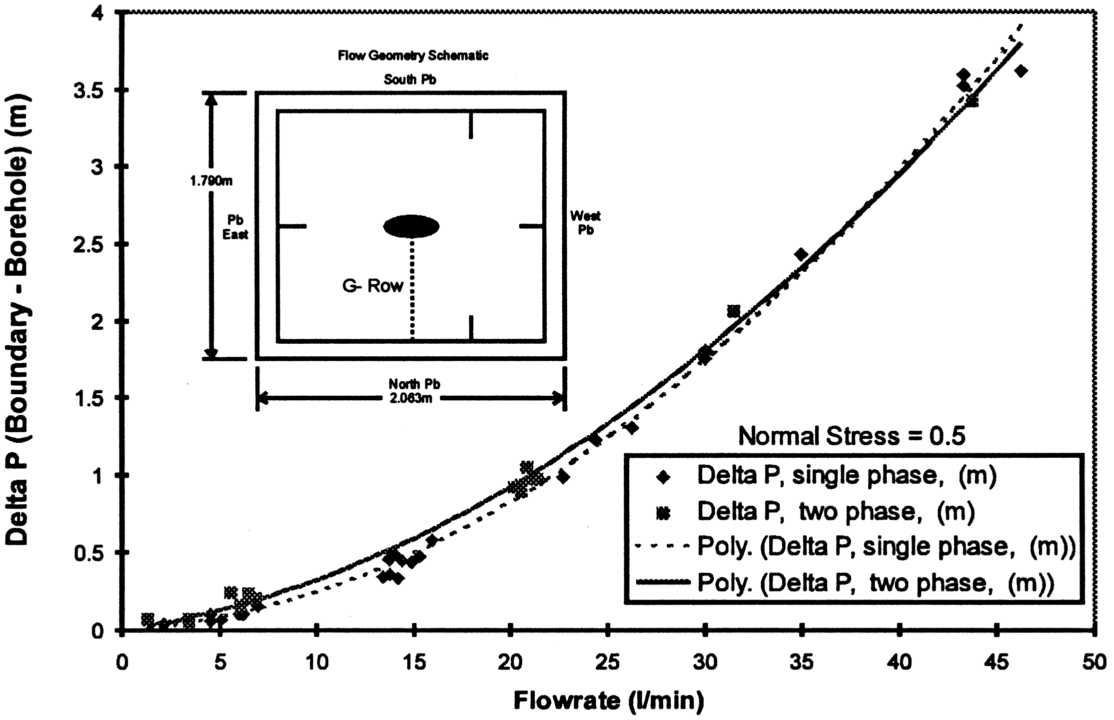


Figure 4-12. Plot of the loss in pressure head (Delat P) as a function of flowrate for both single phase and two phase flow.

The fracture in this LSPM was highly conductive, with a uniform roughness that produced a low gas trapping capacity. Both the raw gas phase that was injected during the two-phase experiments and the gas bubbles that may have evolved during the degassing experiments are assumed to have been swept out of the fracture plane before the gas could form effective blockage of the fracture pore space. However, despite these offsetting impacts, significant reductions in fracture transmissivity during the two-phase flow experiments were measured. It is clear that degassing in field situations will be most apparent in rough fractures with low to moderate transmissivities in which the borehole has a small angle of intersection with the fracture plane.

Degassing experiments were also conducted on four small scale (about 200 mm wide by 300 mm in length) samples of both artificial and natural fracture planes. One sample was formed by sand-blasting a sawcut in a limestone sample. The second sample was constructed from high strength concrete using the geotextile approach that was used to construct the LSPM. The two other fracture samples were obtained by overcoring natural fractures at the Pilot Resin site at Äspö.

These fracture samples were subjected to a series of normal and shear (for the limestone and concrete samples) loading and unloading cycles that, as the fractures closed and opened, generated a range of relative roughness on the fracture planes. Both single phase, air invasion (imibibition) and air injection tests (Gale, 1998) were conducted on the first two samples. The full suite of tests were completed on the two Äspö samples, including a full suite of degassing experiments at different normal stress levels using water saturated either with carbon dioxide or nitrogen at the water injection pressure. The fracture transmissivities were calculated using the measured outflow rates in conjunction with the measured pressure head gradients between three sets of manometers (the location of the manometers in the fracture plane are shown in the figure inset).

For degassing experiments on the first Äspö sample, most of the experiments were conducted with water that was saturated with carbon dioxide gas due to its lower bubble pressure and the higher gas contents that could be achieved at the proposed test pressures. For these experiments, reductions in fracture transmissivity were clearly noted at the different stress levels as the outlet pressure was dropped below the bubble pressure. However, the fracture transmissivity values tended to fluctuate considerably at each pressure step which was assumed to be partly due to a periodic flushing of evolved gas from the fracture plane or capillary pressure effects in the manometer tubes that were used to measure the fluid pressures. This assumption is consistent with the periodic spurts of gas bubbles that were observed in the discharge line. Degassing with nitrogen gas, by comparison with using carbon dioxide gas, produced a much more stable set of fracture transmissivity values as the outlet pressure was dropped below the nitrogen gas bubble pressure.

Degassing experiments on the second Äspö sample produced a clear demonstration of the impacts of evolving nitrogen gas on the transmissivity of a discrete fracture. Figure 4-13 shows a change of about an order of magnitude in fracture transmissivity with time, at 5.0 MPa of normal stress, as the outlet pressure head was decreased from 28.12 m (the bubble pressure head) to 3.45 m of head. For the same sample, at a normal stress of 10 MPa, Figure 4-14 shows a change of about a factor of 4 in fracture transmissivity as the outlet pressure head was decreased from 24.01 to 4.196 m. The single phase fracture transmissivity decreased by about a factor of 2 when the normal stress was increased from 5.0 MPa to 10.0 MPa. Both sets of data showed time dependent changes in transmissivity at each drop in outlet pressure head as well as sudden increases in transmissivity, suggesting both a slow build-up of evolved gas in the fracture pore space and the periodic sweeping of the trapped bubbles from part of the fracture plane. The role of

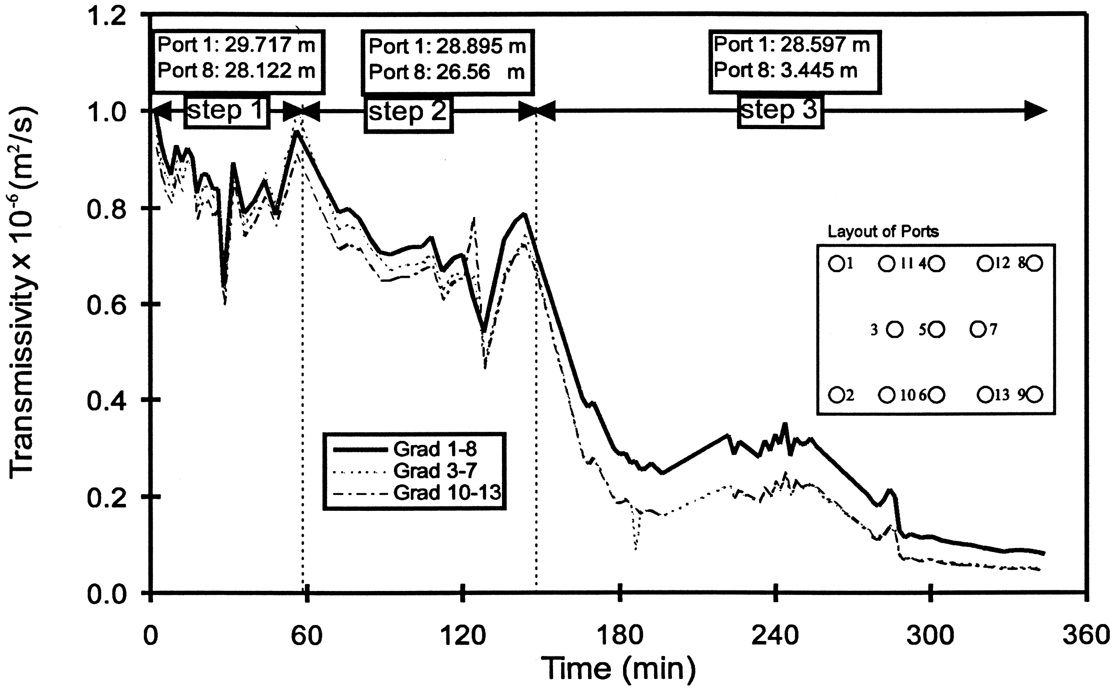


Figure 4-13. Changes in fracture transmissivity with time for the initial flooding step and the three degassing steps at 5.0 MPa, for Äspö Sample #2, KF24A:3 Pressures are shown as meters of water at each port.

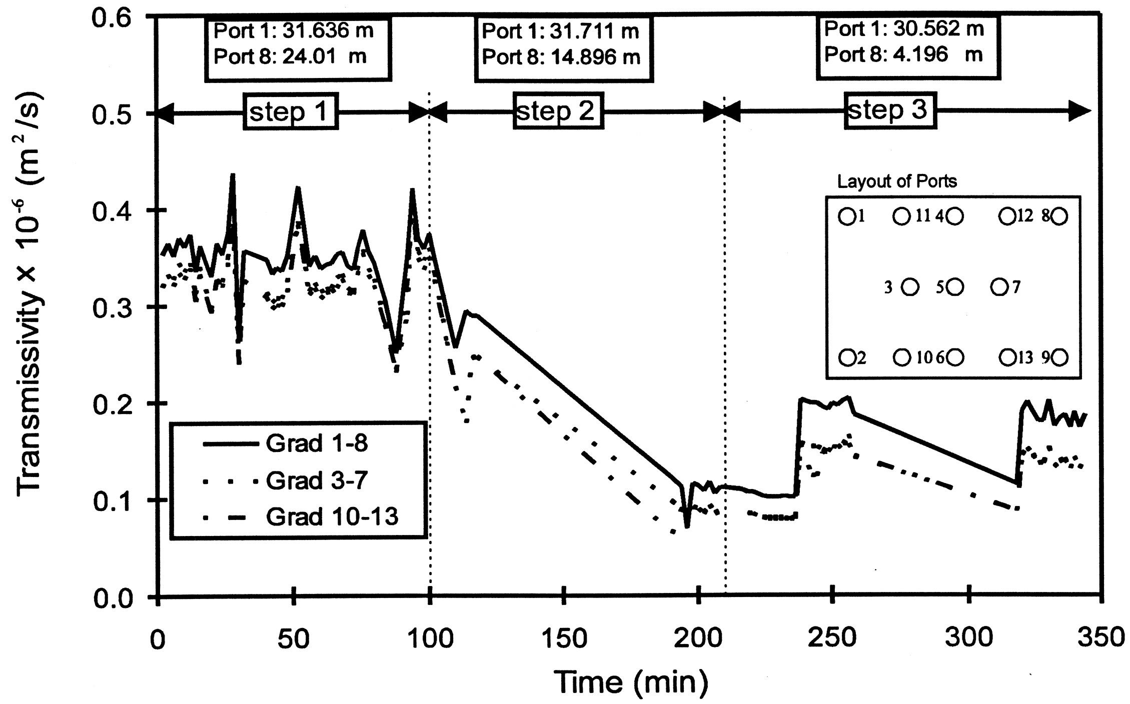


Figure 4-14. *Changes in fracture transmissivity with time for the three degassing steps at 10.0 MPa, for Äspö Sample #2, KF24A:3. Pressures are shown as meters of water at each port.*

other factors, such as head loss due to increased fluid velocity and possible changes in the flow regime from laminar to turbulent flow, in contributing to the observed decreases in fracture transmissivity needs to be assessed.

At the end of each suite of experiments on all four samples, tracer tests were completed at the final loading step, followed by the injection of a room temperature curing resin into the fracture plane. The fracture plane was then sectioned, photographed and the outline of the resin filled fracture plane was digitized. The distribution parameters for the resin filled pore space in each fracture, along with the distribution of the contact areas, were determined for each sample. For the second Äspö sample, the full 200 mm by 300 mm sample plane was mapped along a series of perpendicular profiles, spaced approximately 10 mm apart. These data were analyzed and the semi-variograms for the pore space were generated. The data were then kriged to determine the spatial distribution of the combined fracture pore space and the contact areas. In addition, the kriged data were used to generate the cell values for a 1.5 mm and a 5 mm grid spacing for the porous media model MODFLOW. Flow simulations demonstrated that using the measured pore space as input parameters with which to calculate cell hydraulic conductivities produced an excellent match between measured and computed flowrates, for similar geometry and flow boundary conditions, when the 1.5 mm grid values were used. Averaging the apertures over a 5 mm grid reduced the degree of fit between the measured and the computed flowrates.

A key question is how do the gas bubbles, as they evolve in the fracture plane, reduce the fracture transmissivity. Does the evolving gas fill the large pores or do the bubbles migrate through the pore space and eventually block the smaller pores that form the throats or so called bottle-necks in the fracture pore space? To provide a preliminary assessment of the role of the large and small apertures on the reduction of fracture transmissivity by degassing, the large apertures were selectively removed, from the aperture distribution and the generated aperture or hydraulic conductivity grid, until the measured degassing flowrates and computed flowrates matched the measured flowrates (Figure 4-15). To obtain a match for the second step of the degassing experiment at 10 MPa for the second Äspö sample, the overall pore space of the fracture had to be reduced, by successively removing the large apertures, to 80.5% of the initial pore space (Table 4-2) that was used in the single phase modelling. To fit the numerical model to the measured flows at step 3 of this degassing experiment the pore space had to be reduced to 94.6% of the original pore space of the model (Table 4-3).

To model the effects of blocking of smaller apertures, the smaller apertures were successively removed from the model and set to the minimum value. In the original model, the smallest aperture was 0.002 mm. To match model computed flows to flows measured in step 2, all apertures up to 0.100 mm had to be removed which represented a reduction to 91.9% of the original pore space, reducing the average aperture from 0.158 mm to 0.145 mm. To fit the model to the step 3 data, apertures up to 0.074 mm were removed for a average aperture of 0.152 mm, representing 96.1% of the original pore space.

Attempts to observed the degassing effects in plastic replicas of the fracture surface, that was used in the LSPM experiment and in the concrete sample, confirmed the low trapping capacity of this uniformly rough surface and the sweeping effect produced by the high flowrates through the fracture plane. The relative impact of degassing on fracture transmissivity is determined both by the magnitude of the fracture transmissivity, the fracture roughness or trapping capacity of the fracture plane, the type of gas present in the water phase and the percent of the gas that is dissolved in the water. In addition, the flow geometry and the resulting changes in flow regime with increasing flowrate or increasing hydraulic gradient can both mask changes in the observed fracture transmissivity and amplify these changes.

Table 4-2. Comparison of computed and measured flowrates, showing changes in the largest apertures required to fit the model to the measured data

Step		Measured Q (mL/s)	Single Phase Model Q (mL/s)	Adjusted Model			
				Largest (mL/s) (mm)	Average Aperture (mm)	% of Original Pore Space	Model Q (mL/s)
0	2.1	0.5	0.48	1.091	0.158	–	–
1	5.8	1.39	1.35	1.091	0.158	–	–
2	15.1	1.27	3.53	0.502	0.127	80.5	1.25
3	26.4	3.37	6.14	0.797	0.149	94.6	3.1

Table 4-3. Comparison of computed and measured flowrates, showing changes in the smallest apertures required to fit the model to the measured data

Step	H (m)	Measured Q (mL/s)	Single Phase Model Q (mL/s)	Adjusted Model			
				Smallest Aperture (mm)	Average Aperture (mm)	% of Original Pore Space	Model Q (mL/s)
0	2.1	0.5	0.48	0.002	0.158	–	–
1	5.8	1.39	1.35	0.002	0.158	–	–
2	15.1	1.27	3.53	0.100	0.145	91.9	1.30
3	26.4	3.37	6.14	0.074	0.152	96.1	3.36

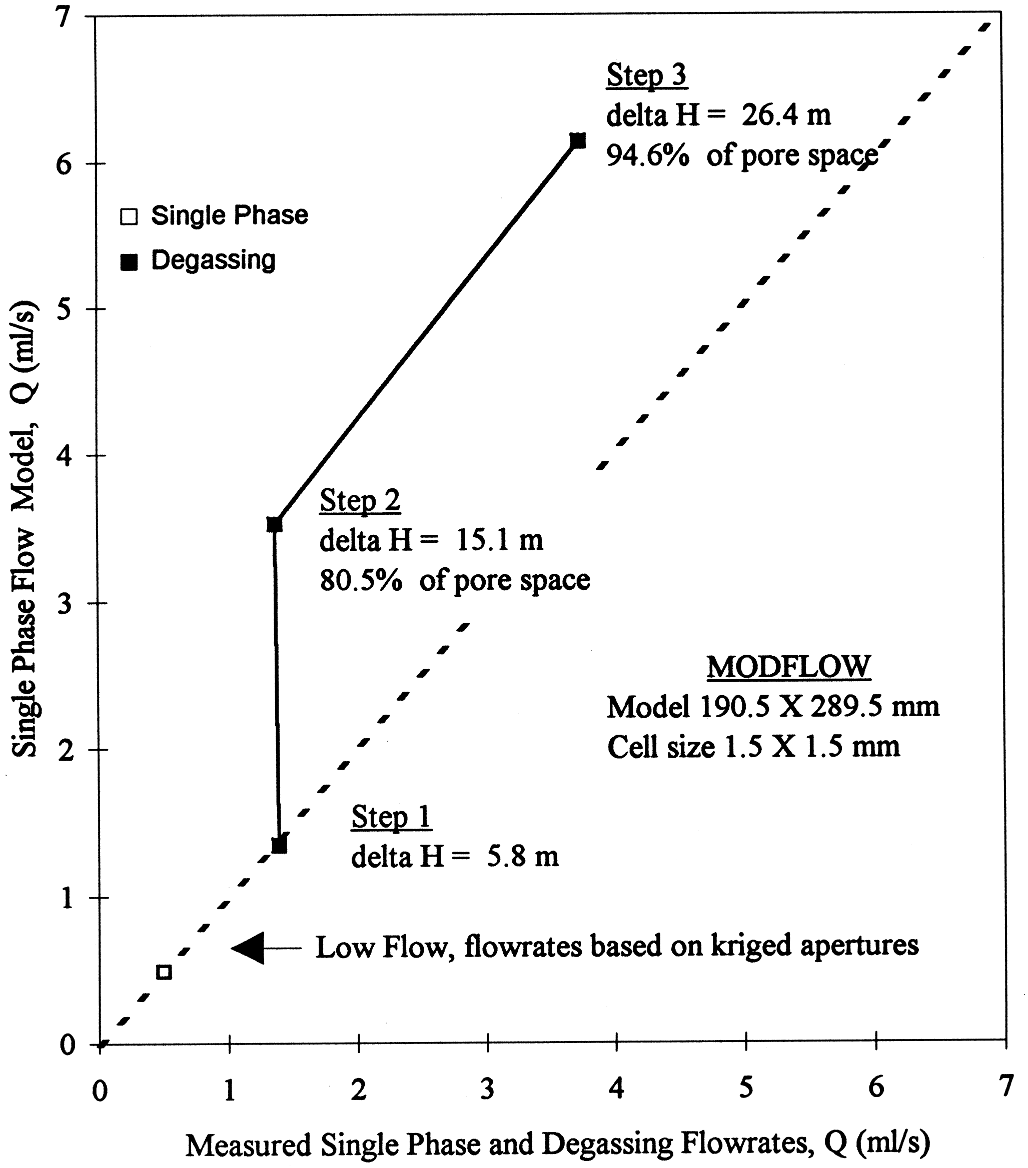


Figure 4-15. *Comparison of measured single phase and degassing flowrates with single phase flow simulation using MODFLOW based on removal of large apertures.*

4.6.3 Data interpretation

In addition to the laboratory investigation described above, we have summarised and interpreted data from other laboratory, field and model investigations addressing groundwater degassing. We have used the data as a basis for hypothesis testing, in order to investigate whether (or in which cases) observed non-linear relations between pressure and flowrate can be attributed to groundwater degassing, and whether these observations are consistent with degassing related models. As previously illustrated in Figure 4-12, there are other phenomena than degassing that can lead to non-linearities in the pressure-flowrate relation. We have now extended the previous analysis of the dipole field experiment (Jarsjö and Destouni, 1997b), in order to investigate whether turbulence could have caused, or contributed to, the flow reductions that were observed in that experiment.

Degassing hypothesis

The extent of the low pressure zone X_{low}, were the water pressure is lower than the bubble pressure, provides an upper limit for the size of the zone around boreholes and drifts where groundwater degassing possibly can occur. One may hypothesise that effects of degassing, such as flow reductions, will (only) be observed as long as X_{low} is greater than a certain length. In the following, we will test this degassing hypothesis through the performance of a consistent interpretation of field and laboratory results in terms of the low-pressure zone extent.

Table 4-4 shows estimates of X_{low} for six different degassing tests or observations. We used the estimation procedure described in Jarsjö and Destouni (1997a), assuming radial flow conditions. The first four tests shown in Table 4-4 are borehole tests performed at the Äspö Hard Rock Laboratory. The two last tests refer to drift inflow measurements in the Stripa mine and laboratory tests conducted in rock fracture replicas, respectively. Table 4-4 furthermore indicates in which cases the measured inflow was reduced, or lower than the predicted inflow using the linear Darcy's law relation between pressure gradient and flowrate.

Table 4-4 shows that the extent of the low-pressure zone during the dipole test was at least 0.4 meters, an order of magnitude greater than the corresponding extents for the single-well tests, where degassing did not cause observable flow reduction. Furthermore, Table 4-4 shows that the value of X_{low} for the laboratory tests (where degassing was the certain cause for observed flow reductions) and the Stripa drift observation (where degassing was one of the plausible causes for the observed flow reduction) was also greater than for these single-well tests, where no flow reductions were observed. Hence, in all three experiments where degassing either did certainly cause the flow reduction (i.e., the laboratory test), or was the most likely cause for the flow reduction (i.e., the dipole test), or was hypothesised to have caused observed inflow reductions (i.e., the Stripa observations), the value of X_{low} is larger than for the three tests where degassing did not cause any significant inflow reductions. The probability for this X_{low}-outcome to occur randomly, i.e., to occur even if there was no degassing based relation between observed flow reductions low pressure zone extent, is only 5% (3/6*2/5*1/4). This implies that our degassing hypothesis can be accepted on a 0.05 significance level.

Table 4-4. Estimates of the low pressure zone extent X_{low}

Test or observation	X_{low} (m)	Reduced inflow?
Single-well test in borehole P2[a]	0.02	no
Single-well test in borehole P4[a]	0.002	no
Dipole test (P4-P8)[a]	≤0.4	yes
Pilot hole test (single-well test)[b]	0.006	no
Stripa drift observation[c]	0.8	yes
Laboratory tests[d]	0.06	yes

[a] from Jarsjö and Destouni (1997b)

[b] from Geller and Jarsjö (1995)

[c] from Olsson (1992)

[d] Laboratory tests with CO_2-gas in replicas of natural rock fractures, from Jarsjö and Geller (1996)

Turbulence hypothesis

The occurrence of turbulence can imply non-linear relations between borehole pressure and flowrate. The reported degassing tests were performed at lower borehole pressures than the preceding tests, implying higher pressure gradients and flowrates. Hence, we need to investigate whether the plausible onset of turbulence effects at these relatively high flowrates have influenced the interpretation of the degassing tests. Specifically, we want to find out whether turbulence effects provide another plausible explanation for the observed non-linear relations between borehole pressure and flowrate during the dipole test (Table 4-4), in addition to the explanation provided by the degassing hypothesis (accepted at the 0.05 significance level). We will therefore compare the conditions prevailing during the dipole test both with the conditions prevailing during the other degassing tests (where linear flow conditions prevailed implying no or negligible turbulence effects) and with studies specifically addressing turbulence in fractures. The basis of this comparison is provided by Reynolds number (Re), defined as:

$$\mathrm{Re} = \frac{Dv}{\upsilon}$$

where D is the hydraulic diameter, v is the pore water velocity and υ is the kinematic viscosity. In analogy with Fourar et al (1993) we use the relation $D=2a_h$, where a_h is the hydraulic fracture aperture. Further, we estimate v as $Q/(2\pi r a_h)$ where Q is the volumetric rate of borehole/ well inflow and r is the radial distance to the borehole/ well centre. As indicated by the resulting expression $\mathrm{Re}=Q/(\pi r \upsilon)$, Re increases with decreasing values of r. The highest value $\mathrm{Re}=\mathrm{Re}_{\max}$ occurs at the wall of the borehole/ well, i.e., at $r=r_w$.

The critical Re-value for which turbulence effects start to evolve differs from medium to medium. In porous media, it is commonly assumed that turbulence causes considerable effects for Reynolds numbers greater than 100, whereas it is assumed that no turbulence effects will occur for Reynolds numbers less than some value between 1 and 10. Further, for flow in pipes the critical value of Re between laminar and turbulent flow is around 2,000. For fractured rock, experimental results reviewed by Romm (1966) showed an onset of turbulence effects for Re-values between 10 and 100 in rougher fractures, and between 100 and 2,000 in smoother fractures.

Table 4-5 summarises the values of r_w, Q, and $\mathrm{Re}_{\max}$ for the degassing borehole tests that have been conducted in the field. Also, single phase flow experiments that were a part of the laboratory degassing tests in rock fracture replicas (Jarsjö and Geller, 1996) are included in Table 4-5. The highest flowrates occurred during the pilot hole test (Table 4), resulting also in the highest value of $\mathrm{Re}_{\max}$ of 1,400. However, the relation between borehole pressure and flowrate was found to be linear, indicating that turbulence effects were absent or negligible. During the dipole test, where a non-linear pressure-flowrate relation was observed, the values of $\mathrm{Re}_{\max}$ were between 1.1 and 4.5, which is about the same range as for the P4 test and below the range for the P2 test; the pressure-flowrate relation was linear in both P4 and P2. Furthermore, in both the laboratory experiments of Geller and Jarsjö (1996) and the experiments summarised by Romm (1966) laminar flow conditions were observed for higher, or considerably higher, values of Re than those prevailing during the dipole test.

In summary, we conclude that the Re-value evaluation shows that there are not any indications of turbulence being a factor contributing to the observed flowrate reductions during the dipole degassing test. Furthermore, the hypothesis that there is a relation between the low pressure zone extent X_{low}, (which is a measure of the size of the zone where groundwater degassing can possibly occur) and the occurrence of flow reductions

Table 4-5. Estimates of the maximum values of Reynolds number (Re_{max})

Borehole test	r_w (mm)	Range of tested Q (m^3/s)	Range of Re_{max} $= \frac{Q}{\pi r_w \upsilon}$	Linear *p-Q* relation for tested Q-range
Single-well test in P2	28	$5.3 \cdot 10^{-7} - 1.3 \cdot 10^{-6}$	6.0–15	yes
Single-well test in P4	28	$9.8 \cdot 10^{-8} - 2.75 \cdot 0^{-7}$	1.1–3.1	yes
Dipole test (P4-P8)	28	$1.1 \cdot 10^{-7} - 4.0 \cdot 10^{-7}$	1.1–4.5	no
Pilot hole test (single-well test)	42.5	$1.0 \cdot 10^{-4} - 1.9 \cdot 10^{-4}$	750–1,400	yes
Laboratory tests (Jarsjö and Geller 1996)	1.6	$8.3 \cdot 10^{-9} - 8.3 \cdot 10^{-8}$	1.7–17	yes

was accepted at the 0.05 significance level, showing that the observed flow reductions indeed are consistent with degassing related models (see Jarsjö and Destouni, 1998 for a detailed description of degassing models).

4.6.4 Planned work

Continue to work on the final degassing report and the integrated analysis of existing data (to be included in the final degassing report). This report will outline any additional work that might be needed to clarify conflecting interpretation.

The two-phase flow investigations will continue by considering boundary conditions that are relevant for gas generation and pressure build-up to determine the applicability of various two-phase flow relations (including those originally developed for degassing conditions). Experimental two-phase flow field data will be obtained through the experiments that are conducted within the German-Swedish programme at the Äspö HRL (headed by BMWi). Through modelling, the conditions prevailing during the field experiment should be reproduced. The results will be reported in the autumn of 1999.

4.7 Hydrochemical stability

4.7.1 Background

The chemical properties of 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 life span of the repository. Important questions concern the understanding of the processes, which influence and control the salinity, and the occurrence, character and stability of both saline and non-saline groundwater's.

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.

4.7.2 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 intervals of 0–100, 100–1,000, 1,000–10,000 and 10,000–100,000 years.
- To develop a methodology to describe the hydrochemical evolution at candidate repository sites, e.g. Olkiluoto.

4.7.3 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 thermodynamic 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 code M3 assumes a complete and complex mixing of the water in the investigated system. The principal assumptions behind this concept is that the varying hydraulic conditions of the past have caused the complex mixing pattern presently observed at Äspö. Mass balance calculations are then made to explain the difference between the ideal mixing and the observations.

The modelling strategy is based on:

- Process identification for Finnish and Swedish sites.
- Geochemical mixing for Äspö and Olkiluoto.
- Site intercomparison with PCA. Comparison between the M3 and NETPATH techniques for Olkiluoto.
- Hydrologic modelling for Äspö and Olkiluoto. Inclusion of the results from Task #5.

4.7.4 Results

A hydrogeochemical groundwater inter-comparison has been performed with the M3 code for six sites in Finland and Sweden: Olkiluoto, Kivetty, Romuvaara, Äspö, Finnsjön and Gideå. This evaluation represents the background information for the future modelling work of the Hydrochemical Stability project.

Task #5 of the Modelling Task Force 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. The starting point of Task #5 was a workshop and start-up meeting, held 4–5 September 1997 at Äspö. The different sub-tasks were discussed, modified and divided into Work Packages. The different modelling groups presented their approach to the modelling task. At the start-up workshop it was agreed that the communication between the modellers was best arranged through Work Group Meetings. Two coordinators were appointed to facilitate the modelling work and to chair the Work Group Meetings. The first Work Group Meeting, on initial and boundary conditions, was held at SKB in October 1997. After that meeting data were sent to the modelling teams.

The second Work Group Meeting was held 16–17 March 1998. All modelling teams had obtained the data delivery, Work Packages A1 to A4, and several groups had already started to work. The third Working Group Meeting was held in connection to the 11th Task Force Meeting.

The first part of the Task #5 modelling was completed and the results were presented at the 11th Task Force Meeting at Äspö 1–3 September.The conclusion of presentations and discussions was that the hydrochemical data in WP A1 to A3 needed to be further developed by the SKB team in order to be useful as boundary and initial conditions to the groundwater flow modellers. Thus the Work package D1 was only delivered by the SKB team and sent to all other modelling teams.

The first groundwater flow modelling sequence of Task #5 is completed. New hydrochemical boundary and initial conditions were provided to the modelling groups soon after the 11th Task Force Meeting at Äspö 1–3 September. The reports will be distributed among the modellers before the next working group meeting 2–3 February.

EQUIP (Evidences from Quaternary Infillings for Palaeohydrology) is an EC project including several of the organisations participating in the Äspö project (ANDRA, ENRESA, NIREX, POSIVA, SKB). The project started in 1997 and is planned to continue for three years. A summary of the SKB contribution to the second project year are:

The Late Pleistocen and Holocene (the last 130,000 years) climate and hydrology with focus on the conditions at Äspö has been compiled by Andersson (1998). Since Äspö is situated on the Baltic east-coast, not only climatic variations but also eustatic (changes in sea-level) and glacio-isostatic movements have changed the hydrogeological and hydrochemical conditions significantly. A conceptual model of the hydrogeological post-glacial evolution is shown in Rhén et al, 1997 (TR 97-03). The conceptual model of the hydrochemical situation at Äspö before the start of tunnel construction is shown in Figure 4-16.

A transient modelling of the groundwater flow of the Äspö area since the postglacial (10,000 year) period has been carried out by Svensson (in manuscript). It can thus be concluded that mixing is a very important processes and is certainly governed by the large variations in hydraulic conductivity.

The sampling for the EQUIP study is concentrated on the deep vertical surface boreholes that pentrate Äspö and Laxemar. Conductive fracture from the sections sampled for groundwater chemistry was collected. In addition to ordinary microscopy and mineral characterisation the mineralogical work has concentrated on two different parts:

1. Analyses of ^{18}O and ^{13}C and trace elements using INA on small homogenized calcite samples.
2. Petrographic characterisation of calcites carried out by Milodowski and co-workers at BGS.

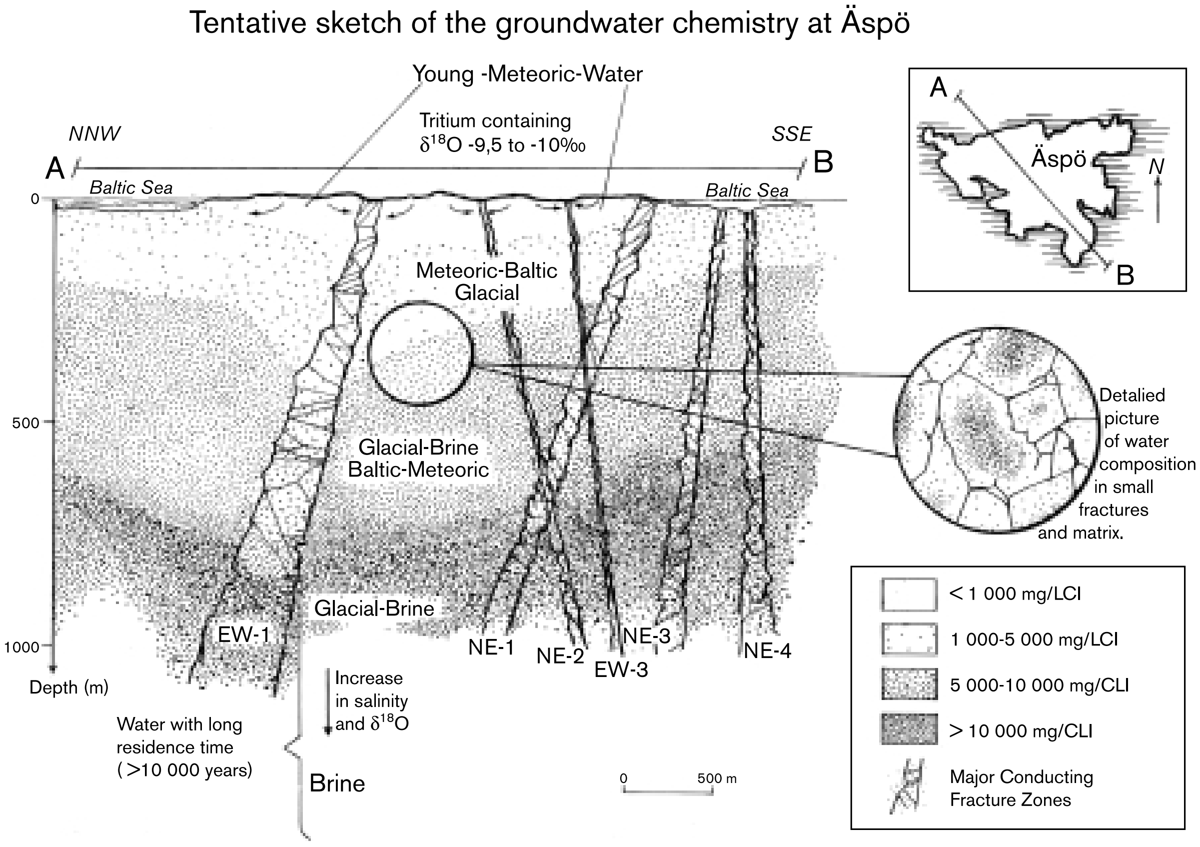


Figure 4-16. *Hydrochemical conceptual model of Äspö.*

Fluid inclusion studies are in progress at Kivieto in Uleåborg. Some preliminary results indicate that it is difficult to analyse the low temperature inclusions. Leakage of the inclusions during storage of the drill cores and sample preparation, have been discussed and additional samples have been prepared.

Stable isotope analyses of fracture calcites have been carried out within a number of studies at Äspö (Tullborg (1997) and references therein) and the results from these studies have partly formed the base for the EQUIP sampling.

4.8 Matrix Fluid Chemistry

4.8.1 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 groundwater's 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, and 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.

4.8.2 Objectives

The main objectives of the task 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.

4.8.3 Experimental concept

The experiment has been designed to sample matrix fluids from predetermined, isolated borehole sections. 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 ongoing 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.

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.

4.8.4 Results

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 minimize the dead volume and provide the representative groundwater samples in a reasonable time. The expected flow is in the order of ml:s per day. Special care was taken to clean the borehole and the equipment from impurities which could cause microbial activity. During drilling and after, the borehole was kept under nitrogen atmosphere before installation of the sampling device. The sampling equipment, specially constructed for this purpose was installed under nitrogen atmosphere in June 1998.

Three months after installation, a pressure increase of 50 kPa was observed in one of the isolated sections. Slight responses are seen in the other two sections. During the first 6 months no extractable groundwater was obtained. Predictive calculations show that it might take more than a year to obtain a water sample. Therefore emphasis will be put on analysing the drill cores from this borehole (and others) in addition to the groundwater sampling.

A review meeting of the Test Plan was held 14–15 December. Slight modifications were made to the Test Plan as a result of the discussions.

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

4.9.1 Background

The Äspö Task Force on modelling of groundwater flow and transport of solutes was initiated in 1992. The Task Force shall be 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 group consists of Task Force delegates as well as modelling expertise from eight organisations and meets regularly twice a year. 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 LPT-2 pumping 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: TRUE – The Tracer Retention and Understanding Experiment, 1st stage. Non-reactive and reactive tracer tests. Detailed scale.
- Task No 5: Impact of the tunnel construction on the groundwater system at Äspö – a hydrological-hydrochemical model assessment exercise. Site scale.

Much emphasis is put on building of confidence in the approaches and methods in use for modelling of groundwater flow and nuclide migration in order to demonstrate their use for performance and safety assessment.

4.9.2 Results

The 11th Task Force meeting was arranged at Äspö September 1–3 1998. The main subjects were Task No 4C-E as well as Task 5.

WEB pages have been prepared that present the work of the Task Force. The pages which have been available on the SKB WEB site (www.skb.se) since late 1998 were made with the following objectives:

- Improve the flow of information from the TRUE project via Secretariat to modellers, specifically data deliveries in the future.
- Provide an up-to-date summary of the status of each Modelling Task.

Task No 4C and 4D –Predictive modelling of non-sorbing tracer tests part of TRUE-1

Tasks No 4C and 4D concern 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. The modelling groups were initially given data from the site characterisation and data on the experimental set-up of the tracer tests. Based on this information, model predictions were performed of drawdown, tracer mass recovery and tracer breakthrough.

The performed predictions shows that the concept of Feature A as a singular well-connected feature with limited connectivity to its surroundings is quite adequate for predictions of drawdown in boreholes and conservative tracer breakthrough. Reasonable estimates were obtained using relatively simple models. However, more elaborate models with calibration or conditioning of transmissivities and transport apertures are required for more accurate predictions. The general flow and transport processes are well understood, but the methodology to derive the necessary parameters for predictions needs development.

The evaluation of the modelling tasks will be presented in an SKB TR report (Elert, 1999).

Task No 4E and 4F –Predictive modelling of reactive tracer tests part of TRUE-1

The Task No 4E exercise was defined with the following overall objectives:

- Develop the understanding of radionuclide migration and retention in fractured rock.
- Evaluate the usefulness and feasibility of different approaches to model radionuclide migration of sorbing species based on existing in-situ and laboratory data from the TRUE-1 site.

Task 4E concerns blind prediction of the test with sorbing tracers (STT-1 and STT-1b) STT-1 is performed with pumping in borehole section KXTT3:R2 and injection in KXTT4:R3 at one flow rate; Q=400 ml/min. STT-1b used the same pumping hole and pumping rate but in this case tracer injection was made in KXTT1. Predictions of STT-1b were presented at the 11th Task Force meeting.

A new Task 4F has been defined as a straight-forward extension of the present modelling task. It will include predictive modelling of STT-2 which uses the same setup as STT-1 but uses a lower flow rate, Q=200 ml/min. The predictions will be presented at the 12th Task Force meeting in April 1999.

Task No 5 –Integration of hydrochemistry and hydrogeology

Task No 5 is a hydrological-hydrochemical model assessment exercise which specifically studies the impact of the tunnel construction on the groundwater system at Äspö. The objectives are as follows:

- Assess the consistency of groundwater flow models and hydrochemical mixing-reaction models through integration and comparison of hydraulic and chemical data obtained before and during tunnel construction.
- Develop a procedure for integrating hydrological and hydrochemical information that could be used in the assessment of potential disposal sites.

A Task 5 modelling workshop was arranged in connection to the 11th Task Force meeting, i.e. August 31st at Äspö. Some preliminary modelling results were presented at the 11th Task Force meeting 1–3 September 1998 from CRIEPI, BMBF-BGR and NAGRA-PSI.

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

5.1 General

Stage goal 4 of the Äspö HRL is to demonstrate technology for and function of important parts of 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.

5.2 The Prototype Repository

5.2.1 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 behaviour 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 Demonstration of Deposition Technology and Canister Retrieval Test.

5.2.2 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 qualify 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 have been achieved with deposited canisters containing spent fuel.

5.2.3 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 (Figure 5-1). 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 will be mechanically excavated by full-face boring with a diameter of 1.75 m and a depth of 8 m. Performance of the boring machine and the boring technique will be analysed. Special considerations will be 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.

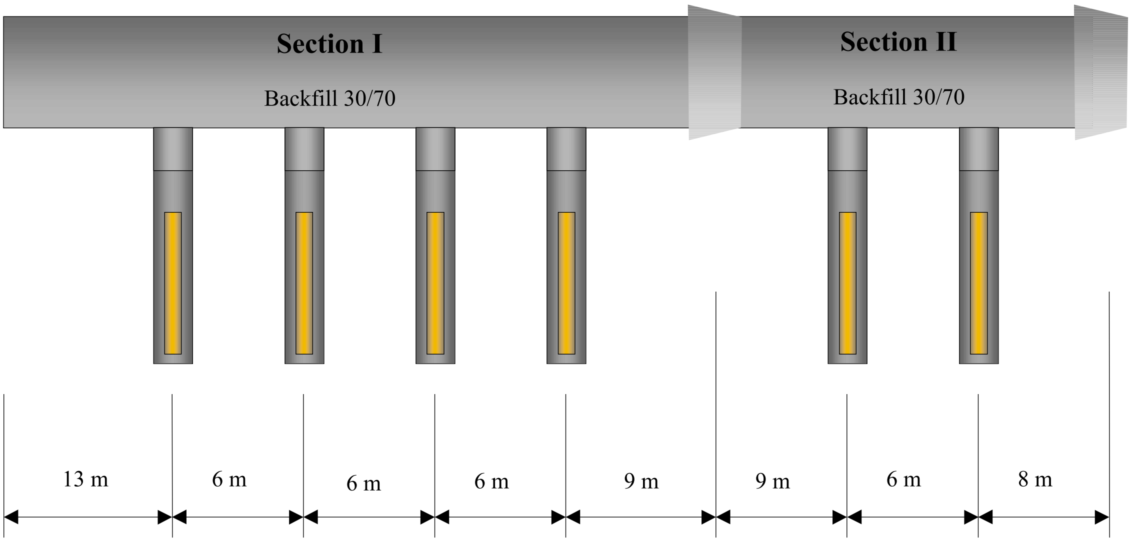


Figure 5-1. *Schematic view of the layout of the Prototype Repository (not to scale).*

The buffer surrounding the canisters will be made of highly compacted Na-bentonite blocks (Figure 5-2). 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 30% Na-bentonite and 70% crushed rock; 10–15% Na-bentonite being the normal grade in fresh water.

Operation time for the experiment is envisaged to be. 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 will be decommissioned after approximately five years to obtain interim data on buffer and backfill performance through sampling.

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

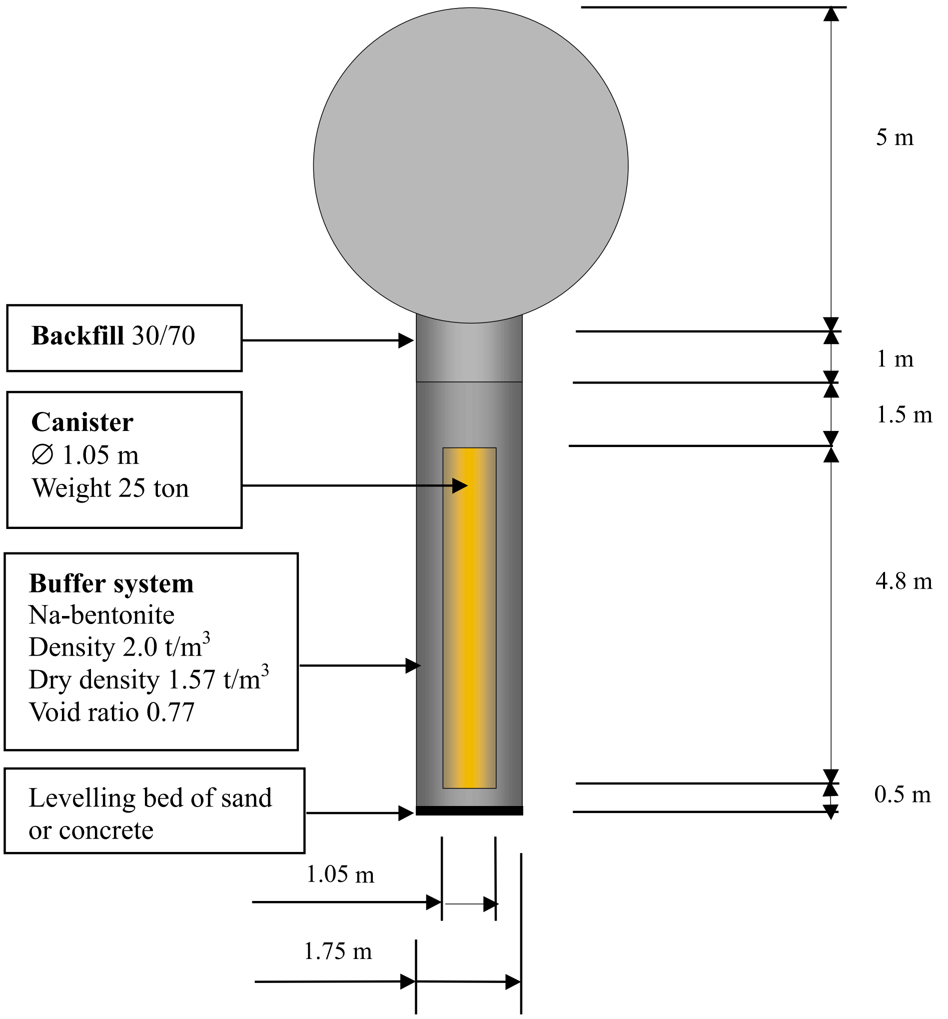


Figure 5-2. *Schematic layout of the deposition holes (not to scale).*

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.
- Gas pressure in buffer and backfill.
- Chemical processes in rock, buffer and backfill.
- Tracer transport.
- Bacterial growth and migration in buffer and backfill.

5.2.4 Results

General planning of the project has been completed and the Test Plan has been printed and distributed. Detailed planning has been continued during 1998, and the experimental set up continuously updated.

SKB:s management has formally decided plan and budget. All six holes, backfill and concrete plugs shall be in place before June 2001. Several international organisations have showed interest to participate in the project and an application for EC funding has been outlined. With due consideration to the extent of the project it was also decided by the SKB management, that the project manager should be an SKB employee and appointed Christer Svemar for this task. Lars-Olof Dahlström's engagement in development of the scientific issues will be continued by his appointment as Scientific Co-ordinator.

A project group has been established. The group is basically composed of the task leaders for the activities involved in the project. The group has been established in order to co-ordinate and plan all activities considering the scientific subject fields from planning to handling of data etc. The group is also assigned the task of information and reporting, so that the scientific use is gained to the extent possible.

Manufacturing of canisters is proceeding as planned. The design of the electrical heaters and other details needed for power output is in progress. A full-scale test of the heating system including measurements of temperature distribution within the canisters has been performed. The results showed an acceptable temperature distribution in the canister.

At present the boring of the deposition holes is planned to start in June 1999. The design of the roadbed and the equipment for emplacement of the buffer and canisters have been decided and manufacturing is proceeding.

The field activities of characterisation of the rock mass around the Prototype Repository have continuously going on. During the year, planned field activities according to characterisation stage 2, has been completed and analyses and reporting work is in progress. The characterisation according to stage 2, include, core drilling of pilot and exploratory holes, BIPS, core logging, in-situ rock stress measurements, in-situ measurements of thermal properties, water sampling for chemical analyses, hydraulic tests and laboratory testing to determine thermal and mechanical properties.

The dominant rock type at the Prototype Repository site is Äspö diorite. Minor parts of greenstone and fine grained granite occur as inclusions bands or veins. The main joint set trends WNW with steep dips. These joints are also the main water bearing structures, which is indicated from tunnel mapping and confirmed by the coring. Another main joint set is semi-horizontal joints trending NE.

Hydraulic testing indicate that water inflow to the deposition holes varies between approximately $1x10^{-5}$ to about 2 l/min.

The thermal properties of Äspö diorite as interpreted from the in-situ measurement where: thermal conductivity 2.8 W/mK, heat capacity 0.6 kWh/m^3K and thermal diffusivity $1.3x10^{-6}$ m^2/s.

In-situ measurements of rock stresses, performed by the over coring method gave the result: σ_H = 26 MPa, and strike 11°, σ_h = 18 MPa, and σ_v = 21 MPa.

Visualisation of characterisation data and modelling in RVS are continuously going on and models updated along with more detailed data.

Scoping calculations considering the temperature distribution in and around the deposition holes, deformation and stress redistribution of the near field rock mass and hydraulic conditions have been performed.

In the thermal calculations two cases where investigated with respect to water bearing capacity of the rock. Both calculations gave as a result a maximum temperature on the canister surface below 90°C. The maximum temperatures calculated where 88.5°C and 86.5°C for dry and wet rock condition respectively.

The mechanical model indicated a maximum tangential stress of about 120 MPa at the upper part of the deposition hole. When including thermal-mechanical loading the maximum stress was calculated to be about 200 MPa.

The discrete feature network model, DFN, set up to simulate the inflow to the deposition holes indicates an average inflow of 0.15 l/min.

Planning and 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 layout has been presented. Final selection and decision on number of each type of instrument and sampling equipment are scheduled to April 1999, immediately followed by purchasing and preparation procedure.

The scope for 1999 is to further detail the planning, prepare the site and furnish key components to the Prototype Repository. Major planned activities are:

- Detail planning of layout, material and monitoring etc.
- Excavation of deposition holes.
- Monitoring of mechanical response.
- Prediction modelling.
- Characterisation of deposition holes.

5.3 Demonstration of Disposal Technology

5.3.1 Background

The development and testing of methodology and equipment for encapsulation and deposition of spent nuclear fuel in the deep repository is an important part of SKB:s programme. In addition to the technical aspects, it is also important to be able to show in a perceptible way the different steps in encapsulation, transport, deposition, and retrieval of spent nuclear fuel for specialists and the public. As part of the overall programme an Encapsulation Laboratory is under construction in Oskarshamn and it will be put in operation late 1988. Demonstration of deposition and retrieval of canisters will be made in the Äspö Hard Rock Laboratory. The demonstration project complements the Prototype Repository and the Backfill and Plug Test which focus on the integrated function of the engineered barriers in a realistic environment.

Demonstration of Repository Technology is organised as a project under the Facilities Department. Development of equipment for handling and deposition of canisters will be the responsibility of the Deep Repository Department while the Äspö HRL will be responsible for the field activities. The description below focuses on the work that will be performed at the Äspö HRL.

The objectives of the demonstration of repository technology are:

- to develop and test methodology and equipment for encapsulation and deposition of spent nuclear fuel,
- to show in a perceptible way for specialists and the public the different steps in transport, deposition, and retrieval of spent nuclear fuel, and
- to develop and test appropriate criteria and quality systems for the deposition process.

The demonstration of deposition technology will be made in a new tunnel south of the ZEDEX drift excavated by drill and blast. This location is expected to provide good rock conditions, a realistic environment for a future repository, and allows transport of heavy vehicles to the test area.

5.3.2 Results

The test area in the laboratory was decided to be at the 420-meter level and a tunnel was excavated to a depth of approximately 53 meters with a width of 6.5 meters and a height of 6.0 meters. The dimensions of the tunnel were selected in such a way that it would be possible to test also horizontal emplacement of either canister and bentonite blocks separately or both together in one package, and vertical emplacement of canister and bentonite blocks in one package, in case any of these methods proves to be a candidate alternative to the reference method – vertical emplacement of canister and bentonite blocks separately.

The program for geological characterization and locating of preliminary places for simulated deposition holes has been completed. Four locations for boring of full scale simulated deposition holes were selected and drilling will be performed early 1999. During 1998 the main effort has been to prepare the drift for drilling of the deposition holes and the arrival of the deposition machine during 1999.

5.4 Backfill and Plug Test

5.4.1 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 have been finished e.g. excavation of the slot for the plug, casting of the first part of the plug, drilling of holes for the through connections, installation of the through connection tubes, installation of all packers for measurement of water pressure in the rock, and installation of the bore hole plugs. The backfilling started at the end of 1998 and the entire test set-up with casting of the final part of the plug will be finished in summer 1999.

5.4.2 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.

5.4.3 Experimental concept

The test layout is shown in Figure 5-3. The test is done in the old part of the ZEDEX tunnel that has been 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 will be left and filled with blocks of highly compacted bentonite/crushed rock mixture and bentonite pellets. The backfill is 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 part is divided into five sections parted by drainage layers of permeable mats. Outside the backfill an approximately 3 meter thick plug is placed with the required function of both being a mechanical support and a hydraulic seal.

The backfill and rock are instrumented with about 230 transducers for measuring the thermo-hydro-mechanical processes. 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. The flow close to the floor and roof respectively as well as in the central part of the backfill will be measured separately. The hydraulic function of the plug will be tested in a similar way. The mechanical interaction between a simulated swelling buffer material and the backfill and between the roof and the backfill will be tested with pressure cylinders fixed to the floor and the roof of the tunnel.

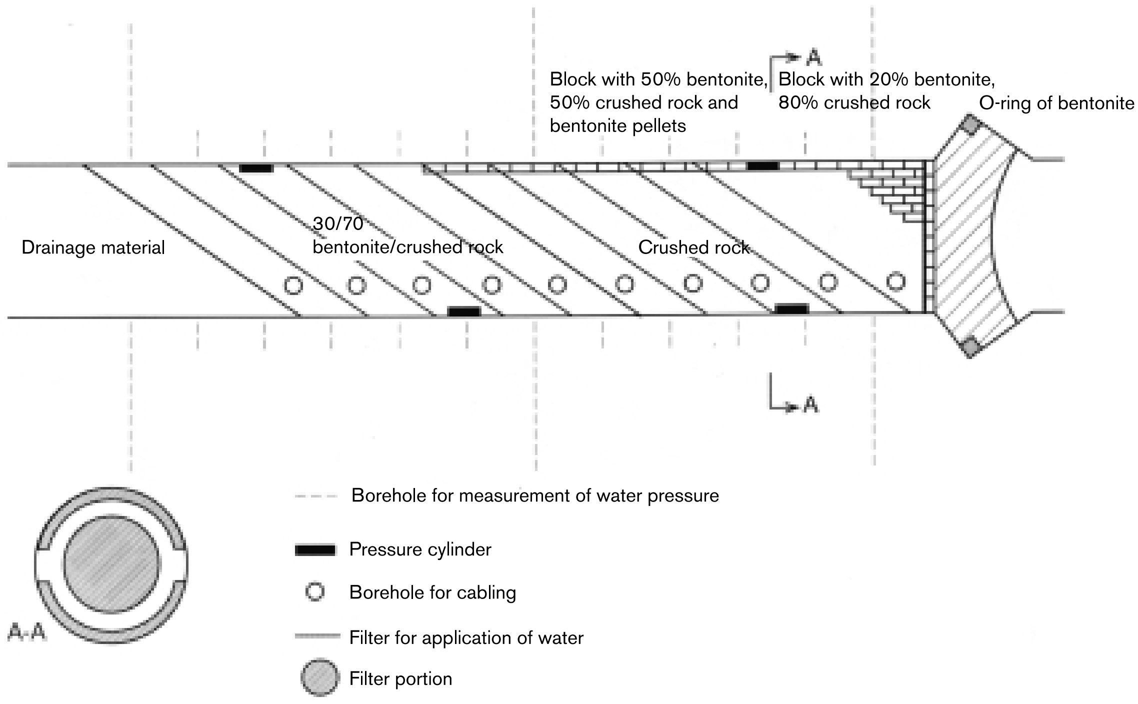


Figure 5-3. An overview of the Backfill and Plug Test.

5.4.4 Results

Characterisation

Hydraulic testing of the instrument holes has been made. Tests of the entire length of the long holes yielded hydraulic conductivity values between $6 \cdot 10^{-10}$ and $\sim 10^{-12}$ m/s with a median value of $5 \cdot 10^{-11}$ m/s. One of the tested holes (KXZSD8HL), which is located in the left wall, has a well defined highly permeable fracture at the test section 10–14 m from the wall. This fracture yielded an estimated hydraulic conductivity of $\sim 1.5 \cdot 10^{-8}$ m/s at the 4 m long test section.

24 out of the 48 short holes (1 m long with the inclination 45 degrees in relation to the rock surface) have been tested. The tests were made in the hole intervals 0.4–1.0 m, which correspond to the distance 0.3 to 0.7 m from the rock surface. The results showed that 4 out of 8 tested holes in the floor are intersected by blast induced fractures that made the hydraulic conductivity too high to be measurable ($>10^{-7}$ m/s). The measured hydraulic conductivity of the other 4 holes varied between $3 \cdot 10^{-10}$ and $1 \cdot 10^{-8}$ m/s which yields a median value higher than $5 \cdot 10^{-8}$ m/s for the floor. The median value of the measured hydraulic conductivity of the roof was $7 \cdot 10^{-11}$ m/s, while it was $4 \cdot 10^{-10}$ m/s in the walls.

Instrumentation

The instruments for measurement of thermal, hydraulic, and mechanical behaviour of the backfill and rock during the saturation and test phases have been procured. The following measurements will be made:

- measurement of the water saturation process in the backfill with psychrometers, resistivity probes and thin Tecalan tubes,

- measurement of water pressure in the backfill and the rock with Druck water pressure transducers and Glötzl water pressure cells,
- measurement of total pressure in the backfill with Glötzl cells and Roctest vibrating string transducers,
- measurement of the deformation properties of the backfill with pressure cylinders,
- measurement of temperatures with thermocouples,
- measurement of local hydraulic conductivity of the backfill with probes developed and installed by ENRESA.

The pressure cylinders, the total pressure cells on the rock surface, and the packers for the water pressure measurements in the rock have been installed.

The cables and tubes for the instruments are lead to the data collection system outside the test area through 12 holes drilled from the left wall of the test tunnel to the neighbouring Demonstration Tunnel. Steel tubes have been installed in all through connection holes and the gap between the tubes and the rock has been filled with fine cement. In order to further improve the tightness, highly compacted bentonite rings have been used for sealing the space between the steel tubes and the rock at a section close to the test tunnel. In the test tunnel the steel tubes end with steel cones, at which steel plates with water tight through connections for each tube or cable, are fixed.

Field work at the test site

Besides the characterisation, the drilling and installation of through connections, and the instrumentation the following main work has been done at the test site:

- The 1.5 m deep triangular slot for the plug has been excavated with slot core drilling and careful blasting. The first inner part of the plug has been cast. It will be used for supporting the retaining wall of concrete beams and for supporting the blocks of the bentonite O-ring.
- All boreholes in the test tunnel that will not be used for measurements have been plugged. The outer 4 m was plugged with bentonite cylinders and the rest of the holes were injected with cement.

Compaction technique

The compaction technique has been further developed and tested. Two vibrators will be used. One with a large vibrating plate for inclined compaction of the 30 cm thick layers and one smaller vibrating plate especially designed and built for compaction close to the roof.

Production of backfill material and bentonite bricks

Mixing and storage of about 1,200 tons of backfill materials has been carried out and the backfill material stored in tents on ground at the entrance of the Äspö tunnel. The composition of the backfill containing bentonite is 52% crushed rock, 13% sand, 5% filler, and 30% bentonite. The composition of the bentonite free backfill is 74% crushed rock, 19% sand, and 7% filler.

The following different types of bentonite bricks or pellets have been produced for either backfilling or sealing purpose:

- 1–2 cm large pellets of 100% bentonite,
- 6×12×24 cm^3 blocks of 100% bentonite for filling the slot between the roof and the bentonite free backfill,
- 6×12×24 cm^3 blocks of 20% bentonite mixed with 80% sand for backfilling near the plug,
- 25×25×10 cm^3 blocks of 100% bentonite for the bentonite O-ring in the plug (not yet produced),
- cm high cylinders of 100% bentonite with different diameters for sealing boreholes,
- cm high rings of 100% bentonite with different diameters for the packers in the water pressure measurement holes in the rock and for sealing the through connection holes.

Laboratory tests

The backfill material that was crushed and mixed in the field and is used in field test has been tested with different laboratory tests. The results showed that the field mixed material has the same properties as the backfill material mixed in the laboratory with one exception. The water saturation rate seems to be slower for the field mixed material, which underlines the need to artificially pressurise the water in the filter mats during the saturation phase.

Preliminary modelling

Scoping calculations with preliminary modelling of the hydrology of the rock around the test site, the water saturation phase, and the flow testing after saturation have been made using the finite element code ABAQUS. During 1998 the flow testing sequence has been modelled in the following way:

After completed water saturation of the backfill sections a series of flow testing will take place. The purpose of the flow testing is to study the hydraulic function and sealing effect of the plug and the axial flow in the backfill and near field rock between the permeable mats. The flow to the mat sections will be measured after successive decrease in water pressure in each mat section. The decrease will start at the filter on the inside of the plug and then continue to the other mats successively.

The expected water flow and water pressure distribution of such tests have been investigated in a number of hydraulic calculations with the geometry of an axial vertical section through the test site. A minor sensitivity analysis of some important parameters has also been performed.

The element mesh in the model is approximately 120 m high and 240 m long. The structure is divided into 14 different property areas with different hydraulic properties. Figure 5-4 shows a plot of those areas. All different backfill materials and filters with the inclination 35° are modelled. The filters are inclined 35° and extend from the floor to the roof. Figure 5-4 also shows a detail of the mesh near the plug. The bentonite O-ring and a small zone between the concrete plug and the rock (for simulating a possible leakage between concrete and rock) are included in the model as well as the disturbed zone in the roof and floor and the two major vertical fractured zones in the rock.

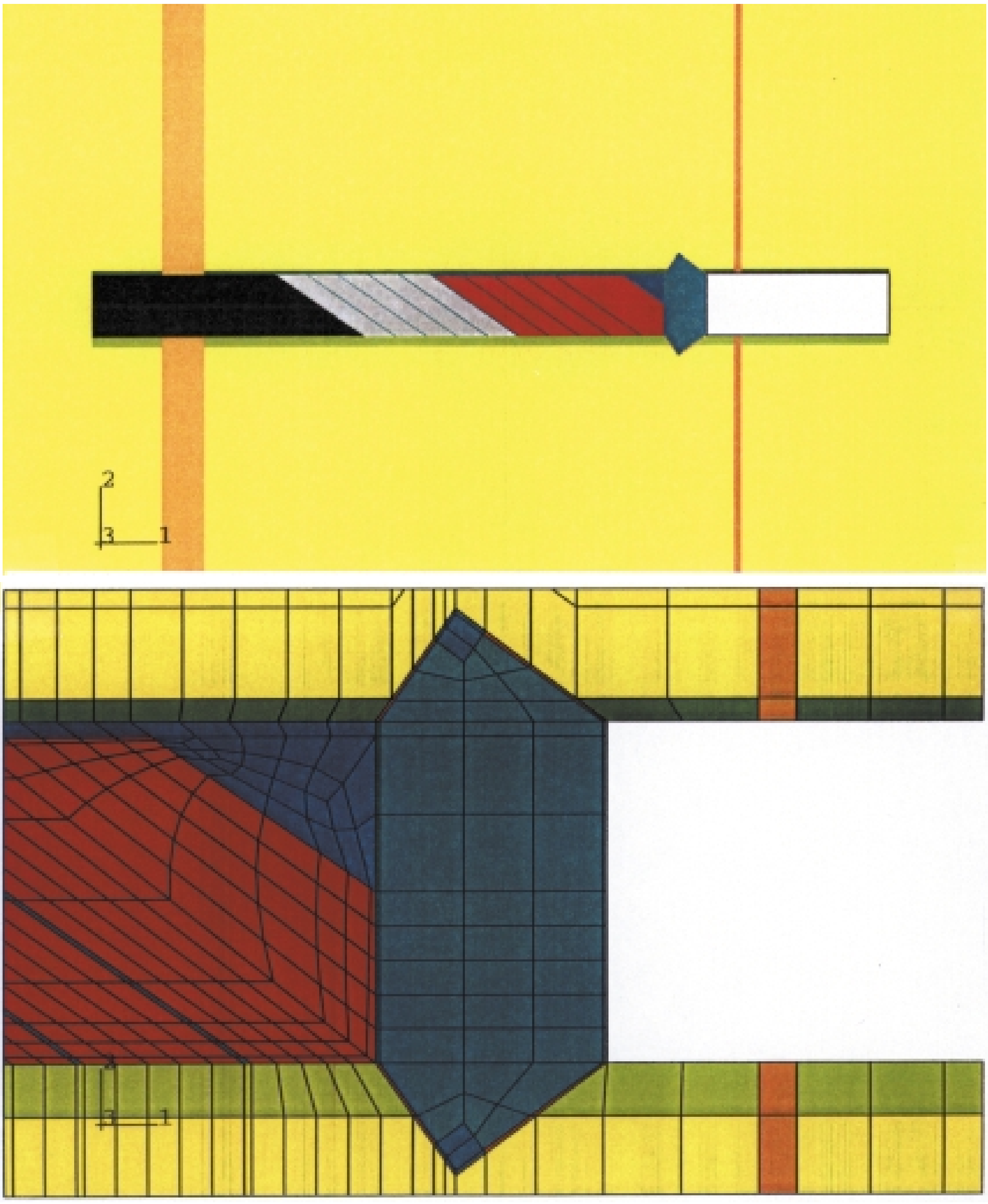


Figure 5-4. *Model geometry showing the materials with different properties and a detail of the element mesh at the plug.*

Figure 5-5 shows as an example the calculated water pressure distribution when equilibrium has been established. The calculation implies that the water pressure in the rock boundary is 3 MPa and that there is no water leakage through the plug or the rock around the plug. The sensitivity analyses yielded the following conclusions:

The system that is modelled is complex with several materials, which have a hydraulic conductivity that is not very well known. The calculations indicate that some of these materials, especially the hydraulic conductivity of the disturbed zone, in some cases may make the evaluation of the results difficult.

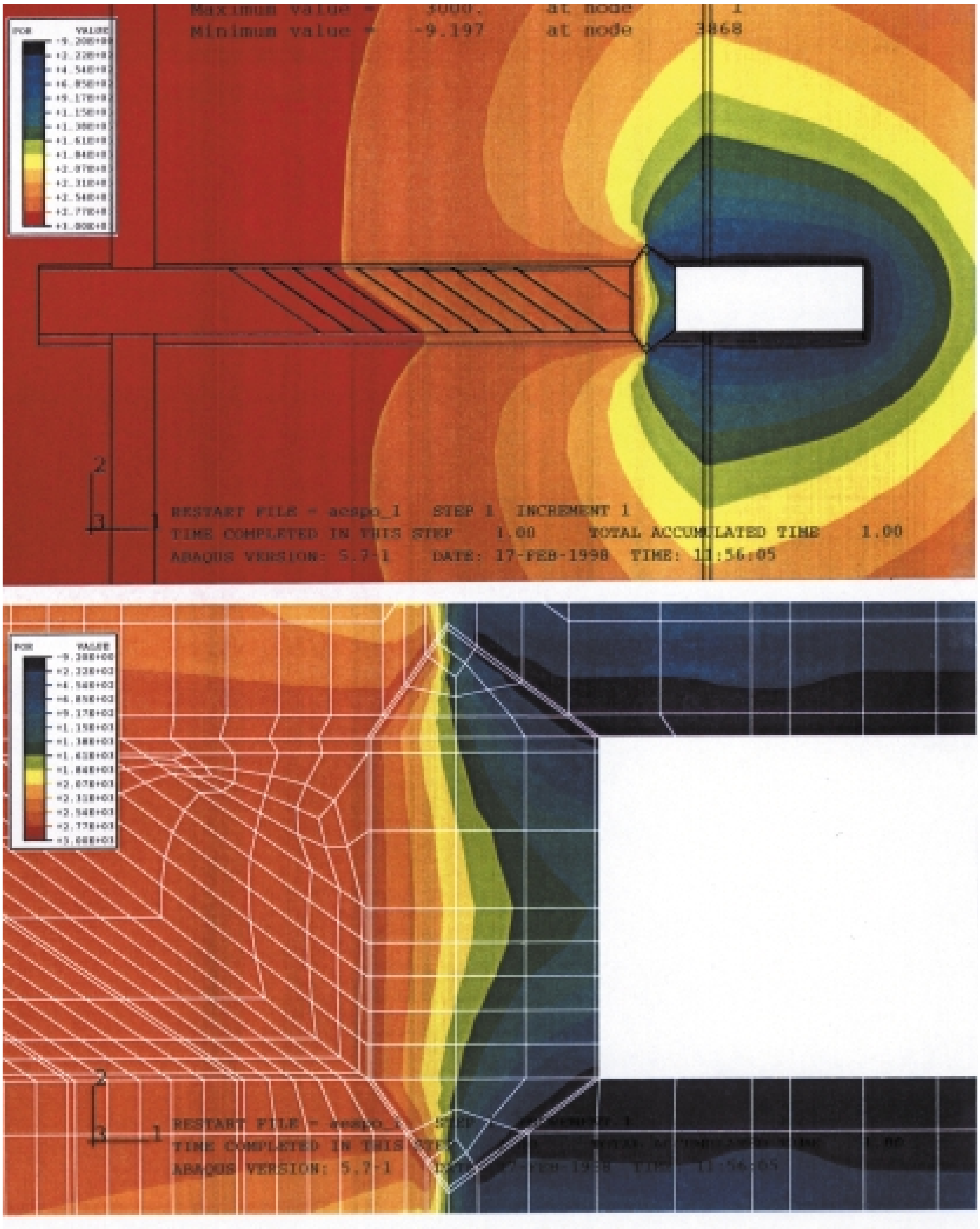


Figure 5-5. *Calculated water pressure (kPa) in the test site when equilibrium has been established.*

The influence of the properties of the inner fractured zone and the inner drainage material of crushed rock is not very high as long as the transmissivity is large enough to supply the inner part of the tunnel with a high pressure.

The properties of the undisturbed unfractured rock surrounding the tunnel have only a small influence on the results. The reason is that the hydraulic conductivity is assumed to be much lower than the hydraulic conductivity of the backfill and the disturbed zones.

The hydraulic conductivity of the disturbed zones is important for the magnitude of the water pressure in the backfill and for the water inflow into the filters during the test sequence.

5.5 Canister Retrieval Test

5.5.1 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.

5.5.2 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:

- Careful and documented characterisation of the rock volume affecting the THM-conditions in the test holes.
- 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 sub-projects that concern also other tests in the ÄHRL.

5.5.3 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 may have the effect that a somewhat 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, and further blocks are emplaced until the hole is filled up to one m from the tunnel floor. On top the hole is plugged with cast concrete. This plug has to be secured against heave caused by the swelling clay. A confined swelling pressure in the clay of 5 MPa yields a total pressure of about 1,000 tones on the plug, which either demands heavy bolting of the plug to the floor or a pillar that takes support against the tunnel ceiling. The tunnel will be left open for access and inspections of the plug support.

The artificial addition of water is done as geometrically regular as possible, either by injecting water into the rock mass close to the hole, or directly into the buffer in the deposition hole. One consideration is that the installation does not cause disturbance for testing and demonstration of retrieval once the buffer has saturated and swollen.

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.

5.5.4 Results

The tunnel for the test, which is an extension of the D-tunnel on 420 m level with about 15 m, has been completed. Geological mapping of the tunnel has shown that the location of the two full-scale deposition holes for the test can very well be placed in accordance with the most suitable geometrical layout for the equipment, that is planned to be used for the retrieval of the canisters.

In these positions pilot holes, one at each place have been cored down to about 8 m depth below the tunnel floor. The geological characterisation indicates very dry conditions, so dry that artificial addition of water is deemed necessary in order to saturate the buffer within a reasonable time period.

Following the location of the deposition holes the floor in the tunnel was cast with concrete. Provisions have been taken for installing rails for the prototype deposition machine, which will be used also in the test of retrieval of the canisters.

Seven holes have been core drilled around the places of the two full-scale deposition holes. They will be instrumented with sensors for measurement of acoustic emission during boring of the deposition holes. Also 8 holes all together have been bored around the places of the deposition holes for sensors for registration of displacement and stress changes during boring of the deposition holes.

Each core has been mapped and each hole equipped with packer for measurements of piezometric head and water flow rate.

Preparations have been made for the actual boring, which at the moment is planned to start in May 1999.

5.6 Long Term Test of buffer material

5.6.1 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.

5.6.2 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.

5.6.3 Experimental concept

The test series (Table 5-2) 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 5-6).

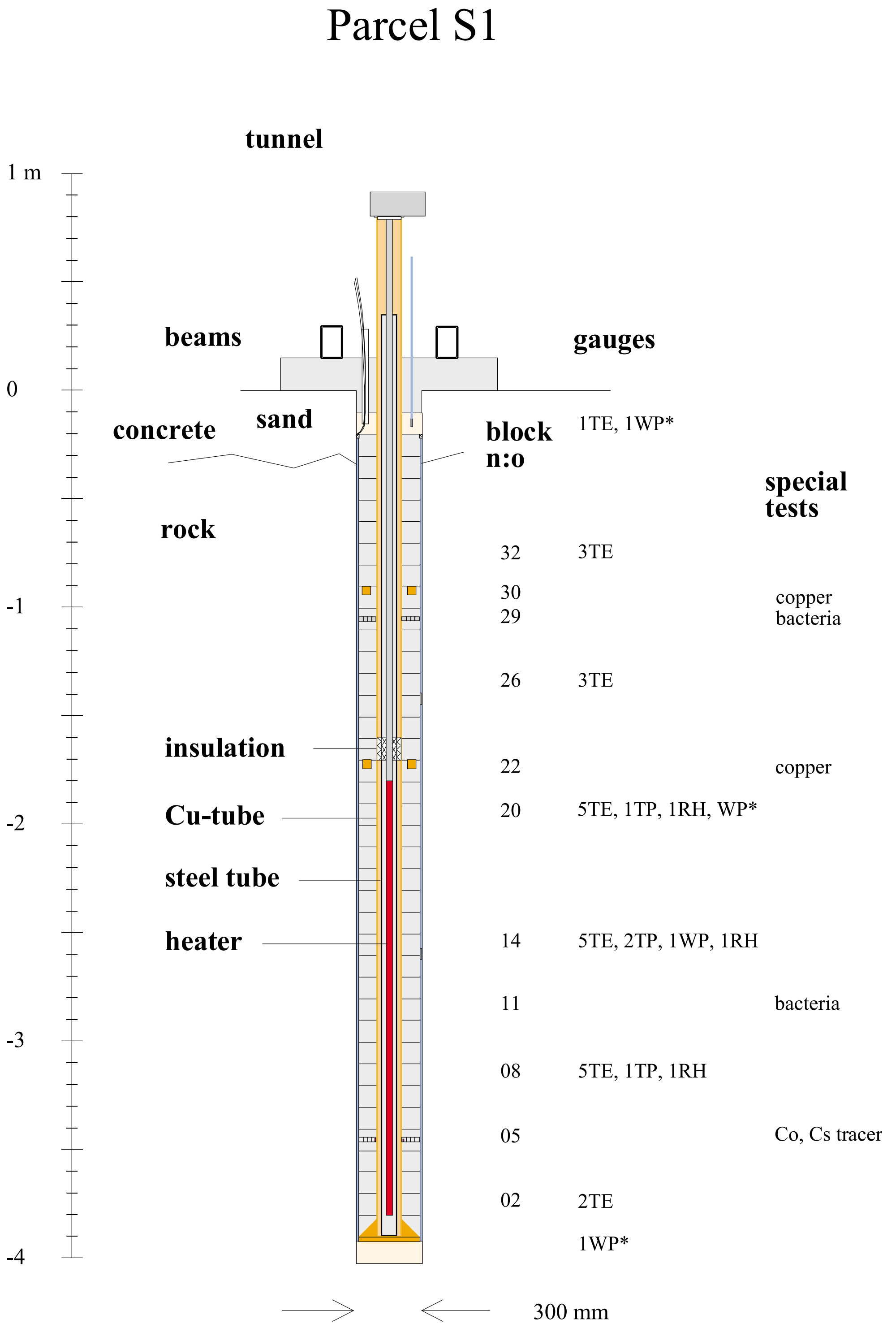


Figure 5-6. *Layout of S1 test parcel. TE denotes temperature gauges, WP water pressure gauges, TP total pressure gauges, RH relative humidity gauges. The figure shows the number of gauges at each level.*

The one year pilot tests A1 and S1 have been completed. The test series have been extended, compared to the original test plan, by the A0 parcel in order to replace the part which was lost during the uptake of the A1 parcel.

Table 5-1. Lay out of the planned Long Term Test series

Type	No.	T °C	Controlled parameter	Time years
A	1	130	T, [K^+], pH, am	1
A	0	120<150	T, [K^+], pH, am	1
A	2	120<150	T, [K^+], pH, am	5
A	3	120<150	T	5
S	1	90	T	1
S	2	90	T	5
S	3	90	T	>>5

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

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 will be 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.

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

5.6.4 Results

Reference material and material from defined positions in the A1 and S1 parcels material have been tested and analyzed.

The following physical properties have been determined for the parcel material (test technique within brackets):

- water ratio (oven drying),
- density (weighing in paraffin oil),
- hydraulic conductivity (oedometer),
- swelling pressure (oedometer),
- bending strength (beam test),
- shear strength (triaxial cell),

and the following mineralogical conditions have been analyzed (methods within brackets):

- element content in the bulk and clay fraction material (ICP-AEM),
- cation exchange capacity (CEC, Chapman's and Cu-trien method),
- mineralogical composition in bulk and clay (XRD, SEM-EDX),
- microstructure (TEM and SEM-EDX).

All tests and analyses except those concerning microstructure have been completed and compilation of the final report is in progress. No unexpected results have been observed. Supporting laboratory tests concerning CEC determination techniques have been made in order improve the determinations with respect to time and accuracy.

Minor mineralogical changes have been observed regarding i.a. exchangable cautions and reduced silica content (Table 5-2). No significant changes in physical properties have been observed.

Table 5-2. Compilation of mean values for the main elements in the S1 parcel (30 analyses) and reference material (R, 10 analyses). B denote total material, C denote the clay fraction, and LOI denote the loss of ignition

	SiO2	Al2O3	CaO	Fe2O3	K2O	MgO	MnO2	Na2O	P2O5	TiO2	Sum	LOI
S1B	63.0	20.1	1.31	3.72	0.53	2.47	0.01	2.34	0.06	0.15	93.7	5.51
RB	64.4	20.0	1.19	3.83	0.52	2.49	0.01	2.26	0.06	0.15	94.8	5.17
S1C	63.4	20.7	1.08	3.72	0.19	2.63	0.01	1.76	0.05	0.14	93.7	5.98
RC	63.8	20.5	0.93	3.78	0.02	2.67	0.01	2.09	0.03	0.13	93.9	5.75

A preliminary report concerning the bacteria analyses have been prepared by Gothenburg University group. The major conclusion is that only spore forming species survived the exposure and in an inactive state.

Analyses at KTH concerning the tracer elements cobalt and cesium have been completed and the results indicate expected discrepancies between the two elements. Calculations and reporting are presently being made.

The copper analyses have been completed and the results indicate a corrosion rate in the range of what was expected for oxidizing conditions.

5.6.5 Planned work

The planning and construction work for the remaining four test parcels have started. Investigation holes will be core-drilled and test concerning inflow and water-pressure will be made during the spring. The successive drilling of test holes are planned to be made by percussion drilling.

The emplacement of the remaining parcels is planned to start in May and will be finished during the summer. Supporting laboratory work will be made parallel to the construction and running of the five new parcels during 1999. The tests and analyses concern i.a. original clay characterization and gas opening pressure.

5.7 Mechanical modelling of cracks in rock caused by mechanical excavation

5.7.1 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.

5.7.2 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.

5.7.3 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 are conducted 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 reluts compared to the measured forces on the cutter in that particular position.

5.7.4 Results

The modelling work has continued with analysis of dynamic fracturing and the influence of heterogeneity on rock fragmentation.

Preparations of the field work has continued with planning of the instrumentation of cutters for installation of strain gauges and with scoping calculations of expected deformations and strains in the shafts and saddles of the instrumented cutters. The two cutters that are going to be used have been sent to Luleå Technical University for calibration before being installed on the bore head in the ÄHRL.

6 Äspö HRL facility operation

6.1 Plant operation

6.1.1 Introduction

The operation of the facility has worked smoothly. A few systems have been exchanged and some new have been installed. Worth mentioning is the underground fire alarm system. The office have got a new wing and the storage facility has been enlarged. Some of the oldest cars have been exchanged to new ones and investments in the environment have also been done. Two smaller cable fires and one accident caused by electricity have occurred. Fortunately without any serious injuries. Work to ensure the different computer systems to operate also in the beginning of nest century has been initiated.

6.1.2 Surface activities

The first half of the year was dominated by the construction of the new wing to the old office. Besides new office rooms also new conference rooms and an exhibition hall were constructed. The old storage building was extended and a chemical laboratory as well as a geotechnical laboratory were besides new storage volumes sited in the new building. The diesel tank has been exchanged to one more kind to the environment in case of leakage. It consists of a tank with double walls placed inside a container.

A new car has been bought and two of the older ones were sold. A new software has been installed in the fire alarm, which hopefully will increase the reliability. Problems with mobile communication, specially the fire brigades, in the vicinity of the office was solved. Some of the internal communication systems were badly shielded.

6.1.3 Underground activities

The fire alarm underground was installed and works quite smoothly although it sometimes seems to bee too sensitive, which has caused a few false alarms. A nisch at the -420 m level has been choosen to be a new rescue chamber and the construction work started at the end of the year. It will be designed for 60 people up to 6 hours with a breathing air regeneration system.

A major part of the electrical system down to the level -220 was exchanged. Cables free from halogen have been used. The old equipment could not stand the harsh environment.

All the big doors underground have been changed to stainless steel types.

To protect installations from dripping water a coated fabric was mounted in several places.

Program for maintenance of the rock tunnel has been modified. For example scaling now takes place more frequent than before.

A new fan now supply the -420 level with fresh air.

6.2 Data management and data systems

6.2.1 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, 1996. The report is written in Swedish, but one of the most interesting figures is here translated into English (Figure 6-1). Behind the balloons in Figure 6-1, indicating data entry, SKB:s Site Characterisation Database and SKB:s Rock Visualization System plays important roles as illustrated in Figure 6-2.

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.

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

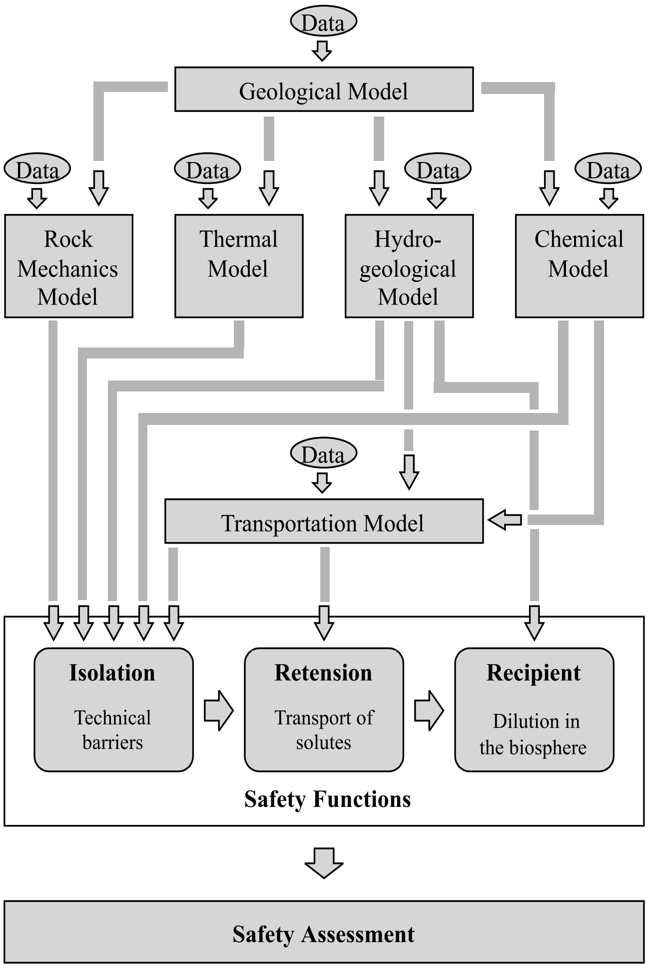


Figure 6-1. *Schematic flow chart describing how information are transferred between different geoscientific models and how these models are used in the safety assessment to be done. The need of different types of input data are shown as balloons marked "Data".*

6.2.2 Results

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.

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.

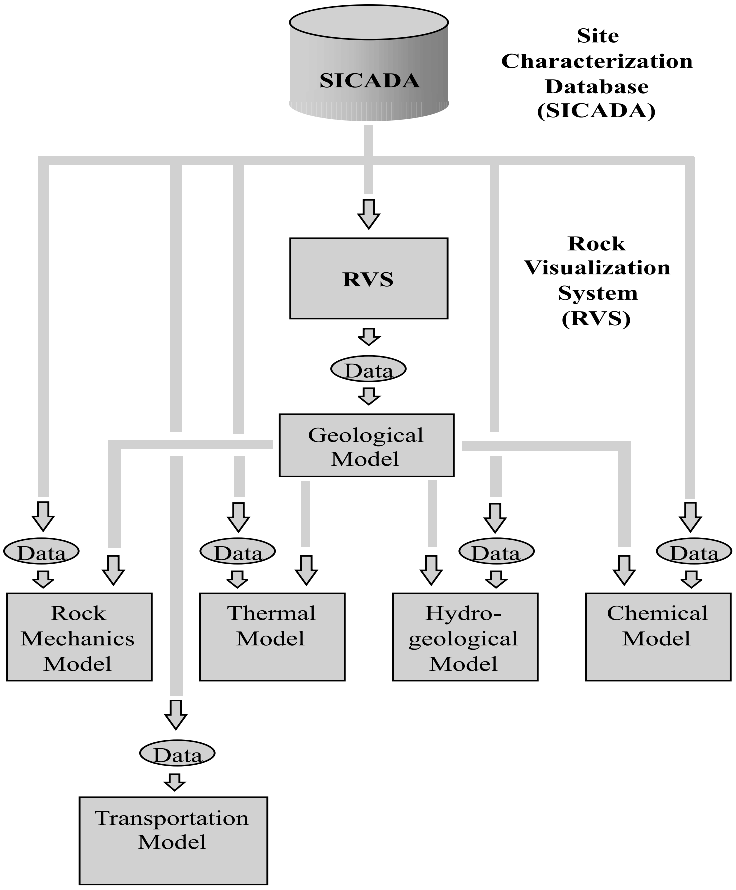


Figure 6-2. Schematic flow chart describing where from data are taken to the different geoscientific models used as a baseline fore the safety assessment to be done. The balloons in Figure 6-1 have been complemented with the origin of data. As indicated SICADA and RVS are highly important tools on the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

The SICADA data model has been improved and documented during 1997. The documentation work is still in progress, but is planned to be completed in the spring 1998.

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 6-1. A set of activities is then associated with each method, but in general there is only one activity in each set.

Table 6-1. 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 pointer 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 have been in operation during 1997, namely:

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.

The major goal during 1998 was to develop and implement a WEB-Interface for the SICADA database. This goal has not been reached. The reason of that was a consequence of that a more effective alternative arised. We then decided to convert the UNIX-based application to the Windows NT environment. Currently there are no plans to restart the WEB-project. The NT applications will be released in February 1999.

6.3 Monitoring of groundwater chemistry

6.3.1 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.

6.3.2 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.

6.3.3 Results

Groundwater sampling was undertaken on two occasions, in March and in September 1998. Many project specific samples were taken in addition to the "monitoring samples". Within and in connection to the monitoring program 43 sections in 35 boreholes (see Table 6-2) are sampled. Sampling and analyses are performed according to SKB:s routines, Chemistry Class no 4 and 5.

6.3.4 Planned work for 1999

The analytical results from the monitoring program undertaken between 1995 and 1998-05-01 will be presented in a report in the beginning of 1999. The results from the sampling period in October will be presented in a Technical Document in the beginning of 1999. The two sampling occasions for 1999 are scheduled to take place in April and in September.

Table 6-2. Boreholes and sections sampled within the Program for Monitoring Groundwater Chemistry

Idcode	Secup/seclow	Class no	Comment
KAS03	533–626 m	4	
KAS03	107–252 m	4	
KAS09	116–150 m	4	
HD0025A	0–200 m	4	
KA1061A	0–209 m	4	
KA1131B	0–203 m	4	
KA1755A	88–160 m	4	
KA2050A	155–212 m	4	
KA2162B	202–288 m	4	
KA2511A	92–109 m	4	
KA2511A	52–54 m	4	
KA2512A	34–37 m	4	RNR
KA2563A	187–196 m	4	
KA2861A	8.69–9.84 m	4	REX
KA2861A	0–8.52 m	5	REX
KA2862A	7.37–15.98 m	4+5	REX
KA2862A	6.82–6.92 m	4	REX
KA3110A	20–29 m	4	
KA3385A	32–34 m	4	
KA3539G	0–30 m	4	
KA3573A	4.5–17 m	4	
KA3573A	18–40 m	4	
KA3600F	4.5–21 m	4	
KA3600F	22–50 m	4	
KI0023B	41.45–42.45 m	4	TRUE BS
KI0023B	70.95–71.95 m	4	TRUE BS
KI0023B	84.75–86.2 m	4	TRUE BS
KI0023B	11.25–112.7 m	4	TRUE BS
KI0025F	164–168 m	4	TRUE BS
KI0025F	86–88 m	4	TRUE BS
KXTT3	12.42–14.42	5	TRUE-1
KR0012B	5.0–10.57 m	5	
KR0013B	7.1–16.9 m	5	
KR0015B	19.9–30.3 m	5	
SA0813B	5.6–19.7 m	4	Only in March due to broken packer
SA1009B	6–19.5 m	4	
SA1229A	6–20.5 m	4	
SA1420A	6–50 m	4	
SA1730A	5.6–20 m	4	
SA2074A	6–38.7 m	4	
SA2273A	5.8–20 m	4	
SA2600A	5.8–19.4 m	4	
SA2783A	5.8–19.9 m	4	
SA2880A	11.92–13.92 m	4	
SA3045A	0–20.7 m	4	

6.4 Technical systems

6.4.1 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 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.

6.4.2 Results

Manual control of the flow in the weirs in the tunnel has been done.

The following boreholes have been taken out of operation: HAS03, HAS11.

Evaluation of a presentations system for the HMS has started in the autumn 1998. The selected system will be installed during 1999

Ultra-sonic transducers has been installed to measure the surface of the water in the weirs.

The core drilling of the borehole KAS06 to remove oldpackers was successful. In the holeKAS07 we removed packers and tecalan tubes until the depth of -263 m. Later we will continue with another method in KAS07.

At boreholes KAS03, KAS06 and KAS09 at the surface we have installed new radiomodems for datatransmission. These works much better than the old electrical networks modem.

6.5 Quality assurance

Quality assurance means to ensure that activities are undertaken with due quality of high effiency. In order to achieve this goal it is required that a smoothly running system are in place to manage projects, personnel, 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). A review of the SKB quality assurance handbook is undertaken every year.

For each major project a separate handbook (QA-programme) will be issued similar to SKB Quality- and Environmental Management Handbook. The intent in applying a quality program is to have the work accomplished in a planned and systematic manner in order to decrease the probability of errors and malfunctions.

A draft project handbook has been produced for the Prototype Repository project.

With the aim to enhance the competence of staff involved with procurement new check lists have been developed and officers given the opportunity to attend courses on the subject. There has furthermore been an adjustment of conditions of delivery for purchases from contractors to comply with the activities at Äspö HRL.

SKB is investigating the prerequisites to become certified according to the ISO 9001 and ISO 14001 standards. Working groups have been established with the goal of certifying SKB by October 2000.

A new handbook for purchasing and requisition has been on review during 1998, with the ambition to publish it during 1999. Thereby complying with the conditions for an ISO-certification.

The work of developing a project handbook was initiated during the year. This handbook will specify the requirement for handling projects at SKB, i.e. how to initiate, administer, report and evaluate projects.

The Äspö Handbook cover issues of decision-making, instructions with regard to procedure, manuals etc. to guide the work as pertaining to quality assurance and environmental issues at the Äspö HRL and to ensure that operations are covered by the criteria specified in SKB-HLK. During the year the handbook has been updated with a number of important documents guiding the Äspö HRL operations.

A software application called Äspö Plan Right for managing time and resources, running under MS Projec, has been further developed with adaptations to the Äspö HRL operation.

7 International cooperation

7.1 Current international participation in the Äspö Hard Rock Laboratory

Ten organizations from nine countries have during 1998 been participating in the Äspö Hard Rock Laboratory in addition to SKB. They are:

- Atomic Energy of Canada Limited, AECL, Canada.
- Posiva Oy, Finland.
- Agence Nationale pour la Gestion des Déchets Radioactifs, ANDRA, France.
- Japan Nuclear Cycle Development Institute, JNC, Japan (formerly PNC).
- 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 Bildung, Wissenschaft, Forschung und Technologie, BMBF, Germany.
- Empresa Nacional de Residuos Radiactivos, ENRESA, Spain.
- Sandia National Laboratories, SANDIA, USA.

In each case the cooperation is based on a separate agreement between SKB and the organization in question. The work performed within the agreements and the contributions from the participants are described under 7.2.

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 organization. The TRUE Block Scale Experiment (see 4.2.3) is an example of such a project.

Specific technical groups so called Task Forces is another form of organizing the international work. A Task Force on groundwater flow and solute transport in fractured rock is ongoing (see 4.9).

A joint committee, the Äspö International Joint Committee, IJC, with members from all participating organizations, 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.

7.2 Summary of work by JNC

7.2.1 Tracer Retention Understanding Experiment

Japan Nuclear Cycle Development Institute (JNC) participated in the Äspö Task Force on Modelling Groundwater Flow and Transport and in the TRUE-Block Scale experiment during 1998. The Task Force work involved analysis of solute transport for Task 4eII and Task 4eIII (Winberg, 1998), and hydrogeochemical pathways analysis for Task 5 (Wikberg, 1998).

JNC activities for the TRUE-Block Scale experiment extended from experimental design and data analysis through conceptual model development and numerical modelling.

JNC efforts for the Äspö Task Force on Modelling Groundwater Flow and Transport and the TRUE-Block Scale Experiment are supported by Golder Associates Inc., Seattle.

Äspö Task Force on Modelling Groundwater Flow and Transport, Task 4eII/III

Background

JNC has participated in all phases of the TRUE-1 experiment from preliminary analysis of site characterization, through support to the identification and quantification of "Feature A" which has become the primary focus of TRUE-1 tracer experiments. During 1997, JNC participated in predictions of the SST-1 sorbing tracer test, Task 4eI. During 1998, JNC participated in Task 4eII and 4eIII, analyzing the predictive exercise for SST-1 and predicting the complementary sorbing tracer test SST-1b.

The JNC modelling team used the JNC/FracMan stochastic discrete feature network (DFN) models to make the STT-1 predictions. The DFN models were conditioned to drawdowns and non-sorbing tracer breakthrough curves of tracer test PDT-3. Conditioned models were used to predict STT-1 by calculating a retardation factor for each sorbing tracer.

The results of the STT-1 tests were made available in March 1998 (Andersson et al, 1998a). Task 4eII involves comparison of the measured and predicted tracer breakthrough curves followed by critical evaluation of the concepts used to make the predictions in light of the experimental results.

In the fall of 1997, two new tracer tests were performed using the same experimental setup as STT-1 but a different pathway. First, a non-sorbing tracer test, PDT-4, was run in order to provide information on the new pathway. Then, a cocktail of sorbing tracers was injected (STT-1b). Task 4eIII involves using the refinements suggested by the evaluation of STT-1 and a transport model of the pathway derived from PDT-4, to predict the sorbing tracer transport on the new pathway (STT-1b).

Objectives

The objectives of JNC participation in Task 4eII and Task 4eIII were to improve the understanding of sorbing transport processes in discrete fractures by better characterizing transport pathways, and to improve our understanding of the derivation of transport parameters from in-situ experiments. Task 4eII provides a critical evaluation of transport processes and parameters used in the Task 4eI prediction, and a basis for the Task 4eIII prediction.

Experimental concept (Task 4eII)

JNC team strategy for Task 4eII considered the following processes in DFN transport in attempting to understand observed SST-1 breakthrough:

- multiple stochastic pathways through stochastic continuum transmissivity fields within each fracture plane of fracture networks,
- advective transport,
- dispersion within fracture planes,
- surface sorption,
- matrix diffusion.

Figure 7-1 and 7-2 illustrates the discrete feature network concept of "Feature A" used in this analysis.

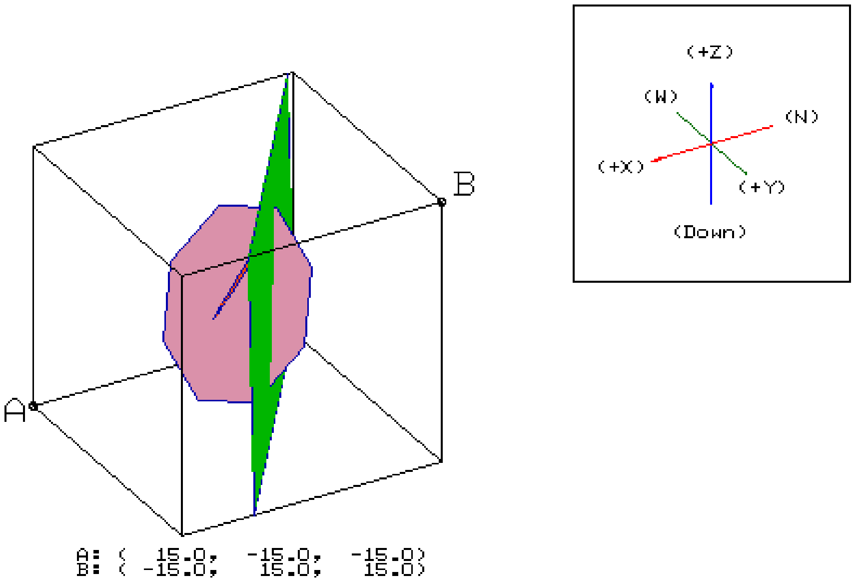


Figure 7-1. Features A, A' and NW-2' in TRUE-1 DFN model.

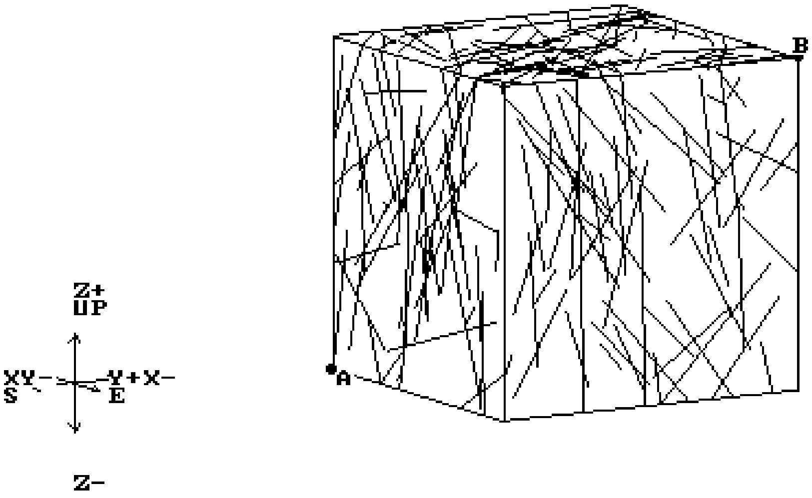


Figure 7-2. Background Fracturing in TRUE-1 DFN model.

Graphical and quantitative analyses were carried out to assess the possible importance of alternative processes of:

- matrix sorption,
- advective exchange between mobile and immobile zones,
- single and dual pathways.

Comparison between predictions and observations generally indicated that pressure response as measured by drawdown, and advective transport, as measured by median breakthrough time t_{50} were well modelled in our SST-1 predictions. However, since our models relied on surface sorption for retardation, the initial breakthrough t_5 was shifted for our predictions, while it was not significantly effected in the measurements. In addition, the tail t_{95} of the measured breakthrough curves was longer than could be explained by dispersion without incorrectly flattening the initial breakthrough. This indicated the possible importance of matrix sorption or other immobile zone exchange processes.

Examination of the measured breakthrough curves also indicated that the breakthroughs could be explained by single to double-pathways or average pathways, due to the lack of additional peaks in the breakthrough curves.

Based on these observations, the JNC/Golder team applied the FracMan/PAWorks LaPlace Transform Galerkin (LTG) transport code to derive transport parameters for single and double-path models including matrix sorption, and the RIP model to derive transport parameters for models including advective immobile zone exchange.

LTG models using retardation values calculated from the laboratory surface sorption coefficients failed to reproduce the long tails observed in the experimental data; therefore, the sorption in the rock matrix was considered, using values somewhat higher than laboratory Kd values. Andersson et al (1998a) also concluded that the laboratory values for surface sorption were too low. Figure 7-3 shows the single and double-pathway fits for the best fits to the SST-1 sorbing tracer test for Strontium, including the effects of matrix sorption.

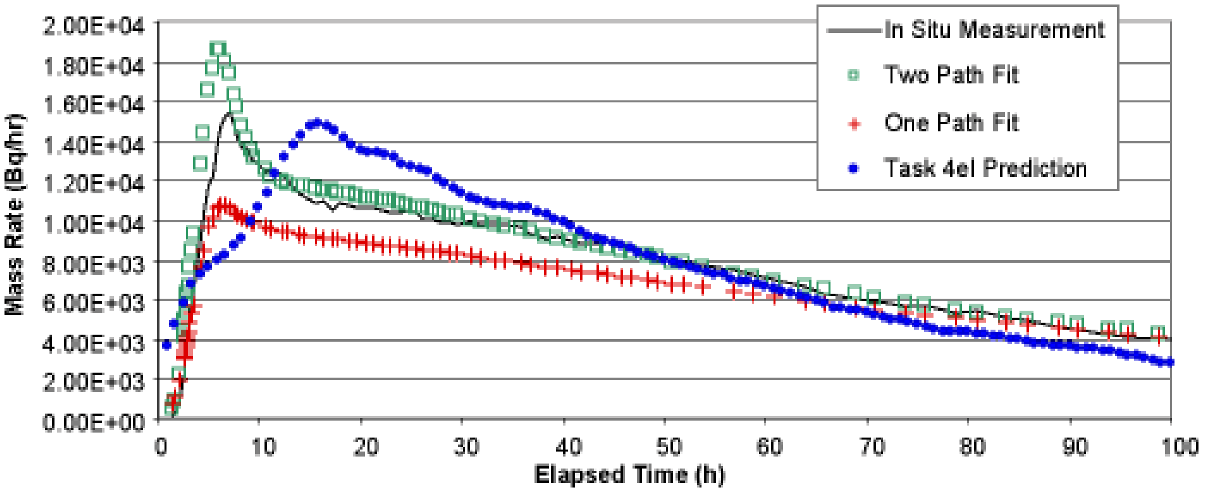


Figure 7-3. *Strontium Breakthrough Curve, Task 4eII (single-path fit, double-path and previous prediction).*

Although the double-path model does not provide a significantly better fit for non-sorbing tracer breakthrough, there are two reasons for continuing to use the double-path model. First, the single path model has a high, possibly unrealistic, porosity compared to the double-path curve. Second, in STT-1 it was found that the double-path model provided better fits to several of the sorbing tracer breakthrough curves.

Results (Task 4eIII)

The JNC/Golder strategy for Task 4eIII sorbing tracer predictions combined the strategies of Task 4eI and 4eII. First, a flow simulation of the PDT-4 pumping geometry was performed on the Task 4e DFN model (Dershowitz et al, 1998). In order to simulate the larger drawdowns observed for this test (Andersson et al, 1998a), the transmissivity of Feature A in the model had to be modified slightly. Next, the non-sorbing Uranine tracer test was simulated using particle tracking in MAFIC. Here the strategy differed from that previously used; instead of trying to match the PDT-4 curve with a particle tracking, the primary goal was to determine a flow-path width and mean velocity. Thus, matrix diffusion was turned off. Next, LTG was used to fit the non-sorbing breakthrough curve of PDT-4. Both a single-path model and a double-path model were fit with transport properties similar to those found for STT-1. Finally, the results of the two methods of estimating flow width and velocity, one derived from particle tracking in MAFIC and the other from an LTG fit of the non-sorbing tracer test, were compared.

Sorbing tracer breakthrough predictions were based on a combination of fitted field scale sorption derived from Task 4eII and, for tracers not used in STT-1 (K, Co), from the laboratory derived sorption. The injection history for each tracer was used to scale the breakthrough curves. Sorbing tracers were predicted using FracMan/PAWorks in order to address the importance of matrix sorption process identified in Task 4eII. Figure 7-4 presents an example Task 4eII sorbing tracer prediction based on the double-path model.

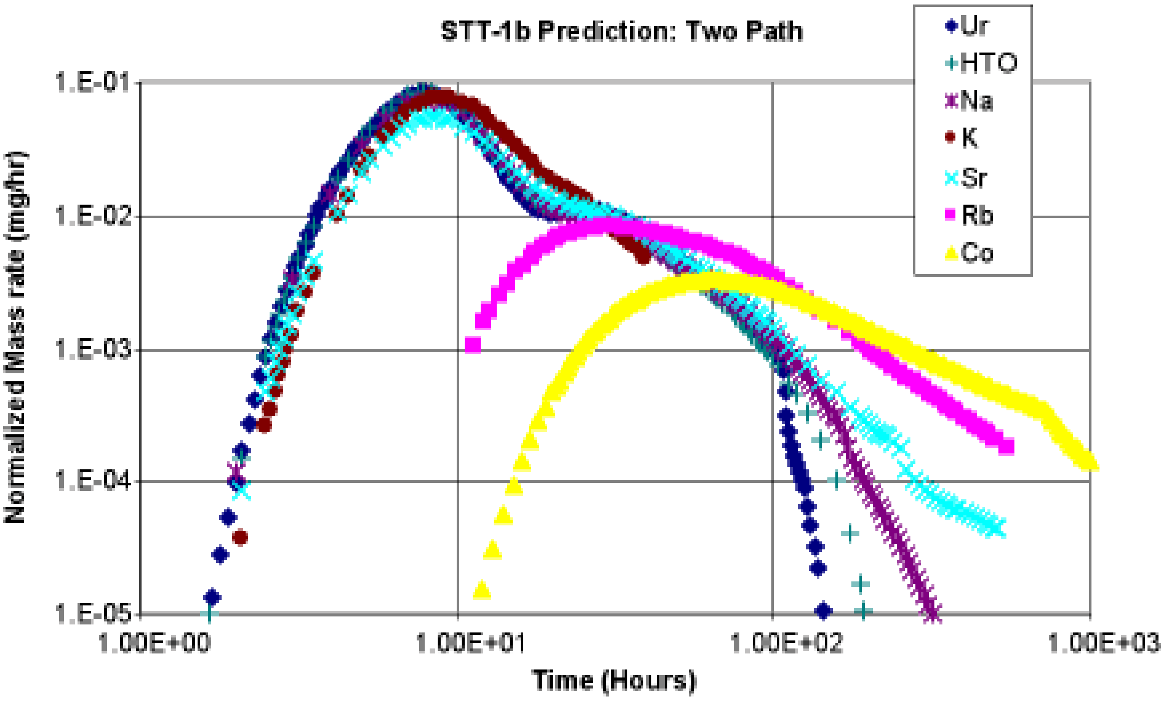


Figure 7-4. *STT-1b Breakthrough Predictions, Task 4eIII.*

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

Background

Task 5 of the Äspö Task Force on Modelling Groundwater Flow and Transport is designed to compare, and ultimately integrate, site scale hydrogeology and hydrochemistry by evaluating the large scale groundwater flow pathways activated by construction of the Äspö tunnels (Wikberg, 1998). This integration is expected to benefit underground radioactive waste repository performance assessment by providing a better understanding of transport pathways at the site scale.

During 1998, JNC participated in Task 5 by developing and demonstrating the PAWorks pathways analysis approach for analysis of combined hydrogeological/geochemical response to reproduce the chemical composition of the groundwater entering the Äspö tunnel. PAWorks pathways analysis procedures developed by JNC during 1998 were designed to predict ratios of four geochemical "end-members," Meteoric, Glacial, Marine and Brine breaking through the Äspö tunnels over time.

Objectives

The objectives of JNC's efforts during 1998 were to:

- Develop a methodology to predict source locations for water recovered to Äspö tunnels.
- Improve understanding of site scale transport pathways using geochemical information.
- Incorporate the effect of varying density into the head solution used to compute the source location of flows into the tunnels.
- Validate the PAWorks pathways analysis algorithms against in-situ geochemical measurements.

Experimental concept

Pathways are identified up-gradient from each of the calibration points and prediction points in the tunnel. These pathways are identified by searching up-gradient from these points, based on the head distribution following construction of the tunnel to 3,600 m. Pathway search identifies every node up-gradient, from the calibration and prediction points to the boundary conditions. This approach is illustrated in Figure 7-5.

These pathways represent the potential sources for the geochemical end-members produced in the tunnels. A depth-first, flux-weighted search is used, which means that the code preferentially follows the higher flow pathways. In the current analysis, the search was limited to finding only twenty pathways per source fracture representing the tunnel calibration and prediction points.

The region modelled by JNC was 2,000 m by 2,000 m in area, with a depth of 1,000 m. This scale was selected to include the Äspö tunnels and extend the boundaries as far as possible given computation time constraints.

The structural model used for these analyses is based on the DFN approach, in which all fluid storage, flow, and transport occurs through a limited subset of "conductive structures" represented by polygonal plates. The structural model is described in SKB ICR 97-03 (Uchida et al, 1997).

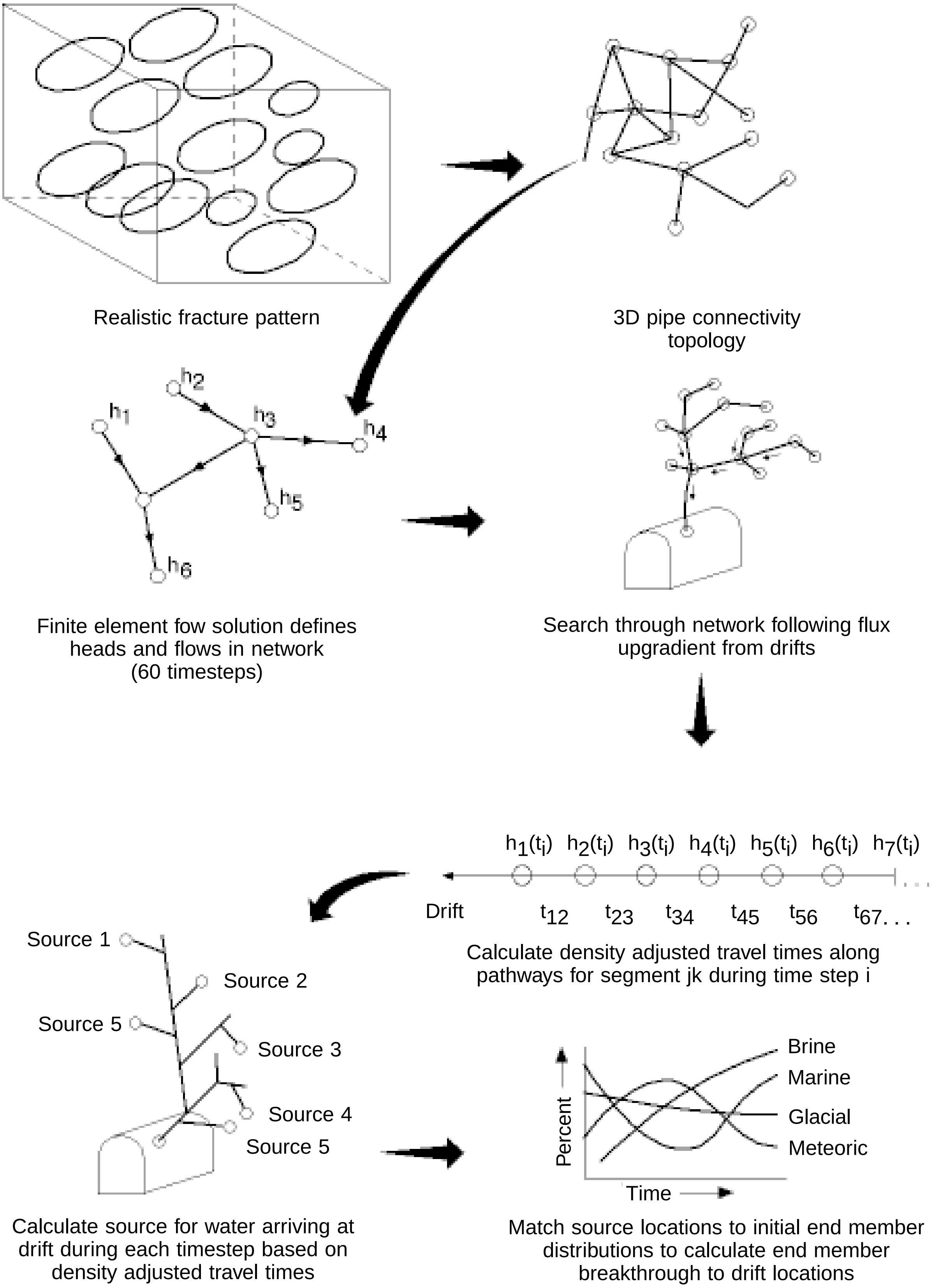


***Figure** 7-5. PAWorks Pathway Analysis Approach for Task 5.*

Results

The PAWorks analysis provides results as the source locations of the water flowing into the tunnels on a monthly basis. These locations have been shown as plots of the source location of the water flowing into the tunnels on a monthly basis. Figure 7-6 illustrates example simulation results for source locations of waters produced to the drift during the first 24 months of construction. Figure 7-7 illustrates an example solution for end-member geochemical breakthrough to the Äspö tunnels during construction.

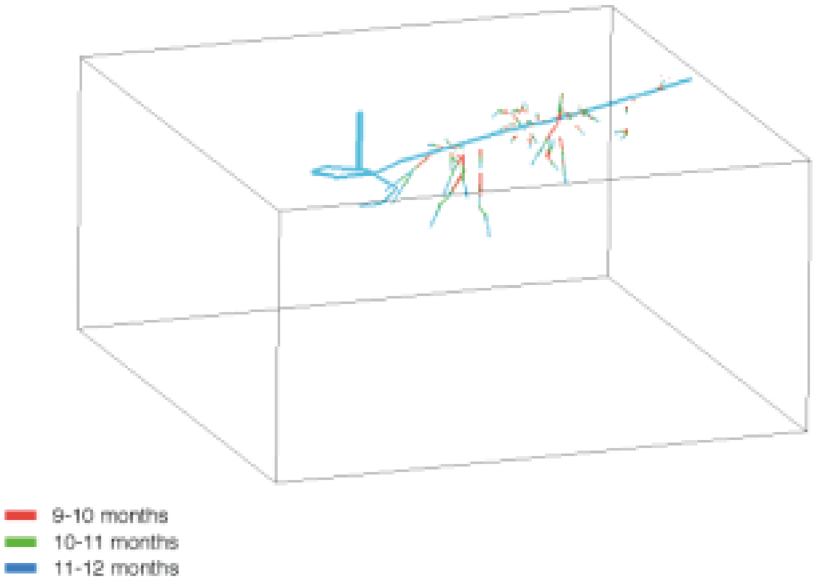


***Figure* 7-6.** *Example Visualization of Source Locations for Water to Tunnel, 9–12 Months.*

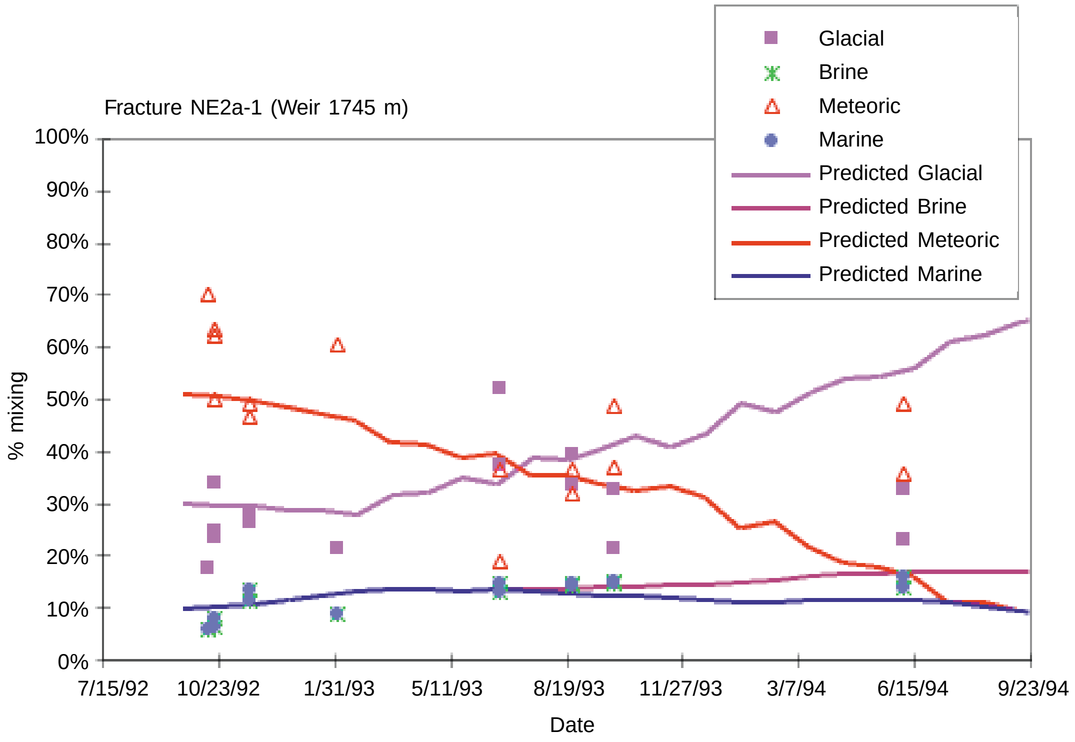


***Figure* 7-7.** *Example End Member Breakthrough, NE2a-1 Control Point.*

Äspö TRUE-Block Scale Experiment

Background

During 1998, JNC started to participate in the TRUE-Block Scale Experiment from the Detailed Characterization Stage. The major activities during 1998 included:

- Analysis of transient hydraulic responses (single well and hydraulic interference).
- Analysis of hydraulic interference (drilling and interference testing).
- Analysis of tracer tests.
- Analysis of fracture data for enhancement of DFN models.
- Preliminary implementation of channel network models.
- Development of hydraulic/structural models.
- Support to Experimental Design (Tracer Tests, Borehole Installations).

JNC's most intensive efforts during 1998 focused on analysis of pressure responses to borehole drilling, and analyses of pressure interference tests (Andersson et al, 1998b), which were performed after the drilling, and instrumentation of the KI0023B borehole. These nineteen interference tests have been reported in Andersson, et al, 1998b, and cover testing activities between March 11 and May 20, 1998.

Objectives

A major goal of JNC activities for TRUE-Block Scale during 1998 was to use hydraulic data to infer the locations and conductive features in the experiment areas. Over the past two years, the project has developed a structural model of the geologic features in the block (Hermanson, 1998). This model has synthesized data from cores, borehole television logs, other geophysical measurements, and flow logs (Winberg, 1998). During 1998, JNC assisted the project in integrating hydraulic data to update the structural model.

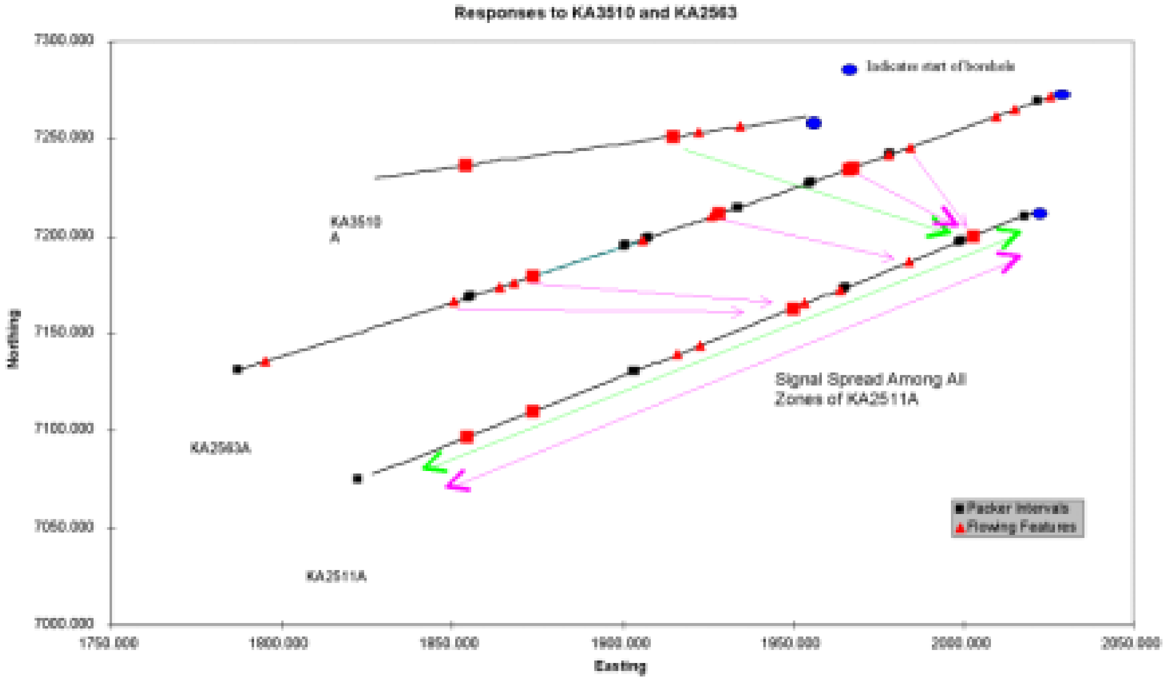
Experimental concept

Drilling is an invasive process that changes the hydraulic geometry of a flow system. The effects are particularly strong (1) when drilling from underground locations and (2) when drilling in rock with a fracture-dominated flow system. Under these conditions the borehole "short-circuits" conductive features at relatively high pressures (or potentials) to the underground openings, which are at atmospheric pressure.

Individual conducting features or fracture networks may be isolated hydraulically from underground openings until borehole penetrations make the connections. When a borehole intersects a conducting feature, the flow rate to the hole being drilled increases, and the pressure in observation holes that are connected to the conductor decreases. The careful analysis of the timing of these flow changes and pressure responses is a powerful tool for mapping conductive features.

Results

The primary result of JNC efforts during 1998 was to support updating of the project's structural/hydraulic model, which provides the basic framework for all project activities. Figures 7-8a and 7-8b illustrates these results.



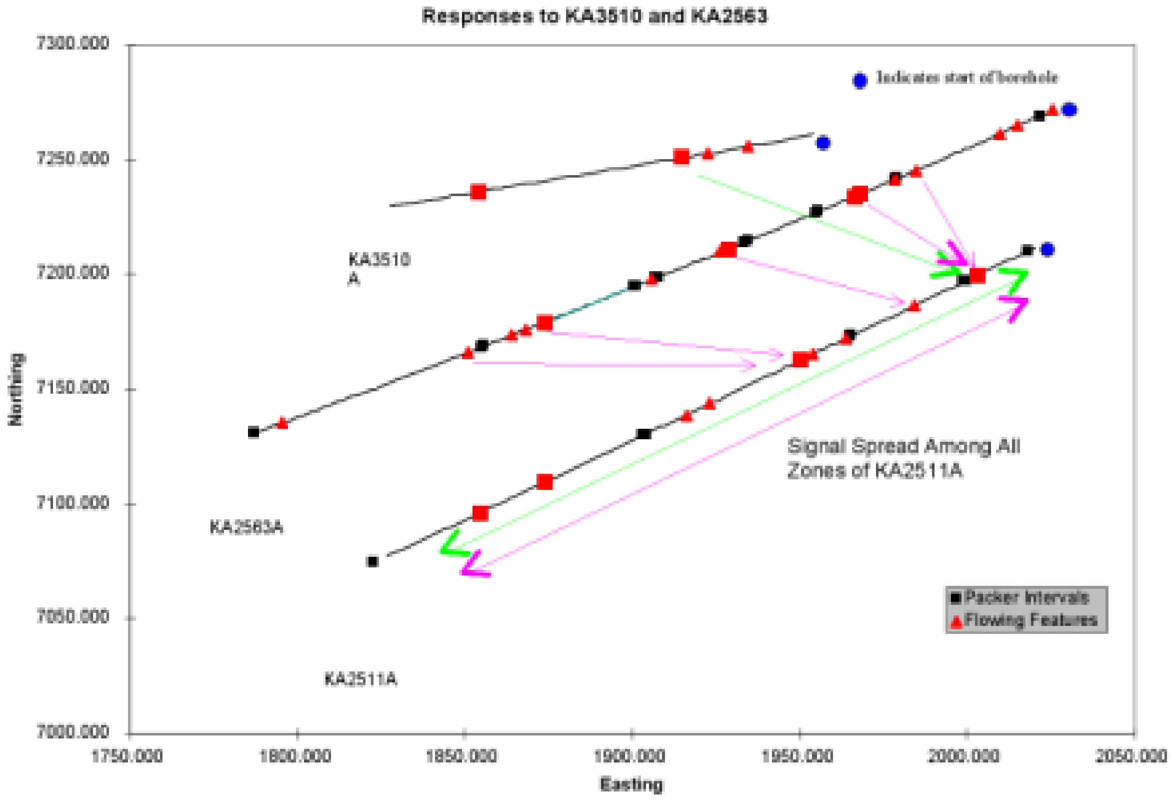
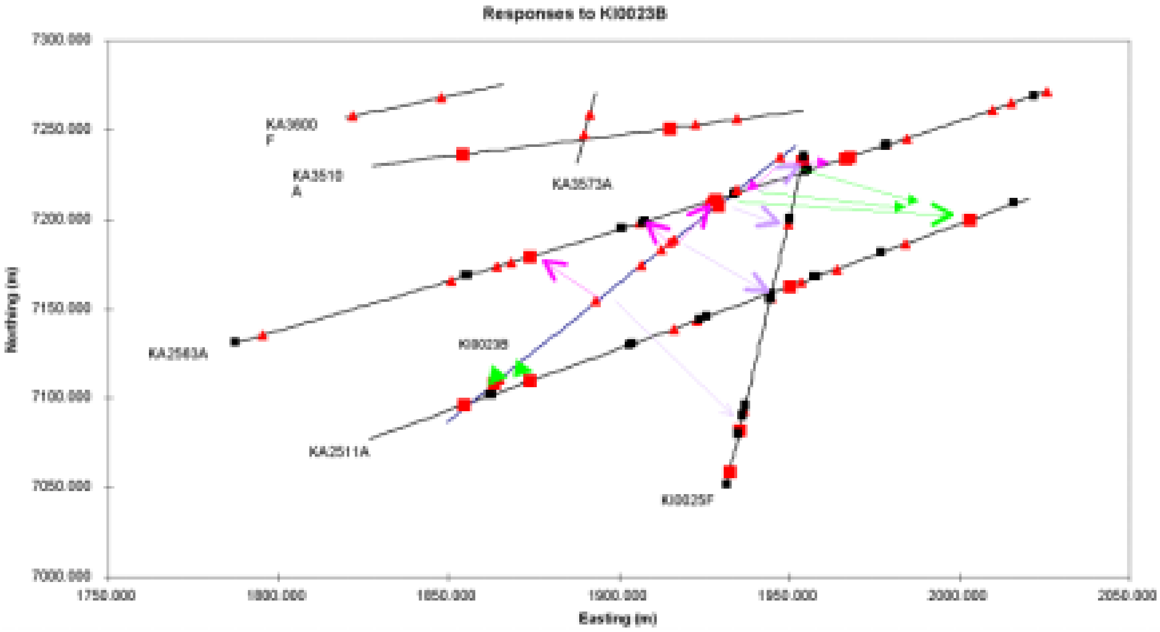


Figure 7-8a. *Horizontal Plane Visualizations of Hydraulic Connections and Conductors Interpreted from Pressure Responses to Drilling.*



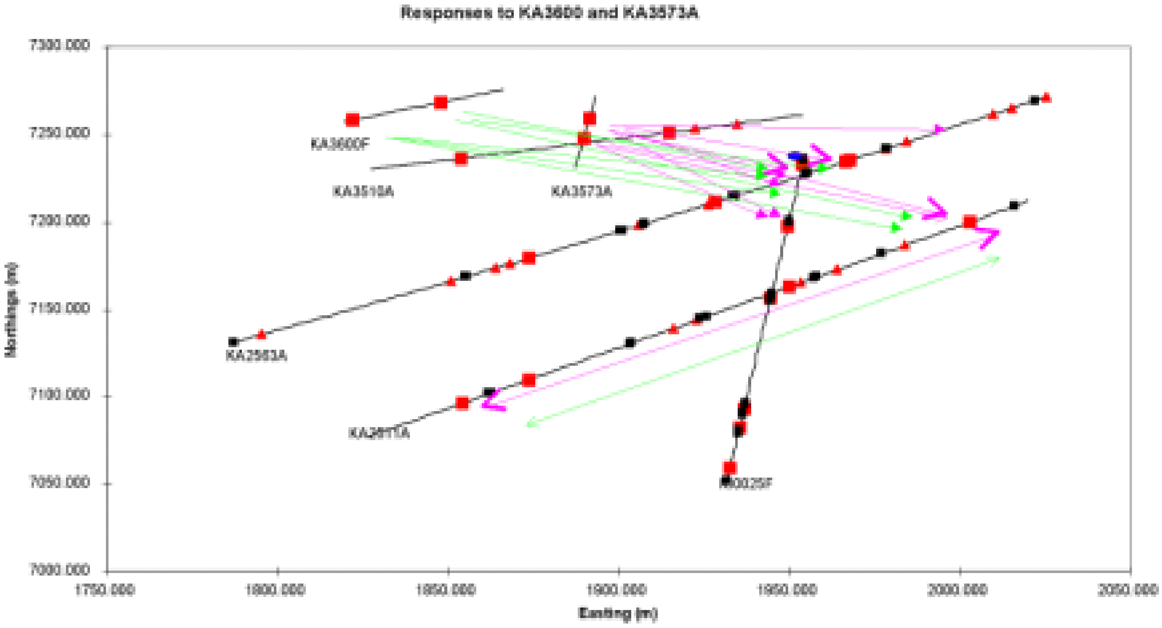


Figure 7-8b. *Horizontal Plane Visualizations of Hydraulic Connections and Conductors Interpreted from Pressure Responses to Drilling.*

In the analysis a number of conductors with a high hydraulic conductivity compared to the surrounding rock, and with consistent distance-drawdown relationships have been identified. Three main types of distinct conductors were identified from the analysis.

1. A near-collar, major NW zone readily identified in all boreholes (including KA3510A, KA3573A and KA3600F). The width of this zone is in the order of tens of meters.
2. Three well defined discrete conductors traceable between KI0023B, KI0025F and KA2563A.
3. One isolated conductor connecting the bottom of KI0023B with the bottom of KA2511A.

In addition to these inferred conductors, a conductive feature appears to provide hydraulic connections along the length of KA2511A. The shallowest zones of this hole respond strongly to the near-collar conductive interval described above, and this response propagates rapidly to all the intervals of KA2511A. Subsequent to this initial "hit", all of the intervals of KA2511A have similar pressure responses. Furthermore, the hole does not appear to respond to drilling interference responses from other conducting zones, except for a strong connection to KI0023B in a conductor at the bottoms of these holes where they have their closest passage.

7.2.2 Redox Experiment in Detailed Scale (REX)

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.

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.

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 1996.

For Year 1, a series of batch experiments and a complete interpretation of the results were conducted. For Year 2, a series of flow through columns have been set up under anaerobic conditions. Early in year 3, it was found that the columns containing bacteria were blocked. Preliminary investigations suggest that the blockages are caused by microbially mediated mobilization of "fines" and secondary smectite formation. In stead of the column experiments, continuously stirred tanks reactor (CSTR) experiments have been started in this year (Year 3). The final interpretation of the results on CSTR experiments will be conducted early in 1999.

Results to date

1. The anaerobic batch experiments have been shown that bacteria from the HRL site have an effect on groundwater chemistry and there appears to be a link between their presence and primary mineral dissolution. The sulphate reducing bacteria appeared to have a greater effect on groundwater chemistry than the iron reducers.
2. Both sulphate reducing bacteria and iron reducing bacteria grew in the low nutrient environment albeit for a limited period because of the sealed nature of the systems.

7.2.3 Kamaishi Mine In-situ Experiments Concerning Earthquakes

Introduction

At the Kamaishi Mine, earthquake occurrence and groundwater pressure were monitored over a span of eight years from 1990 to 1998 to ascertain the relationship between earthquakes and changes in groundwater pressure. The results showed that the greatest dynamic fluctuation in groundwater pressure associated with earthquakes was in the main dynamic element of the seismic S-wave. It also became clear that the maximum amplitude of groundwater pressure corresponded to the change in maximum velocity amplitude.

Observation outline

Water pressure was monitored by placing water pressure strain meters at the opening of three bore holes (lengths ranging approximately between 390 m and 540 m) drilled horizontally from the 550 m drift of the Kamaishi Mine. AD conversion was made of the water pressure data at 10-second sampling time in order to examine the static fluctuation in water pressure. Upon occurrence of an earthquake, digital record was taken with AD conversion made at 200 Hz sampling time along with monitoring of the acceleration rate obtained from the seismometer placed near the bore hole opening.

Observation results

Over the eight-year period, 344 earthquakes were observed. Among them, 92 earthquakes with maximum acceleration above 1 gal and maximum change in water pressure greater than 0.03 kgf/cm^2 were analyzed as below.

1. Comparison of Seismic and Water Pressure Waves. Since the short period component of over 10 Hz were predominant in the observed seismic waves, a 10 Hz high-cut filter was applied before comparing the seismic and water pressure curves. Compared to the water pressure wave, the acceleration wave in either case was dominated by the short period component and thus the two waves cannot be said to have any resemblance. In the case of velocity wave obtained by once integrating the acceleration wave, the curves do not resemble one another, but the major phases and peaks parallel more closely those of the water pressure wave than of the acceleration wave. This trend becomes more conspicuous when the seismic S-wave is at a simple wave form.
2. Relationship Between Seismic Wave and Time Lag in Maximum Fluctuation of Water Pressure. The static change in water pressure occurs in stepwise pattern upon occurrence of an earthquake as reported by Shimizu et al (1996). However, the water pressure returns to its original level within approximately one week.

3. The dynamic change in water pressure also occurs in the initial part of P-wave. However, the greatest change in water pressure is seen in the major dynamic part of S-wave when the fluctuation in seismic wave is at its highest. To verify this point, the time lag was examined between the maximum fluctuation in seismic wave and maximum change in water pressure. It was found that the time lag between the peak point of the acceleration wave and that of water pressure change was distributed around 0 second with a one second margin, provided there is a slight difference depending on bore holes. In the case of the velocity wave, the water pressure showed a tendency to reach its maximum level within one second after the velocity wave reached its peak.

4. Relationship Between Seismic Wave and Maximum Fluctuation in Water Pressure
   There is a direct correlation between maximum seismic wave (average between the two horizontal components) and maximum water pressure change. The relationship between the two is especially conspicuous in velocity, showing a clear correlation as compared to acceleration. It can be thus said that the dynamic change in water pressure is proportional to velocity in seismic motion.

5. Mechanism of Dynamic Water Pressure Change Triggered By Earthquake
   Up to now, the S-wave was considered not to involve change in volume and thus an S-wave was not expected to cause any change in water pressure. However, as indicated by the above results, dynamic change in water pressure is assumed to occur in proportion to the major dynamic element of the S-wave. Water pressure undergoes a change in the following cases: (a) when the rock volume changes; and (b) when a sonic wave of an observable level occurs in the water within the borehole upon occurrence of an earthquake. As for the latter if the wavelength of the sonic wave triggered by an earthquake within the borehole is approximately the same as that of the bore hole length, considerable water pressure is estimated to occur. The task yet remains to ascertain the mechanism of dynamic water pressure change accompanying an earthquake.

7.3 Summary of work by Posiva

7.3.1 Introduction

Posiva Oy, was founded in 1995 by the Finnish power companies Teollisuuden Voima Oy (TVO) and Imatran Voima Oy (IVO) to manage the final disposal of their spent nuclear fuel. At present the site selection process is at it's final stage called detailed site selection and four sites are being characterised for the site selection in 2000. The Project Agreement, called Joint Project, was prolonged for the years 1998–2000 and it covers the cooperation of SKB and Posiva in the Äspö HRL today.

The work within the Joint Project comprises three main areas:

1. Detailed investigation methods and their applications for modelling the repository sites.
2. Test of models describing the barrier functions of the bedrock.
3. Demonstration of technology for and function of important parts of the repository system.

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

The following text comprises the work done in 1998 according to the Joint Project and the TBS agreement:

7.3.2 Detailed investigation methods and their application for modelling the repository sites

Evaluation of flow measurement methods for characterising the underground flow

Posiva and SKB have a joint interest in testing the usefulness and applicability of different investigation methods for potential use in characterisation of future repository sites. The objective of the subtask a) is to test the flow measurement methods for characterising the hydraulic properties of the bedrock close to the tunnel walls and the groundwater flow in-situ at a greater distance.

In connection to the task PRG-Tec Oy carried out measurements with Posiva Flowmeters in two boreholes at Äspö HRL. Difference flow measurements (DIFF) were conducted in boreholes KA3510A and KA2598A. Both boreholes were first measured using detailed logging mode. The method provided a detailed distribution of the flow in the boreholes and the depth and thickness of the water conductive zones/fractures with a depth resolution of 10 cm. In borehole KA3510A difference flow measurements were continued with 5 m section length in chosen sections. Hydraulic heads and conductivities were calculated on basis of the results.

Transverse flow measurements (TRANS) were carried out for the first time in underground conditions with the Posiva Flowmeter. The equipment is constructed to measure flows across a borehole in fractures or fracture zones. The measurements were performed in borehole KA3510A. The representativeness of the results obtained was questionable because of the technical problems encountered due to the high-pressure gradient towards the tunnel, which caused leakage around the additional packers causing uncontrolled flow conditions.

The results obtained with DIFF and TRANS measurements and the technologies will be compared with other methods used earlier for similar purposes in characterising hydrogeological properties of the bedrock in the same boreholes.

7.3.3 Test of models describing the barrier functions of the bedrock

Task Force on Modelling Groundwater Flow and Transport

Posiva Oy has participated the work done in the Task Force on Modelling Groundwater Flow and Transport of Solutes. Work has been done both in Task 4 and Task 5.

In Task 4 the subtasks 4C-D have been reported and concluded in the Äspö ICR Report series 98-03: Modelling of the tracer tests in radially converging and dipole flow fields in the first phase of the TRUE project by Antti Poteri and Aimo Hautojärvi. The difficulty to predict tracer tests without proper knowledge on the flow field was noticed. The flow field is especially with low pumping rates and far away from the discharge location very sensitive to the background flow field. The heterogeneous transmissivity distribution of the fracture introduces some additional uncertainties. Nevertheless a reasonably good overall prediction and understanding of transport of conservative tracers in a single feature could be demonstrated.

Further the test STT-1 with sorbing tracers has been evaluated and explanations looked for the behaviour of the tracers. Predictive modelling was performed for the test STT-1b and presented in the 11th Task Force meeting.

For Task 5 (Impact of the tunnel construction on the groundwater system at Äspö, a hydrological-hydrochemical model assessment exercise) the model used in Task 3 was updated and some preliminary calculations done using the code FEFTRA. The code is used to solve both the coupled equations of pressure and concentration and the transport equations of the different water types. The model was calibrated using data from boreholes at Äspö. Main flow directions can be determined from the calculated pressure contours. The reporting is in preparation and a draft report "Task 5: Groundwater Flow Modelling Concepts" by Eero Kattilakoski, VTT Energy, December 1998 has been distributed.

TRUE Block Scale

In the TRUE Block Scale project Posiva has assisted with participating the Steering Committee and Technical Committee work to guide the project together with the Project Manager and other participants. The modelling work contribution has been planned to be focussed on transport problems and tracer experiments, which will start in 1999.

The flow difference measurement techniques (flow logging) using the Posiva flowmeter has been applied to find out and characterise in detail the fracture intersections with the boreholes where flow takes place and seen at the same time in BIPS images. This provides a good basis for the detailed planning and designing of the tracer tests. The equipment was used also to check for flow connections by opening and closing a distant borehole and registering possible flow changes. Clear signals could be seen and they are analysed in the project teams. The work done first in the borehole KI0025F02 is reported in ÄHRL Technical Note TN-98-35b and parallel in Posiva R&D Report 98-12.

The detailed characterisation phase has resulted in a well-established geological, structural and hydraulical model of the TRUE Block site. The flow observations by means of dilution tests will determine finally the possible configurations for the oncoming tracer tests.

Hydrochemical stability

Posiva participates in the *Hydrochemical Stability Project* aiming at clarifying the general hydrochemical stability of importance for the site performance. Basically the aim is to get an overall understanding of the geochemical evolution of the groundwater, by characterisation and evaluation of the present conditions and factors affecting these. This will form the basis for the evaluation of future evolution of the groundwater. The project is scheduled for the years 1997–1999 (2000). The final report is planned to give the procedure for how hydrochemical stability can be assessed at any repository candidate site, based on the evaluation of site specific conditions at Äspö and other investigated sites in Sweden and Finland.

The groundwater evolution-modelling project will quantify the processes taking place in a repository system, in order to deal with the questions mentioned above. The modelling test plan was defined in 1998. In addition to Äspö the sites to be interpreted are Kivetty, Olkiluoto and Romuvaara from Finland and Finnsjö and Gideå from Sweden. For the Finnish sites extensive geochemical interpretation and modelling are available. The reference data are used to extend over the disturbed situations which are expected at Äspö during the next glacial cycle over the next 100,000 years and these are used in the model calculations for Äspö. Geochemical modelling of the Finnish sites have been concentrated on the reporting for site evaluation to support Posivas site selection. The outcome will be modified in order to fit the Hydrochemical Stability project modelling plan.

Posiva has also participated in the planning and commenting of the test plan for Matrix fluid chemistry. The test started in the borehole at the level of -450 m in the Äspö tunnel in June 1998. Posiva also participated in the Matrix Fluid Chemistry Review meeting in December 1998.

A plan has been set up for future investigations in the deep borehole KLX 02 include the testing of Posivas Difference flow measurements and PAVE groundwater sampling equipment to depths of 1,400 m. In addition to testing of equipment the results of the measurements are essential for the understanding of the hydrogeological, hydrogeochemical properties of the borehole and its surrounding. The third goal of the investigation is to provide additional knowledge to the general understanding of the origin and the stability of the deep highly saline groundwater and especially in case of KLX 02 for saline waters at depth below 1,100 m.

The *Hydrochemical Stability Project* also includes the SKB and Posiva participation in the EC EQUIP project as well as the modelling Task 5 within the framework of the Äspö Task Force for Groundwater Flow and Transport of Solutes. The Task 5 modelling is planned to principally be performed according to the integrated approach of geochemical mass balance modelling and numerical flow simulation as in the earlier Redox block scale work. Posiva also contributed by a paper to the Äspö Special Issue of Applied Geochemistry (Pitkänen et al "A combined Mass-Balance Flow Simulation Exercise of the Redox Zone at Äspö").

In addition several papers on the Finnish Site investigation programme and recent results from Hästholmen and Olkiluoto (Anttila et al, Ruotsalainen & Snellman, Rouhiainen, Saksa et al) were presented at the 3rd International Äspö seminar in June 1998.

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

Characterisation of excavation disturbance around full-scale experimental deposition holes

In a nuclear waste repository, rock in the excavation-disturbed zone adjacent to the walls of deposition holes for waste canisters is one potential pathway for the transport of corrosive agents and radionuclides. Rock characteristics in the excavation-disturbed zone also play a role in saturation of the bentonite buffer and in gas release. To assess the characteristics of rock in the disturbed zone, three experimental holes of the size of deposition holes (depth 7.5 m and diameter 1.5 m) in a KBS-3 type repository were bored in hard granitic rock in the Research Tunnel at Olkiluoto. Details of the boring technique, previous characterisation of the excavation disturbance caused by boring, and the He-gas method have been reported earlier.

The characterisation of the excavation disturbed zone by using He-gas and ^{14}C-PMMA methods together with scanning electron microscopy and porosity determinations was continued in 1998. The work included further development of the ^{14}C-PMMA method, which has improved the accuracy of the technique. To study the accuracy of porosity values determined by using the ^{14}C-PMMA method reference porosity measurements were carried out for a set of paired samples representing three different types of rock by using different techniques according to the round robin approach. The paired samples included one sample with disturbance and one without.

He-gas methods were used to establish the degree of rock disturbance in terms of porosity, effective diffusion coefficient and permeability. Measurements were based on either the diffusion or flow of helium through a rock sample saturated with nitrogen gas, and included porosity determinations using He-gas pycnometry. Two types of sample geometries were used for He-gas measurements. Disc samples with a central hole (i.e. rings) were used to establish the total permeability and diffusion coefficient. Cubic samples were used to measure the same properties in two different perpendicular directions.

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 45° to the schistocity. Studies of the microstructure of the rock carried out using SEM, fluorescent microscopy and ^{14}C-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 summary reporting of the characterisation of the excavation disturbed zone adjacent to the walls of experimental full scale deposition holes is in progress and shall be finished in 1999.

Excavation disturbance caused by TBM excavation

The properties of the disturbed zone around deposition tunnels may have an effect on the groundwater flow and the transport of radionuclides. To study the disturbance caused by TBM-excavation at Äspö a set of 8 samples was taken from the Äspö TBM tunnel at selected locations. The samples have been studied in 1998 by using ^{14}C-PMMA method, petrographical thin section microscopy and scanning electron microscope. The work, which is being reported at the moment, involved also determination of physical properties of the rock.

In-situ failure test

The aim of the work is to develop a method to carry out in-situ failure tests and to assess the applicability of the present numerical modelling techniques used in the design of the deep repository. The experiences have shown that even if conventional numerical modelling methods imply rock failure, it may well be a quite localised phenomena and in many cases the deformation of underground space has tendency to find the proper stable state and shape. Experiences from deep underground facilities such as deep mines in crystalline rock have proved that it is feasible to construct underground facilities even if rock failures occur upon condition that the deformation of rock reaches a stable state.

To be able to design stable underground space in high stress environment the mechanisms and processes that cause the rock to fail has to be understood. The key factor in assessing the stability of the excavated opening in case of failure is to be able to define if the deformation of rock can be controlled and reaches a stable state by seeking a favorable shape of opening, which has been observed many cases in the field, or if it turns out to be a violent rock burst the worst case. In any case rock fracturing must occur for the rock to be damaged and therefore a significant component in the progressive failure is fracture propagation. The modelling of progressive failure should therefore include mechanism for simulating fracture propagation.

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. One of the main tasks in the in-situ failure test is to carry out modelling of rock failure in the in-situ failure test by using a conventional modelling method without fracture propagation and a more sophisticated method capable of modelling the fracture propagation process. The failure of the test geometry and results of modelling shall be compared and evaluated.

The preliminary design of the failure test carried out in 1998 was the first phase of the in-situ failure test and included a study of the rock strength, in-situ rock stress with respect to sample size, orientation and saturation state. The work included also – as the first step in the design phase – the modelling of the failure test in three dimensions (3D) by using Flac^{3D} code and a complementary modelling using a modified test geometry, which was carried out in 1998. Other tasks included in the work were study of rock properties, study of in-situ stresses and development of technique to use the expansive agent. The reporting of the design of the failure test, which shall summarise all the studies carried out by the end of 1998 is in progress and shall be completed before the actual field test starts.

7.4 Summary of work by UK Nirex

Background

United Kingdom Nirex Limited (Nirex) has provided support from AEA Technology plc to provide modelling support 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

Nirex's support has taken the form of establishing:

- a reasonable site-model, that includes the influence of the HRL, tunnel system and Äspö island; and
- a local scale model of the TRUE Block on a 500 m scale.

During 1998 a site-scale model has been established that includes both the discrete features of the site (fracture zones) and the effects 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 7-9 shows a site model showing the salinity distribution with a representation of background fracturing (to account for groundwater flow into and out of the rock mass between the large-scale features). The blue area shows the fresher water area associated with the presence of Äspö island. The red area indicates the deeper saline waters.

At the TRUE Block scale, fracture network models, based on the site structural model, have been used to understand the results of experiments performed in the TRUE Block. This has included the hydraulic responses observed in existing boreholes at the TRUE Block site due to drilling-induced drawdown of newly constructed boreholes (for example borehole KI0025F02). An interpretation of these responses has helped the process of identifying the connectivity between various parts of the block. This is useful as a first step in preparation for later hydraulic interference testing and tracer testing. An illustration of the spatial distribution of responses is given in Figure 7-10 This is a plan view of the TRUE Block site (the red lines indicate the trace of the fractures identified in the structural model). The spheres illustrate the position of the centres of packer intervals, the colours represent their relative drawdown, largest drawdown is red, the least drawdown blue. The path of the drilled borehole is illustrated by the largest diameter white cylinder.

The spatial distribution of drawdown show some interesting behaviour. Some packer intervals deeper into the block show larger drawdown than those intervals closest to the hydraulic disturbance caused by drilling. This type of observation provides information on overall connectivity of the block and helps design later stages of the project.

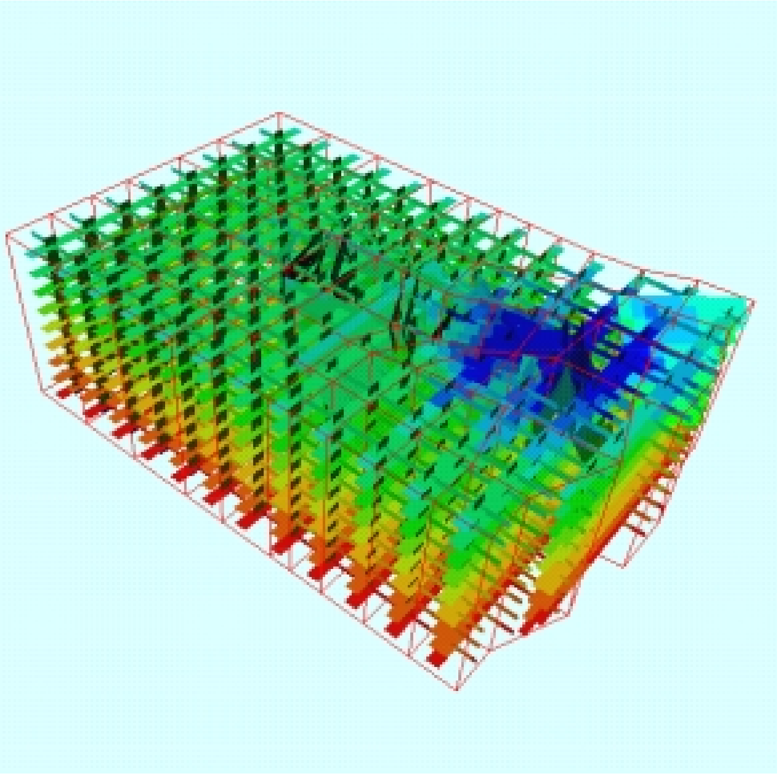


Figure 7-9. *A site-scale fracture network model showing the distribution of salinity.*

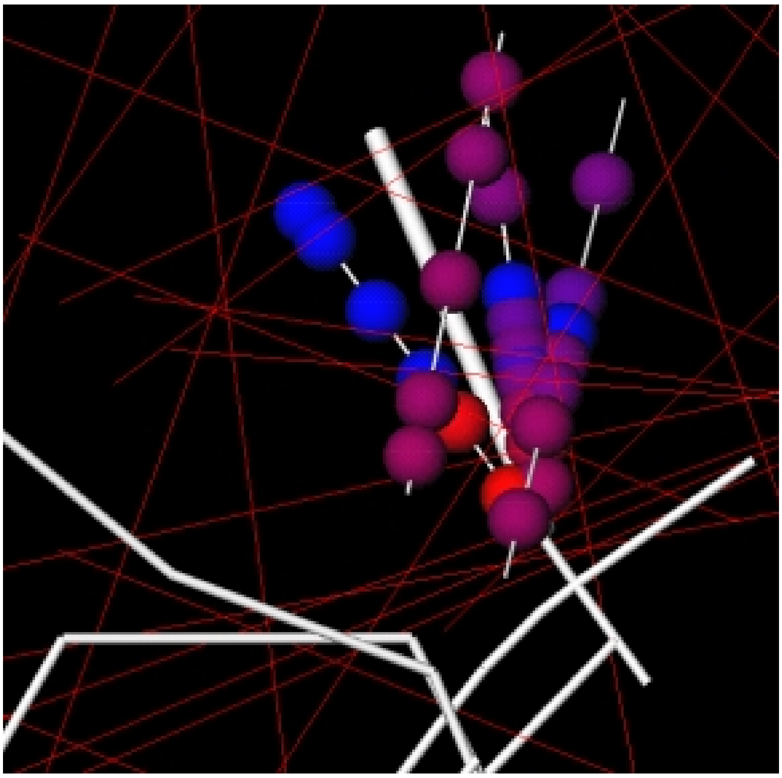


Figure 7-10. *An illustration of the spatial distribution of hydraulic responses due to the drilling of borehole KI0025F02.*

Future modelling work will concentrate on the design, understanding, and prediction of tracer experiments to be performed in the TRUE Block.

Scope for 1999

Future modelling work in 1999 will concentrate on the design, understanding and prediction of tracer experiments performed in the TRUE Block. In particular, this will cover:

- Transfer of existing structural models to the NAPSAC software (scheduled to be completed in February-Task 3.3.92).
- Perform a review of the stochastic continuum work performed as part of the TRUE Block Scale Project (scheduled to be complete in April-Task 3.3.10.2).
- Using the updated NAPSAC structural model to devise test designs (scheduled to be complete in April-Task 3.3.11.1).
- Perform interpretation of cross-hole and dilution tests (complete May-Task 3.3.12.1).
- Perform additional predictive modelling as part of the tracer test stage planned to take place in the Autumn of 1999.

It is anticipated that additional modelling activities will be undertaken on behalf of the TRUE Block Scale Project but at the time of writing this has not been finalised.

Further Collaboration

Nirex is interested in the possibility of links between the Äspö HRL programme and European Commission supported projects and will support the development of projects which address important, safety-relevant issues or aspects of repository design which are relevant to the disposal of long-lived intermediate-level wastes (TRU).

7.5 Summary of work by BMWi

7.5.1 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. Four research institutions are performing the work on behalf of BMWi: BGR, FZK/INE, GRS, and TUC.

7.5.2 Activities performed in 1998

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 2,715 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 3D-simulations of a multiphase-multi-component system, and the computer code "GMTM Tracer Transport by Gas Flow" was tested.

Task Force on modelling of groundwater flow and transport of solutes

BGR continued its participation in the international modelling activities concerning the simulation of tracer transport in fractured water conducting rock in Feature A of the TRUE testfield by modelling and interpreting the behaviour of radioactive and sorbing tracers. The results were presented at the 11th Task Force Meeting and at the ICHE'98 in Cottbus, Germany.

BGR's activities concerning Task #5, hydrogeological and hydrochemical modelling to study the effects of tunnel construction on the Äspö groundwater system, were continued. In 1998, a flow and transport model was made to study five partly connected fracture systems.

Geochemistry

TUC is working on problems concerning the mobility of radionuclides in crystalline rocks. The investigations deal with 1) the mobilization and immobilization of selected trace elements in different granitic rocks and fluids and 2) the mobilization behaviour of Uranium and Thorium as natural analogue for the actinide mobility in granitic rocks by investigating secondary carbonates.

Based upon the analyses of rocks and minerals, the mineralogical composition of all samples was calculated. The material exchange between primary and secondary phases caused by the interaction between hydrothermal solutions and rock in the mm-range was determined.

The content of trace elements in the mineral phases titanite, biotite and calcite was analyzed by Laser-Ablation-Mass-Spectroscopy. Biotite and calcite contain only minor amounts of lanthanides, Hafnium, Thorium, and Uranium, but, both phases show a remarkable content of Barium, Rubidium, Cesium, and Cobalt. Additionally, fine dispersed aggregates of REE-enriched phases were detected. The content of epidote in Äspö granites was analyzed. Epidote becomes unstable by incorporating trace elements available in the hydrothermal solutions and transforms into allanite. The epidote concentration in the granites can be considered as measure for the retardation capability of granitic rocks against trace elements.

28 calcite samples were isolated from Äspö-granite drill cores and analyzed by RDA and ICP-MS. 17 samples mainly consist of calcite, whereas 11 samples contain a large amount of impurities like quartz or fluorite.

8 samples were analyzed by TIMS with regard to the Uranium and Thorium distribution and the secular equilibrium. For all samples investigated a disturbed secular equilibrium was observed. The disturbance occurred during the past 60,000 to 400,000 years.

The FZK/INE activities comprise geochemical investigations dealing with the behaviour of natural colloids and the transport of radionuclides, esp. Actinides. In 1998, the work was concentrated on laboratory experiments to prepare the in-situ “Actinide Retention Experiment”. Batch and column experiments were performed to study the sorption and migration behaviour of Americium, Neptunium, and Plutonium within samples from a fractured Äspö-granite. For Neptunium the influence of redox-kinetic was observed, therefore additional experiments are necessary and will be carried out. First experimental and modelling results are available to describe the hydraulic performance of a fracture.

Using groundwater samples from the Grimsel test site, the mobile LIBD-device which will be used in the measurements of colloid transport was tested.

A measuring cell to be used in the CHEMLAB-experiment was developed and tested.

Underground measurements methods and instruments

The characterization of a fractured rock area by geoelectrical tomography was continued and the interpretation of data was improved by inverse modelling. In the ZEDEX-area the test drift was prepared for resistivity measurements. The investigations to determine the gas content and gas release from rock and formation waters were continued. The composition of released and water-dissolved gas was analyzed. Nitrogen is the most important dissolved component of the formation water. By heating drill cores, the gas components bound in the rock were determined. (The experiments are carried out in connection with the two-phase flow experiment).

7.6 Summary of work by ENRESA

7.6.1 Local permeability measurements in a selected zone of the backfill

Purpose of the experiment

The purpose of this part of ENRESA's contribution is to develop and test a dynamic pore pressure sensor based on the piezocone principle, for the direct measurement of local saturated permeability in the backfill. The sensors will be installed in a specific section of the 30/70 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.

Theoretical approach

Basic equations of the pulse test

The measurement of backfill permeability using mini-piezometers may be performed using *variable head* or *constant head* techniques. From a theoretical point of view both cases were analytically solved by Gibson (1963) on the basis of the following assumptions:

- Spherical piezometer (this condition may be relaxed by using appropriate intake factors).
- Rendulic's hypothesis regarding total stress changes during consolidation (this assumption is strictly correct if the behaviour of the soil is linear isotropic elastic).

Another possibility is to make use of the extensive hydrogeological literature on transient analysis of permeability borehole tests (e.g. Cooper et al, 1967; Bredehoeft and Papadopulos, 1980; Sageev, 1986). The solutions have very similar characteristics but the hydrogeological authors invariably assume radial flow, a reasonable assumption given the large lengths of the borehole intervals generally tested. Given the limited dimensions envisaged for the mini-piezometers, it is felt that Gibson's analytical solutions provide a more adequate basis for preliminary design, although the differences with the solutions using the radial flow hypothesis are small.

Concentrating on the *variable head test*, it is assumed that a sudden rise (or reduction) of piezometer pressure will be applied. Afterwards, the variation of water pressure versus time will be monitored until an equilibrium value similar to that existing before the test is sufficiently approached. From a practical point of view, the interpretation of these tests is sometimes difficult and dependent on the use of a good performance procedure. In this section, only theoretical issues are addressed.

According to the analytical solution, the equalization ratio of the water pressure depends mainly on the combined non-dimensional variable µT where:

$$\mu = \frac{F^3}{16\pi^2}\frac{m}{f}$$

$$T = \frac{16\pi^2}{F^2}\frac{kt}{m\gamma_w}$$

The symbols used are:

μ : non-dimensional system stiffness
T : non-dimensional time variable
F : intake factor
k : backfill permeability
t : time
f : pressure measurement flexibility
γ_w : water density
m : soil compressibility

The intake factor (*F*) depends on the geometry of the piezometer tip. Assuming a cylindrical shape and a length/diameter (L/D) ratio of 2, *F* can be approximately estimated as:

$$F = 4\pi\,(0.346\,L)$$

The pressure measurement flexibility (*f*) is defined as the change of volume required to measure a variation of a unit pressure. It includes the flexibility of the transducer itself, the compressibility of water and the deformability of the entire hydraulic system. The pressure measurement flexibility should not be confused with non-dimensional system stiffness, µ. The latter includes also the backfill compressibility.

It is interesting to compute the value of measurement flexibility required to obtain measurements in a reasonable amount of time. The value of *f* can be calculated from:

$$f = \frac{1}{\mu\,T}\frac{Fkt}{\gamma_{\omega}}$$

It should be noted that the value of *f* is proportional to the permeability of the soil and required testing time.

As an example, let us take a typical case in which the length of the piezometer is 100 mm and the permeability of the backfill 10^{-13} m/s (typical of a bentonite). A value of μT equal to 2 ensures an equalization ratio of over 90% in most situations (Gibson, 1963). Assuming that such a ratio has to be reached in 20 minutes, the resulting measuring flexibility is:

$$f = 2.66 \times 10^{-3}\ \text{cm}^3/\text{MPa}$$

This is quite a small value that may be obtained, for instance, by the compressibility of 6 cm^3 of water assuming the rest of the measuring system to be rigid. No additional elements in the mini-piezometer arrangement are therefore required. If the system is more flexible than that value of *f*, then more time is required to reach the equalization ratio indicated.

Requirements for the measuring system

The theoretical relations presented above show the importance of the flexibility of the system from the point of view of the results. In fact, the low value of *f* has additional consequences for interpretation. The value of μ is quite high (of the order of 2000 for a value of soil compressibility, *m*, of, say, 0.01 MPa^{-1}). One consequence of this is that the test is sensitive to the product *mk* and not to *k* only. Therefore, the determination of hydraulic conductivity requires an independent estimation of the compressibility of the backfill material. In summary, the low value of the backfill permeability leads to the adoption of a fairly rigid measuring system if reasonable testing times are to be achieved. In turn, this low flexibility ratio makes interpretation less straightforward.

If the permeability of the backfill was much higher (for instance 10^{-10} m/s), the value of *f* would be proportionally higher (2.66 cm^3/MPa). This might perhaps require the addition of special testing elements to increase the flexibility of the measuring system. The higher hydraulic conductivity of the backfill also leads to values of μ in the range where independent estimation of permeability, *k*, is possible.

Finally, regarding the pressure to be applied in the pulse, obviously the higher the pressure the more discriminating the measurements can be. However, the pressure applied should be limited by the possibility of hydraulic fracture. Therefore, the maximum additional pressure applied should always be lower than the minimum effective stress at the piezometer location. Ultimately, it will be controlled by the swelling pressure achieved in the backfill after saturation. Total pressure measurements will provide a useful clue to decide the pressure to be applied, although caution should be exercised in order to take into account the possibility of local stress variations near the instrument. A way to avoid the possibility of hydraulic fracture is to lower the pressure in the piezometer instead of increasing it.

In order to be able to measure a wide range of permeability values, a procedure to control the flexibility of the system has been designed. Basically the pipes used in all the circuits are designed to be sufficiently rigid, and their compressibility is neglected if compared with water compressibility. Within the circuit, three water tanks of 10, 50 and 50 litres have been included. The circuit is designed in such a way that those tanks can be connected or not to the system. Therefore, the flexibility of the system is controlled by the volume of water included, and may be changed accordingly.

Design of the measuring system

Transducer design: Measuring principle

The 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 7-11 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.

The DPP sensors will 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

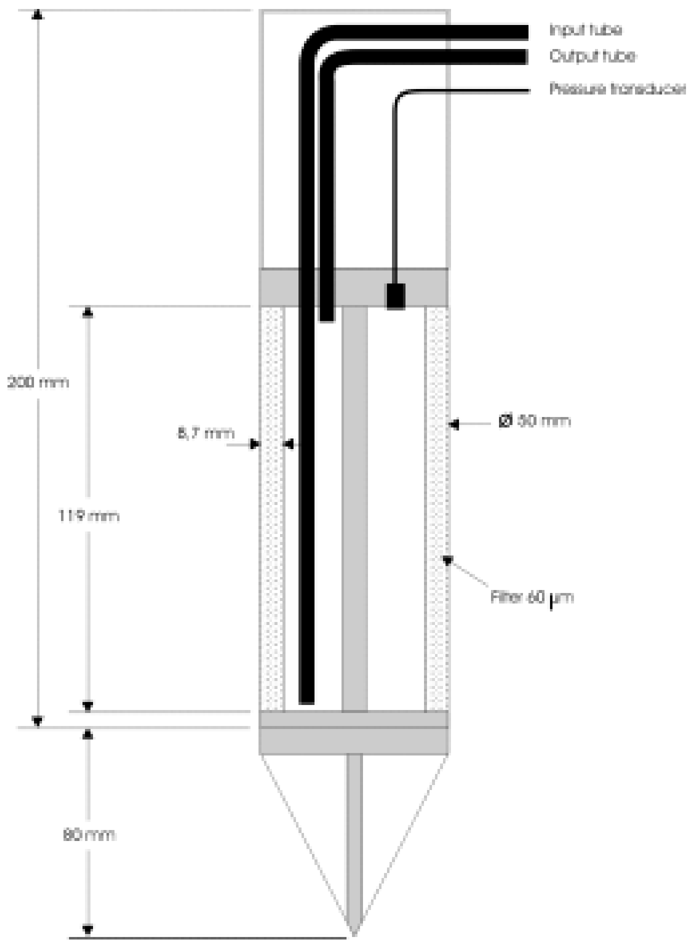


Figure 7-11. *DPP sensor description.*

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 (estimated initially in 13 units), and a common measuring system, which is located outside the backfill area.

The measuring and control system will perform 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 7-12. The two hydraulic tubes of all the DPP sensors will be 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.

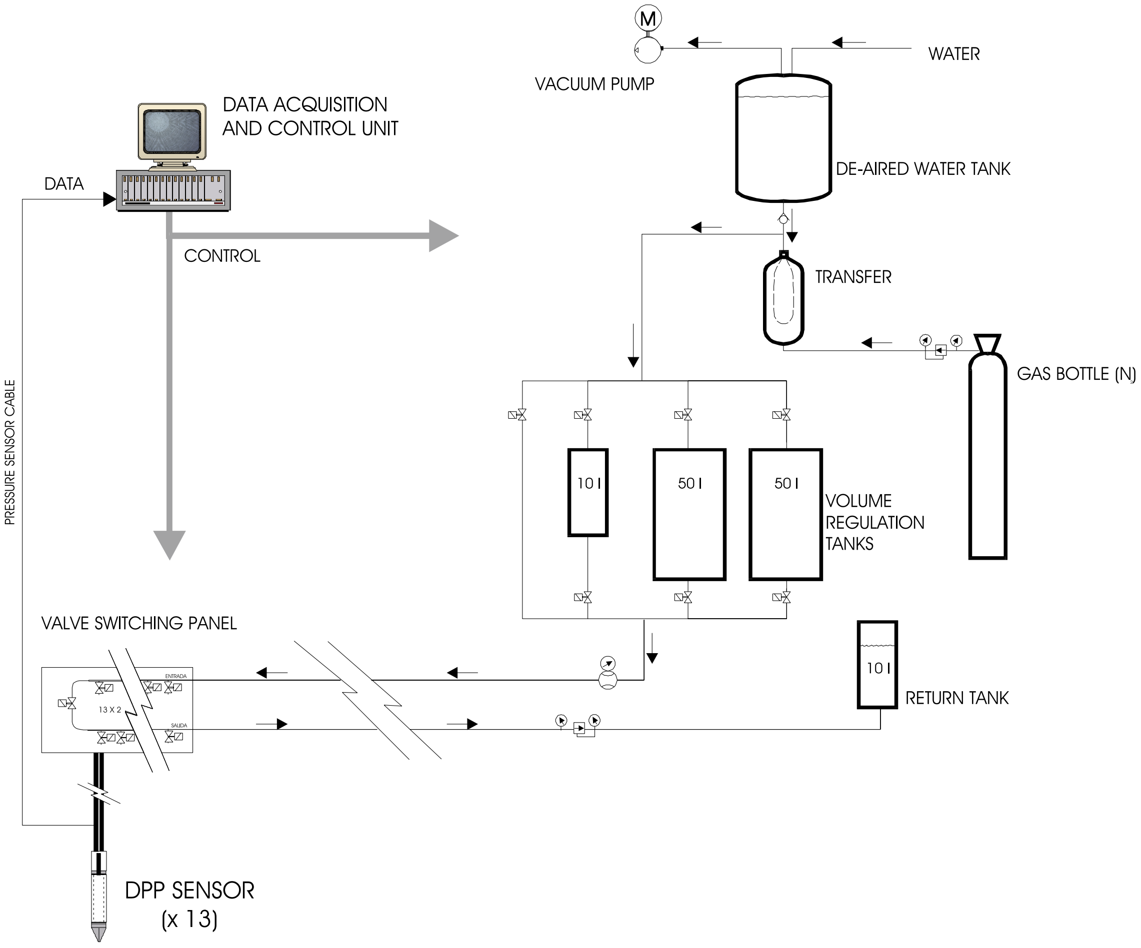


***Figure** 7-12. Control system scheme.*

The switching panel is controlled by the data acquisition and control unit (DAC), which will 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.

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 permeabilities 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 permeabilities. This will be accomplished by introducing in the primary circuit an auxiliary tank (designated as volume control tanks in Figure 7-12). 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 will be 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, which 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 will be carried out manually, although some of the operations will be automated (specially valves control) to simplify the process, making it more accurate and repetitive, and avoid misoperations. Data will be recorded automatically.

Development of the measuring system

System layout

The system layout is given by Figure 7-13.

All cables and tubings from DPP sensors are 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. Figure 7-14 shows the glands distribution on that flange.

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 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 consist on 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 cards and interfaces, ...) integrated inside a cabinet called "data acquisition system".

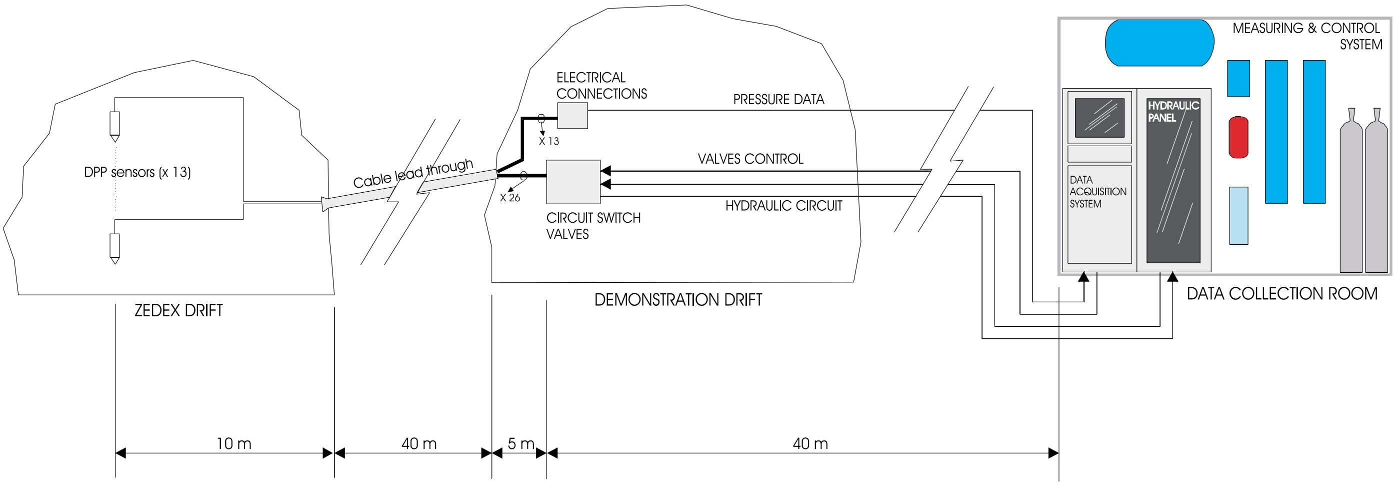


***Figure 7-13.** System layout.*

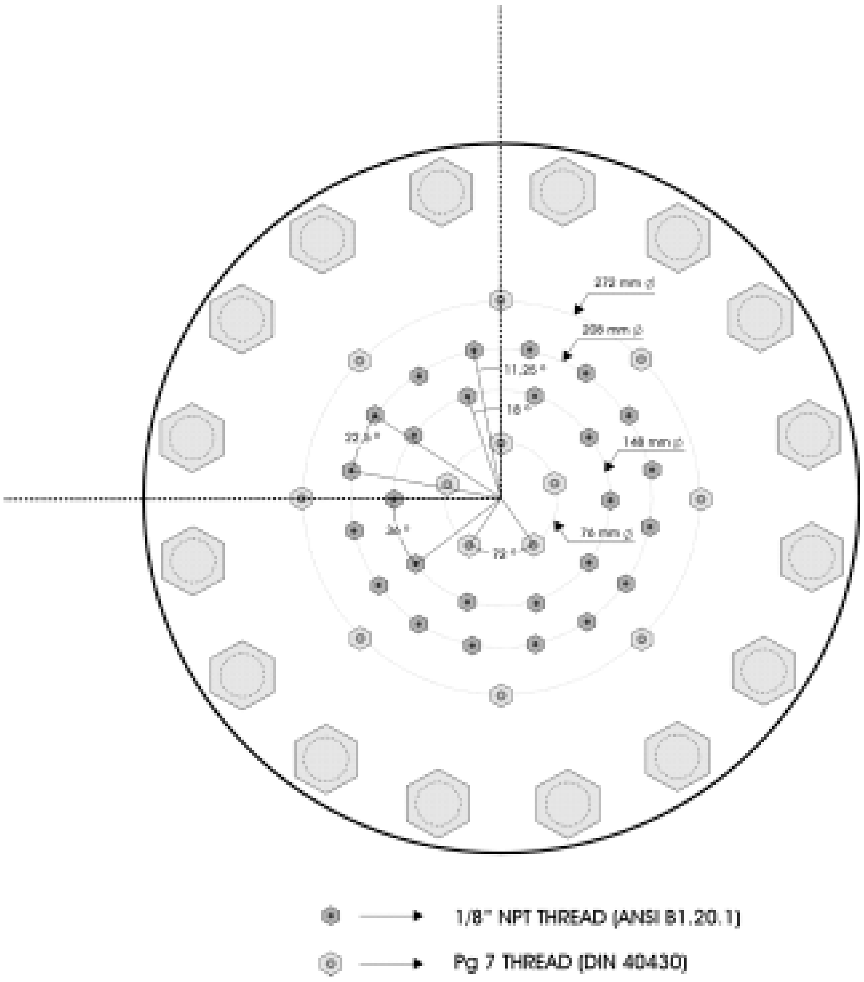


***Figure* 7-14.** *Spanish flange, glands distribution.*

Sensors

After tests carried out in a first prototype, a total of thirteen units have been constructed. All these DPPs have been provided with 60 m long cable and tubings. The construction of a DPP is shown in Figure 7-15.

Measuring and control system

During 1998 the measuring and control system has been completely developed and constructed. All its components (tanks, transfer, vacuum pump, hydraulic panel and data acquisition system) have been mounted in a stainless steel rack. Figures 7-16 and 7-17 gives information about rack dimensions and elements disposition. The obtained measuring and control system is shown by Figure 7-18.

The circuit switch valves box (see Figure 7-19) and electrical junction box have been also constructed.

The acquisition and control software has been developed under Windows 95 and it is based on a commercial SCADA called FIX DMACS from Intellution Inc. (USA). As an example, a control screen is shown by Figure 7-20. The system will be linked with AITEMIN's office in Madrid by modem in order to check sensor measurements from time to time or modify control routines if necessary.

***Figure* 7-15.** *View of a dynamic pore pressure sensor (DPP).*

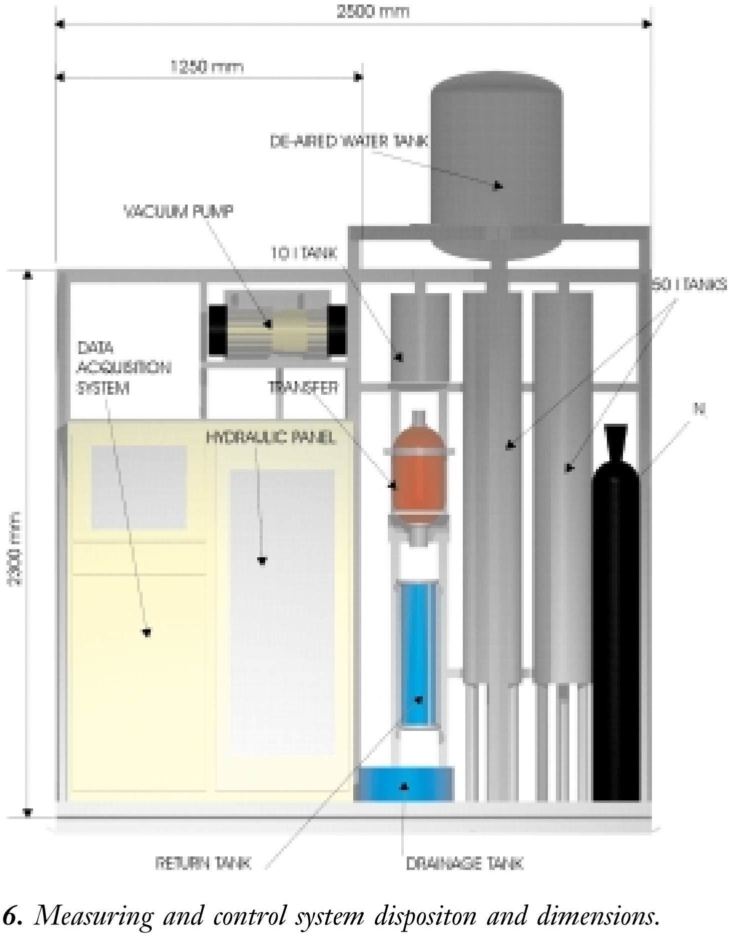


***Figure* 7-16.** *Measuring and control system dispositon and dimensions.*

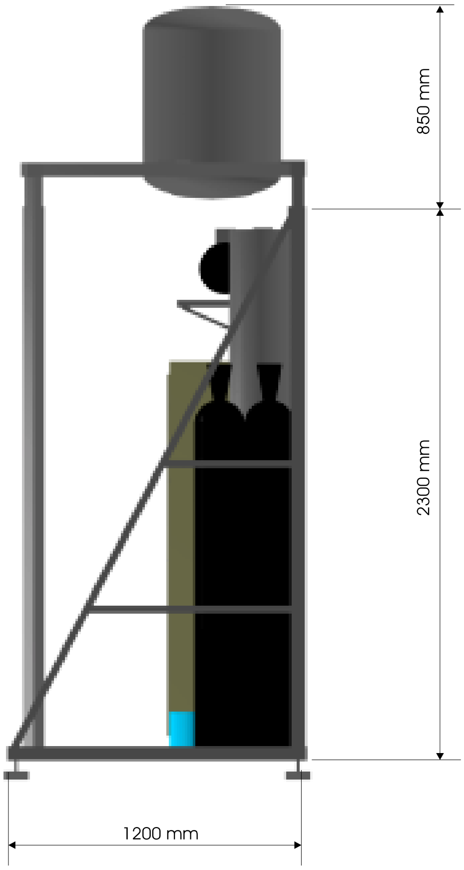


***Figure* 7-17.** *Measuring and control system disposition and dimensions (side view).*

***Figure* 7-18.** *Front view of measuring and control system.*

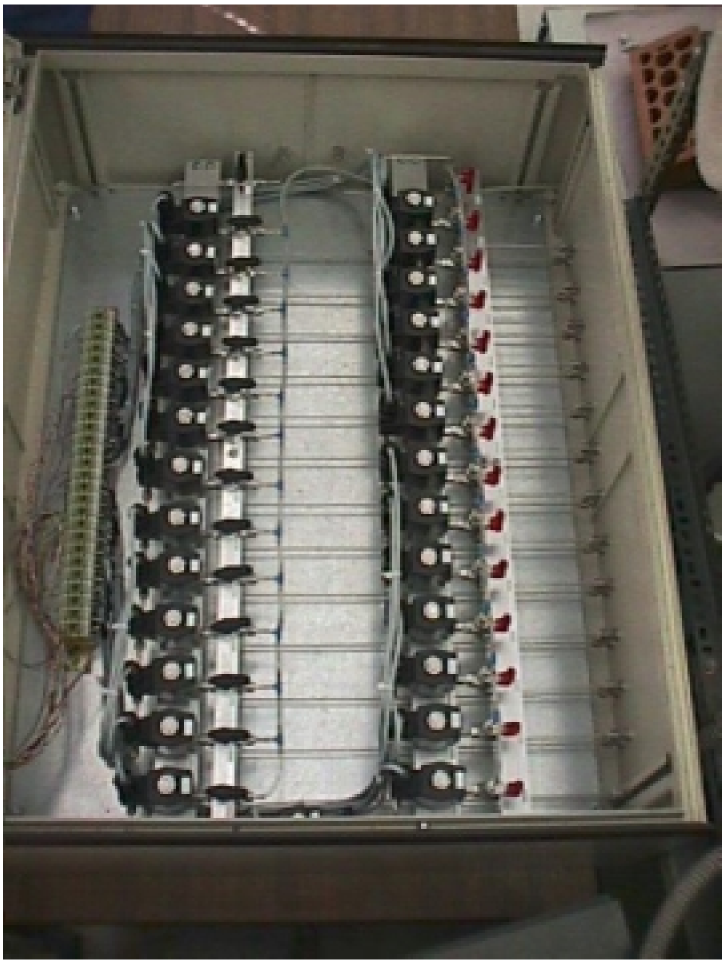


Figure 7-19. View of circuit switch valves box.

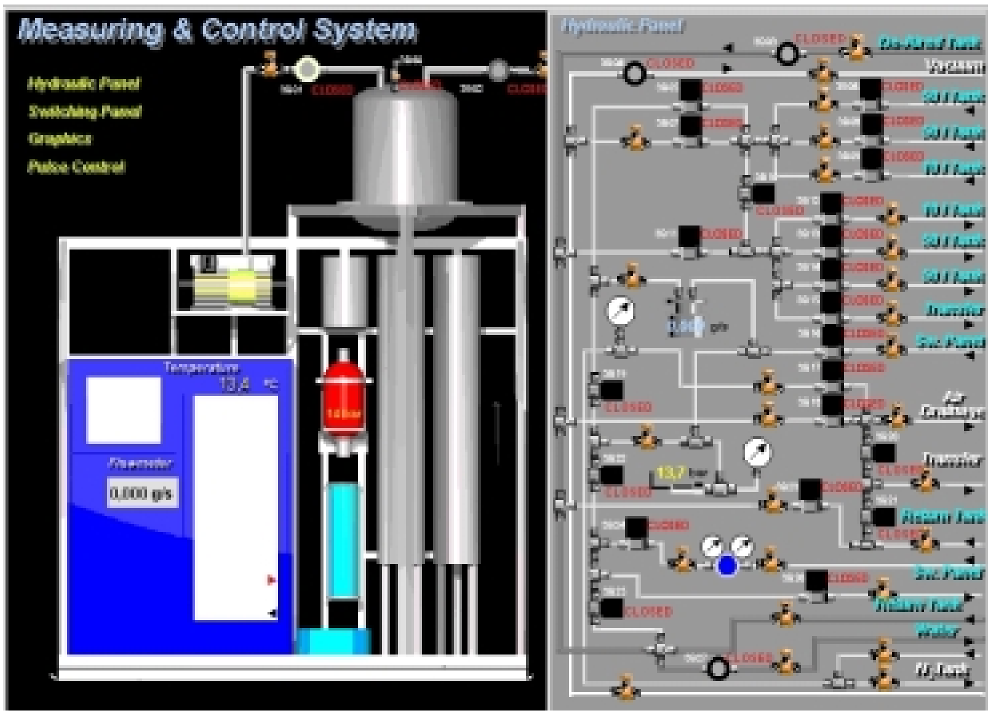


Figure 7-20. Example of control screen.

Field installation

The total number of sensors is thirteen and the measuring points, placed within A4 section of the 30/70 backfill, is given by Figures 7-21 to 7-23.

As it is shown in these figures, to reduce mechanical damage to the DPP sensors, these will be installed in their positions after the corresponding 20 cm thick layer has been compacted, drilling or excavating a well-formed hole for DPP sensor insertion. Special precautions will be taken to keep the walls of these excavations as uniform as possible, to avoid a low density space around the DPPs.

DPP laboratory calibration

Laboratory calibrations of the DPPs have been performed, in order to check the correct behaviour of the transducer. A calibration cell developed by UPC has been used for this purpose. A cross-section of this cell is shown in Figure 7-24.

The DPP sensor (prototype unit) was installed before compacting the mixture material in the cell. The final soil density was similar to that expected in the experiment, and compaction energy has been adopted accordingly.

Soil saturation has been achieved in the cell by flushing water from its top and bottom, and also from the lateral boundary. After 5 months saturation was assumed complete. In fact, that situation was controlled at different times by performing pulse tests. When the material was unsaturated, the final pore pressure at the DPP sensor was smaller than the initial pressure before the test. Then, a few pulse tests were performed, in order to check the reliability of the whole procedure.

A typical result for a pulse test carried out in the laboratory is presented in Figure 7-25. From the water pressure decrease measured at the sensor, the parameters that best simulate those measurements have been found using a least squares identification procedure. Note that the theoretical problem depends not only on the permeability, but also on the compressibility of the material. That is, the values $c_v = 6.67\ 10^{-6}$ m^2/s and $\mu = 6.22$ have been found, which correspond to a confined elastic modulus of $E_m = 534$ MPa and to a permeability of $1.25\ 10^{-10}$ m/s. Note that the flexibility used in this case is due to the GDS equipment that produces the pulse, and it has been estimated in $f_{GDS} = 1.6\ 10^{-13}$ m^3/Pa. The case presented in Figure 7-24 corresponds to a pulse test with pure water and the 70/30 mixture used in the initial experiments.

These results are consistent with the values obtained for the backfill material, and are in the expected range. However, an independent measurement of the permeability and the compressibility will be performed for the material used in the calibration cell by 1999. From the results obtained so far, it can be stated that the DPP sensor is an appropriate tool to measure in-situ local permeability and compressibility. However, additional work will be done in order to check the reliability of the results in different situations.

System calibration

Several preliminary operative tests have been performed using the complete measuring system. The same cell used for the sensor calibration was also used to test and calibrate the measuring and control system. The calibration cell is shown in Figure 7-26. To this purpose, the calibration cell had been saturated to 10 bar before starting the test.

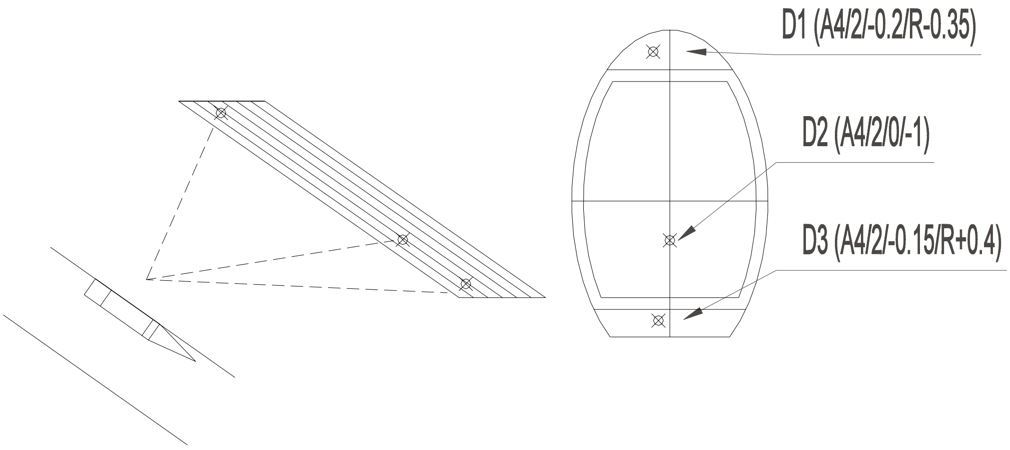


***Figure* 7-21.** *Location of DPP sensors at layer number 2.*

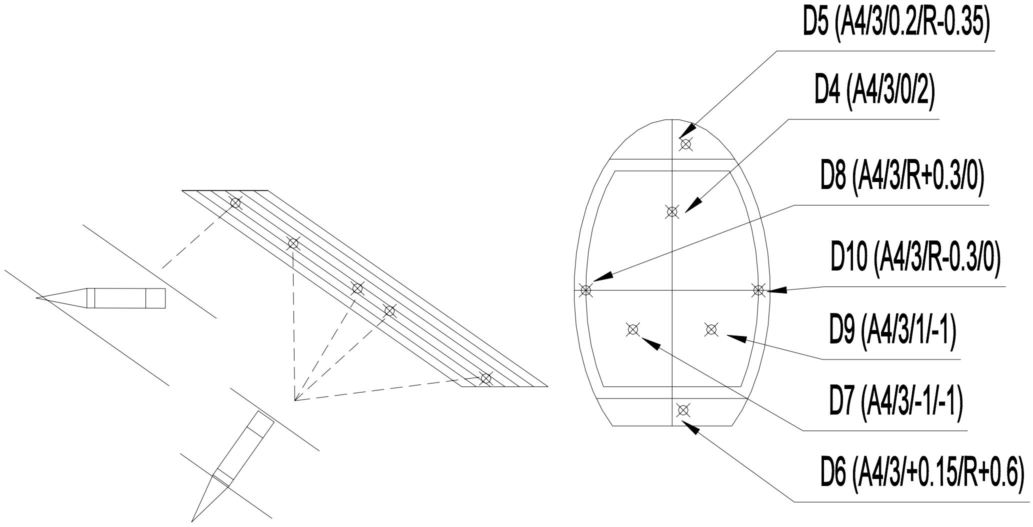


***Figure* 7-22.** *Location of DPP sensors at layer number 3.*

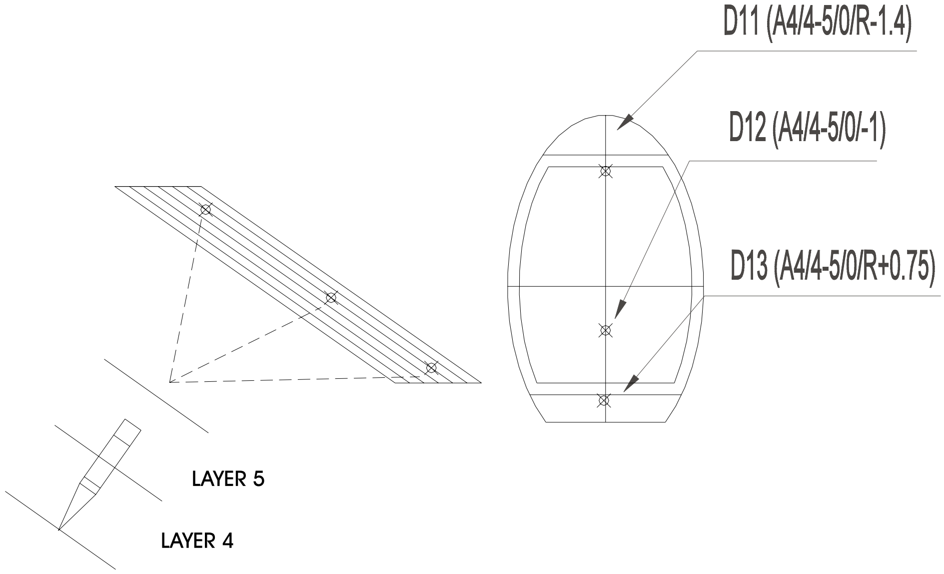


***Figure* 7-23.** *Location of DPP sensors between layers 4 and 5.*

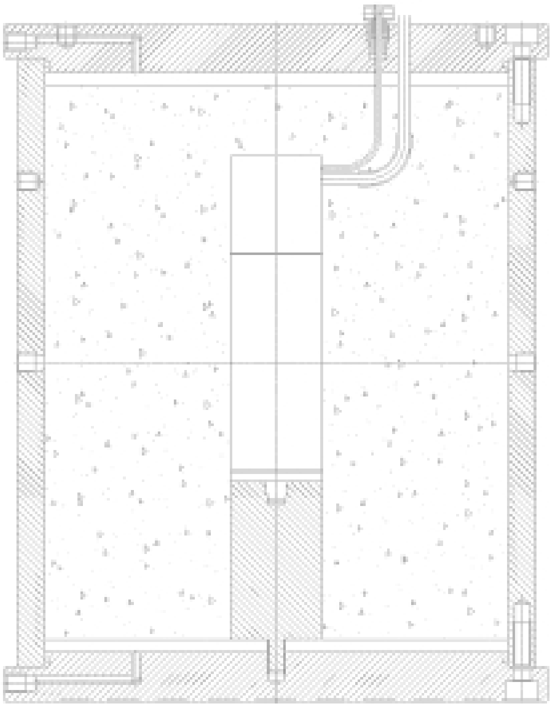


Figure 7-24. *Scheme of the calibration cell for the DPP sensor.*

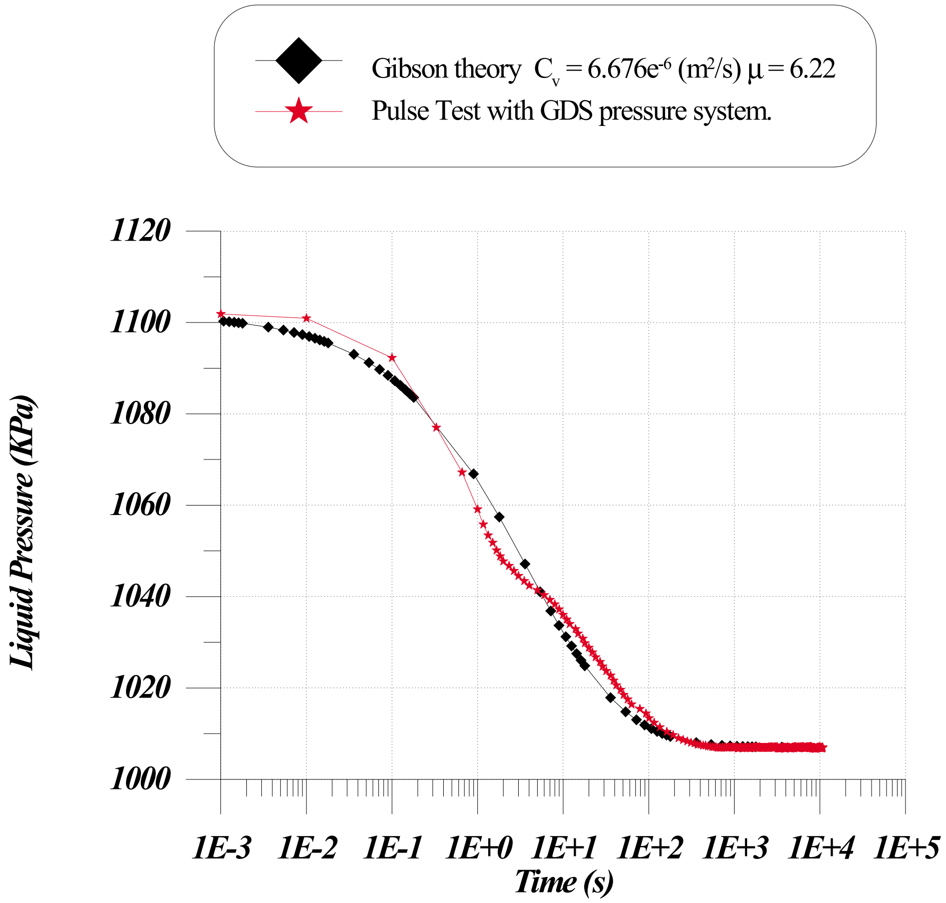


Figure 7-25. *Fitting (least squares method) of a laboratory pulse test performed with a GDS pressure system. The Gibson theory was employed for this analysis (Gibson, 1963).*

***Figure** 7-26. View of calibration cell.*

The calibration tests have been carried out as follows:

First of all, water and air circuits of the system were tested to check they work properly, and water was circulated through the sensor to remove the air in the circuit.

Three type of pulse tests have been performed:

1. Pulse without any tank in the measuring circuit.
2. Pulse with 10 l tank.
3. Pulse with 50+50 l tank.

Pressure and temperature evolution in the calibration cell was recorded and analysed. A record example is shown in Figure 7-27.

7.6.2 Modelling hydration and flow processes in a selected zone

Introduction

The modelling work to be performed by ENRESA refers to a particular slice where the sensors described before will be installed. This modelling work will be performed in four stages:

- scoping calculations,
- pre-operational modelling,
- modelling during performance of the test,
- modelling after dismantling the experiment.

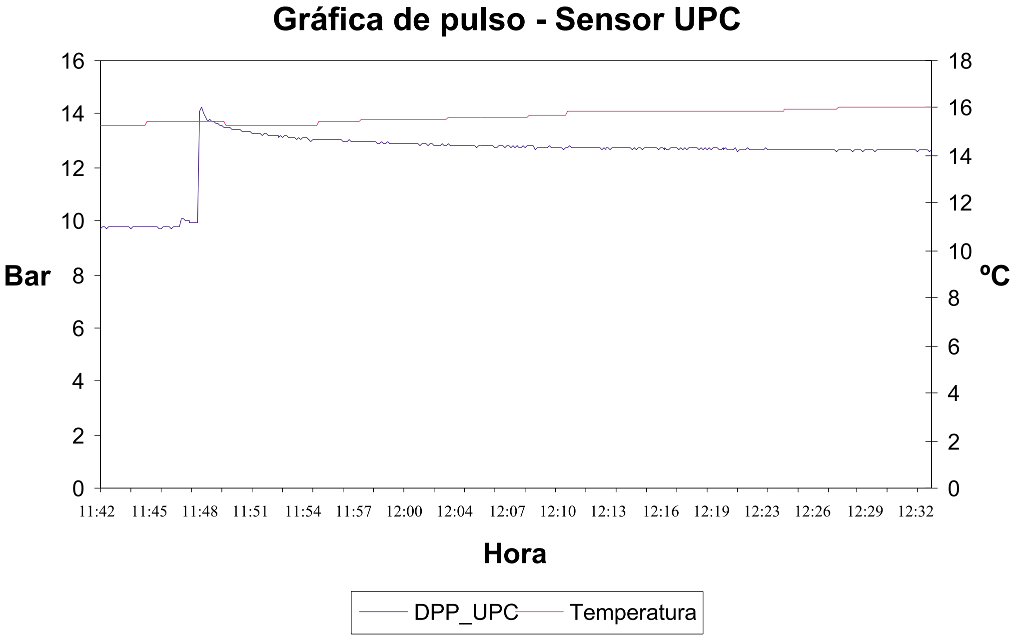


***Figure** 7-27. Pulse record example.*

The problem to be analyzed is of water flow in a deformable, porous, initially unsaturated medium. The water flow affects stress/strain variables (i.e. stresses, displacement, porosity) that in turn influence the hydraulic problem. Therefore a coupled hydro-mechanical analysis is necessary. The computations are being carried out using the computer code CODE_BRIGHT, especially designed "in house" for the analysis of problems associated with radioactive waste repositories. The code was initially developed for saline media (Olivella et al, 1996), but has been extended to cope with clay type materials. An elasto-plastic constitutive model that considers explicitly the effect of deformations due to saturation simulates the mechanical behaviour. Because CODE_BRIGHT is an "in house" development, additional modelling requirements may be accommodated.

During 1998, modelling work has been devoted to the simulation of the hydration process mainly. This is due to the fact that the protocol for the hydration process has been not defined yet. In fact, the material that is going to be used as backfill, has slightly changed during last months. This has been due to problems in reproducing the grain size distribution and in the mixing procedure. These changes in the material have originated unexpected changes in the material parameters as well, so the scoping calculations have been continuously performed during 1998.

Calibration with laboratory tests

As a general rule, a comparison between the codes used by SKB (code ABAQUS used by CT) and by ENRESA (CODE_BRIGHT from UPC), has been always performed, using a simple 1 dimensional hydration problem as basic case. It corresponds to an experiment performed by CT consisting of a 10 cm soil column hydrated from one side in which the evolution of the degree of saturation with time was measured. During 1997 the test was performed for different initial water contents and for the initial 30/70 material (Äspö

1997 annual report, ENRESA contribution). In 1998, the test was repeated for the new and definite material.

The experimental results showed that the material mixed using the new procedure and the filler, in order to reproduce the desired grain size distribution, had different properties than the previous material used in the tests during 1997. That is, using the same density, similar grain size distribution and the same water content (about 13%), the saturated permeability was found more than 5 times smaller than the original material. The reason for that could be explained in terms of soil structure, which is very sensitive to the mixing technique.

The unsaturated permeability, K_{unsat}, has been estimated using the law:

$$K_{unsat} = K_{sat}\,(Sr)^n$$

where K_{sat} is the saturated permeability, Sr is the degree of saturation and n is a parameter. For the old material, the values obtained in 1997 were (Äspö Annual Report, 1997):

$$K_{sat} = 3.9\ 10^{-11} \text{ to } 5\ 10^{-11}\ \text{m/s}\ ,\ \text{and } n = 10$$

whereas for the new material the values

$$K_{sat} = 4.5\ 10^{-12}\ \text{m/s}\ ,\ \text{and } n = 3.4$$

have found to be more consistent with the experimental results.

Figure 7-28 shows the comparison between the measured water contents in the uptake test and the computed values using these parameters. Note that the corresponding intrinsic permeability estimated in this case is $K_{int} = 4.5\ 10^{-19}\ m^2$.

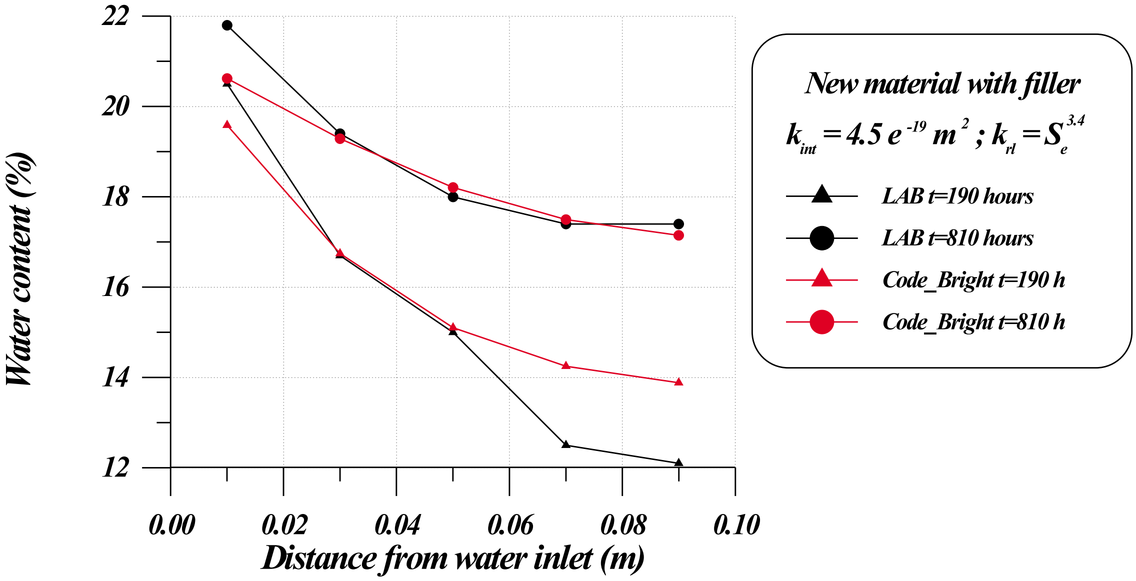


Figure 7-28*. Measured and computed water content profiles obtained in 1_D uptake experiments. This fitting gave us the intrisic permeability (k_{int}) and the exponent (n) for the potential law of the relative liquid permeability.*

Water retention curve for the new material has not been obtained yet, and therefore, the old version has been used instead. However, in order to analyse the sensitivity of the results to that, different curves have also been used in the simulations. Figure 7-29 shows the water retention curves used in the computations: curve (1) was obtained for the old material, and it is expected to be very close to the actual one for the new material.

Scoping calculations

The analyses presented in this report refer to the saturation process. In this case one of the purposes of the simulation is to estimate the time required for reaching saturation under different initial and boundary conditions. This is crucial as the total time needed to carry out the whole project depends directly on the time required for saturation.

The parameters indicated in previous section have been considered. However, it should be pointed out that the results are based on just a few calibrations. Therefore, any further improvement of the hydration simulation will require to perform more laboratory tests, as the parameters are not definite at all.

Three groups of analyses have been carried out regarding the simulation of the backfill hydration. Group A refers to the simplest cases in which only one single section and the surrounding rock has been considered. In group B analyses, two sections with the surrounding rock have been used as basic geometry. Finally, cases corresponding to group C consider two sections without the rock. A simple representation of the geometry used in each case is indicated in Figure 7-30. Note that cases A and B do not take into account the gas phase in the computations, whereas case C does. Also, the simulations from group A assume that water pressure is injected in the right mat, keeping the left mat impervious and assuming seepage boundary conditions on it. Finally, analyses from group B and C consider water injection in all mats so as to speed the hydration process.

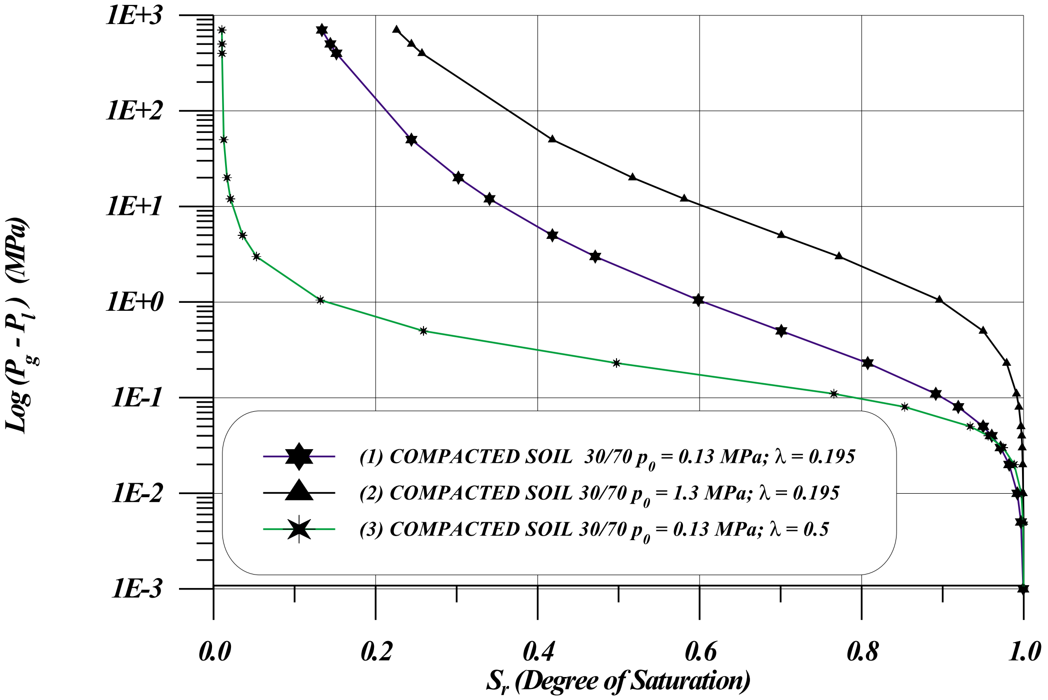


Figure 7-29. *Water retention curves (1), and (3) used in the analyses (PO and l are the parameters corresponding to the Van Genuchten model for water retention curves.*

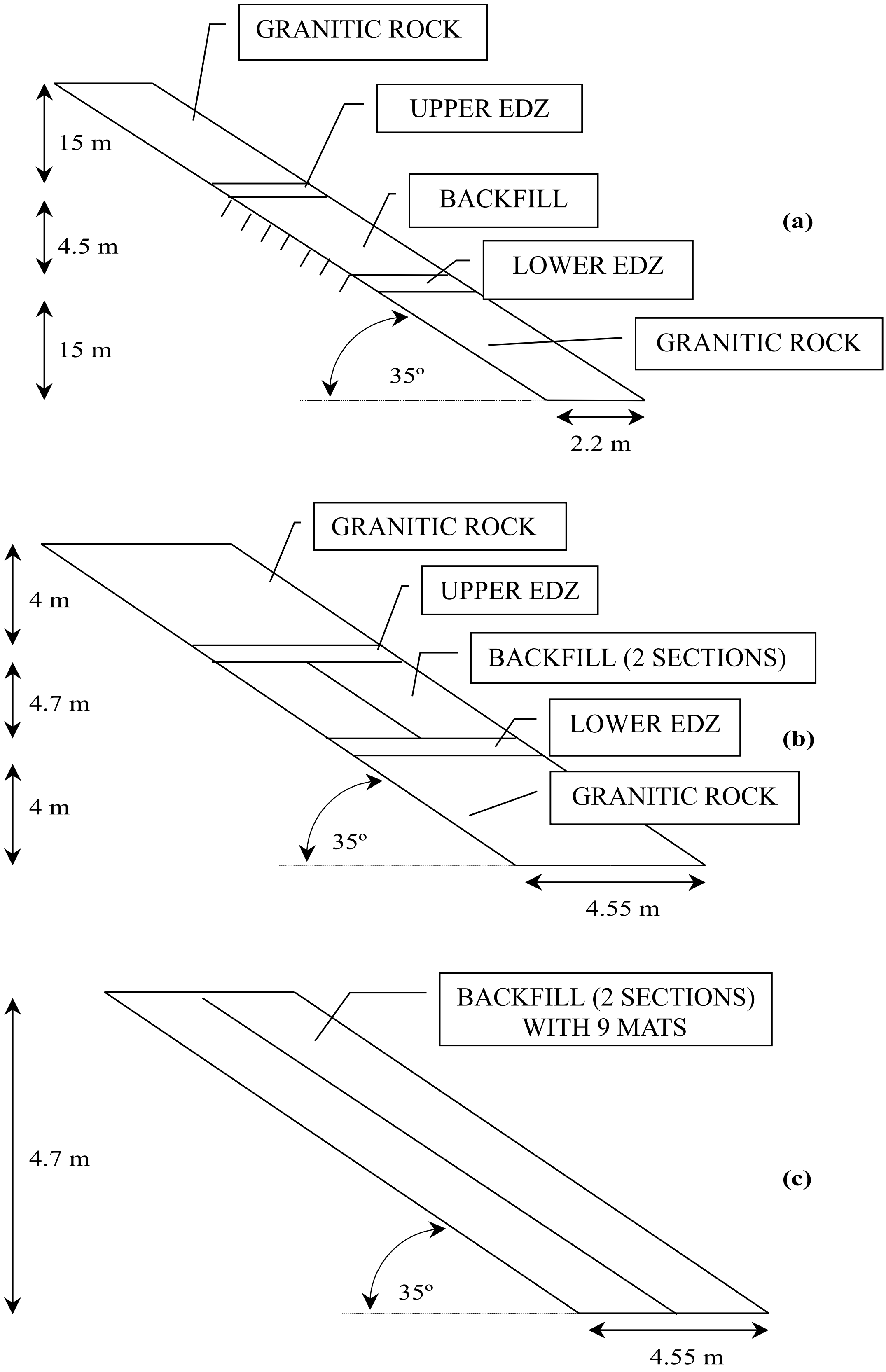


Figure 7-30. *(a) Geometry including one backfill section and the rock. (b) Geometry including two backfill sections and the rock. (c) Geometry including two backfill sections only.*

Table 1 includes a summary of all the cases considered. The main result is the hydration time required for each case, which has been determined considering two values:

t_0 = time required for a degree of saturation above 95% in all nodes

t_1 = time required for a degree of saturation above 99% in all nodes

Note that all the cases corresponding to group "A" give large hydration times and therefore, their boundary conditions can not be applied in the actual test if a shorter duration is desired. Also, the results depend on the water retention curve used in the simulation, so a laboratory determination of such curve becomes very convenient in order to check the reliability of the modelling.

To reduce the hydration time, water can be injected from all the mats. Injection pressure can also reduce that time, but that requires checking in the laboratory the risk of hydraulic fracture when increasing water pressure in the backfill. Cases included in B and C assume that boundary condition. Note that case B2, for instance, represents a likely situation, applying after 2 months, 1 MPa in all mats. In that case, time for saturation is around 1.6 to 1.8 years. Figure 7-31 shows the main results corresponding to that case.

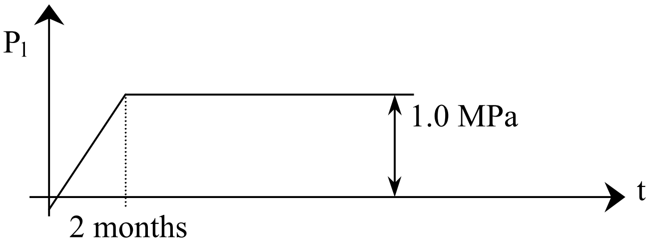
Despite cases B reproduce many aspects of the hydration process, they do not take into account the gas balance equation. In this problem, where gas as well as liquid is quite confined, it is worthwhile to check that effect. Cases included in group C have been solved including the gas equation and are summarised in table 1b.

The key parameter controlling the gas flow is the relative permeability to the gas of the backfill, and that has not been measured. However, a sensitivity analysis has been performed assuming a conductive situation in which gas can move through the backfill either very fast (K_{rg} = 10,000 Sr^2) or very slow (K_r = 10 Sr^2). In the latter case gas bubbles are very frequent and gas is dissolved by diffusion. Cases C1 and C2 can be compared with this respect. To show this effect, saturation and gas profiles have been plotted. Figures 7-32 and 7-33 refer to case C1, whereas Figures 7-34 and 7-35 to case C2. Note that the saturation profiles are quite similar in both cases, comparing Figures 7-32 and 7-34. However, the gas pressure profiles are totally different, as in case C2, gas pressure can reach up to 1 MPa. In this simulation, rock is assumed to be impervious to gas, for simplicity, and that can explain the gas pressure increase towards the rock boundaries in Figure 7-35.

Note that hydration time depends on the permeability of the backfill to the gas, as expected. That time increases when the gas can not move freely. However, the values used in the analyses are not realistic, and they have been used for comparison purposes only. Most probably the real case will be more similar to case C1 than to case C2, especially at the beginning with a low water content. Therefore, the time for saturation is expected to be close to 683 days or 1.8 years (t_0 for case C1), which is slightly higher than case B2 without gas effects (1.6 years).

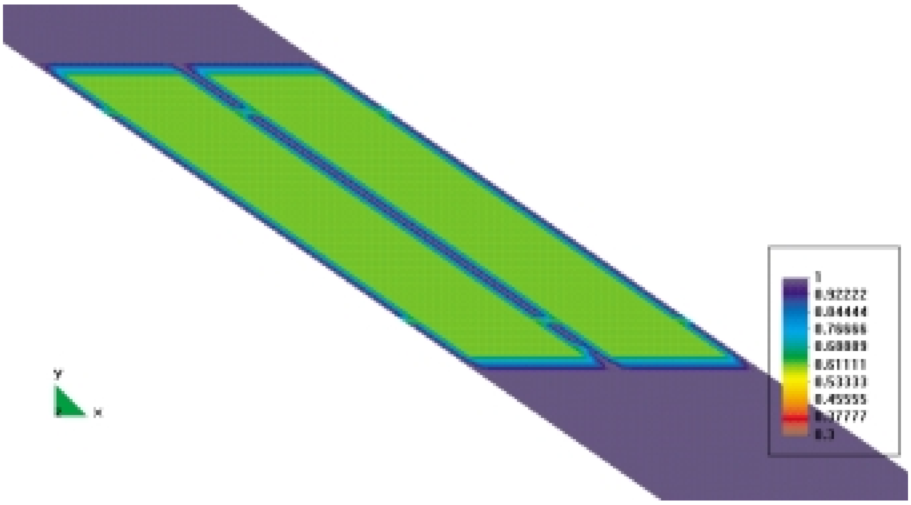
Cases C3 and C4 were also computed to analyse the possibilities of reducing the hydration time and gas bubbles formation. In case C3, one inner mat had 0.8 MPa of liquid pressure while all the surrounding mats had 1 MPa, in order to produce a directional flow. On the other hand, case C4 corresponds to a situation in which one upper and one lower mat have 0.8 MPa, and the other surrounding mats have 1 MPa as liquid pressure. It can be seen in table 1b that hydration times do not decrease with respect to previous cases, and therefore, they are not a good strategy for this purpose.

CASE B2
$P_0 = 0.13$ MPa, $\lambda = 0.195$
Without gas/Rock considered.



$t_0 = 605$ days for $0.95 < S_r < 0.99$ and **$t_1 = 656$ days for $S_r > 0.99$**

Degree of saturation at 0 days.



Degree of saturation at 343 days.

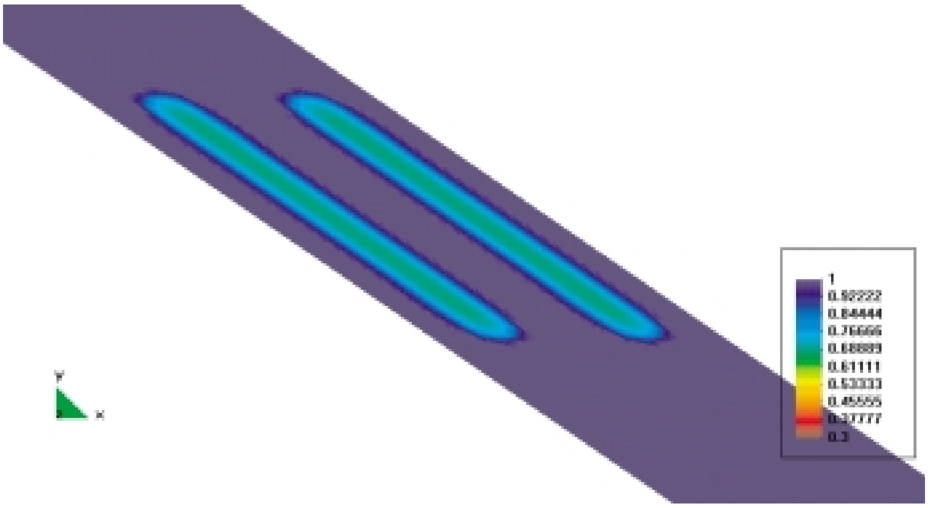
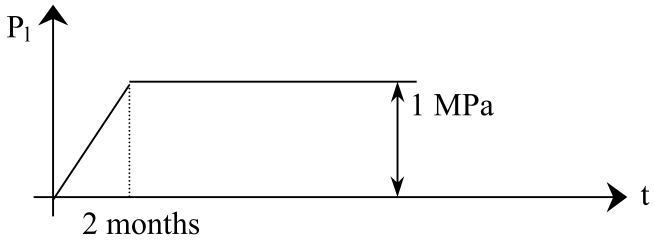


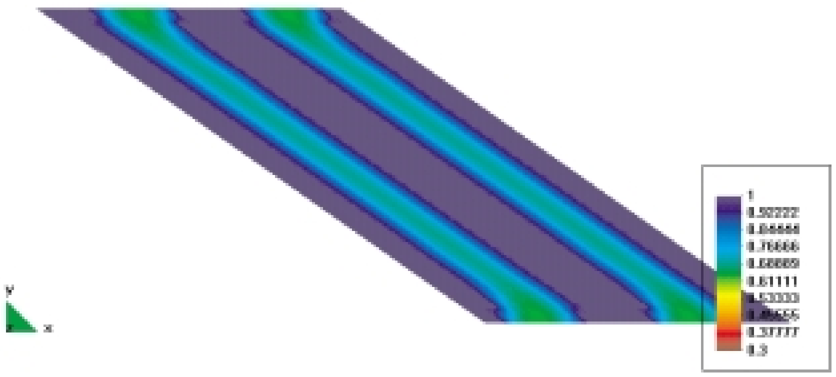
Figure 7-31. *Hydration process evolution for case B2, considering the rock and two sections of backfill, but without gas.*

CASE C1
$P_0 = 0.13$ MPa, $\lambda = 0.195$
$K_{rg}=10000\ S_{eg}^2$ (gas rel. perm.)



$t_0 = 683$ days for $0.95 < S_r < 0.99$ and **$t_1 = 753$ days for $S_r > 0.99$**

Degree of saturation at 365 days.



Degree of Saturation at 730 days.

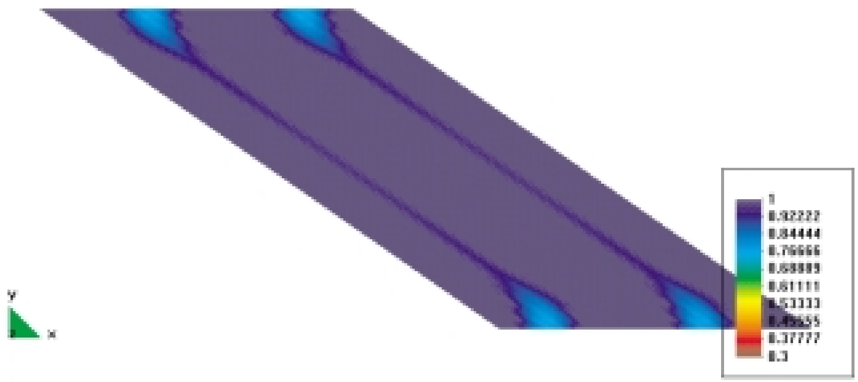
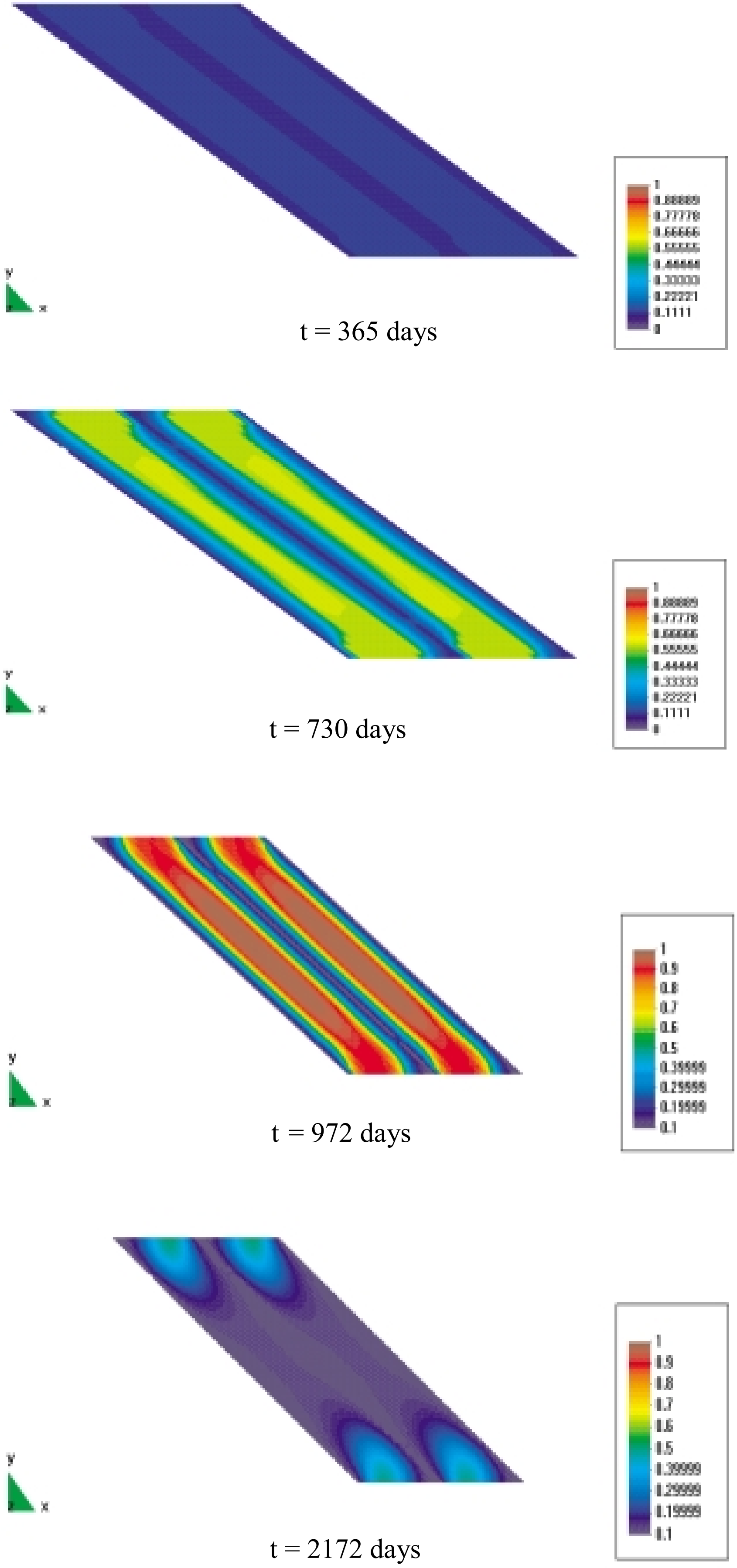


Figure 7-32. *Hydration process evolution for case C1, without the rock. Only two backfill sections were considered and the gas balance equation was solved.*



t = 365 days

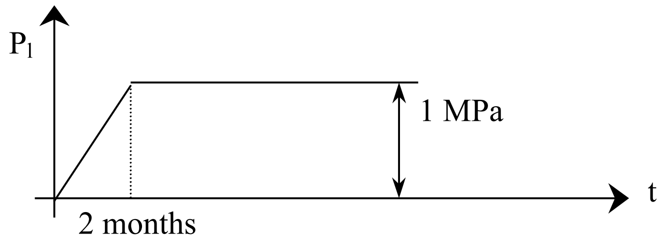
t = 730 days

t = 972 days

t = 2172 days

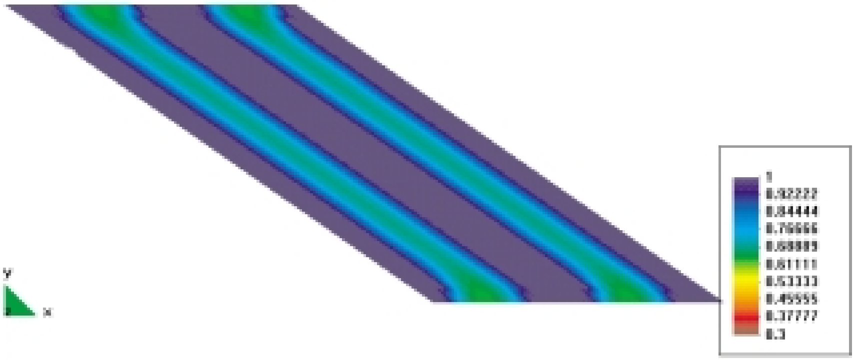
Figure 7-33. *Gas pressure evolution for case C1, with the highest relative gas permeability.*

CASE C2
$P_0 = 0.13$ MPa , $\lambda = 0.195$
$K_{rg}=10\ S_{eg}^{2}$ (gas rel. perm.)



$t_0 = 1026$ days for $0.95 < S_r < 0.99$ and **$t_1 = 1761$ days for $S_r > 0.99$**

Degree of saturation at 365 days.



Degree of Saturation at 730 days.

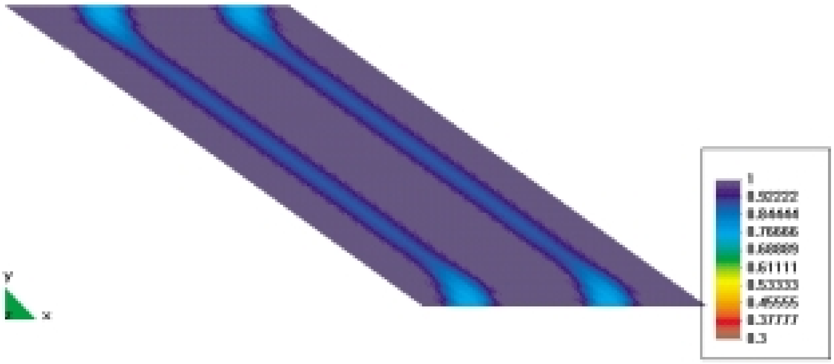
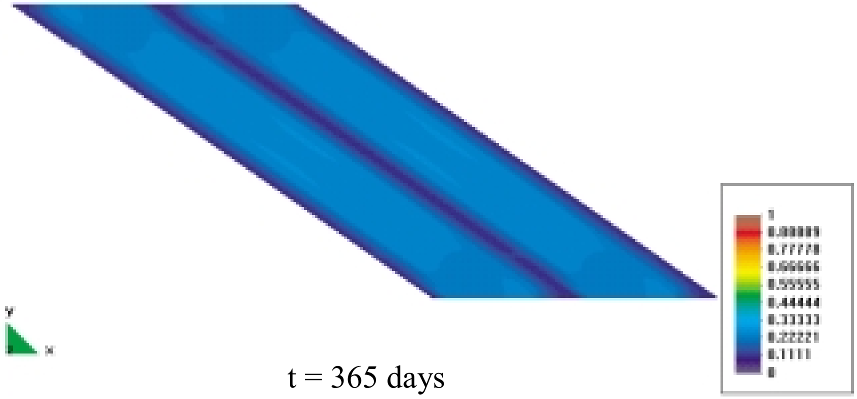
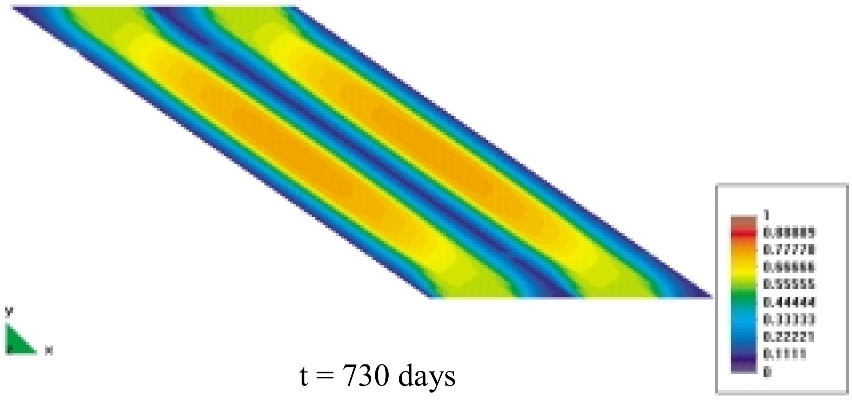


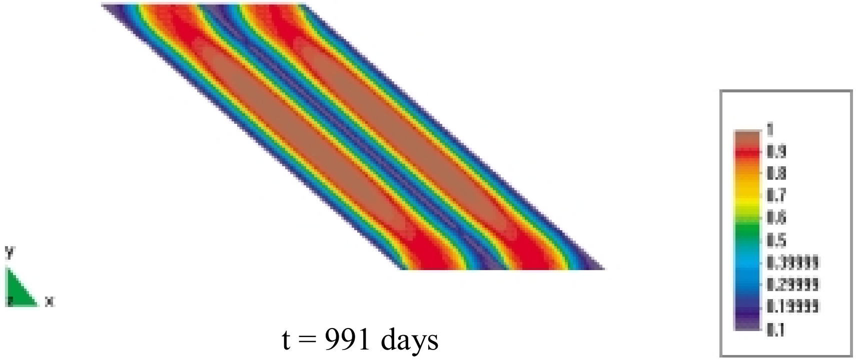
Figure 7-34. *Hydration process evolution for case C2, without the rock. Only two backfill sections were considered and the gas balance equation was solved.*



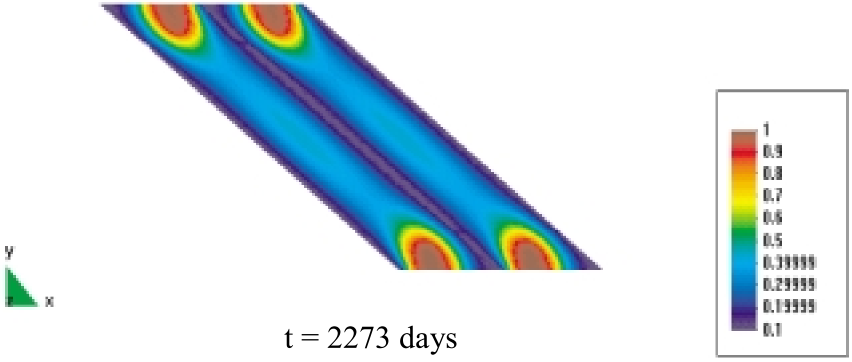
t = 365 days



t = 730 days



t = 991 days



t = 2273 days

Figure 7-35. *Gas pressure evolution for case C2, with the lowest relative gas permeability.*

Conclusions

The modelling work has been mainly devoted to the estimation of the hydration time and this has been a difficult task because of the unexpected changes during 1998 when selecting the final material for the backfill. Indeed basic parameters like hydraulic conductivity are high dependent on the mixing technique and the emplacement and compaction process. The simulations presented are based in only one uptake test and therefore, the reliability of these results is very limited. Thus more laboratory tests should be performed during 1999 to complete the basic information of the new backfill material.

Despite the uncertainties associated to the simulations, they are very useful to decide the test protocol for the hydration period. Most probably that hydration time will be around 1.6 or 1.8 years, although that value should be confirmed once the new laboratory information is available, and according to the final hydration procedure.

7.7 Summary of work by USDOE/Sandia

A framework for cooperative work between the United States and Sweden is provided by the "Agreement Between the U.S. Department of Energy and the Swedish Nuclear Fuel and Waste Management Company Concerning a Cooperative Program in the Field of Radioactive Waste Management". In 1998, specific collaborative activities were initiated with respect to experimental and modelling work being done at Äspö. This specific collaboration was initiated by the signing of a bilateral agreement between the U.S. Department of Energy Carlsbad Area Office (DOE/CAO) and SKB.

An implementing agreement between Sandia National Laboratories (SNL) and SKB was signed in September, 1998. The work accomplished in 1998 included: technical interactions on transport modelling and experimental techniques culminating in the development of a technical planning memorandum; participation in the 3rd Äspö International Seminar on Characterization and Evaluation of Sites for Deep Geological Disposal of Radioactive Waste in Fractured Rocks in June 1998; participation in the International Joint Committee meeting in June, 1998; and participation in the 11th Äspö Modelling Task Force meeting in September, 1998. The three tasks defined in the technical planning memorandum are discussed in detail below. Participation in the 3rd Äspö International Seminar including presentation of two WIPP papers.

7.7.1 Task 1: Modelling of TRUE-1 results with multirate model

Background

A recent development in the modelling of solute transport in fractured rocks has been the consideration of multiple rates of mass transfer in the predictions of solute movement. This "multirate" model has been applied successfully in modelling the results of several non-sorbing tracer tests conducted at the WIPP site (New Mexico, USA). In this application, a classical single-rate model could not reproduce the observed mass-recovery curves.

Objectives

The multirate model has not previously been applied to the results of a sorbing tracer test in fractured rock. Work begun in late 1998 will apply the multirate model to the STT-1b tracer tests conducted at Äspö as part of the TRUE-1 series of experiments. The objectives of this work are to estimate solute transport model parameters and predict the outcome of future experiments. These activities will allow the WIPP project to gain confidence in the multirate model by testing it on a different set of tracers in a rock environment different from that at WIPP.

Experimental concept

In the multirate model, the various mechanisms that transfer solute mass between the matrix and the fracture systems can be conceptualized as a continuous distribution of rates each with a corresponding capacity in the matrix. Multiple rates of mass transfer may occur at Äspö due to the presence or absence of fault gauge, variations in the weathering of the host rock, variations in the mineralogy along the fracture walls, etc.

Results

This work began in late 1998 and no results were obtained by the end of the year. Work has continued in 1999 and a draft report of results obtained with the multirate model on the STT-1b tracer test data has been submitted to SKB. This draft report is currently being reviewed by SKB for publication as an International Cooperation Report (ICR) in 1999. Future work includes blind prediction of the results of the STT-2 tracer tests using the multirate model. As well as numerical studies to determine the relative sensitivity of solute transport to varying rates of sorption and diffusion processes.

7.7.2 Task 2: Visualization of diffusion processes in low porosity material

Background

The Flow Visualization Laboratory at Sandia National Laboratories has developed state of the art X-ray transmission techniques for visualizing and quantifying the movement of solutes in rock samples. These techniques have been used successfully to visualize the migration of solutes in rock fractures and the surrounding matrix for the Yucca Mountain (Nevada, USA) and WIPP (New Mexico, USA) nuclear waste repositories. This method is also being tested on lower porosity Kurihashi granodiorite (Kamaishi Mine, Japan). However, it is anticipated that a different experimental technique will be needed to visualize the migration of solute in very low-porosity rocks.

Objectives

The objectives of this task are to develop a technique for visualizing mass transfer in low-porosity rocks such as the Äspö granodiorite. Once a technique has been developed, the goal will be to design and run appropriate visualization experiments for the Äspö rocks.

Experimental concept

Quantitative visualization of the movement of solutes in rocks samples is a valuable tool for understanding potential retardation processes in the transport of radionuclides. Current SNL X-ray based technology is capable of producing high resolution digital images of diffusing solute in moderate porosity rock. The experimental concept is to extend these techniques to very low-porosity environments (e.g. Äspö granodiorite), possibly using other imaging technologies.

Results

In 1998, this task was defined through a Technical Planning Memorandum. Various techniques were researched through literature review including: Nuclear Magnetic Resonance (NMR), Laser Scaning Confocal Microscopy, Microtomography, and ^{14}C-PPM Impregnation/Autoradiography.

7.7.3 Task 3: Scaling of transport parameters

Background

Both SKB and SNL are faced with the task of scaling transport parameters measured in laboratory experiments and in field tracer tests up to the time and length scales of performance assessment.

Objectives

Objectives for this task are to examine defensible means for upscaling transport parameters to the performance assessment scale. Initial work will compare ideas proposed within SKB to concepts being pursued within the WIPP program.

Experimental concept

Initial work will involve numerical simulations to determine the sensitivity of solute transport at PA time and length scales to different transport parameters. Initial results will focus scaling efforts to parameters and critical regions of joint parameter space that matter to PA results.

Results

Work will commence in 1999.

Documents published 1998

During 1998 the following reports and documents have been published.

International Cooperation Reports

Gylling B, Khademi B, Moreno L, 1998. Modelling of the Tracer Retention Understanding Experiment Task 4C–D using the channel network model.
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4 Technical Documents were produced during 1998.

Technical Notes

37 Technical Notes were produced during 1998.

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