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Äspö Hard Rock Laboratory

Annual Report 1997

Svensk Kärnbränslehantering AB

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Abstract

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

The final reports for the Stage Goal "Verification of pre-investigation methods" are now completed. The surface and borehole investigations and the research work performed in parallel with construction have provided a thorough test of methods for investigation and evaluation of bedrock conditions for construction of a deep repository.

The objective of the ZEDEX project was to compare the mechanical disturbance to the rock for excavation by tunnel boring and blasting. The results indicate that the role of the EDZ as a preferential pathway to radionuclide transport is limited to the damaged zone. The extent of the damaged zone can be limited through application of appropriate excavation methods.

The Tracer Retention Understanding Experiments are made to gain a better understanding of radionuclide retention in the rock and create confidence in the radionuclide transport models that are intended to be used in the licensing of a deep repository for spent fuel. The experimental results of the first tracer test with sorbing radioactive tracers have been obtained. These tests have been subject to blind predictions by the Äspö Task Force on groundwater flow and transports of solutes.

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 in bentonite using ^{57}Co, ^{134}Cs, ^{85}Sr, ^{99}Tc, and ^{131}I were conducted.

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 characterization of the rock mass in the area of the Prototype repository in progress.

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 new drift south of the ZEDEX drift.

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 1997.

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 has been raised to 90 and 130°C, respectively.

Nine organisations from eight 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.

Slutrapporterna från etappmålet "Verifiera förundersökningsmetoder" har nu färdigställts. De undersökningar som genomförts på markytan och i borrhål från markytan samt det omfattande forskningsarbete som genomförts i samband med byggandet av laboratoriets underjordsdelar har givit en heltäckande prövning av olika metoder för att undersöka och utvärdera berget inför byggandet av ett djupförvar.

ZEDEX-projektet har genomförts för att jämföra mekaniska skador på berget vid TBM-borrning respektive sprängning. Resultaten från ZEDEX indikerar att den störda zonens roll som en preferentiell transportväg för radionuklider begränsas till den av brytningen skadade zonen närmast ortväggen. Storleken på den skadade zonen, som är den hydrauliskt sett viktiga delen, kan begränsas genom användning av lämplig brytningsmetod.

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. De första resultaten från spårförsök med sorberande ämnen har nu erhållits. Dessa försök har använts för prediktiv modellering av Äspös arbetsgrupp för modellering av grundvattenflöde och transport.

En speciell borrhålssond, CHEMLAB, har konstruerats för att genomföra flera olika retentionsexperiment under förhållanden som är representativa för ett djupförvar. Sonden levererades till Äspölaboratoriet under 1996 och de första försöket påbörjades i början av 1997. Under 1997 har tre försök i syfte att verifiera modeller för diffusion av radionuklider (^{57}Co, ^{134}Cs, ^{85}Sr, ^{99}Tc, och ^{131}I) i bentonit genomförts.

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.

Projektet Demonstration av deponeringsteknik syftar till att utveckla, prova och demonstrera metodik och utrustning för inkapsling och deponering av använt kärnbränsle. Demonstrationen av hantering och deponering av kapslar kommer att genomföras i en ny ort som brutits ut söder om ZEDEX-orten på 420 m nivån.

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 1997.

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 har höjts till 90 respektive 130°C.

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

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Executive Summary

The Äspö Hard Rock Laboratory constitutes an important part of SKB's work to design and construct a deep geological repository for spent nuclear fuel and to develop and test methods for characterization of selected 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 are now completed. There are five final reports. One providing an overview of the investigations performed at Äspö and the surrounding region during the first 10 years. Three reports on the comparison of predictions based on pre investigations and outcome. Finally, there is a report presenting the current model of Äspö based on investigations performed to date.

Regional and site scale three-dimensional groundwater flow models have been produced for Äspö. The site model was made to get a better resolution of the flow field below Äspö that should be useful for the evaluation of the groundwater chemistry, modelling pressures and flows in the rock mass outside the tunnel for planning of future experiments and, finally, with the intention that the model should be used for calculating the boundary conditions for a local detailed laboratory model. The site model was finalised during summer 1997.

Stage Goal 2 – Finalise detailed investigation methodology

The detailed characterization 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.

To obtain a better understanding of the properties of the disturbed zone and its dependence on the method of excavation ANDRA, UK Nirex, and SKB have decided to perform a joint study of disturbed zone effects. The project is named ZEDEX (Zone of Excavation Disturbance Experiment). Significant in-kind contributions to the project have also been provided by BMBF and NAGRA. The experiment was performed in two test drifts near the TBM Assembly hall at an approximate depth of 420 m below the ground surface. The TBM test drift constitutes part of the main access tunnel of the Äspö HRL, the test section is 35 m long and located directly after the TBM assembly hall. The first four test rounds in the D&B test drift were used for testing the "smooth blasting technique" based on low-shock explosives and the remaining five rounds were used for testing the effects of "normal blasting". A number of boreholes were drilled axially and radially relative to the test drifts to assess the properties and extent of the EDZ.

The results from the ZEDEX Project have shown that there is a damaged zone, close to the drift wall dominated by changes in rock properties which are mainly irreversible and that there is a disturbed zone beyond the damaged zone that is dominated by changes in stress state and hydraulic head and where changes in rock properties are small and mainly reversible. The changes in rock properties and rock stress with distance from the rock wall of the excavation is gradational and there is hence no distinct boundary between the two zones.

The damaged zone caused by the excavation methods applied has been identified by several measurement techniques. Monitoring of Acoustic Emission (AE) events is the most sensitive method which indicates minor damage due to crack opening and slip. For the Drill&Blast (D&B) drift significant AE-activity was observed up to 1 metre from the drift wall while the corresponding extent for the TBM drift is a few tens of centimetres. Changes in seismic velocity indicate a larger increase in crack density. The dye penetration tests performed in the slots cut from the drift has shown the extent of macro fracturing, which in the floor of the D&B drift has extended to about 50 centimetres. The hydraulic measurements performed in the damaged zone showed little if any change in permeability of the rock matrix.

The disturbed zone is characterized by elastic displacements and no induced fracturing. There are only very few AE-events observed in the disturbed zone and these have been found to correspond to slip on existing fractures. The AE-event density in the disturbed zone is also similar for both the TBM and D&B drifts. The hydraulic tests performed before and after excavation have not revealed any significant changes in hydraulic properties due to excavation.

The results from ZEDEX indicate that the role of the EDZ as a preferential pathway to radionuclide transport is limited to the damaged zone. The extent of the damaged zone can be limited through application of appropriate excavation methods. By limiting the extent of the damaged zone it should also be feasible to block pathways in the damaged zone by plugs placed at strategic locations.

The Rock Visualization System (RVS) is developed to obtain a tool for interactive 3D interpretation of characterization data collected in boreholes, tunnels and on the ground surface. The RVS system is linked to SKB's site characterization 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. The system has now been put into use within some of the projects undertaken at Äspö HRL. A training program for SKB staff and consultants has been initiated.

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

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

The objectives of the Fracture Classification and Characterization project are to develop methodology for characterization of fractures with respect to tectonic evolution, infillings and wallrock alteration and to use this information for classification of fractures in terms of their importance for radionuclide transport. Five different fracture classes have been identified based on mapping of the water conducting features that intersect the tunnel. The classification is based mainly on their geometrical properties. The developed methodology has been applied at the TRUE-1 site where mapping and analysis of the small scale fracturing has been made. This included the integration of tunnel and borehole information. A generic conceptual model has been presented.

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 non-reactive 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 cycle is expected to contribute data and experience which will constitute the necessary platform for subsequent more elaborate experiments within TRUE. The TRUE-1 tests are performed over distances of about 5 m in a fracture at approximately 400 m depth.

The experimental results of the first tracer test with sorbing radioactive tracers, STT-1, were presented in conjunction with presentations of model predictions of the experiment at the 10^{th} Äspö Task Force Meeting held in Kamaishi, Japan, in November 1997. The experiment was started in mid July 1997 with injection of two conservative (Uranine and HTO) and six weakly/moderately sorbing tracers (^{22}Na, ^{85}Sr, ^{86}Rb, ^{47}Ca, ^{133}Ba, and ^{137}Cs).

The results indicate relative breakthroughs of tracer in the pump hole which reflect the previously laboratory derived volumetric distribution coefficients for the tracers used. Uranine and tritiated water (HTO) show comparable breakthroughs in terms of time. In succession follows ^{22}Na, ^{47}Ca, ^{85}Sr, ^{86}Rb, ^{133}Ba, and ^{137}Cs. After 3170 hours (close to 19 weeks) the recovery of ^{137}Cs was only 29%. It was considered to be of great interest to follow the complete *in situ* breakthrough of Cs from a performance assessment perspective. Hence, it was decided to continue the test until the end of March 1998 and to perform a second tracer test, STT-1b, without disturbing the current flow field in parallel. The tracer injection for STT-1b was performed early December 1997. A tracer cocktail consisting of ten tracers, four conservative (Uranine, HTO, ^{82}Br, and ^{131}I) and six sorbing (^{99m}Tc, ^{42}K, ^{22}Na, ^{85}Sr, ^{86}Rb, and ^{58}Co) were injected as a four hour finite pulse. Five of these were also used in STT-1 (Uranine, HTO, ^{22}Na, ^{85}Sr, and ^{86}Rb). As a consequence of the extended duration of these tests, the planned STT-2 was postponed and will be integrated with the next detailed TRUE stage, TRUE-2, scheduled to start up during the Fall 1998.

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. During 1996 resin was injected in a fracture intersecting one of the drifts at the 450 m level. The fracture has been sampled by several large diameter cored boreholes and the aperture distribution of the samples has been measured. The pore volume is measured in a number of sections/slices of the fracture using a combination of photographic and microscopic techniques and subsequent image processing. The obtained data is planned to be used to reduce uncertainties in the description of the heterogeneity of the studied feature.

Laboratory tests are performed to develop and test sorbing radioactive tracers suitable for use in studying sorption processes in the chemical environment met at the Äspö HRL. During 1994–1997, laboratory experiments have been underway on both generic Äspö material (Äspö diorite and Fine-grained granite) and material from the TRUE-1 site. The experiments comprise both through diffusion and batch sorption experiments, the latter on different size fractions. Key results from the laboratory tests were presented at the Migration'97 conference in Sendai, Japan. The Äspö diorite shows a heterogeneous and mineral specific porosity distribution. Mineral grain boundaries were not observed to form the main migration pathways in the diorite matrix. Instead, the migration network consists of a complex mixture of minerals dominated by biotite, plagioclase and chlorite all having small (<0.5 mm) grain sizes. The porosity pattern of Fine-grained granite was uniformly distributed. The high porosity minerals are not observed to form a connecting network as observed in the Äspö-diorite. The results from in-diffusion experiments could be adequately described by a double porosity network. Approximately one order of magnitude lower K_d-values are obtained from diffusion experiments compared to batch experiments using large particle size fractions. Compared to batch K_d even larger differences are observed with even smaller size fractions (<2mm). This is probably a result of increased porosity and increased surface areas due to the crushing of the material. Irreversible sorption is observed for some of the studied elements. A significant part of the mass could according to the batch experiments be irreversibly lost and will not be transported at all.

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 has been initiated as a joint project between ANDRA, Nirex, Posiva, and SKB. Enresa and PNC joined the project during 1997. A set of desired experimental conditions have been defined and a flexible iterative characterization strategy has been adopted. During 1997 two 76 mm boreholes, KI0025F and KI0023B, have been drilled into the investigated rock volume. The results from borehole KI0025F indicate only a few (N=5) significant hydraulic anomalies are present in the borehole. In the bottom of the borehole a major fractured zone was intercepted. The transmissivity of the interpreted structures have been quantified both using double packer flow logging and selective flow and pressure build-up tests. The results of the selective flow and pressure build-up tests show transmissivities on the order of $5 \cdot 10^{-7}$ – $5 \cdot 10^{-6}$ m^2/s. During the year two major updates of the structural model has been performed. The first in March 1997, and the most recent one made in October 1997. Sensitivity analysis of entities in the fracture network has been made in simulations on a smaller block. One of the problems faced in simulation of flow and transport in a fracture network is the large number of generated fractures, which the full inclusion of is limited by the available computer resources. Included in the study is an analysis of the effect of imposing a cut-off at different threshold transmissivities. The analysis shows that no significant effects are seen on the calculated effective permeabilities of the block with a cut-off at $T=1 \cdot 10^{-9}$ m^2/s. However, the two point connectivity as inferred from the DFN flow model is reduced with about 50%.

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 2861 m. The equipment necessary for the field test has been set-up and tested. Measuring devices have been designed and tested both in the laboratory and in the field. The aim of the field study is to isolate the innermost part of the borehole and to monitor the oxygen consumption as a function of time. 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.

Measurements of dissolved gases (methane, hydrogen, etc) in Äspö groundwater have been performed. They have been combined with the measurements of bacteriological oxygen consumption in Äspö groundwater. These results show that oxygen may be consumed by methanotrophic bacteria in a closed nuclear waste repository. Structures that are believed to be fossil bacteria have been found in calcite samples from Äspö. This shows that bacteriological activities have occurred underground for long periods of time, and they are expected to proceed in the future.

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 were conducted. These were the diffusion in bentonite using ^{131}I and ^{57}Co, followed by a similar experiments with ^{134}Cs and ^{85}Sr. The last diffusion experiment with ^{99}Tc and ^{131}I was terminated due to malfunction of the equipment. A simplified version of the CHEMLAB probe is planned to be constructed and manufactured during 1998. The purpose of this probe is to speed up the entire experimental sequence so that the spent fuel experiments can be started as soon as possible.

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. The *in situ* test program began with a pilot test with the objective to get data on the magnitude of degassing effects on permeability, time scales required for resaturation, and requirements on equipment for subsequent tests. The test showed no two-phase flow effects due to too low gas contents of the groundwater to cause degassing effects. In the second *in situ* test a flow reduction of 50% was observed when the pressure in the withdrawal hole was reduced to atmospheric. In this test the gas contents of the water was artificially raised to 17%. Degassing is considered to be the most likely explanation for the flow reduction.

Flow reduction due to degassing is considered to be caused by bubble trapping in the fractures. Laboratory experiments indicate that the geometry of the fracture pore space has a major impact on degassing within natural fractures. If the large apertures are filled with gas bubbles, fluid flow will be restricted to the small apertures which form only a small part of the aperture field in the fracture plane of one of the tested samples. It was assumed that this pore space structure would be very effective in reducing the transmissivity of the fracture plane and this was certainly consistent with the large reductions in transmissivity that were measured during the degassing experiments on this sample. Fractures with uniform roughness seem to have a low gas bubble trapping capacity and hence show a small reduction in transmissivity due to degassing. A methodology for calculating a probability for bubble trapping based on fracture aperture statistics has been developed. Based on these assumptions expressions for gas saturation and relative transmissivity of a fracture has been developed. The model predictions show reasonable agreement with experimental results from laboratory experiments.

The hydrochemical stability programme aims at evaluating the possible changes and evolution of the groundwater chemistry during the repository life time. Important questions concern the understanding of the processes which influence and control the 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.

Modelling of the groundwater flow of the Äspö area during the postglacial (10 000 year) period indicate very dynamic situations with rapidly changing groundwater compositions. It appears that at a depth of 450 m at Äspö, brackish Yoldia and later Litorina water, has totally replaced glacial melt water. The model shows meteoric and brine water to be the only groundwater components present today. When comparing the modelled water composition with the measured $\delta^{18}O$ and Cl values it is obvious that the origin of the groundwater includes several components in addition to brine and present meteoric. It can thus be concluded that mixing is a very important processes and is certainly governed by the large variations in hydraulic conductivity of the fractures not accounted for in this flow simulation. The $\delta^{18}O$ and $\delta^{13}C$ ratios of the fracture calcites show large variations indicating that different events have been recorded in the calcites. Calcites with marine $\delta^{18}O$-values have been detected in a few fractures down to 300 m and values corresponding to brackish water down to 500 m. The depth distributions of the isotopic values in the calcites is in good agreement with the interpretations of the groundwater chemistry prior to the tunnel construction.

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.

The evaluation of the modelling work on Task No 3 (the hydraulic impact of the tunnel excavation at Äspö) has been completed. The first part (3A) addresses how robust are site scale groundwater flow models based essentially on pumping tests results and does extrapolation from such models provide reasonable results. The second part (3B) uses the data set available up to the first turn of the spiral of the Äspö tunnel for improving the site scale groundwater flow models. In Task 3A it became evident that important hydraulic connections were missing. These were necessary in order to explain the detailed hydraulic responses to the elevator shaft. Task 3B demonstrated that a detailed analysis of the transient pressure responses due to tunnel construction will provide an improved structural model. Model calibration gave an insight into the features and their connectivity; however a successful calibration exercise is very time consuming.

Tasks No 4C and 4D concerns predictive modelling of the non-sorbing tracer tests part of TRUE-1. Seven modelling groups participated. Concerning Task No 4C (radially converging test), a preliminary comparison between model predictions made by the Äspö Task Force and the experimental results, shows that most modelling teams predicted breakthrough from all four injections, although some teams predicted distinctly lower mass recoveries from the two injections which *in situ* did not produce a breakthrough. The breakthrough times predicted by the modelling teams are also in accordance with those observed in the experimental results. Concerning the modelling of Task No 4D (dipole tests), it seems there are larger differences among the predictions when compared to the predictions of Task No 4C. This fact will be further investigated within the evaluation process which is now on-going.

Task 4E concerns blind prediction of the test with sorbing tracers (STT-1). At the 10th Task Force meeting, eight different modelling groups presented predictive modelling results for the performed tests with sorbing tracers STT-1. No evaluation of the performed modelling has been initiated so far.

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. Main processes that will be studied include:

- Water uptake and pressure in buffer, backfill and rock.
- Temperature distribution in canister, buffer, backfill and rock.
- Swelling pressure and displacements in buffer and backfill.
- Chemical processes.

Other processes that are of interest in the intended test layout are:

- Stresses and displacements in the near field rock.
- Tracer transport in the buffer.
- Gas transport from the canister.
- Bacterial migration in buffer.

The characterization of the rock mass in the area of the Prototype repository in progress. The evaluation of the characterization data obtained from the deposition tunnel has been reported and exploratory drilling is in progress. The dominant rock type at the Prototype Repository site is Äspö diorite. The total quantity of in-flowing water to the Prototype Repository is about 5 l/minute. Most of this water comes from the inner 20 m of the TBM tunnel. In-situ rock stress measurements have been performed by the overcoring method, and the primary stresses obtained were σ_H=26 MPa and strike 11°, σ_h=18 MPa and σ_v=21 MPa.

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 new drift south of the ZEDEX drift. The new drift was excavated by drill and blast. The program for geological characterization and locating of preliminary places for simulated deposition holes has been put into operation, and the first phase of the program, addressing floor mapping and preliminary geological modeling, was carried out during 1997. Four locations for boring of full scale simulated deposition holes were tentatively selected.

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.

Supplementary laboratory tests on backfill material for investigating the influence of salt in the pore water and degree of saturation on the hydraulic conductivity have been made. The results show that the influence of a salt content corresponding to Äspö water is very strong on the hydraulic conductivity of backfill material with 10–30% bentonite. The hydraulic conductivity increases with increasing salt content. The influence increases with decreasing bentonite content and decreasing density but is insignificant in backfill without bentonite. For densities corresponding to 90% Proctor the increase in hydraulic conductivity is a factor 10–100 for backfill with the bentonite content in the range 10–30%.

The water saturation phase between two filter mats in backfill with 30% bentonite has been modelled with a 2D finite element model. The calculations have used the preliminary material models derived from the laboratory tests. The results show that the time until saturation may be up to 10 years if no water pressure is applied in the filter mats.

The Retrieval Test is aiming at demonstrating the readiness for recovery 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. Heaters installed in the canister simulate the heat emission from spent nuclear fuel. The test will be located at the 420-meter level in the laboratory, in an extension of the D-tunnel.

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 tests have in principle delivered the expected data concerning temperature, moisture and pressure. Moisture gauges in the S1 parcel, placed halfway between the rock and the central tube, showed that the buffer in this position was fully water saturated after approximately 40 days after test start. The S1 and A1 pilot parcels will be extracted in February and March 1998 respectively and physical, mineralogical and microstructural analyses and tests will be made.

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. 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.

Facility operation

Excavation for new experimental sites took place in the beginning of the year. The new tunnels will mainly be used for the Demonstration of technology and Long Term Test of Buffer material projects. In the beginning of the year a lot of ice was formed in the ventilation shaft due to insufficient heating of the inlet air in combination with a lot of water in the shaft. Two electrical heaters have now been installed in the heat exchange system for the ventilation air. Two new transformers have been installed to meet the requirements from the coming experiments. Electric supplies and lights have also been installed in the tunnels that were excavated in the beginning of the year. The work with the new office, laboratories and storage started during September. According to the plan all new buildings will be ready during spring 1998.

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 characterization. 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. At present the SICADA data structure contains the sciences engineering, geology, geophysics, geotechnics (introduced during 1997), groundwater chemistry, hydrology, meteorology and rock mechanics.

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. To date (31 December 1997) the monitoring network comprise a total of 62 boreholes most of which are equipped with inflatable packers, measuring the pressure by means of pressure transducers. The measured data is relayed to a central computer situated at Äspö village through cables and radio-wave transmitters. Once a year the data is transferred to SKB's site characterization database, SICADA. The computers of the measurement system have been exchanged to PC:s. Also the software has been changed to the operative system Windows NT4.0, with the application software Orchestrator modified to included the measure software.

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

Nine organisations from eight countries are currently 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 Dechets 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**.
- Empresa Nacional de Residuos Radiactivos **ENRESA**.

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 ZEDEX project and the TRUE Block Scale Experiments are examples of such projects.

1 General

1.1 Background

The Äspö Hard Rock Laboratory constitutes an important part of SKB's work to design and construct a deep geological repository for spent fuel and to develop and test methods for characterization of a suitable site. In the R&D Program of 1986 SKB proposed to construct an underground laboratory. A proposal that was positively received by the reviewing bodies. 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. 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 (Figure 1-1). 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 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.

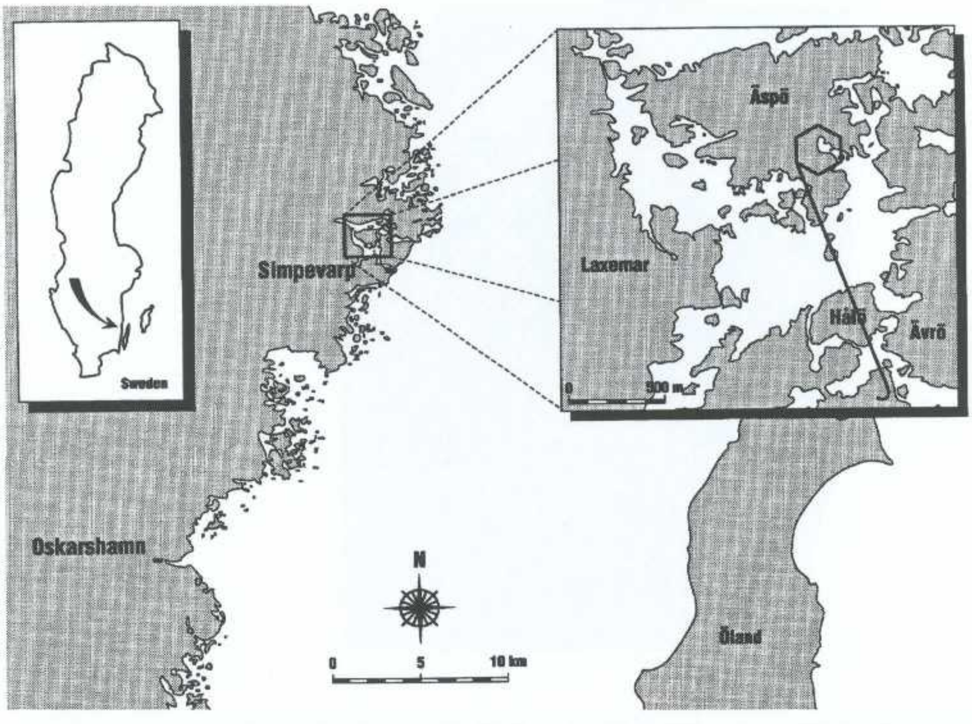


Figure 1-1. *Location of the Äspö HRL*

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 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 (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 progress of detailed planning of the experiments and the addition of new research and demonstration projects successively made it evident that excavation of new experiment drifts was required. During the winter 1996/1997 the underground part of the Äspö HRL facility was expanded by approximately 200 m of new experimental drifts at depths of 420 m and 450 m below the ground surface. In January and February of 1998 approximately 30 m of additional experimental drifts were excavated.

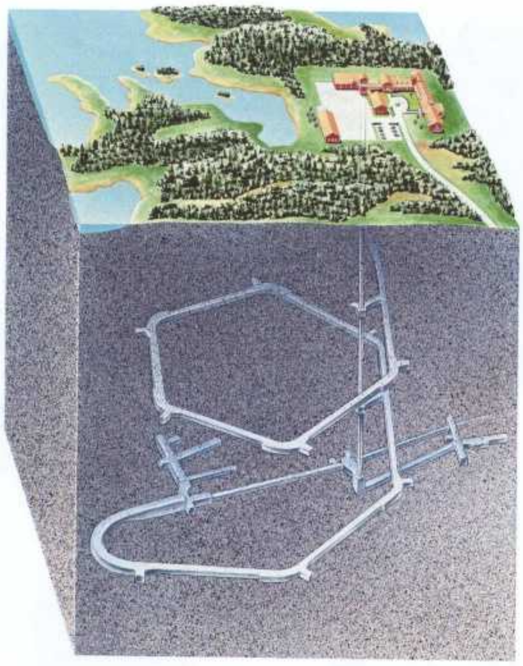


Figure 1-2. *Schematic design of the Äspö HRL. The lower part of the facility has been excavated by a 5 m diameter Tunnel Boring Machine.*

Figure 1-3. Aerial view 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. During the Operating phase priority will be given to projects which aim

- 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, and
- to demonstrate technology that will 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.
2. **Finalise detailed investigation methodology;** refine and verify the methods and the technology needed for characterization of the rock in the detailed site investigations.
3. **Test models for description of the barrier function of the host rock;** further develop and at repository depth test methods and models for description of groundwater flow, radionuclide migration, and chemical conditions during operation of a repository and after closure.

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

1.3 Organisation

A schematic chart of the organisation of the Äspö HRL valid from January 1995 is shown in Figure 1-4.

The Äspö Hard Rock Laboratory has so far attracted considerable international interest. As of December 1997 nine foreign organisations were participating in the Äspö HRL in addition to SKB. These organisations were: Atomic Energy of Canada Limited (AECL); Power Reactor & Nuclear Fuel Development Corporation (PNC), Japan; Central Research Institute of Electric Power Industry (CRIEPI), Japan; Agence National Pur la Gestion des Dechets Radioactifs (ANDRA), France; POSIVA Oy, Finland; Nirex, United Kingdom; Nationale Genossenschaft für die Lagerung von radioaktiver Abfälle (NAGRA), Switzerland; Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie (BMBF), Germany; and Empresa Nacional de Resuidos Radioactivos (ENRESA), Spain. The agreement with ENRESA was signed in February 1997 covering the time period until the end of 2000.

The agreements with Nirex and Nagra have been prolonged until the end of 1998 and 2002, respectively.

1.3.1 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

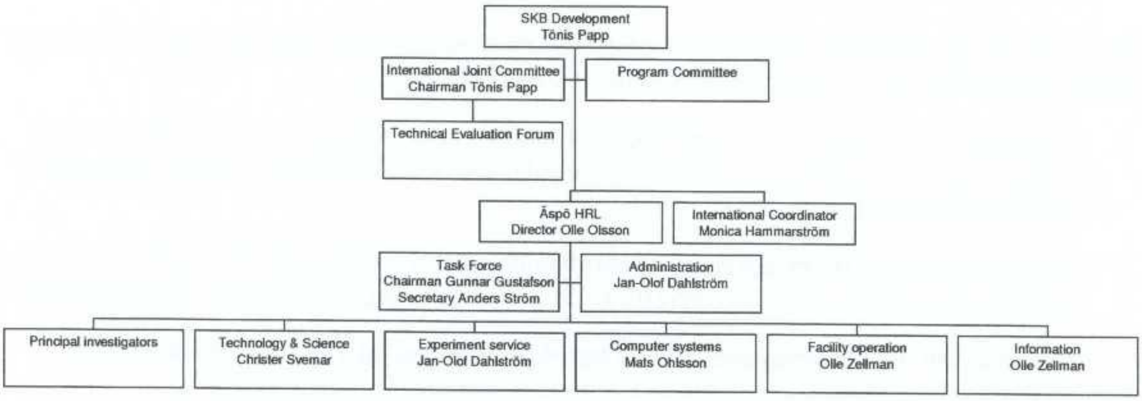


Figure 1-4. *Organisation of the Äspö Hard Rock Laboratory valid from September 1997.*

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 (March 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.

1.3.2 Project Groups and the Äspö HRL Site Office

The Äspö Hard Rock Laboratory and the associated research, development, and demonstration tasks are managed by the Director of the Äspö Hard Rock Laboratory (Olle Olsson). The Operations Manager (Olle Zellman) is responsible for the operation and maintenance of the Äspö HRL facilities.

Each major research and development task is organised as a project which is led by a Project Manger. Each Project Manager will be assisted by an On-Site Coordinator 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.

During 1997 the staff at the Site Office has consisted of about 21 full time employees.

Work is conducted according to the guidelines provided by the Äspö Handbook (in Swedish).

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

The Technical Coordinating 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 (March 1998) is Gunnar Gustafson, CTH and secretary Anders Ström, SKB.

1.4 Planning of experiments

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 Programs will be prepared outlining the objectives and overall scope of the programs, which will be divided into stages with a 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 program 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. Experimental sites have been allocated to keep interference between different experiments as small as possible. The current allocation of experimental sites within the Äspö HRL is shown in Figure 1-5.

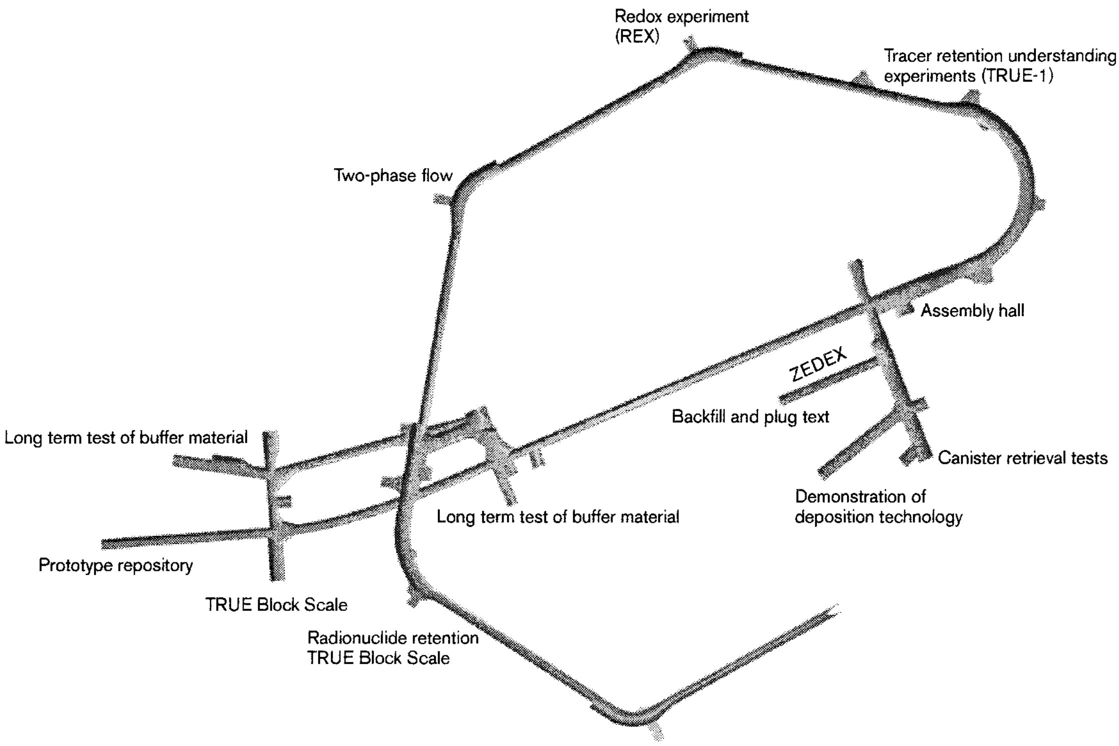


Figure 1-5. Underground excavations at the 300–450 m levels and current allocation of experimental sites.

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 characterization,
- provide data for planning of detailed site characterization.

It is thus important to show that pre-investigations provide reasonable and robust results.

In order to verify the pre-investigations methods, a strategy was set up, Figure 2-1.

This strategy entails predictive statements of certain rock properties. These statements have been structured to different geometrical scales for different key issues. The predictions have been reported in Gustafson et al. (1991). During construction of the facility these predictions of the bedrock are checked against the data collected during the construction work.

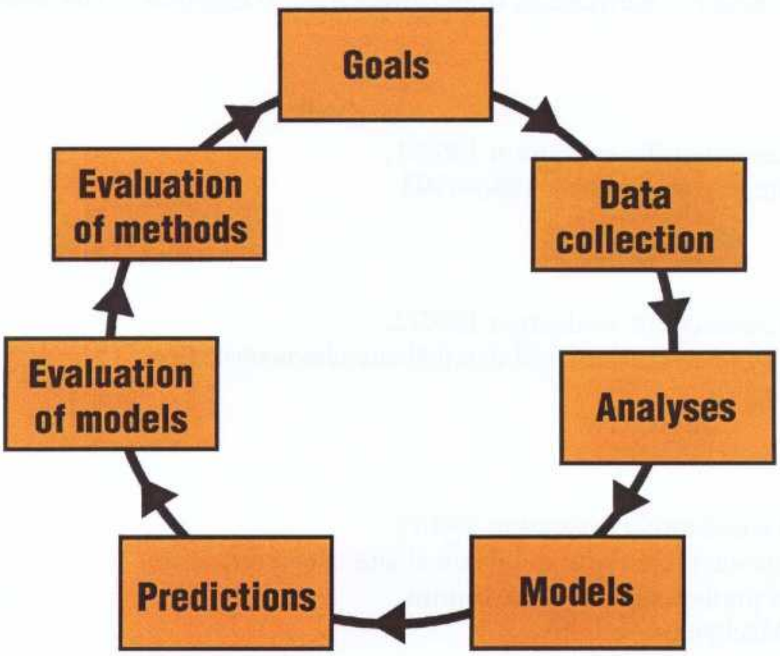


Figure 2-1. The strategy for the verification of the pre-investigation methods.

The evaluation of the models will be used to evaluate the methods used in the pre-investigation phase. This evaluation covers strategy for the pre-investigation, methods for data collection, analyses, predictions and evaluations.

The knowledge will be applied in the planning for and execution of site investigations on the candidate sites for the deep repository.

2.2 Evaluation of models and methods

2.2.1 Background

The first stage goal for Äspö HRL is:

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.

Reporting on the comparison of predictions based on surface and borehole data and observations (outcome) in the tunnel has been made in order to evaluate the reliability and correctness of the prediction models. The reporting has been divided into four parts, related to the length coordinate along the tunnel.

An assessment of the agreement between prediction and outcome has been made for the first part, 0–700 m (depth 100 m) (Stanfors et al., 1992). The comparison of prediction and outcome up to tunnel section 700–2,874 m (depth 200 m) has been reported previously.

2.2.2 Results

The work during 1997 has been focused on the final reviewing and re-writing of the final reports for the project "Verification of pre-investigation methods". The titles for the final reports are:

REPORT 1
Äspö HRL – Geoscientific evaluation 1997/1.
Overview of site characterization 1986–1995
(186p)

REPORT 2
Äspö HRL – Geoscientific evaluation 1997/2.
Results from pre-investigations and detailed site characterization.
Summary report.
(312p)

REPORT 3
Äspö HRL – Geoscientific evaluation 1997/3.
Results from pre-investigations and detailed site characterization.
Comparison of predictions and observations.
Geology and Mechanical stability
(142p)

REPORT 4
Äspö HRL – Geoscientific evaluation 1997/4.
Results from pre-investigations and detailed site characterization.
Comparison of predictions and observations.
Geohydrology, Groundwater chemistry and Transport of solutes
(396p)

REPORT 5
Äspö HRL – Geoscientific evaluation 1997/5.
Models based on site characterization 1986–1995.
(558p)

The purpose with the first report is to give a short information of what has been done and an easier access to data presented in different reports.

The second to forth reports give a detailed description of the comparison between predictions and outcome for tunnel section 700–2,875 m, which to a large extent have been presented in 12 Progress Reports. The evaluation focused on the validity of conceptual models and evaluation methodology used and also the feasibility and robustness of methods and investigation strategy (sequence, amount etc). Nagra, Posiva and Nirex reviewed the second report.

The fifth report gives a short description of classification systems used, the model development and a new integrated model over Äspö HRL. Posiva reviewed the report.

All reports have been printed as Technical Reports (Stanfors et al. 1997a, Rhén (ed) et al. 1997a, Stanfors et al. 1997b, Rhén et al.1997b, Rhén (ed) et al. 1997c). The evaluation of models and methods is thereby completed.

2.3 Code development/modelling

2.3.1 Background

As a basis for a good optimisation of the repository system and for a safety assessment as a basis for the siting application, which is planned to be submitted a couple of years after 2000, it is necessary to:

Test models for groundwater flow and radionuclide migration

- refine and test on a large scale at repository depth methods and models for describing groundwater flow and radionuclide migration in rock.

At Äspö HRL several numerical models have been tested and are tested and developed in order to meet this stage goal.

2.3.2 Regional groundwater flow model

The objectives and some results for the regional groundwater flow model reported in Äspö Hard Rock laboratory Annual report 1996. The report has now been printed (Svensson, 1997a).

The objectives for the regional groundwater flow model reported in Äspö Hard Rock laboratory Annual report 1996 were extended because of modelling needs for the SKB project SR97. The code used was PHOENICS. The sensitivity studies indicated that the possible ranges for the anisotropy of the effective hydraulic conductivity found at Äspö has a significant impact on the location of the location of recharge and discharge areas. It pointed out the need for an effective way of including anisotropy in the present used code.

The simulations, made with computational qubic cells with sides of about 100 m, indicate that the deterministic assigned fracture zones has some influence of the flow pattern with the best estimate of the transmissivities (two classes of transmissivities were used: $0.35 \cdot 10^{-5}$ and $10 \cdot 10^{-5}$ m^2/s). If these transmissivity values are increased by a factor of ten the flow pattern clearly indicate where the fracture zones are. If these transmissivity values are decreased by a factor of ten the flow pattern does not indicate where the fracture zones are.

The simulation also showed that the salinity in the model has a significant impact of the flow field at larger depth.

2.3.3 Site scale groundwater flow model

The site model was made to get a better resolution of the flow field below Äspö that should be useful for the evaluation of the groundwater chemistry, modelling pressures and flows in the rock mass outside the tunnel for planning of future experiments and, finally, with the intention that the model should be used for calculating the boundary conditions for a local detailed laboratory model. The site model was finalised summer 1997 and the results were reported in Svensson (1997b). Some of the results are presented below.

For the site model a stochastic continuum approach was chosen and the code used was PHOENICS.

Process description

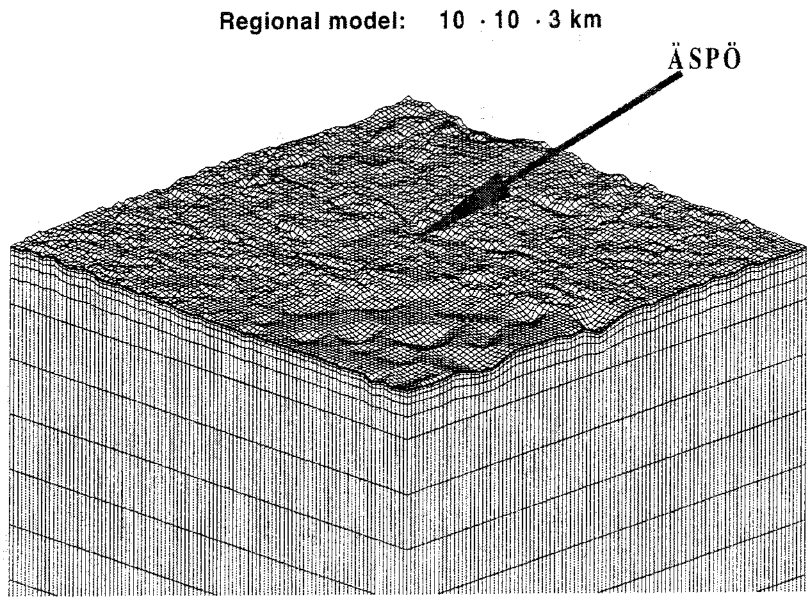
The flow was based on the following equations:

- Continuity equation (mass balance equation).
- Equation of motions (Darcy's law including density driven flow).
- Transport equation.
- Equation of state (Salinity-density relationships).

The dispersion used was proportional to the local Darcy velocity. The simulations were steady state simulations. See Svensson (1997b) for details of how the relations above were treated in PHOENICS.

Geometric framework and parameters

The model covers an area of $1.8 \cdot 1.8$ km^2 and down to a depth of 1 km. The model consists of 445,500 cells and the cells are 20 m cubes below a depth of 100 m. Above 100 m depth in the model the height of the cells decreases and the uppermost cells follow the topography on land as well as the topography of the sea bottom, see Figure 2-2. BFC (Body Fitted Coordinates) net is used. The site scale hydraulic conductor domains and hydraulic rock mass domains are defined according to Rhén et al. (1997c).



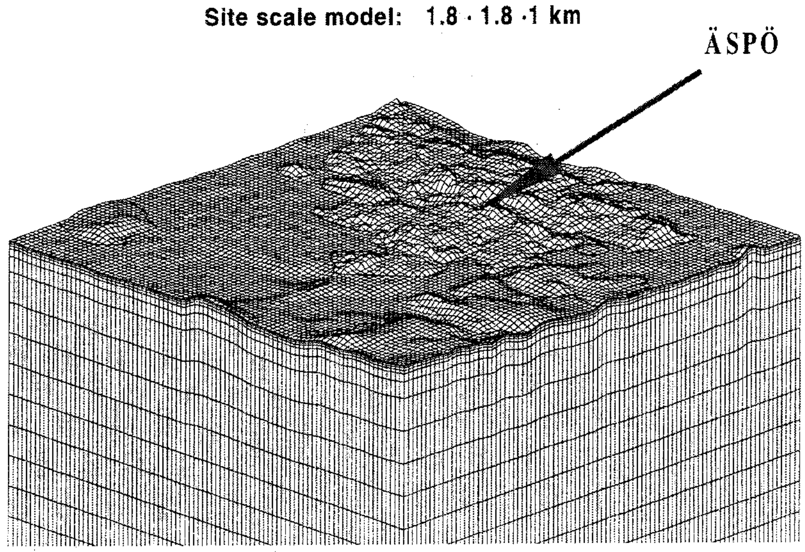


Figure 2-2. *Top: Finite-volume net close to surface for the regional model. View from south-east with Äspö in the centre. (Vertical scale is magnified about 15 times). (Svensson, 1997a). Bottom: Finite-volume net close to surface for the site scale model. View from south-east with Äspö in the centre. (Vertical scale is magnified about 7 times). (Svensson, 1997b).*

Material properties

The material properties assigned to the bedrock before calibration has started are described in Rhén et al. (1997c). Transmissivities of the hydraulic conductor domains are constant for each domain and hydraulic rock mass domains are described as a stochastic continuum. The hydraulic conductor domains described in the site scale model in this report were simplified in the regional scale due to the large cells in the regional model.

Properties for the hydraulic rock mass domains are based on the hydraulic tests in 3 m test scale, which are scaled to target scale 20 m. The model properties are shown in Svensson (1997b). The uppermost five cells (down to about 10 m below ground surface) in the model are given constant hydraulic conductivities somewhat higher than the geometric mean hydraulic conductivity for the uppermost part of the domains. This is made in order to make the sub-program treating the unsaturated zone to work properly.

Below the Baltic a clay layer of a few metres thickness is normally found. This was modelled by placing a 3 m thick layer with a hydraulic conductivity of 10^{-9} m/s 5 m below the sea bed.

Spatial assignment method

Zonation was chosen as the assignment method for the hydraulic rock mass domains, see Svensson (1997b) for details. No correlation between the hydraulic conductivities for the cells is assumed. Each hydraulic conductor domain was assigned a constant transmissivity.

Large drawdown and the algorithm for the unsaturated zone, see Svensson (1997b), were found to generate isolated water columns above cells with very low hydraulic conductivity. This was considered not realistic, and therefore a minimum vertical hydraulic conductivity of $5 \cdot 10^{-9}$ m/s was used for the cells above the tunnel spiral down to a depth of 140 m.

Boundary conditions

Upper boundary:

Net precipitation (P-E, P: Precipitation, E: Evapotranspiration) on the upper boundary was set 200 mm per year for the regional model and 100 for the mm per year for the site scale model for the upper surface not covered by the sea. Calculated net groundwater recharge locally depends on elevation of topography and the elevation of the water table, see the algorithm for the unsaturated zone presented in Svensson (1997b) 200 mm per year correspond approximately to the mean run-off for the area around Äspö. In the site scale model it was needed to decrease the (P-E) to 100 mm per year in order to get a fresh water lens to the depth during natural conditions that approximately corresponded to the measured values.

The sea surface was modelled as constant pressure. The salinity of the Baltic Sea is assumed to be 0.6%. Precipitation is assumed to have a salinity of 0%.

Side boundary:

Boundary conditions from regional model except for the uppermost 100 m in the model where zero flux conditions were used due to the difference in resolution of the regional and site scale computational nets.

Lower boundary:

Boundary conditions from regional model.

Internal boundaries:

Tunnel: Flow rates into the tunnel assigned to hydraulic conductor domains intersecting the tunnel for two tunnel face positions; 2,875 and 3,600 m.

Calibration

Four test cases were used: Natural (undisturbed) conditions, pumping test LPT2 (pumping of borehole KAS06) and the drawdown by the Äspö HRL when the tunnel was at chainage 2,875 and 3,600 m. Calibration was made to match the measured piezometric levels for all cases and the salinity of the groundwater for natural conditions by adjusting the transmissivities and the arithmetic mean of $Log_{10}(K)$, (K: hydraulic conductivity) by trial and error approach.

Simulation results

Below some results are presented.

Recharge- and discharge pattern

The groundwater flow field close to the surface, at approximately 450 m depth is illustrated in Figure 2-3 for natural conditions and with Äspö HRL present in Figure 2-4.

The recharge- and discharge pattern is also illustrated by the vertical flow component shown as isolines, for downwards and upwards flow, in Figures 2-3 and 2-4 for depth 450 m. The recharge and discharge pattern is rather diffuse near the surface but at 100 and 450 m depth much of the vertical flow takes place in the hydraulic conductor domains.

The flow pattern, mainly on southern Äspö, changes considerably with the Äspö HRL present, see Figures 2-3 to 2-5. The flow rates around the tunnel system are also larger than for the natural conditions.

Salinity distribution

North-south vertical section through the model is shown in Figure 2-5. The section intersects the centre of the tunnel spiral. As can be seen in the figure the maximum depth of the fresh water lens (0.1% salinity iso-line) is about 300 m below Äspö under natural conditions. The flow into the Äspö HRL tunnel changes the distribution of the salinity mainly below Äspö. Upconing of saline water can be seen in the figure.

The updated site scale model mentioned in section 2.2.2, was 1996–1997 used to make a new model realisation of Äspö HRL and to do remodelling of the Äspö HRL's impact on the groundwater flow.

A laboratory model will be made that has a smaller cell size than the site model and focused around the lower part of the spiral. The laboratory model will take the boundary conditions from the site model.

The transformation of boundary conditions from one model to another should be improved as well as the presentation of results. Generating the hydraulic conductivity field for the rock mass outside the deterministic zones with some correlation and anisotropy is of interest to develop. So far no correlation between the cells has been included in models made with the PHOENICS code.

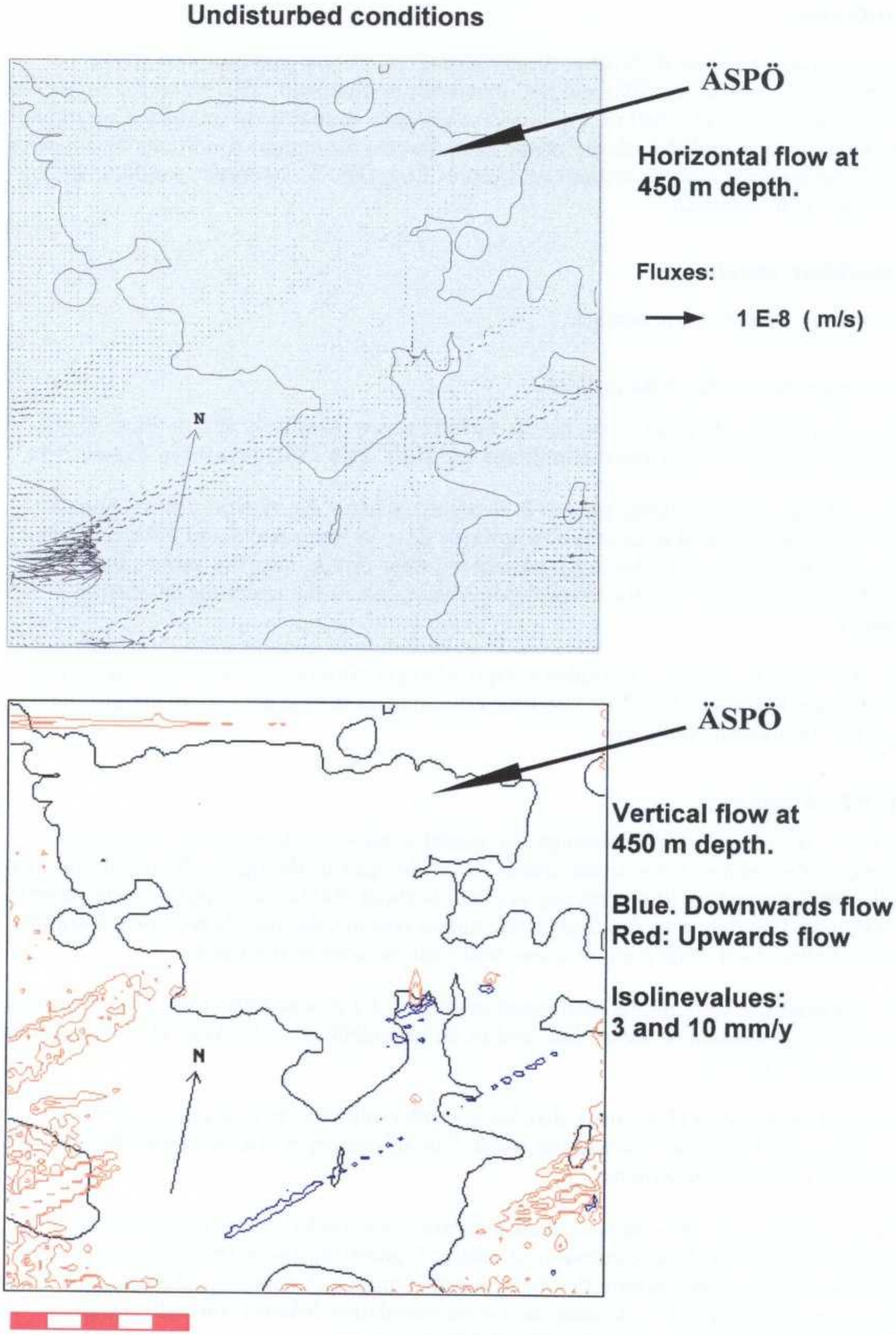


Figure 2-3. Site scale groundwater flow model. Natural conditions. Blue colour indicates downwards and red upwards flow (Svensson, 1997b). Top: Horizontal flow at 450 m depth. Bottom: Vertical flow at 450 m depth.

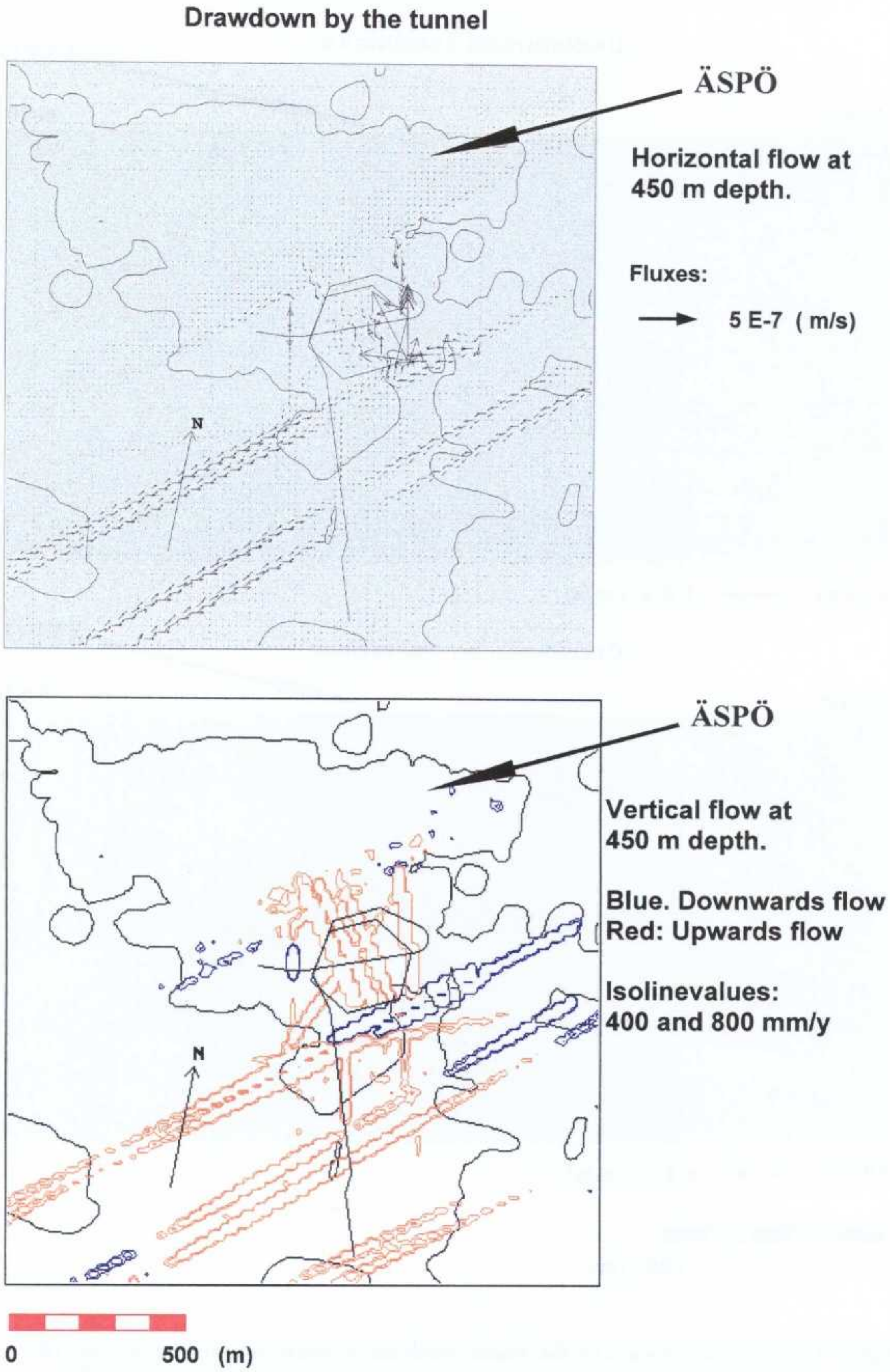


Figure 2-4. *Site scale groundwater flow model. Drawdown due to inflow to Äspö HRL. Blue colour indicates downwards and red upwards flow (Svensson, 1997b). Top: Horizontal flow at 450 m depth. Bottom: Vertical flow at 450 m depth.*

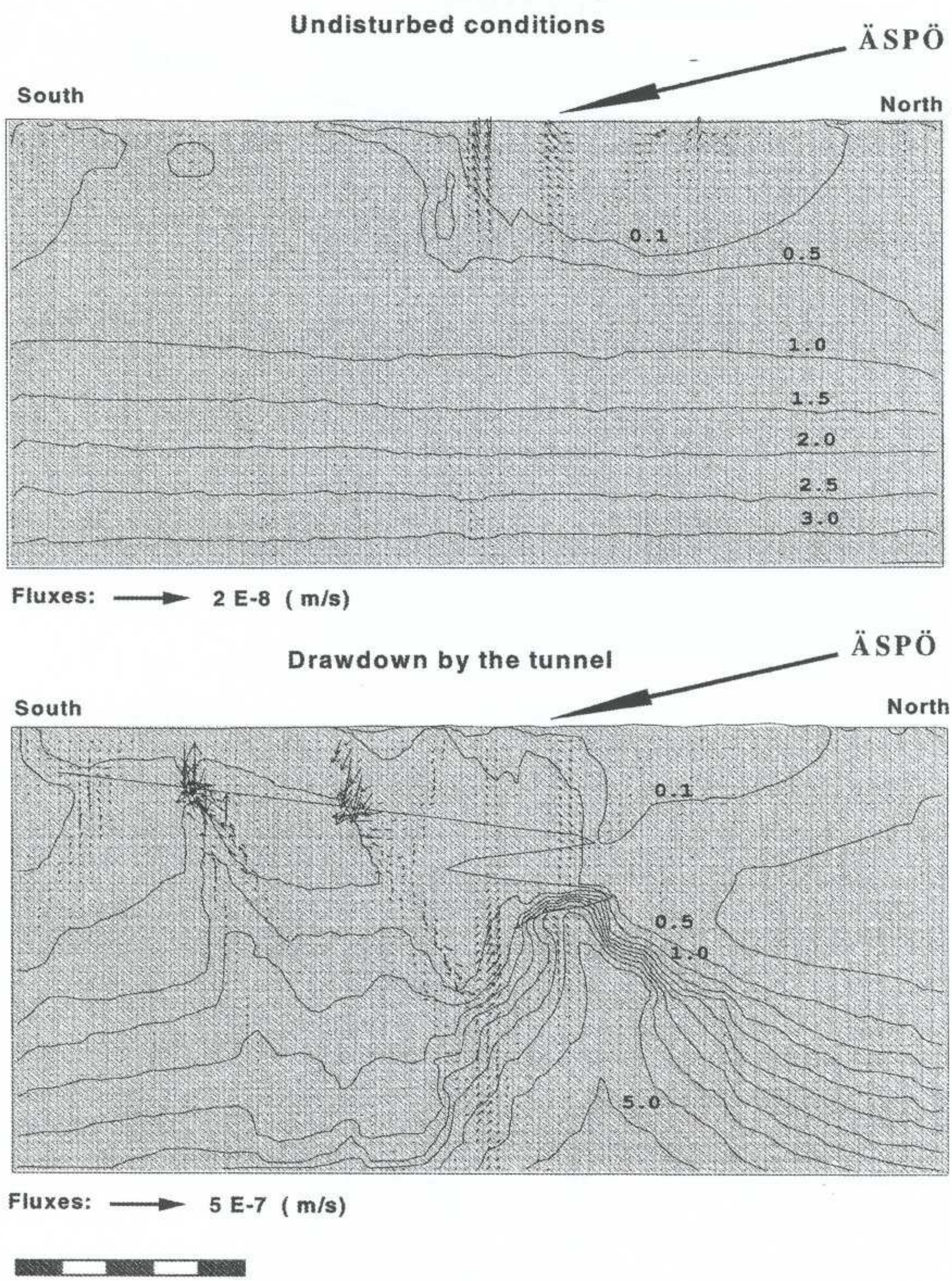


Figure 2-5. Site scale groundwater flow model. North-South vertical sections through Äspö HRL. Salinity fields in %. Top: Natural conditions. Bottom: Drawdown due to inflow to Äspö HRL. (Note: Flow field from surface down to 20 m depth is not shown). (Svensson, 1997b)

2.4 Publishing of results

2.4.1 Background

So far the results have mainly been published in a large number of Progress Reports and a few Technical Reports. A number of papers have also been presented in conferences during the years, covering experiences from Äspö HRL or evaluation of some specific data from Äspö HRL.

2.4.2 Results

A workshop was organised by OECD/NEA 1-3 September 1997 in Borgholm Sweden. Based on a presentation an article concerning hydrogeological and hydrochemistry modelling has been sent in for the documentation of the workshop. An overview paper has also been presented in Tunnelling & Underground Space Technology, see bibliography of articles.

3 Methodology for detailed characterization of rock underground

3.1 General

Detailed characterization 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 characterization 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 characterization 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 planned to meet this Stage Goal include detailed characterization 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 characterization from underground tunnels and boreholes.

3.2 ZEDEX – comparative study of excavation induced disturbance

3.2.1 Background

To obtain a better understanding of the properties of the disturbed zone and its dependence on the method of excavation ANDRA, UK Nirex, and SKB decided to perform a joint study of disturbed zone effects. The project is named ZEDEX (Zone of Excavation Disturbance EXperiment). The objectives of ZEDEX were:

- to understand the mechanical behaviour of the Excavation Disturbed Zone (EDZ) with respect to its origin, character, magnitude of property change, extent, and dependence on excavation method,
- to perform supporting studies to increase understanding of the hydraulic significance of the EDZ, and
- to test equipment and methodology for quantifying the EDZ.

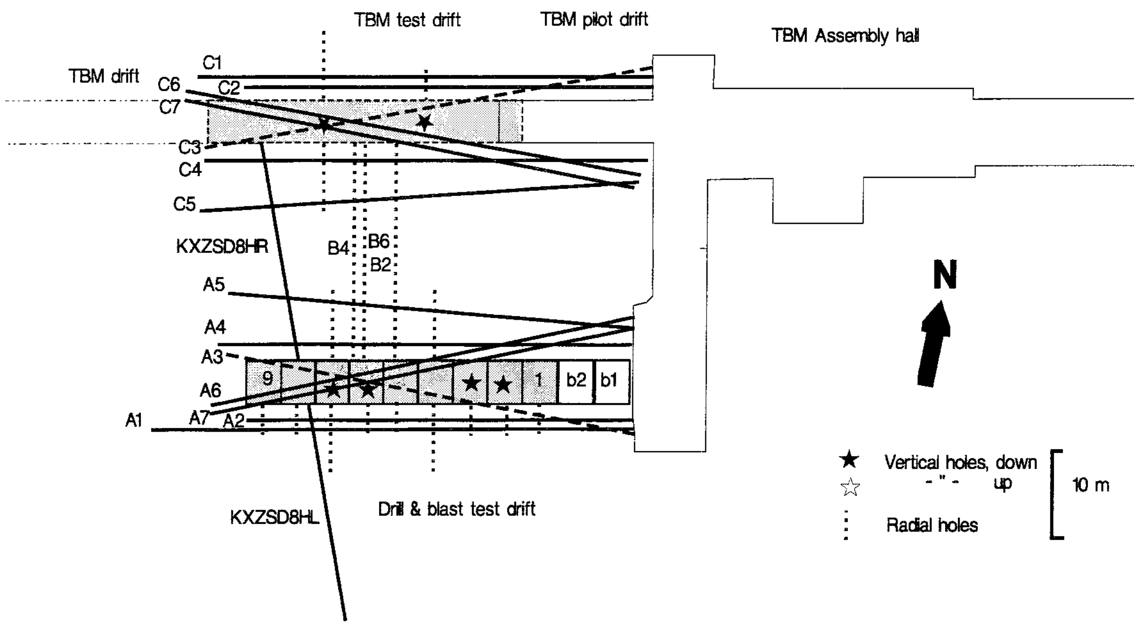


Figure 3-1. Configuration of test drifts and investigation boreholes for the ZEDEX study.

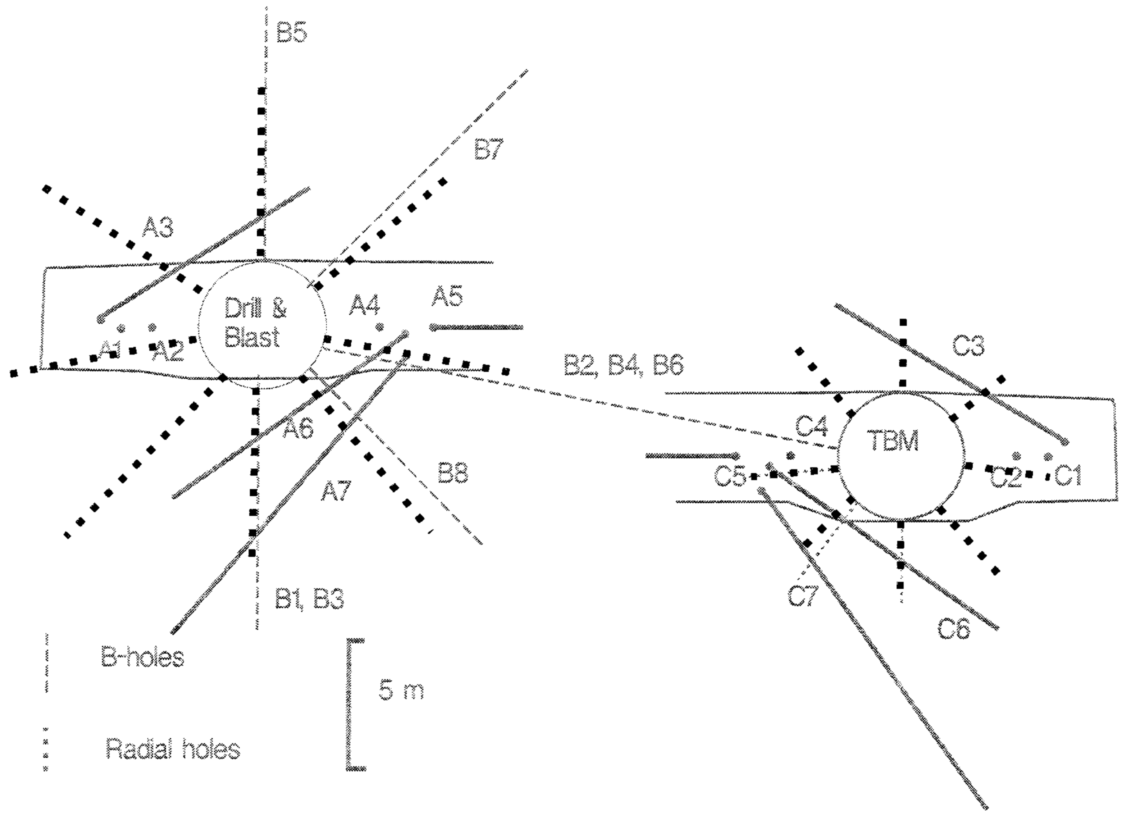


Figure 3-2. Vertical section showing location of boreholes in relation to the test drifts.

The ZEDEX project was started in conjunction with the change of excavation method from drill & blast to tunnel boring that took place during the summer of 1994. The originally planned experimental activities, which were outlined in a Test Plan published as Äspö ICR 94-02 have been completed and reported (Äspö ICR 96-03). These results showed that further data collection and more thorough analysis of existing data would be beneficial for a better understanding of the extent and properties of the disturbed zone for different excavation techniques. Hence, ANDRA, UK Nirex, and SKB agreed on an extension of the ZEDEX Project including additional data collection, thorough analysis of available data and predictive modelling efforts. The scope of the Project Extension is defined in a Test Plan (ICR 95-07). Significant contributions to the project have also been provided by BMBF and Nagra.

The experiment was performed in two test drifts near the TBM Assembly hall at an approximate depth of 420 m below the ground surface. Measurements of rock properties were made before, during, and after excavation. The investigation program included measurements of fracturing, rock stress, seismic velocities, displacements, and permeability. The experimental configuration is outlined in Figures 3-1 and 3-2.

3.2.2 Results

Measurements during Excavation

During TBM excavation, vibration measurements showed that only about 0.03% of the energy used to excavate the drift and bore through the rock was radiated into the surrounding rock as seismic energy. Maximum particle velocities determined 3 metres from the drift wall during cutting were only about 1 mm/s. For the D&B drift, it was estimated that 4–7% of the energy applied in the form of explosives was converted into seismic energy. Accelerations measured 3 metres from the drift wall reached values in excess of 500 g in peaks of very short duration. The seismic energy input to the rock mass was somewhat lower for rounds excavated using the smooth blast design than the normal blast design. These data showed that the TBM requires much more cumulative energy to create a similar length of drift compared to a drill and blast round. However, the time required for excavation and the minimal seismic efficiency of the TBM means that drill and blast methods may input somewhere in the region of a million times more power into the rock as seismic waves or ground vibration.

Acoustic Emission (AE) monitoring was performed when TBM excavation was stopped overnight at 9, 15, 22 and 25 metres measured from the start of the TBM drift. When the TBM stopped at 9 metres the majority of the recorded and subsequently located AE activity (232 events) defined a narrow zone directly in front of the position of the TBM face. Additionally other events were located around the drift, generally within 1 metre of the drift perimeter and ahead of the drift face. For the TBM drift the majority of AE-events occurred at the face within a few tens of centimetres from the advancing face.

In the D&B drift AE monitoring was undertaken after each blast round. The spatial distribution of AE events was similar for both drifts but the AE-event density was approximately a factor of 10 higher for the D&B drift compared to the TBM drift and was high out to one metre from the drift wall (Figure 3-3).

Analysis of the Acoustic Emission (AE) events have shown that AE-events occurred at deviatoric stress levels of approximately 25 MPa which is well below the typical range of crack-initiation stresses (Figure 3-4). Source mechanism analysis of AE events showed that the great majority of events could be fit to shear-slip mechanisms. Other mechanisms

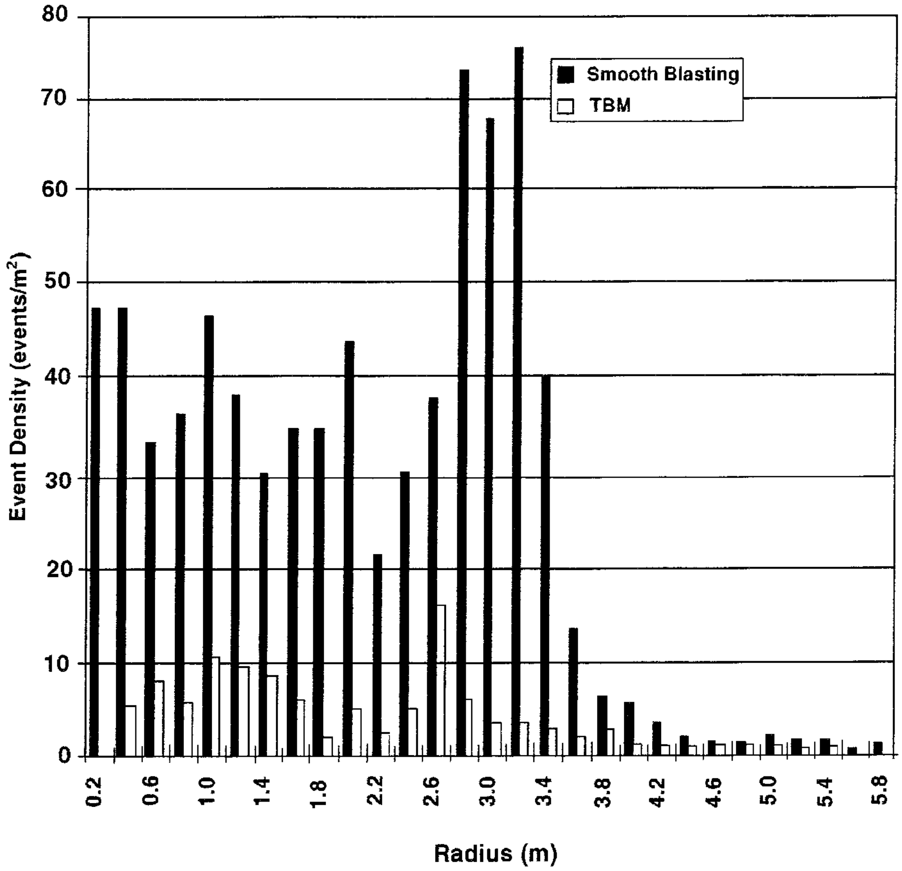


Figure 3-3. Average AE event density as a function of radial distance from the centre of the drift for the TBM and blasted drift.

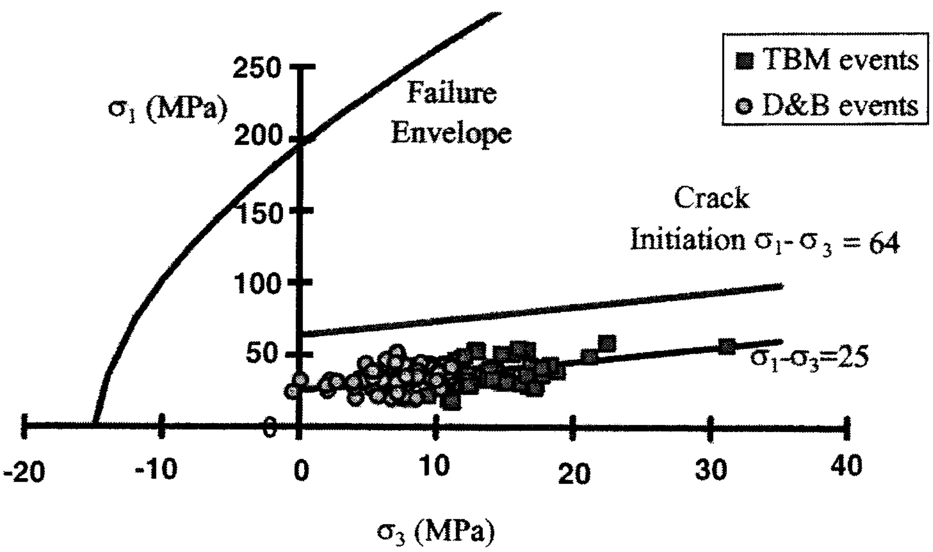


Figure 3-4. Differential stress at AE source locations in the TBM and D&B drifts. A Hoek-Brown failure envelope for Äspö diorite is shown for reference as is the unconfined laboratory crack initiation stress (σ_a=σ_1–σ_3=64 MPa).

considered were explosive (crack-opening) events and implosive (crack-closure) events. The highest proportion of implosive events were recorded from rounds R2 and R6 which were described as partially failed rounds, i.e. a blast round that failed to completely excavate the design volume of rock. The majority of the activity from these rounds occurred in the blasted but intact volume, which may have cracks initially opened by the blast gases and the implosive events may represent the closure of such cracks. There was also some evidence that the damage also extended further into the walls around the failed rounds than for successful blasts. Of the nine rounds within the D&B drift only four did not require corrective action, the others were considered to have failed or partially failed.

Convergence measurements were made at two sections, 9 and 24 metres, along the TBM drift. The results indicated predominantly horizontal convergence in both sections (3.6 and 1.3 mm, respectively), with little convergence in the vertical direction. This pattern of convergence is consistent with the in situ stress measurements which indicate a horizontal to vertical stress ratio of about 3:1. The magnitude of the displacements is consistent with the expected magnitudes of initial stress with a mass modulus in the range 50 to 60 GPa.

In the D&B drift, displacements were measured after each blast round. Measured displacements were generally less than 1 millimetre and most of the displacement occurred when drift excavation advanced one blast round. The small displacements measured were partly due to the fact that the convergence pins had to be installed about 2 metres behind the centre of the face due to its curvature.

Measurements after Excavation

The seismic tomography results showed no effects of excavation on the seismic properties of the rock at distances larger than 1.5 metres from the drift wall for any of the excavation methods. In the D&B drift a low velocity zone extending up to about 1 metre from the drift floor was observed.

A large number of hydraulic pulse test data were collected from 26 tested short radial boreholes. The re-analysis of pulse tests in 9 selected boreholes has produced a new set of permeability data that characterizes the rock properties in the damaged zone. The principal conclusions suggested that any change of hydraulic properties in hard rock due to the EDZ is attributed to enhanced aperture and/or connectivity of discrete features and not to deformation or alteration of the rock matrix itself. This is in agreement with the geomechanical conceptual model of the ZEDEX study that indicated that the effects of EDZ would be seen as the propagation of discrete fractures which were either pre-existing (and re-activated) or newly developed discrete planes of weakness rather than an alteration or deformation of the rock matrix. As the damaged zone testing was only applied in boreholes drilled after the drift excavation a direct comparison of before/after in situ properties could not be undertaken and it is not clear whether the measurements reflect the effect of the excavation (EDZ). The results do, however, suggest that there is no well defined and significant increase of permeability of rock mass in the damaged zone in the vicinity of drift excavation which could be observed systematically in the analysed data.

Hydraulic pressure build-up tests performed before and after excavation have also been re-analysed and have contributed to the development of a better overall understanding of the formation response in the disturbed zone. These tests were made at distances of approximately 2 and 6 metres from the drift wall. The significance of changes in hydraulic properties of the disturbed zone was evaluated largely on the basis of observed changes in formation response. Significant changes in hydraulic properties of the far-field were detected in 13% of the tests, all of which are related to the D&B drift excavation. In the disturbed zone of the TBM drift, the observed changes were less evident and described as detectable in 16% of all tests.

The results of the measurements made in the short radial boreholes to assess the near-field damage (permeability, seismic velocity, and fracture mapping) can be summarised as follows:

- The comparison of results from the different measurement types in general showed strong correlation.
- The vertical boreholes in the floor of the D&B drift indicated the presence of a larger zone of damage than observed in boreholes with other orientations. This can be explained by the high lifter hole charging and the large radius of the flat floor.
- The extent of the damaged zone in the D&B drift is estimated to be 0.8 metres in the floor and about 0.3 metres in the walls. In the TBM drift there is very little evidence of damage.
- The results showed no significant or consistent differences between the two blast designs.

The laboratory measurements provided a check on the in situ measurements in terms of providing data on rock properties by alternative techniques. In general, the laboratory measurements corroborated the results obtained in situ and provided greater confidence in the interpreted extent of the damage zone. In addition, the laboratory measurements provided data on parameters such as micro-crack porosity, compressibility and micro-cracking not directly obtainable from in situ methods.

Conclusions

The ZEDEX results show that it is appropriate to divide the EDZ into a damaged zone, close to the drift wall dominated by changes in rock properties which are mainly irreversible and a disturbed zone beyond the damaged zone that is dominated by changes in stress state and hydraulic head and where changes in rock properties are small and mainly reversible. The changes in rock properties and rock stress with distance from the rock wall of the excavation is gradational and there is hence no distinct boundary between the two zones (Emsley et al., 1997).

The ZEDEX experiment was performed in a rock mass with low stresses which resulted in mainly elastic behaviour and no induced damage or failure due to stress concentrations at the drift perimeter. The damaged zone caused by the excavation methods applied has been identified by several measurement techniques. Monitoring of AE-events is the most sensitive method which indicates minor damage due to crack opening and slip. Sparse AE-activity monitored in the disturbed zone is not expected to correspond to measurable changes in rock properties. However, a large number of AE-events indicates intense micro-cracking and is expected to produce a macroscopically detectable increase in crack density. For the D&B drift significant AE-activity was observed up to 1 metre from the drift wall while the corresponding extent for the TBM drift is a few tens of centimetres. Changes in seismic velocity indicate a larger increase in crack density. The dye penetration tests performed in the slots cut from the drift has shown the extent of macro fracturing, which in the floor of the D&B drift has extended to about 50 centimetres. The hydraulic measurements performed in the damaged zone showed little if any change in permeability of the rock matrix. The larger permeabilities observed have been associated with the induced and pre-existing fractures.

Two different blast designs were used during excavation of the D&B drift. Measurement results show only minor differences in terms of damage between the blast designs used. Differences in initial conditions, coupled with relatively small differences between results from the two drill and blast designs, make it difficult to draw any precise conclusions regarding the differences between the effect of excavation method between low-shock energy smooth blasting and normal smooth blasting. However, failed rounds of both designs have shown more damage than successful rounds.

The disturbed zone is characterized by elastic displacements and no induced fracturing. There are only very few AE-events observed in the disturbed zone and these have been found to correspond to slip on existing fractures. The AE-event density is also similar for both the TBM and D&B drifts. The hydraulic tests performed before and after excavation have not revealed any significant changes in hydraulic properties due to excavation.

The results from ZEDEX indicate that the role of the EDZ as a preferential pathway to radionuclide transport is limited to the damaged zone. The current view of the characteristics and extent of the damaged and disturbed zones are shown in Figure 3-5. The character of the damage to the rock by blasting and TBM excavation are actually quite similar. There is normally a zone of crushed rock around the blast hole and the TBM groove from which radial cracks extend. The extent of the cracks is however significantly different being some tens of millimetres for TBM excavation compared to some tens of centimetres for blasting. It is not trivial to define the extent of the damaged zone as induced cracks may extend far from the blast hole leaving pieces of intact rock in between. Measures of damage zone extent may thus vary depending on the location of the observation point. The extent of the damaged zone is significantly greater around the drift excavated by blasting compared to the drift excavated by the tunnel boring machine. However, the extent of the damaged zone, which is the hydraulically significant part, can

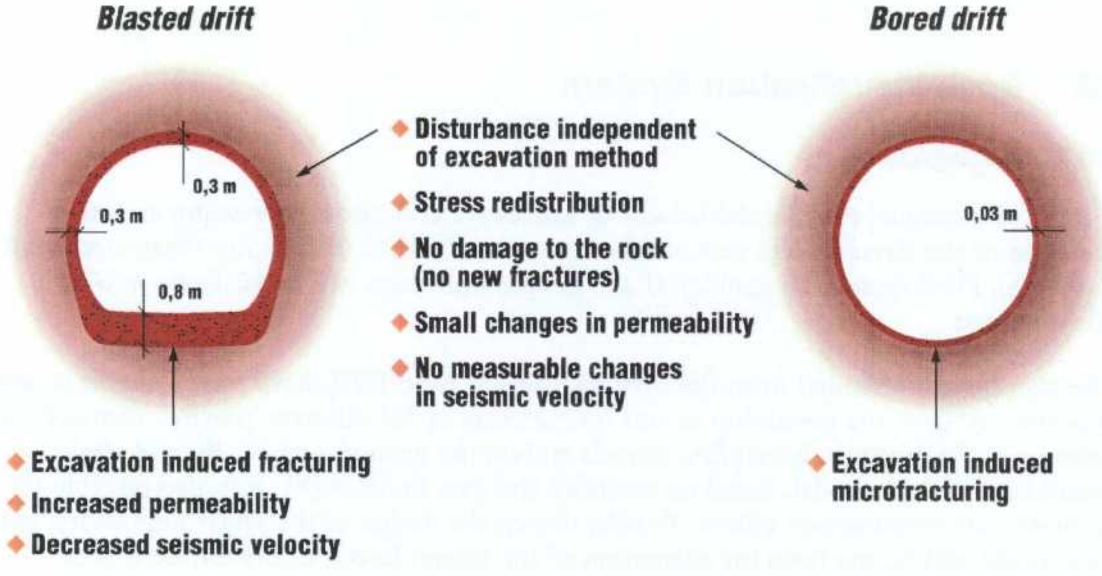


Figure 3-5. Summary of main findings of the ZEDEX project. The extent of the damaged zone is significantly greater in the drift excavated by blasting compared to the drift excavated by a tunnel boring machine.

be limited through application of appropriate excavation methods. By limiting the extent of the damaged zone it should also make it feasible to block pathways in the damaged zone by plugs placed at strategic locations.

There appears to be no experimental evidence, neither from ZEDEX nor other experiments, in support of an increased permeability in the disturbed zone affected by the stress redistribution caused by the void, as suggested by Olsson and Winberg (1996). The stress redistribution will of course lead to changes in fracture aperture, both opening and closure. In a general three-dimensional fracture network it is unlikely that fractures would open and connect in such a way that a permeable path opened along the drift. The risk of a connected pathway is of course greater if drifts are oriented parallel to one of the main fracture sets.

The ZEDEX Project has been successful, particularly in the mechanical aspects and met the objectives set out for the project. The project applied and tested an integrated suite of measurement techniques to the characterization of the damaged and disturbed zones. Great emphasis was placed on the integration of the different data sets and the redundancy of data proved to be very useful and provided a consistency in the interpretation of the "boundary", albeit gradational in nature, between the damaged and disturbed zones developed around the drifts. Further it has demonstrated the link between damage and the excavation method and has shown that a difference, in terms of damage, can be determined. It has also indicated that there is some lithological control on damage, with the more "brittle" lithologies showing more damage.

The range of methodologies employed during the ZEDEX project has allowed equipment to be tested and to assess the applicability of certain equipment and methods to quantifying the EDZ and the change in properties in the EDZ around the drifts. Some of the equipment utilised was specially designed and constructed to address the problem of measuring the EDZ and the funding organisations anticipated that they would use the equipment developed within their own programmes. Most of the techniques applied have been successful in quantifying the extent of the EDZ or characterizing the geological setting of the experiment.

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 Characterization 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 labelled 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 3-6. By using the object selector, an unique feature in the system, objects can be turned on (visible) or off (not visible).

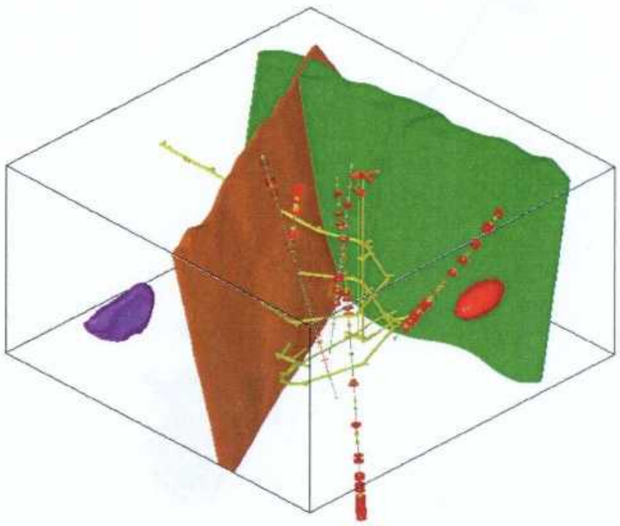


Figure 3-6. *Objects can be turned on (visible) or off (not visible), by using the object selector. The rock mass visualised in this case includes visible objects of several types including borehole data, modelled objects (a fracture zone in brown, a lens in red and two arbitrary rock bodies in purple 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 parts are presented in the following text.

RVS / Borehole Visualisation

RVS offers a number of possibilities to visualise mapping and measured parameters in boreholes. The format for the visualisation is controlled through a LookUp Table (LUT) which defines the attributes of the visualisation as a function of the parameter value.

The parameters are divided into *three groups*, point data, from-to data and fracture data. *Point data* are stored as a depth in the borehole and a value. Such data can be visualised as a view-independent curve or symbols. *From-to data* are stored as from-depth, to-depth in the borehole and a value. Such data can be visualised as Lines, Cylinders, Triangular Tubes or View-independent Diagrams. For Lines, Cylinders and Tubes the attributes such as line style, colour, weight, diameter (for Cylinders and Tubes only) and material can be varied as a function of the parameter value. *Fracture data* are stored as a depth in the borehole and orientation for the fracture. Fractures can be visualised as discs along the borehole. An example of a typical visualisation of data along a borehole is shown in Figure 3-7.

Figure 3-7. *A set of borehole parameters visualised by lines (rock type), cylinders (rock quality) and triangular tubes (water leakage).*

RVS / Modelling

RVS offers a number of modelling functions.

- Surfaces
- Fracture zones / Discontinuities
- Rock Bodies
- Drape Map
- Block Model

The surfaces are modelled surfaces from point data. In each project, one top rock surface, one ground surface, unlimited groundwater surfaces and rock boundaries can be created. All these surfaces are stored as surfaces and not as volumes although the boundaries of the modelled rock mass can be used as input when generating the rock bodies. All surfaces are finally used as input to generate a block model of the rock mass modelled. An example of a typical surface is shown in Figure 3-8.

The fracture zones are also modelled from point data. They can be modelled as plane or undulating shapes. They can be stored as surfaces but should always be transformed into and stored as volumes. This could be done by entering a thickness or by modelling two (or more) surfaces which are connected into a volume as shown in Figure 3-9.

The rock bodies could be created from connecting modelled rock boundaries into a volume. There are also some possibilities to model single rock bodies (often with limited extension). The single bodies can be modelled as a series of cross-sections (shapes) connected into a volume or a lens-shaped body with user-defined size, proportions and orientation. Another rock body is the dyke which is defined through its horizontal cross-section, strike and dip. There is also a possibility to model an area containing distributed, lens-shaped bodies. Some examples of rock bodies are shown in Figure 3-6.

The drape map function offers the possibility to drape map information over a modelled, undulating ground surface.

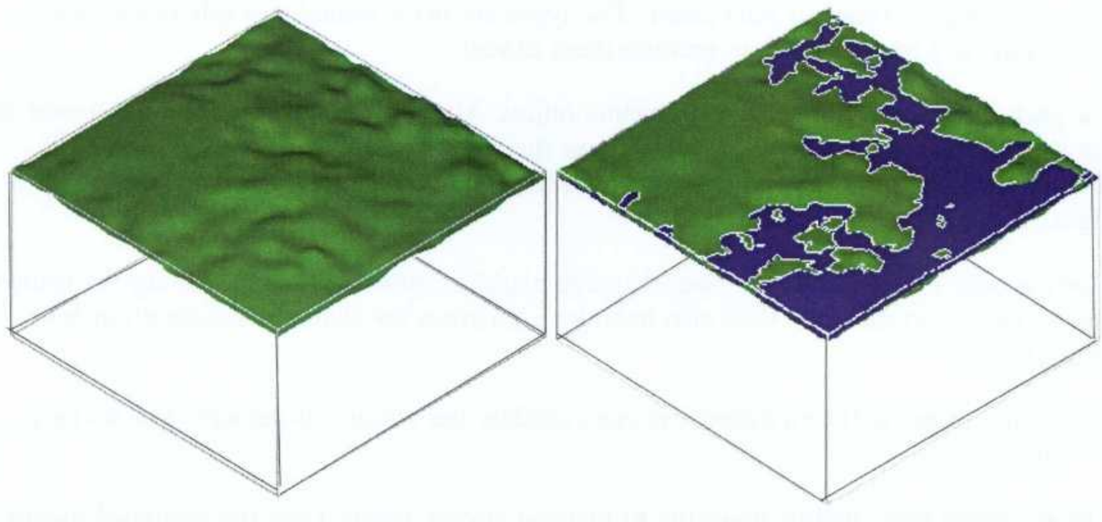


Figure 3-8. *The ground surface (a) is a typical example of an surface that can be generated with the surface toolbox in the system. To the left (b) the mean level of the Baltic is visualised, and then the southern part of the Äspö island is recognised.*

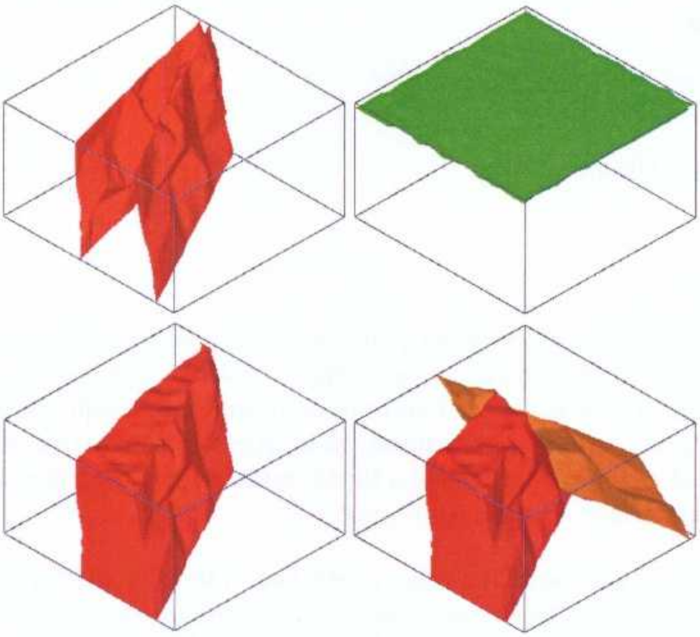


Figure 3-9. This example shows how a fracture zone, intersecting the whole rock mass, is built up. First (a) the inclined borders of the zone is modelled as surfaces and the topography (b) as well. Finally, a solid body is generated (c) by using the borders of the rock mass as ter-minators. It is also possible to terminate a zone (d) against another zone.

The block model function are to be used before a model release when all objects above are modelled as good as possible for the area. Input to the block model are the above mentioned surfaces, discontinuities and rock bodies. New volumes, with attributes inherited from the "parents", are created where the objects above intersect.

RVS / Tunnelling

When placing a tunnel, you have first to place a tunnel start object. This object defines the tunnel type, name and start point. The types are main tunnel and side tunnel where side tunnel is a branch from an existing main tunnel.

For each tunnel you can place a centreline object. After this you can make a 3D model of the tunnel by extruding cross-sections along the centreline. The cross-section doesn't necessarily have to be centred over the centreline. This work flow is also explained by Figure 3-10.

There is also a function for placing chainage marks at optional distances along the tunnel line as a guide to the user. RVS also includes a function for chainage presentation for illustrations.

When the tunnel is 3D modelled you can calculate the volume along any stretch along the tunnel.

The modelled rock quality along the tunnel can also be listed. Lists the modelled quality of all modelled volumes penetrated by the selected tunnel stretch and is best used when a block model exists over the area.

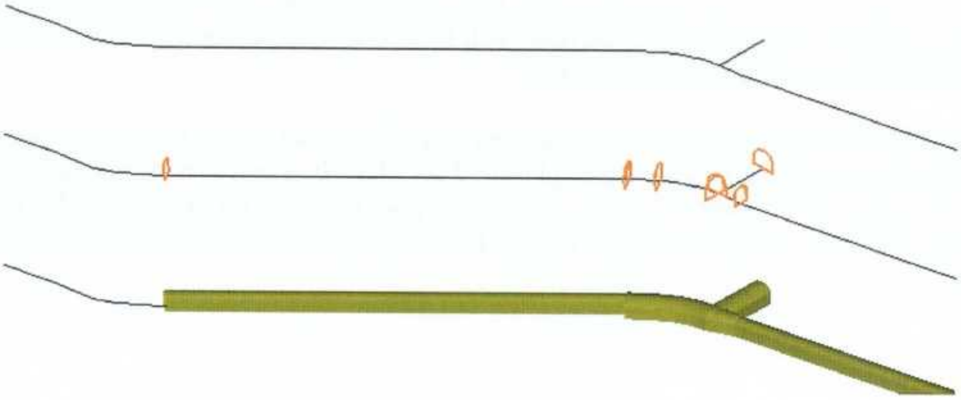


Figure 3-10. A tunnel design is built up in three steps. First a chain of tunnel path lines are defined (a), and then in the next step a set of tunnel sections are connected (b). The tunnel section profiles should be pre-defined by the user, by application of a parametric approach which is supported by the system. Finally (c), a three-dimensional tunnel shape is generated.

RVS / Animation

The animation possibilities in the system are of the types parameter and fly-through.

The parameter can be of a changing magnitude with a fixed location or with a fixed magnitude, moving in time. Animated as triangulated surfaces with changing colours (and/or) location.

During a fly-through animation the system allows the user to go forward and backwards looking at any direction and to stop and point at any element for information.

RVS / Drawings

Includes functions for rendering a view with a section trough the 3D-model with selected objects cut the section plane and other displayed with the display depth. Objects outside the display depth can be chosen to be visible. The rendered view does not have to be parallel to the section plane.

It is also possible to place a cube which limits the volume to be displayed, and to place an open box with labelled coordinate axes in a view as a navigation help in 3D views and plots.

When working with the drawing functions in RVS, all standard MicroStation tools can be used to add traditional drawing information to the visualisations displayed on the screen.

Experiences and future plans

When the first version of RVS was developed, several new valuable functions were identified. Some of these new functions have high priority, and are planned to be released before June 30th, 1998. Other functions with lower priority will be delayed, because it is important, when starting up with a new system, to evaluate the response from the users. The experiences from the use of RVS during the first half of 1998 will be analysed and documented in detail before the programming of RVS version 2.0 is initiated. Depending of the situation in August 1998 a decision will be taken if the development of RVS version 2.0 should start immediately or later.

During 1998 SKB will decide in what way external organisations will have the possibility to use RVS in cooperation with other clients than SKB. In general it would be an advantage to distribute the system to as many users as possible, but in that case SKB needs assistance from the external companies that have been involved in the development of the system.

4 Test of models for groundwater flow and radionuclide migration

4.1 General

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. In Performance Assessments of a repository different models describe the function of the host rock as a barrier.

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. An important part of this work is performed in the Äspö Task Force on Groundwater Flow and Transport of solutes. The work in the Task Force is closely tied to ongoing and planned experiments at the Äspö HRL. Well-specified tasks are defined where several modelling groups work on the same set of field data. The modelling results are then compared to experimental outcome and evaluated by the Task Force delegates.

Studies are also performed of the geochemical and hydraulic disturbances induced by excavation and operation of a repository on the host rock barrier to ensure it has no negative effect on the long-term safety of a repository.

Major projects planned to meet this Stage Goal include the Tracer Retention Understanding Experiments (TRUE) which focuses on retardation processes important for radionuclide transport, studies of reaction rates for oxygen with rock minerals (REX), degassing and two-phase flow near drifts, hydrochemical modelling, and verification validation of chemical models and verification of laboratory data through in-situ experiments in a borehole laboratory (CHEMLAB).

4.2 Fracture classification and characterization

4.2.1 Background

Small-scale geological, hydrological and hydrochemical features are highly variable in characteristics (lithology/mineralogy, transmissivity etc.), while radionuclide transport models rely on simplified concepts e.g. water flow through a channel with constant water chemistry, hydraulic gradient, wallrock mineralogy and porosity across the whole flow path.

Groundwater flow and nuclide transport is taking place in water conducting paths that are transmissive due to their genesis. Therefore eventually parameter values used in the numerical transport calculations should reflect the type of water conducting feature.

Fracture characterization and classification aim at suggesting suitable types of fractures for tracer tests and at giving parameter values for modelling of relevant flow paths for nuclide migration.

4.2.2 Objectives

The objectives of the study are:

- to develop a methodology for characterization of fractures with respect to rock type, tectonic evolution, infillings and wallrock alteration,

and by means of this characterization be able:

- to develop a methodology for classification of different features/fractures (fracture sets) in terms of their importance for radionuclide mass transfer.

4.2.3 Experimental concept

The methodology of investigation included a stepwise procedure:

- Compilation of an inventory of existing data (geology, hydrogeology and hydrochemistry) and the boundary conditions on how water conducting features can be explored (e.g. boreholes, open tunnels), and definition of scale at which the investigation should be targeted.
- Preliminary characterization of a limited number of typical water conducting features with the objective to understand the processes that governed the evolution of water conducting features and so to define a set of geologic parameters that adequately describe the feature.
- Full characterization of a large number of water conducting features and acquisition of database containing all relevant parameters that can be observed or measured.
- Data base analyses (which parameters are common to all features and which vary systematically) and derivation of fracture classification scheme.
- Derivation of simplified conceptual models of all types of water conducting features, including geometric and lithologic (mineralogic and porosimetric) information needed for transport modelling in any scale (<1m, 1–10 m, 10–100 m and >100 m).

4.2.4 Results

A characterization of a large number of water conducting features has been completed and reported in ICR 97-01. Main findings are:

The preliminary characterization stage indicated that on an observation scale of meters – decametres, all water-conducting features are related to faults.

The full characterization included 88 water-conducting features whose traces cross cut the entire tunnel cross-section (smaller features were not included in the study). Most of the faults dip steeply, and strike directions are NW-SE (dominant) and NE-SW (subordinate). Many of the faults follow pre-existing structural inhomogeneities, such as ductile shear-zones of lithified cataclastic shear-zones.

On the basis of the geometric arrangement of master faults and splay cracks in faults, 5 types of water-conducting features are distinguished, see Figure 4-1:

Type 1 – single fault
Type 2 – swarm of single faults
Type 3 – fault zone
Type 4 – fault zone with rounded geometry
Type 5 – parallel fault zones with long connecting splays

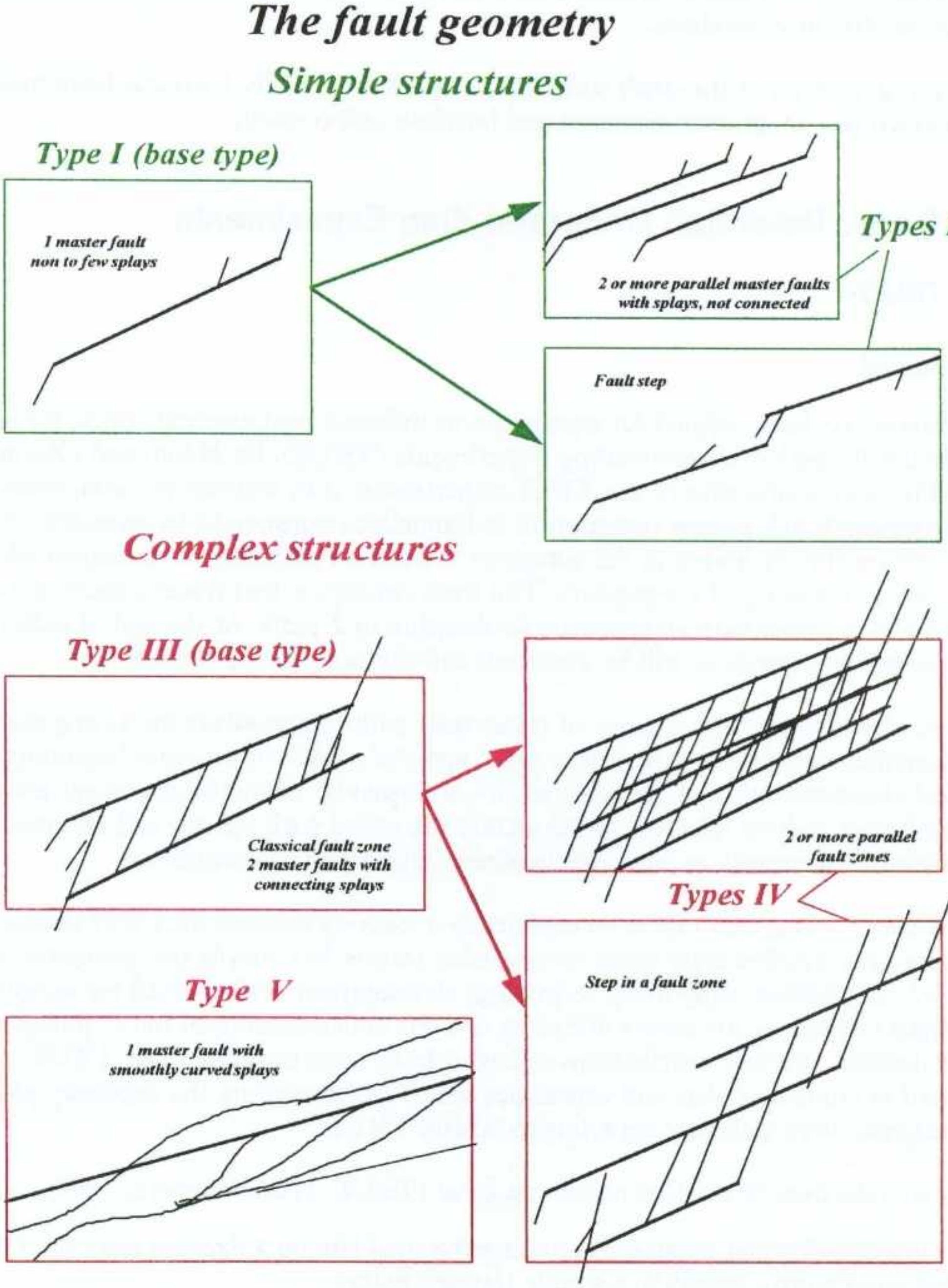


Figure 4-1. The five different fracture types identified by the FCC project.

Both direct observations and theoretical principles indicate that the internal geometry on which the classification is based is not a unique characteristic of a fault i.e. the type may vary along the strike of a fault. The length of segments with constant properties (i.e. same type) is in the range of meters to many decametres. The application of the classification scheme is limited to smaller-scale considerations, while in the case of largescale transport, the results of the study indicate that due to the common genetic history, water flow in the underground of Äspö is dominated by one single family of waterconducting features.

The brittle fault rocks are expected to strongly interact with radionuclides or tracers transported in the flow porosity by means of sorption (presence of sorbing phases such as clay minerals and Fe-oxyhydroxides) and matrix diffusion (large interconnected porosity). These processes are weaker in mylonites due to the low porosity and the scarcity of low-temperature alteration products.

Mapping and analyses of the small scale fracturing at the TRUE-1 site has been made. This included the integration of tunnel and borehole information.

4.3 Tracer Retention Understanding Experiments

4.3.1 TRUE-1

Background

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

The basic idea is to perform a series of tracer tests with progressively increasing complexity. In principle, each tracer experiment will consist of a cycle of activities beginning with geological 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 4-2. 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.

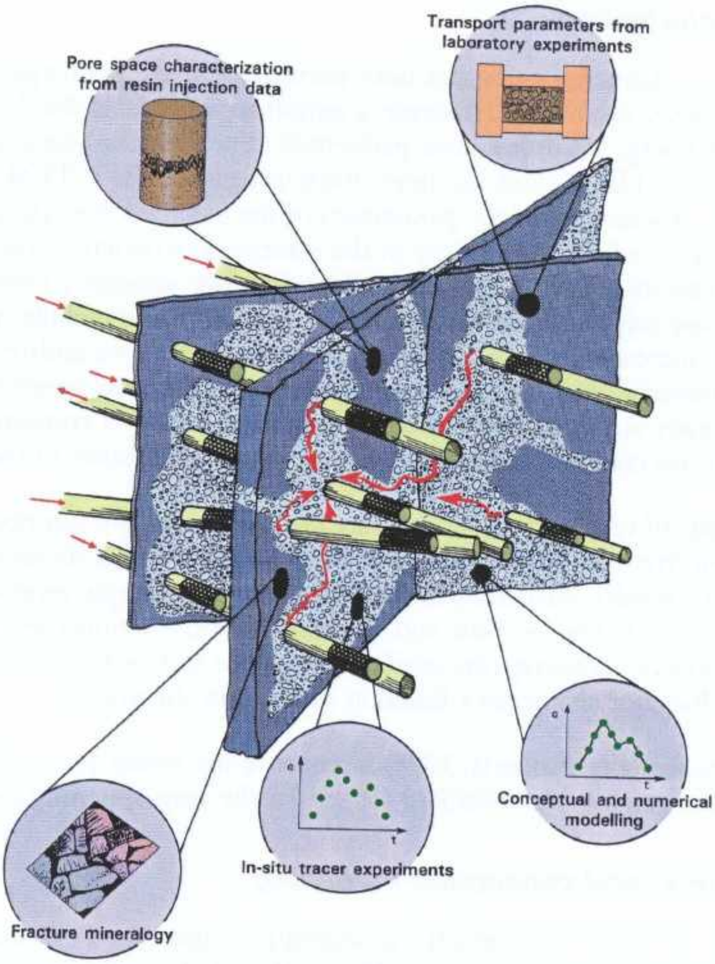


Figure 4-2. Principal outline and components of the TRUE-1 experiment.

- 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 Tracer test cycle. Initially, plans were to start up the tests with sorbing tracers during late 1996. However, due to development of new underground openings at Äspö HRL during the last quarter of 1996 and the first quarter of 1997, the tests start of these tests with sorbing tracer were postponed to the end of the second quarter 1997. Accordingly, the timetable for conclusion of TRUE-1 has been postponed with final reporting scheduled to be finished by September 1998.

TRUE-1 characterization

During the year no characterization has been performed in the field, apart from the performed tracer tests, see below. However, a partial re-analysis of the flow and pressure build-up tests (Winberg, 1996) has been performed. The focus has been on tests performed in Feature A. The analysis has been made using the code GTFM developed by Intera. Apart from assessment of the parameters of the assumed flow model, the code also allows assessment of the uncertainty in the estimated parameters. Data from the tests in general indicate a flow dimension greater than two (Roberts, 1998). This greater-than-radial response can result from a number of factors. These include connectivity to fracture network, increasing aquifer thickness, leakage from above and/or below, or a constant-head boundary. The high flow-dimension estimates from several of the tests indicate that the tests are most likely affected by leakage and/or a constant-head boundary. These results are compatible with the present conceptualisation of the TRUE-1 site.

Conceptual models of varying complexity were used to match the test responses. An increase in complexity was typically achieved by allowing the flow dimension to vary with distance within the model. Variations in the flow dimension simply represent variations in the flow geometry (including no-flow and constant-pressure boundaries) and/or hydraulic properties. The source geometry (the surface area of the test section) in the model used for the analyses does not change as a function of the flow dimension.

Estimates of transmissivity (Roberts, 1998) indicate values which are 3–20 times lower than what has been reported by Winberg (1996) for the corresponding tests.

TRUE-1 structural and conceptual modelling

The TRUE/FCC collaboration includes an attempt to apply the FCC methodology to the available data from the TRUE-1 site. The work includes address of both the deterministic, stochastic and hydraulic nature of the TRUE-1 site.

One of the basic studies constitute a detailed core mapping of the TRUE-1 cores with the purpose of constructing a structural geological database. The mapped entities include;

- fracture location (borehole length, m),
- fracture orientation (strike/dip, Äspö Local North),
- orientation of foliation (strike/dip, Äspö Local North),
- fracture mineralization (9 columns),
- ductile deformation (subjective scale, 0–3),
- cataclastic deformation (subjective scale, 0–3),
- alteration (subjective scale, 0–3),
- rock type,
- rock contacts (borehole length, m),
- rock texture.

The subsequent deterministic structural modelling has comprised;

- Preparation of data (drill core and borehole TV data including fracture orientations, lithological and mineralogical data. Integration of tunnel map information.

- Evaluation and visualisation of data: Construction of a 3D CAD model of the TRUE-1 block where the five boreholes, lithologies, and all types of structures are contained. Construction of 2D sections through the block using the deterministic data set (drill core and borehole data).

- Interpretation of the structural data and derivation of deterministic structural conceptual models of the TRUE-1 block.

In the derivation of possible conceptual models, four different models have been derived.

- A Base case obtained directly from the database. In this case an enhanced fracture frequency is noted around mylonites.
- A Case 1 with minimal interpretation where obvious deterministic structures have been interconnected.
- A Case 2, or the "Feature A" solution, where 1) individual fractures are composed to elongated "fracture zones" with an enhanced fracture frequency, and 2) the fracture zones are arranged such that they contain Feature A. The fractures defining Feature A all lie in zones with ductile precursors (mainly mylonites) with increased fracture frequency. Feature A exhibit a nearly N-S orientation.
- A Case 3, or network solution, which deals with the fact that the fracture frequency generally is very high. Consequently, one big network may exist connecting practically all fractures in the TRUE-1 block. The orientations are mainly NW with a subordinate NE set. Areas with high fracture frequency basically map the fracture zones shown in Case 2, but are more extended and thus build a network over the whole block.

The model/-s are presently being enhanced with stochastic structural information which can be used to model the block with discrete fracture network models.

Work is presently under way to test the presented model/-s against information available from hydraulic tests (interference and single hole tests) and performed tracer tests at the site.

TRUE-1 tracer test programme

During the first quarter of 1997 a comprehensive experimental plan for the planned tracer tests with sorbing tracers was produced (Andersson et al., 1997). Performed scoping calculations indicated that matrix diffusion would most likely not be a measurable process considering the time frames allocated for the planned tests. Instead the experimental concept of the tests with sorbing tracers was focused on assessment of surface sorption using a series of three tracer tests with three different flow rates, Q=400, 200 and 100 ml/min, respectively. All injections will involve injection of a cocktail of tracers with varying volumetric sorption coefficients, ranging from weakly sorbing ^{22}Na to moderately-strongly sorbing ^{137}Cs. In addition the cocktail is complemented with different radioactive and non-radioactive conservative (non-sorbing) tracers.

The step from tests with non-radioactive conservative dyes to radioactive sorbing tracers is a large one. During the first quarter of 1997 the experimental site was refurbished to allow performance of the tests, including separation of injection and sampling procedures in two containers. In addition a portable HPGe-analysing equipment was fitted in the injection container to allow on-line monitoring of the injection function. Further, a radiochemical laboratory, BASLAB, was furnished on the nearby CLAB premises to allow on-site analysis of the collected samples.

A series of preliminary design tests (PDT) were performed prior to starting up the first test with sorbing tracers (STT-1). In addition the tracer dilution tests performed in October 1995 were repeated to check for any changes in the "natural" flow in Feature A, and its environs.

Preliminary design tests

Two preliminary design tests, PDT-1 and PDT-2, aimed at finding the optimal conditions (flow geometry) for the tracer test with sorbing tracers were performed in April 1997. The results showed that the flow path KXTT4:R3 to KXTT3:R2 is the flow path that will result in the highest mass recovery. The results also showed that the mass recovery of any possible flow path at Q=100 ml/min is too low to allow tests with radioactive sorbing tracers under sufficient control. Consequently, the planned test with radioactive sorbing tracers at Q=100 ml/min (STT-3) will not be performed. A third design test, PDT-3, was performed late June with the objective to check the procedures and routines (injection, sampling, radiation protection, transports, laboratory work and analysis) for handling the radioactive tracers. PDT-3 was performed in a radially converging flow geometry with injection in section KXTT4: R3 and pumping in section KXTT3:R2 at Q=400 ml/min, which is the flow path chosen for STT-1. The tests also involved test of a modified injection procedure with a finite pulse injection with a length of 4 hours and a test of four conservative tracers; Uranine, Tritiated water (HTO), ^{82}Br, and one weakly sorbing tracer; ^{22}Na.

The injection and breakthrough curves for PDT-3, presented in Figure 4-3 (only Uranine presented), show a relatively smooth breakthrough with a first arrival of less than 2 hours. Most of the mass (80%) is injected during the first four hours. It is thus very important to determine the injection flow rate accurately during this time period. Results from analysis of the tracer dilution during injection showed a variability between 12 and 41 ml/hr. This resulted in a variability in calculated recovery varying between 90 and 100%.

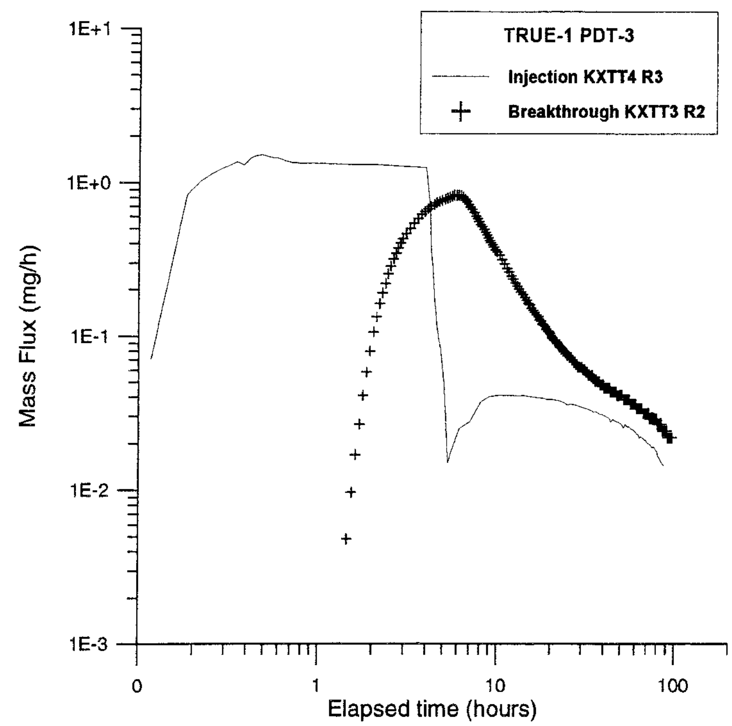


Figure 4-3. *PDT-3: Comparison between injection and breakthrough curves for conservative tracer (Uranine) (log-log).*

STT-1

The first tracer test with sorbing radioactive tracers, STT-1, was started mid July with injection of two conservative (Uranine and HTO) and six weakly to moderately sorbing tracers (^{22}Na, ^{85}Sr, ^{86}Rb, ^{47}Ca, ^{133}Ba, ^{137}Cs). The injection and pumping procedures were exactly the same as for PDT-3, i.e. pumping in KXTT3:R2 with a flow rate of 400 ml/min and injection in KXTT4:R3 with a 4-hour pulse. The associated injection curve for Uranine, presented in Figure 4-4, shows that the exchange of tracer solution with unlabelled water after four hours of injection was not as good as during PDT-3, cf. Figure 4-3. The concentration increases again shortly after the exchange procedure. Recent analysis has attributed this effect to less efficient mixing in the injection section during STT-1 (than in PDT-3). Apparently the injection system is very sensitive to small variations in flow rate resulting in less mixing in parts of the borehole section. At the end of the exchange procedure, traced water from these stagnant parts of the section slowly mixes with the remaining volume rising the concentration in the section as seen in Figure 4-4, and also to lesser degree in Figure 4-3. The recovery calculated for Uranine in the former case turned out to be >100%. The recovery was, however, overall found to be the same as that for PDT-3. Thus the calculated recovery was attributed to assigning a too small borehole section volume for KXTT4:R3. By increasing the volume by 13% from 1898 ml to 2154 ml (corresponding to increasing the diameter by a few tenths of a millimetre) a recovery of 100% is obtained.

The breakthrough of all species but ^{47}Ca are shown in Figures 4-5 and 4-6, respectively. The reasons for omitting ^{47}Ca are high uncertainties in the data due to the short half-life of ^{47}Ca in combination with high analysis errors. In Table 4-1, the calculated tracer travel

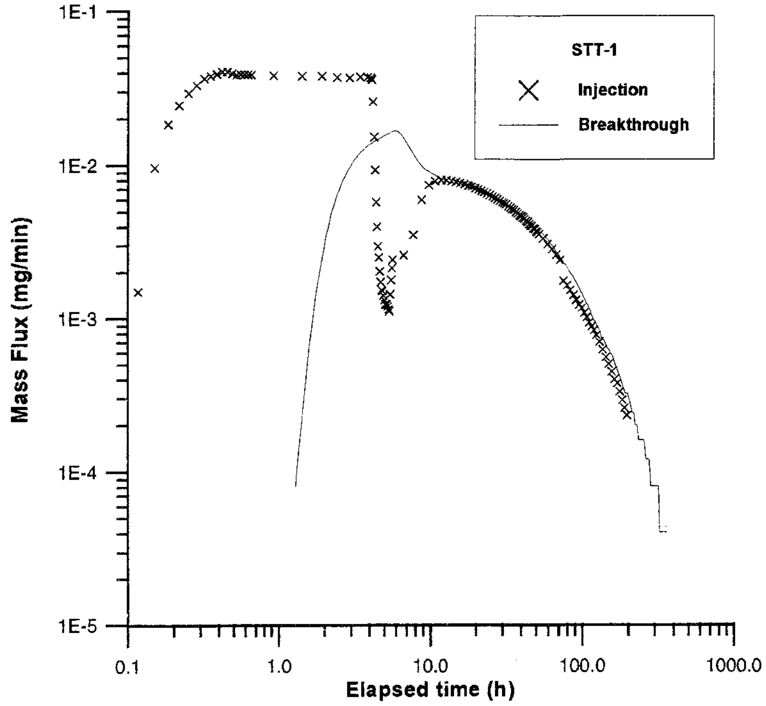


Figure 4-4. *STT-1: Comparison between injection function and the corresponding breakthrough for conservative tracer (Uranine) (log-log).*

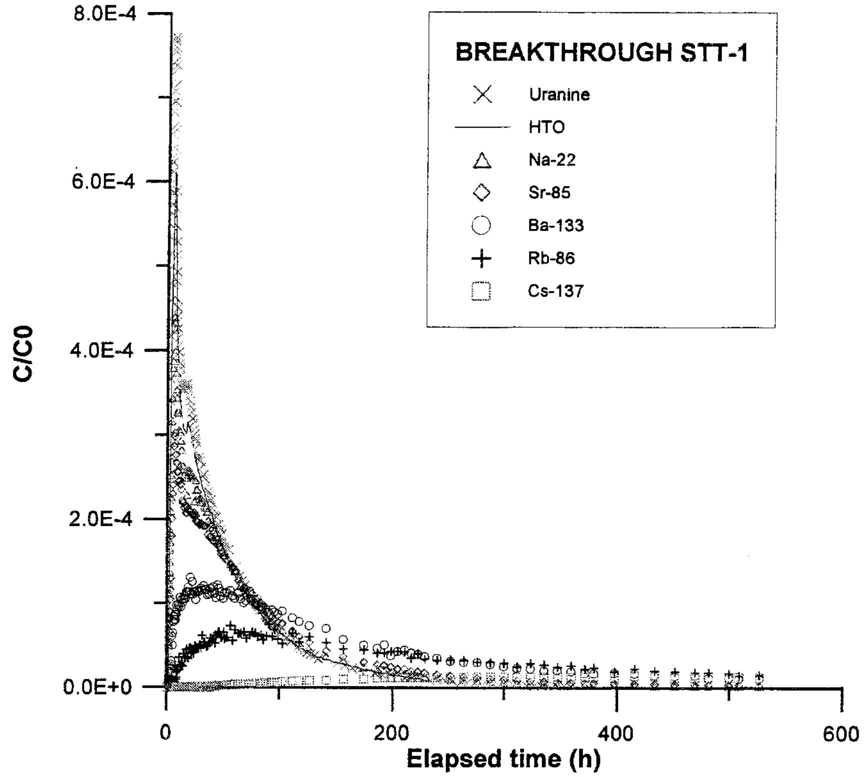


Figure 4-5. *STT-1: Comparison between the relative breakthrough of radioactive sorbing tracers (lin-lin).*

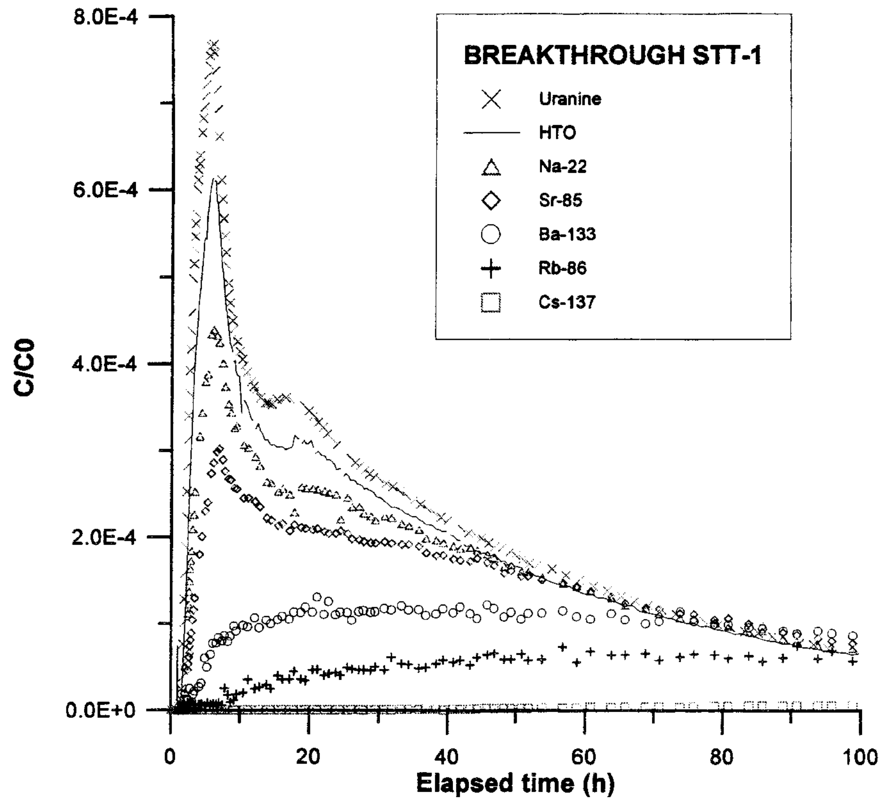


Figure 4-6. *STT-1: Comparison between the relative breakthrough of radioactive sorbing tracers (early time data) (lin-lin).*

Table 4-1. Tracer travel times, t_5, t_{50} and t_{95} based on recovered mass at t_{100} for tracers injected during STT-1.

Tracer	t_5 (h)	t_{50} (h)	t_{95} (h)	t_{100} (h)
Uranine	4.5	36	175	360
HTO	4.9	37	161	229
^{22}Na	6.0	48	240	527
^{85}Sr	7.5	60	304	527
^{47}Ca	14	300	507	527
^{133}Ba	19	146	930	1,350
^{86}Rb	31	177	470	527
^{137}Cs	150	640	1,265	1,350

times for STT-1 are presented. The times t_5, t_{50} and t_{95} are defined as the times when 5, 50 and 95%, respectively, of the recovered mass at the stop of sampling (t_{100}) has arrived. Some of the calculated travel times are strongly dependent on the recovered mass at t_{100}, especially Cs, but also Rb and Ba. The values are for reasons given above highly uncertain. The relative order of the t_{50} more or less reflects the relative K_d:s of the sorbing tracers.

Experimental results from STT-1 were presented at the 10th Task Force meeting in Kamaishi, Japan, in November 1997 and compared with prediction made by modelling groups using different modelling concepts, cf. Section 4.8.

Complete recoveries have been obtained for Uranine and HTO, ^{22}Na, ^{47}Ca, and ^{85}Sr. In the case of ^{86}Rb, ^{133}Ba the recoveries are 64 and 88 % after 526 and 1350 hours, respectively. In the case the ^{137}Cs the recovery is 29% after 3170 hours. The breakthrough curve for ^{137}Cs shows a very small increase, cf. Figures 4-5 and 4-6, and had at the time of the presentations of results in Kamaishi not reached a plateau. Model projections based on the available breakthrough data suggested a need for at least a 6000 hr monitoring to obtain a complete breakthrough curve. This would take us to the middle of March 1998. However, at this time with the noted activity decline rate, only about 35–40% of the injected mass would be recovered. This implies that 60–65% of the injected mass of ^{137}Cs may potentially be irreversibly sorbed in Feature A.

It was identified from a performance assessment perspective to be of great interest to follow the complete *in-situ* breakthrough of ^{137}Cs in Feature A. Information embedded in the breakthrough can shed light on the degree of irreversibility and possible kinetic effects in sorption of Cs. It was thus proposed to SKB to postpone the start of STT-2 (Q=200 ml/min) and instead follow the full breakthrough of Cs. In addition it was proposed to perform a second tracer injection in another flow path in the presently established flow field (KXTT1:R2 to KXTT3:R3). In mid October SKB decided to follow the proposed avenue of approach. As a consequence, the planned STT-2 test is postponed and will be integrated with the next detailed TRUE stage, TRUE-2.

STT-1b

During November, 1997 preparations were made for the second tracer injection with sorbing tracers, STT-1b. The preparations involved some modifications of the existing equipment for tracer injection and withdrawal, as well as a preliminary design test, PDT-4.

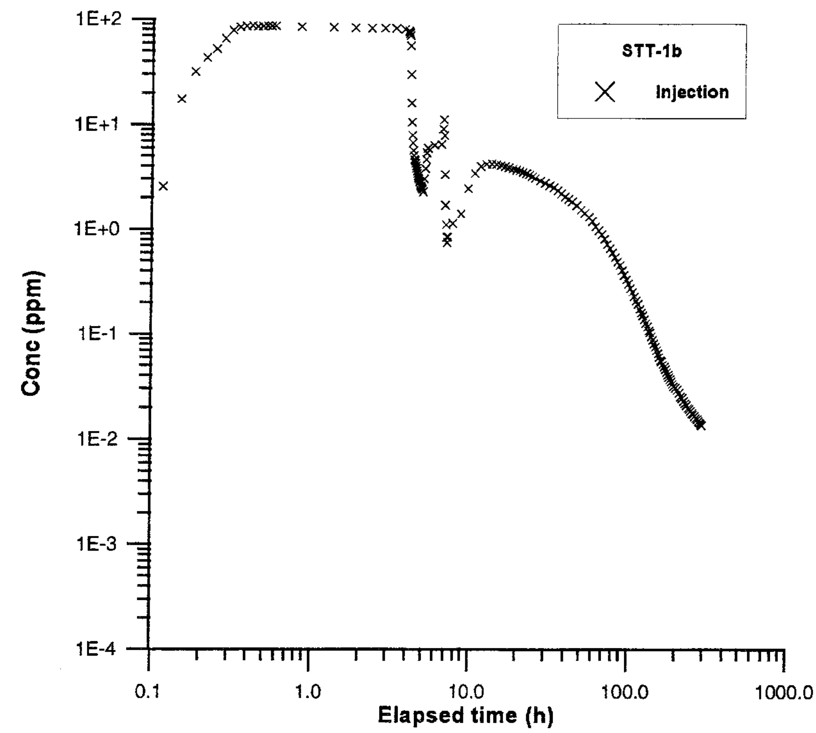


Figure 4-7. *STT-1b : Input function for conservative tracer (Uranine) (log-log).*

The preliminary design test, PDT-4, was performed in order to assure that the tracer recovery for the additional flow path KXTT1:R2 to KXTT3:R2 was high enough (>90%) to enable injection of sorbing radioactive tracers. PDT-4 was performed by injecting Uranine as a three-hour finite pulse in KXTT1:R2. A somewhat modified tracer exchange procedure was applied in order to increase the efficiency of the exchange procedure.

The tracer injection for STT-1b was performed early December 1997. A tracer cocktail consisting of ten tracers, four conservative (Uranine, HTO, ^{82}Br, ^{131}I) and six sorbing (^{99m}Tc, ^{42}K, ^{22}Na, ^{85}Sr, ^{86}Rb, ^{58}Co) were injected as a four hour finite pulse. Five of these were also used in STT-1 (Uranine, HTO, ^{22}Na, ^{85}Sr, and ^{86}Rb). The additional three tracers used in STT-1 could not be used due to difficulties in finding a supplier (^{133}Ba and ^{47}Ca), and an urge to avoid long duration and tailing (^{137}Cs). Both ^{82}Br and ^{131}I were added to enable on-line measurements of the conservative input function. The tracer solution was exchanged with untraced water after four hours. This procedure was repeated to achieve an efficient exchange (>90%). The input function for Uranine is shown in Figure 4-7. The results of STT-1b will be presented and compared with model predictions at the 11th Äspö Task Force in September 1998.

Modelling

During the year model predictions have been performed for STT-1, cf. Section 4.8.
In conjunction with the planning of the tests with sorbing tracers, a scoping study was performed using an inverse parameter estimation scheme (Nordqvist, 1998). This study shows the importance of using multiple tracers with different diffusivities and sorption

characteristics, and also a well-controlled injection of tracer. The estimation is not seriously affected by the length of the pulse as long as most of the breakthrough is measured.

In addition, a framework for evaluating the tracer tests with sorbing tracers in single fractures has been devised. The framework is based on the stochastic Lagrangian transport description (e.g. Cvetkovic and Dagan 1994; Cvetkovic et al., submitted). All mass transfer reactions are assumed to be linear. The two main simplifying assumptions are; 1) diffusion in the rock matrix is one-dimensional, perpendicular to the fracture plane, 2) the tracer is displaced within the fracture plane by advection only. In addition, for analysing the effect of diffusion into stagnant water, a simplified flow configuration is considered where the water adjacent to a flow path is immobile. Three mass transfer processes (diffusion-sorption in the rock matrix, sorption in the fracture and diffusion into stagnant water) are coupled through a convolution process. A simple sensitivity analysis has been made where the relative effects of different retention processes are quantified.

Heat as an ideal non-sorbing tracer

A need has been identified for obtaining an ideally non-sorbing tracer with a high diffusivity that could be used to assess surface available for diffusion (and sorption). Both helium gas and heat has been considered. In both cases there are in-situ experiences from the NAGRA Grimsel test site. Helium gas has been put second in priority while degassing in conjunction with helium analysis at Äspö HRL may cause large uncertainties. Instead the avenue of using heat has been pursued.

A compilation has been made of the available experimental and theoretical premises for utilisation of heat as an ideal non-sorbing tracer. The scoping calculations show that a full 3D address of the problem is required. The results also show that over a distance of approximately 5 m between pumping and injection sections, a pumping rate of 0.37 l/min and a heat source of 280 W, a temperature increase of a few °C can be measured at the pump well. A report which compiles theoretical and practical aspects on the use of heat has been produced (Birgersson, 1998). It concludes that the use of heat as a tracer is feasible if the natural temperature variation is low compared to the resolution in the temperature measurements. A high background variation can be overcome by increasing the temperature. However, a too high temperature may disturb the flow conditions and may potentially change the chemical characteristics of the studied fracture. The performed scoping calculations assume homogeneous conditions. Potentially, heterogeneity in fracture aperture (transmissivity) may reduce the possibility to obtain a measurable temperature increase at the pump well.

Pilot measurements with a highly sensitive conventional temperature transducer are presently under way in conjunction with the ongoing STT-1b.

Resin technology

During the end of 1996, a series of three 196 mm cored boreholes were drilled towards the resin-impregnated fractures at the Pilot Resin site. During the recoveries of these large diameter cores, dislocation of the core pieces, in some cases along resin impregnated fractures, was experienced. This effect was attributed to insufficient bonding between the anchor bolt in the pilot holes and the pilot hole in combination with the high mass of the sub-horizontally retrieved cores. In January 1997 a series of three additional large diameter cores were drilled in order to improve the outcome of the sampling. The technique also employed drilling of a 36 mm pilot borehole, as in the previously used method. However, the 20 mm steel rod inserted in the pilot hole was cemented in using epoxy. In addition, a 146 mm triple tube coring technique was employed to further reduce disturbance from the sampling. The results of this drilling showed an improved performance with regard to core integrity. However, although the three new boreholes where drilled close to and parallel to the previous set of 200 mm holes, there where no clear indications of resin in the fractures sampled by the new three boreholes. Fortunately, there are a number of intact analysable fractures from the preceding 200 mm drilling which are interpreted to carry resin. Samples from these fractures were selected as main targets for analysis of pore space.

The objective of the subsequent measurements on the sectioned core material is to produce spatial aperture distributions from the resin filled fractures. Measurement will be conducted at by Fracflow at Memorial University of Newfoundland and at by Itasca at KTH. The method used by Fracflow involves use of a photomicroscope and a digitizer. The method used by Itasca employs automated measurements on binary images from the microscope using an image analysis system (IBAS).

A principal representation of two samples is shown in Figure 4-8. Sample 3 is a shear fracture with in-filling material consisting of fragments of quartz and feldspar from the wall rock, and chlorite and clay minerals. The contact area (area with no measurable aperture) is therefore large. Due to the in-filling material, some areas have not been penetrated with epoxy resin. Sample 1 is a less weathered fracture that has experienced only a small displacement, in the order of 0.3 mm. The fracture minerals are calcite and pyrite growing inside the fracture opening. The contact area of this fracture is, in contrast to sample 3, very small and the fracture surfaces are fairly rough. However, the mean and standard deviation of the resin layer thickness are similar for both fracture samples, cf. Table 4-2.

In Table 4-2 results from the two analyses methods are exemplified. The results indicate similar average apertures and variability when comparing results from the two fractures.

Table 4-2. Example of results from aperture measurement on two samples from the pilot resin experiment site.

Fracture sample	1 b				3b			
Measurement by	Itasca		Fracflow		Itasca		Fracflow	
Quadrant	II		IV		III		IV	
Profile	X01	Y01	X01	Y01	X03	Y01	X01	Y01
Mean aperture*) [mm]	286	272	335	280	227	308	278	197
Coeff. of Variation*) [%]	23	35	52	28	43	27	38	55
Contact length [%]	0.0	0.5	0.0	0.0	55	17	16	14

*) Contact points are *not* included. Also, data points at void or branching are not included.

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.

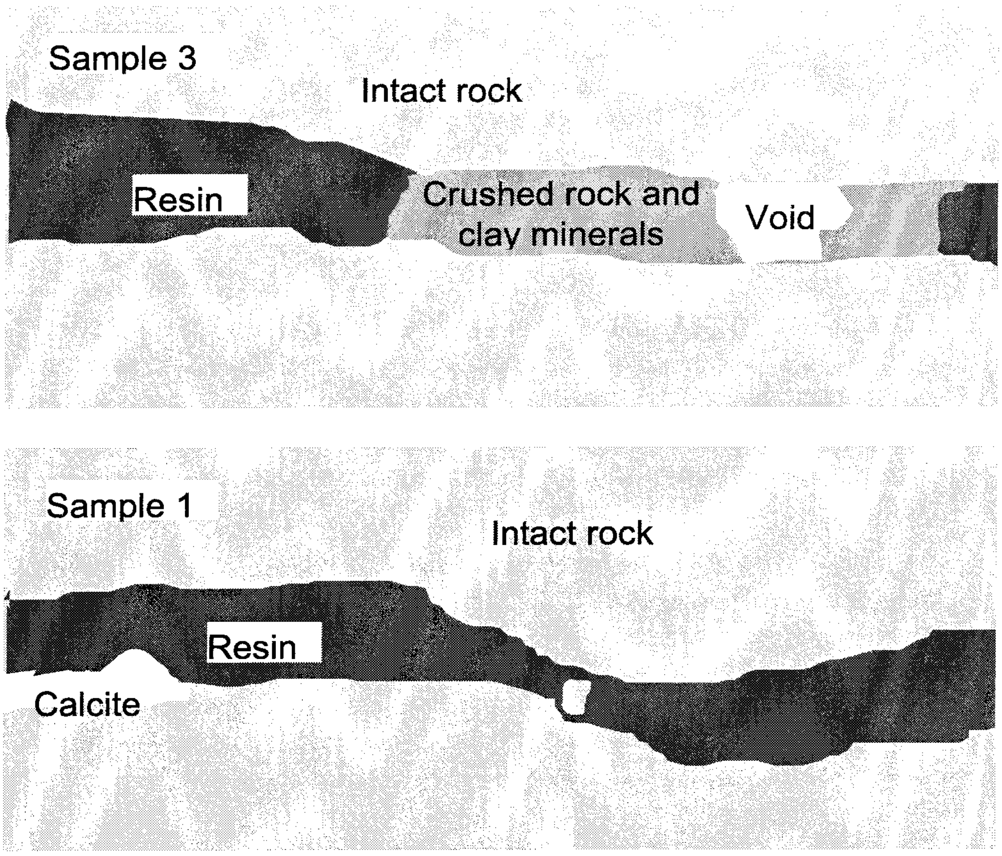


Figure 4-8. Conceptual appearance of the two analysed fracture samples.

4.3.2 Development of tracers

Background

A number of in-situ tracer experiments are planned for the Operating Phase of the Äspö HRL. In these experiments the transport of weakly sorbing tracers will be studied. A project of supporting laboratory tests has been defined to develop and test such tracers before they are used in-situ. The objectives of this project are:

- to develop and test performance of new (or rarely used) tracers before they are applied in the in-situ performance,
- to provide laboratory data on transport parameters (distribution coefficients and diffusivities) for comparison with in-situ derived parameters and/or for evaluation of in-situ results, and
- to show that the tracers do not sorb on equipment used in the in-situ experiments.

During the year a few diffusion cells with site specific material from Feature A (TRUE-1 site) and the radionuclides (^{133}Ba and ^{137}Cs) have been analysed, this since the break-through concentrations have not reached steady state.

Some of the longer diffusion cells (2–4 cm), where no breakthrough has been observed (after close to 2 years), have been dismantled and the rock samples have been sawed into thin slices. Activity analysis have been performed on the surfaces of the slices to determine the concentration profiles within the studied rock cylinder. In addition autoradiography investigations have been made on the rock slices to determine the distribution of radionuclides, i.e. with the aim to characterize the diffusion pathways.

Results

The results of the ^{14}C PMMA impregnation and the analysed concentration profiles of Ca, Ba and Cs in the 2 cm samples are shortly summarised below based on the contribution to the Migration'97 conference (Johansson, et al. 1997).

Porosity Distribution of Äspö-diorite and Fine-grained granite (^{14}C PMMA-method)

The Äspö diorite shows a heterogeneous and mineral specific porosity distribution. Mineral grain boundaries were not observed to form the main migration pathways in the diorite matrix. Quartz and large K-feldspar crystals were not impregnated and can be classified as non-porous minerals. The dark (porous) areas in the autoradiographs of ^{14}C-PMMA form a connected network of migration pathways with relatively high porosity. This network consists of a complex mixture of minerals dominated by biotite, plagioclase and chlorite all having small (<0.5 mm) grain sizes.

The porosity pattern of Fine-grained granite was uniformly distributed although a slight foliation could be observed in the autoradiographs. The foliation is also clearly observed in the texture of sawed rock surfaces. The high porosity minerals are not observed to form a connecting network as observed in the Äspö-diorite

Concentration profiles of $^{45}Ca^{2+}$

The migration pathways observed for $^{45}Ca^{2+}$ within Äspö diorite are consistent with the pore system that was characterized by the ^{14}C-PMMA method. In quartz and K-feldspar grains of Äspö diorite, no tracer activities were found by autoradiography. Two pathways are clearly seen having totally different tracer concentrations indicating different migration behaviour.

The distribution of $^{45}Ca^{2+}$ in Fine-grained granite shows a consistency with the ^{14}C-PMMA autoradiographs, but the activities were too low to get a reliable evaluation of the concentration profile by autoradiography. Activities were only found in dark spots, associated with plagioclase containing muscovite or sericite. The sample of Fine-grained granite contained visible filled micro-fissures, crossing the bulk rock structure of the sample. No activity increase caused by sorption appears, however, in the micro-fissures observed in the autoradiographs. However, in other samples micro fissure fillings that had higher porosity have been observed by the ^{14}C-PMMA method.

Concentration profiles of $^{133}Ba^{2+}$ and $^{137}Cs^{+}$

An example of the penetration profiles obtained in the experiments is shown in Figure 4-9. None of the profiles could be fitted satisfactorily by using one set of D_e and a (equivalent to a single D_a). The measured profiles appear to consist of two parts, one slower process for the short penetration depths and one faster process for the deeper penetration. Assuming that the experimentally obtained concentration profiles are the

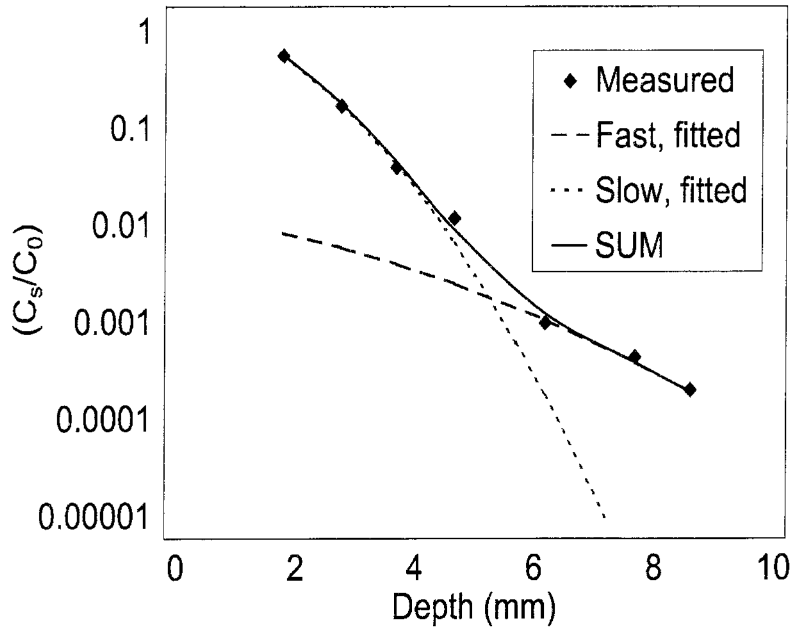


Figure 4-9. *TRUE-1: Concentration profiles for ^{137}Cs in Äspö diorite. The fast pathway constitutes a small part of the available transport pathways and has low sorption. The slow pathways are dominating, but richer in biotite and are therefore much more sorptive, which slows down the transport rate.*

sum of diffusion in the two separate networks, approximate values of D_e and a can be obtained by curve fitting to the measured data. Double migration pathways are sufficient to reproduce the shape of the concentration profiles obtained for the rock types used in these experiments, which is indicated by the sum of the theoretical profiles in Figure 4-9. Multiple pathways have also been considered in other studies. A double porosity system was also seen in the autoradiographs in these experiments. It is important to keep in mind that this is an oversimplification of the system, since in reality a whole distribution of porosity exists.

A comparison of the formation factor ($F = D_e / D_w$, where D_w is the water diffusivity) for $^{137}Cs^+$ and $^{133}Ba^{2+}$ with the formation factor for HTO, shows a factor of ~2 smaller formation factor for Cs^+ and Ba^{2+}. This indicates that the pore system is approximately equal for the diffusion of Cs^+, Ba^{2+}, and HTO. Consequently, by using the rock formation factor and water diffusivities, the D_e can be reasonably well estimated for Na, Ca, Sr, Ba and Cs.

A comparison of K_d-values obtained in batch experiments with crushed material is presented in Table 4-3. Approximately one order of magnitude lower K_d-values are obtained from diffusion experiments compared to batch experiments using large particle size fractions. Compared to batch K_d even larger differences are observed with even smaller size fractions (<2mm). This is probably a result of increased porosity and increased surface areas due to the crushing of the material. Similar results were earlier obtained for Na^+, Ca^{2+} and Sr^{2+}. By definition K_d describes the reversible distribution of a species between a solid phase and solution. Since this work, cf. Table 4-3, and earlier batch experiments showed that among the alkaline and alkaline earth metals, Cs, Ba, and Rb are to some extent irreversibly sorbed within the time frame of the experiments, the usefulness of batch K_d in transport and diffusion experiments could be questioned. The K_d values evaluated by the through diffusion experiments are therefore more adequate for

Table 4-3. K_d from batch experiments using crushed material of 2–4 mm particle sizes and 14 days contact time. Desorption K_d values were obtained by replacing the spiked groundwater with new groundwater without radionuclides for a contact time of several months. K_d for the diffusion experiments is evaluated from the short penetration depths (slow migration pathways) of this study.

Radio-nuclide	Rock type	K_d batch exp. (m^3/kg)	K_d desorption batch exp. (m^3/kg)	K_d diffusion exp. (m^3/kg)
$^{133}Ba^{2+}$	Fgg	$6 \cdot 10^{-4}$	$4 \cdot 10^{-4}$	$6 \cdot 10^{-5}$
$^{133}Ba^{2+}$	Äd	$9 \cdot 10^{-4}$	$5 \cdot 10^{-4}$	$2 \cdot 10^{-4}$
$^{137}Cs^{+}$	Fgg	$6 \cdot 10^{-3}$	$1 \cdot 10^{-3}$	$3 \cdot 10^{-4}$
$^{137}Cs^{+}$	Äd	$3 \cdot 10^{-2}$	$4 \cdot 10^{-3}$	$8 \cdot 10^{-4}$

predicting the transport rate. However, since irreversible sorption is observed for some of the studied elements it is not possible to say that the total mass is transported by the observed diffusion rate. A significant part of the mass could according to the batch experiments be irreversibly lost and will not be transported at all.

Qualitative estimation of mineral specific sorption of Cs^+ and Ba^{2+} was made from the autoradiographs. Sorptive minerals were difficult to identify. All autoradiographs showed dark and light areas indicating double migration pathways. In Äspö diorite, it was found that large K-feldspar grains did not sorb caesium or barium and that the high intensities were found in regions rich in biotite. Cs^+, which has the highest K_d-value of the studied tracers, showed most mineral specific sorption in the Fine-grained granite. In the Fine-grained granite, dark veins of plagioclase containing inclusions of chlorite and muscovite are found to contain the radionuclides, but it was difficult to distinguish exactly the specific minerals containing Cs^+.

Conclusions

- The in-diffusion results could not satisfactorily be described by one set of D_e and a using homogeneous models. Still using common transport modelling, a double porosity network could, however, be used to describe the results using a double set of D_e and a.
- Batch experiments overestimate K_d for alkali- and alkaline earth-metals in crystalline rock, compared to K_d evaluated from diffusion experiments. This is probably caused by the creation of new surfaces when crushing the material for batch experiments.
- The use of batch K_d in transport modelling could be questioned due to the irreversible sorption observed for some elements (Cs, Ba, and Rb) within the time frame of the experiments. Further studies of the sorption mechanisms together with long term kinetic studies are therefore essential in order to access reliable transport parameters for e.g. Cs^+.
- Porous mineral areas are found to be consistent with the sorptive mineral areas in Äspö-diorite. Autoradiography studies indicate two migration pathways having different porosities and retention capacities. The penetration of the cations $^{45}Ca^{2+}$, $^{133}Ba^{2+}$ and $^{137}Cs^+$ follows the migration pathways that are found with the ^{14}C-PMMA method used for porosity determination in Äspö-diorite.

- In Fine-grained granite, the different porous phases could not be clearly found with the ^{14}C-PMMA method and the porosity pattern was uniform although a slight foliation was observed. Only diffusion of Cs^+ (which has the highest K_d-value of the studied tracers) shows mineral specific sorption in the Fine-grained granite, where dark veins in the autoradiographs follow the foliation of the mineral texture.

4.3.3 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 50m. 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 characterization strategy has been adopted (Winberg, 1997). The project is divided into five basic stages;

1. Scoping Stage.
2. Preliminary Characterization Stage.
3. Detailed Characterization Stage.
4. Tracer Test Stage.
5. Evaluation (and reporting) Stage.

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

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

Results of characterization

During the first quarter no fieldwork was possible due to the ongoing work to create new underground openings. During the remainder of the year two 76 mm boreholes, KI0025F and KI0023B, have been drilled into the investigated rock volume. The characterization in the boreholes included;

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

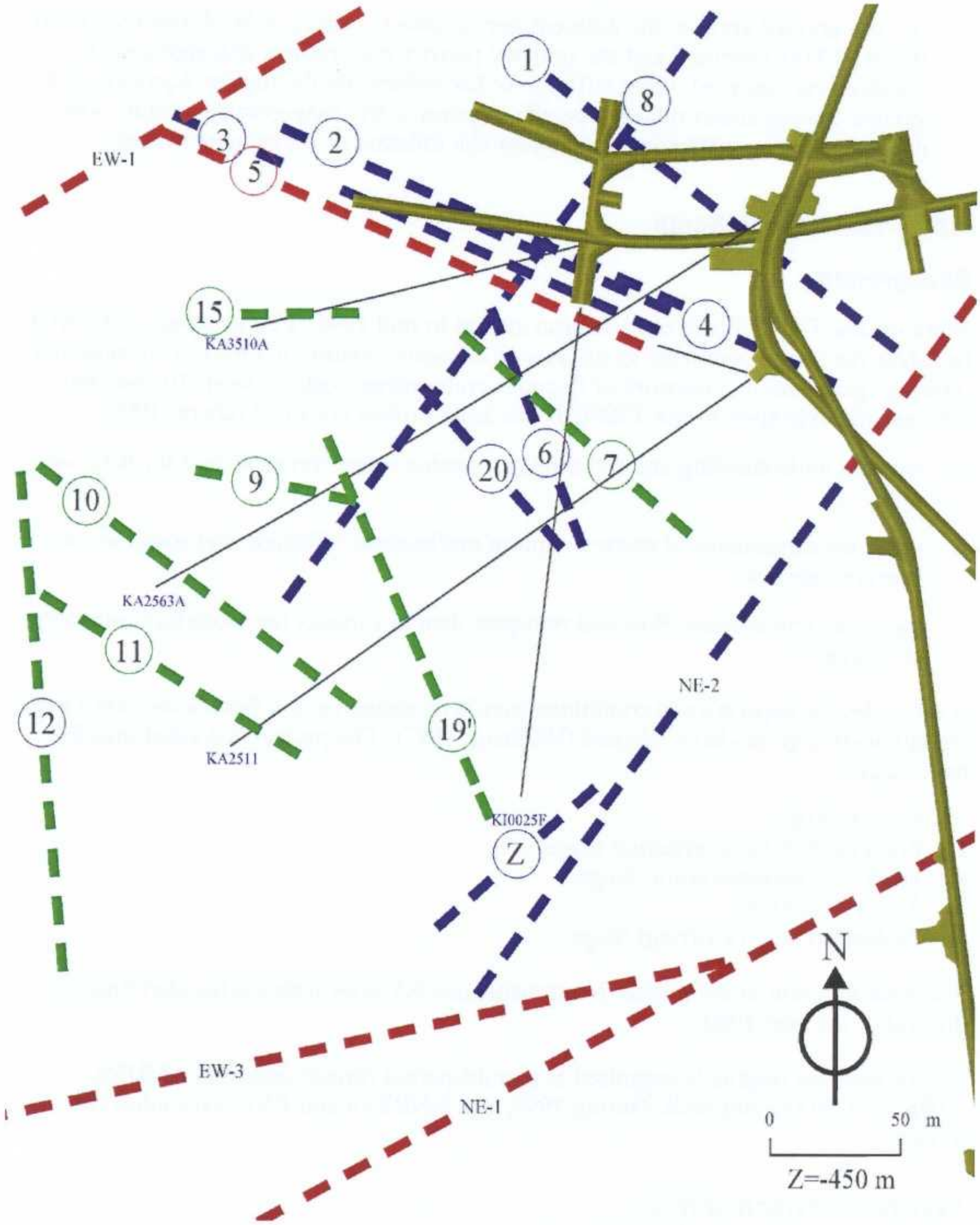


Figure 4-10. *TRUE Block Scale: Horizontal section through the structural-hydraulic model (March 1997 version). Red = certain, Blue = probable, Green = possible. Numbering refers to internal labelling for Fracture zones.*

- Selective flow and pressure build-up tests.
- Core logging using the BOREMAP system which makes use of the BIPS images.

The results from borehole KI0025F indicate only a few (N=5) significant hydraulic anomalies are present in the borehole. In the bottom of the borehole a major fractured zone was intercepted, associated with successively more problematic drilling and increased inflow. As a consequence the drilling was terminated at L=194 m, rather than the planned 210 m, cf. Figure 4-10. The transmissivity of the interpreted structures have been quantified both using double packer flow logging and selective flow and pressure build-up tests. The results of the selective flow and pressure build-up tests show transmissivities in the order of $5 \cdot 10^{-7}$–$5 \cdot 10^{-6}$ m^2/s.

During the year a need was identified to elevate the information stature of borehole KA2511A to the same level as the other boreholes. To this end, the borehole was logged with the BIPS system and double packer flow logging was performed in the interval 50–175 m. Four major inflow points are identified. Interpretation of the data indicate transmissivities varying between the measurement limit ($1 \cdot 10^{-10}$ m^2/s) up to $3 \cdot 10^{-6}$ m^2/s. These data complement the 3 m flow and pressure build-up tests which were conducted earlier in the interval 172–265 m (Olsson et al., 1994). Similarly, complementary double packer flow logging was also performed in borehole KA3510A between 50 and 150 m. The results indicate one major inflow point at L=118 m, and 2–3 subordinate inflows. Interpreted transmissivities range from values on the measurement limit up to $9 \cdot 10^{-7}$ m^2/s.

In October-November, the 200 m long KI0023B was drilled from a collar position near KI0025F. The borehole showed five major hydraulic anomalies. The borehole provided support for the interpretation and conceptualisation provided by the data in KI0025F.

Deterministic structural model

During the year two major updates of the structural model has been performed. The first in March 1997, and the most recent one made in October 1997. The October 1997 model is shown in Figure 4-10.

The main (structural) geological findings of the Oct '97 model are:

- None of the existing structures in the March 1997 model could be rejected on the basis of data from drilling and characterization in KI0025F.
- The extent of Structures #7, 5 and 6 have been better defined.
- Structure #9 is only defined in one intercept KA2563A at L = 266 m (only included for sake of reference).
- The extent of Structure #7 is interpreted to be limited to boreholes KA2563A, KA2511A and KI0025F. No intercept has been found in borehole KA3510A.
- Structure #6 is interpreted in all four boreholes. Its extent and importance as a hydraulic structure is not yet fully understood (addressed by this proposal).
- Structure #5 is defined in all boreholes.
- Sub-horizontal structures are interpreted and put forward as being an important part of the connectivity in the TRUE Block Scale rock volume.

- Three new structures have been interpreted on the basis of the new data from drilling and characterization in KI0025F, namely Structures #20, #19 and Z.
- Structure #20 is interpreted to intersect KA2563A, KA2511A (non-conductive intercept) and KI0025F.
- Structure #19 is interpreted to intersect KA2563A, KA2511 (non-conductive intercept) and KI0025F.
- Structure Z intersecting KI0025F at L = 187 m is probably a minor branch of either NE-1 or EW-3. It is the single largest geological structure in the block.

Stochastic data set

Using the data from boreholes KA2511A, KA2563A and KA3510A input data has been derived for discrete fracture network modelling. The analysis of the orientation data has identified three sets, including a sub-horizontal one. Fracture size has been inferred from data collected in the TBM extension. Attempts have been made to estimate size using the whole fracture population, and using individual sets. The method using bootstrapping on the whole population yields a mean size (radius) of 6 m with a standard deviation of 3 m.

Analysis of the double packer flow logging data has been performed to obtain distributions of fracture transmissivity. Results based on 5 m data and a set conductive fracture intensity of 2 fractures/m yield a mean fracture transmissivity (log10) of -11.7 with a log10 standard deviation of 1.7. It has been observed that the mean fracture transmissivity is low. Attempts to subjectively determine the conductive fracture intensity based on BIPS and core data is planned for 1998.

Modelling work

An analysis has been performed on the grout invasion in a DFN model. The results show that a safety zone of about 40–50 m should be assigned around the injection points in boreholes KA2563A and KA3510A.

During the year sensitivity analysis of entities in the fracture network has been made in simulations on a smaller block. One of the problems faced in simulation of flow and transport in a fracture network is the large number of generated fractures, which full inclusion is limited by the available computer resources. Included in the study is an analysis of the effect of imposing a cut-off at different threshold transmissivities. The analysis shows that no significant effects are seen on the calculated effective permeabilities of the block with a cut-off at $T=1 \cdot 10^{-9}$ m^2/s. However, the two point connectivity as inferred from the DFN flow model is reduced with about 50%.

As part of the Preliminary Characterization Stage the following main activities will be performed during 1998:

- 3D seismic survey.
- Optimisation of the borehole array to cater to planned cross-hole interference tests.
- Cross-hole interference tests including injection of tracers. The tests will be used to check the validity of the present structural model and check different hypotheses for the observed connectivity in the studied block. In addition the possibility to conduct tracer tests in the interior of the investigated volume will be investigated. The tests will also include estimation of the resulting flows in selected observation sections

using the tracer dilution technique. For a limited number of tests breakthrough of tracer will be analysed.

- Evaluation of interference tests using developed models. Calibration of models on existing data.
- Assessment of the frequency of conductive fractures using the available borehole TV logs and drill core to make estimation of fracture transmissivity distribution and conductive fracture intensity less ambiguous.
- Reporting of the Preliminary Characterization Stage.

This will be followed by the Detailed Characterization Stage where boreholes targeted on the interior of the studied block will be drilled and characterized.

4.4 The REX experiment (= REDOX experiment in detailed scale)

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 2861 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.

The set-up for the laboratory experiments at Bradford University has been tested with some Swedish mineral samples. Rock and fracture filling mineral samples were collected from the Äspö tunnel wall in December 96 and they are being used within the research program at Bradford. Fracture filling samples have also been collected from the NW-3 fracture zone using the "triple tube" technique to drill a new 3 m long borehole: KA3066A. The core from this borehole has been sent to REX participants for mineral characterization (in Sweden) and laboratory testing (at the University of Bradford). Some oxygen consumption rates have been determined for a few samples. A status report is in print.

Measurements of dissolved gases (methane, hydrogen, etc) in Äspö groundwater have been performed. They have been combined with the measurements of bacteriological oxygen consumption in Äspö groundwater. These results show that oxygen may be consumed by methanotrophic bacteria in a closed nuclear waste repository. The results on bacteriological oxygen consumption experiments performed in the field at Äspö are given in a report that is in print.

Structures that are believed to be fossil bacteria have been found in calcite samples from Äspö. This shows that bacteriological activities have occurred underground for long periods of time, and they are expected to proceed in the future.

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 drill core has been sent to CEA (Cadarache, France) where a replica of the field experiment will be performed during 1998. Complete characterization of this borehole has not been possible during 1997 because of malfunction of the packer system. However, the packer has been reconstructed and tests performed under December 97 show that it is now fully operational.

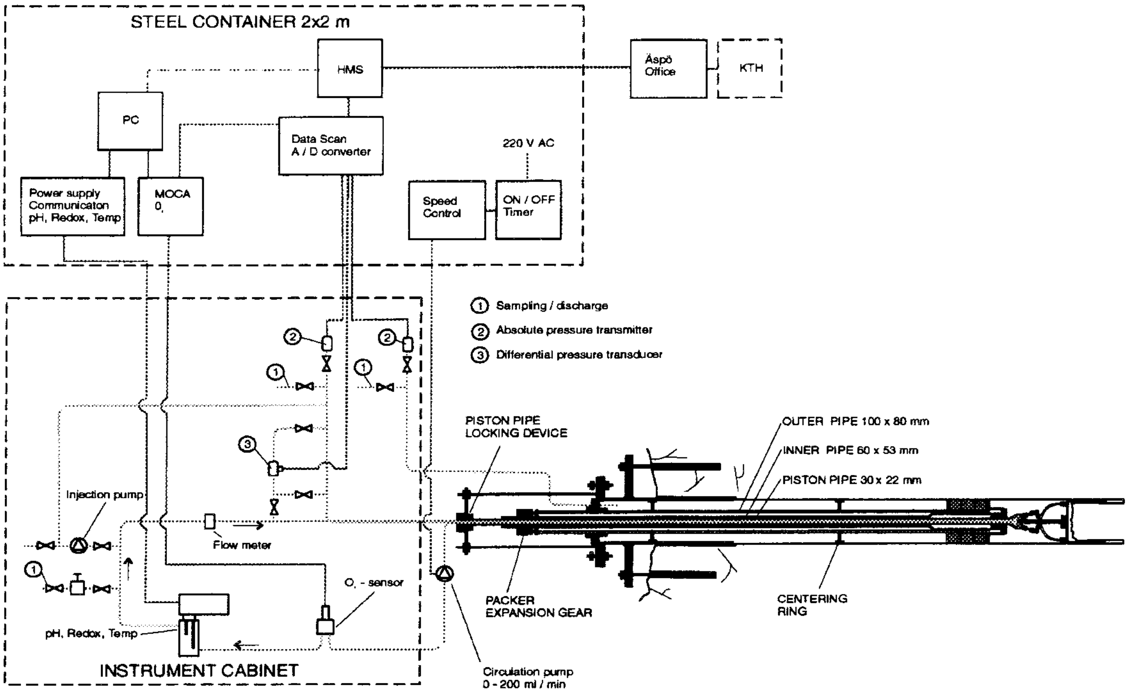


Figure 4-11. Schematic illustration of the REX field experiment.

The equipment necessary for the field test (Figure 4-11) has been set-up and tested. Measuring devices have been designed and tested both in the laboratory and in the field. This is a necessary step prior to the experiment in the ≈200 mm borehole (KA2861A). The aim of the field study is to isolate the innermost part of the borehole and to monitor the oxygen consumption as a function of time.

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 retardation processes the sorption could well be irreversible and thus the migration of the nuclides will stop as soon as the source term is ending. This is supported by the interpretation made on the data collected in the natural reactor in Gabon in Africa, which was active two billion years ago, and where the signs of e.g. plutonium are found in a radius of only a few metres from the centre of the reactor.

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

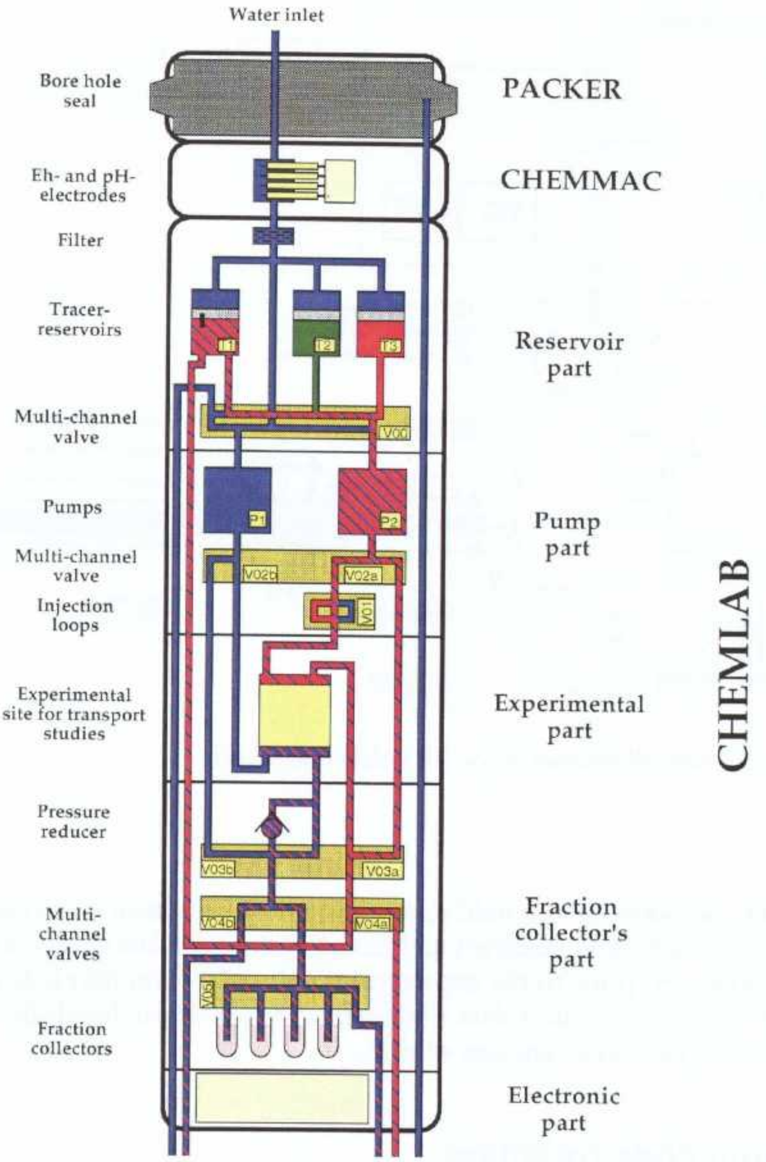


Figure 4-12. Schematic illustration of the CHEMLAB probe.

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 4-12, 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 retardation 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 retardation 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.

4.5.4 Previous results

A programme for the CHEMLAB experiments has been compiled in progress report HRL-97-01. The full suite of planned experiments is:

- Diffusion of radionuclides in bentonite clay.
- Migration of redox sensitive radionuclides.
- Radionuclide solubility and actinide speciation.
- Desorption of radionuclides from the rock.
- Migration from buffer to rock.
- Radiolysis.
- Batch sorption experiments.
- Spent fuel leaching.

The different experiments are listed in an increasing order of complexity that does not reflect the time sequence in which they are planned to be conducted.

The manufacturing of the CHEMLAB probe was completed during 1996, and the first experiments were started early in 1997. A simplified version of the CHEMLAB probe is planned to be constructed and manufactured during 1998. The purpose of this probe is to speed up the entire experimental sequence so that the spent fuel experiments can be started as soon as possible. The new probe will contain 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. With these limitations the total length of the probe is expected to be about 8 metres, which is less than half the length of CHEMLAB (18.5 m).

4.5.5 New results

During 1997 three experiments were conducted. These were the diffusion in bentonite using ^{131}I and ^{57}Co, followed by a similar experiment with ^{134}Cs and ^{85}Sr. The last diffusion experiment with ^{99}Tc and ^{131}I was terminated due to malfunction of the equipment. Figure 4-13 presents the diffusion profile for caesium in the bentonite plug.

A computer programme for automatic control of the experiments has been developed tested and accepted. The system incorporates two computers, which makes it possible to re-program the experiments both from the tunnel gallery and from the office. A set of illustrations was included in the development, in order to visualise the experiments and the purpose of them.

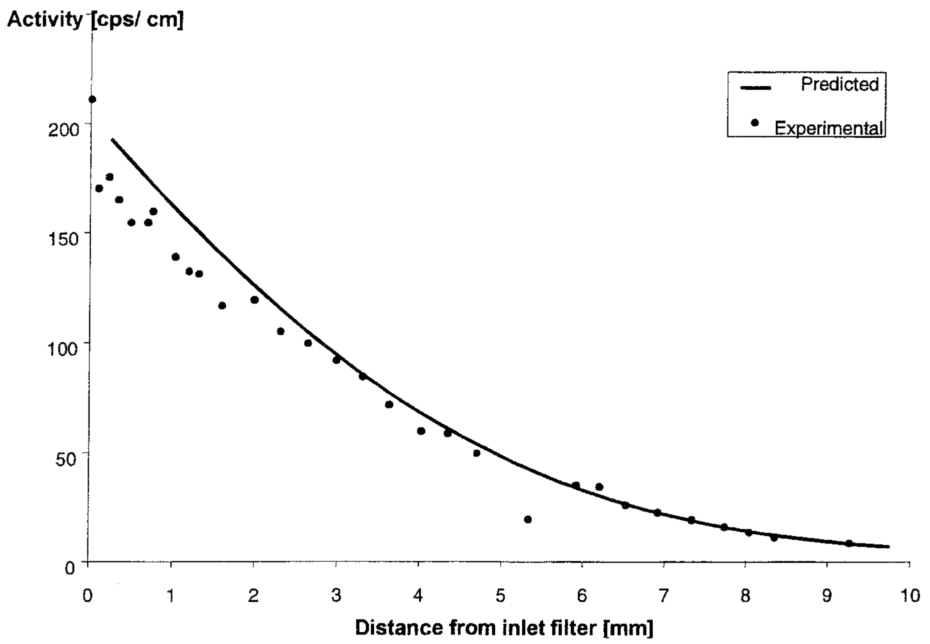


Figure 4-13. Break through curve for Cs.

4.6 Degassing and two-phase flow

4.6.1 Background

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 understanding 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.

This project has been performed as one of the bilateral cooperation projects between USDOE and SKB for studies at the Äspö Hard Rock Laboratory in the Areas of Site Characterization and Repository Performance. Contributions to the project are also provided by NAGRA and PNC. A revision of the project scope has been made as a consequence of the USDOE leaving the Äspö HRL cooperation in April 1996. Since 1996 there has been two main activities; 1) an in situ test of degassing in a fracture and modelling for design and evaluation of field tests performed by Water Resources Engineering at the Royal Institute of Technology and 2) laboratory experiments performed by Fracflow Consultants, St. Johns, Newfoundland.

4.6.2 Model development

Groundwater degassing can under certain conditions lead to unsaturated fracture flow in the low-pressure zone around monitoring boreholes and drifts. For porous media, numerous investigations have addressed relative conductivity relations and the trapping of non-wetting bubbles or blobs, whereas the available information on fractured media is limited. The probability for bubble trapping may be considerably lower in fractured media as compared with porous media, both because of high water velocities in wide fractures and small capillary pressure differences in smooth fractures.

We develop models for (I) evaluation of the probability of bubble trapping in fractures with different aperture distributions at different hydraulic gradients, and (II) the relation between the bubble pressure of water (P_b) and the steady-state fracture gas saturation (S) and the transmissivity (T) reduction due to degassing. The model predictions are compared with experimental laboratory observations of Jarsjö and Geller (1996).

(I) Bubble trapping probability

To analyse the influence of fracture roughness on the bubble trapping probability, given the hydraulic gradient over the fracture and the fracture aperture distribution, we extend the analysis of Jarsjö and Destouni (1997). The point of departure is that a bubble will get trapped in the fracture only if the difference in capillary pressure upstream and downstream the bubble (ΔP_c) equals the corresponding difference in water pressure (ΔP_w; caused by the hydraulic gradient over the fracture).

Using the notation of Figure 4-14, and assuming that the pressure gradient is (dP/dx) along the flow direction, the difference in water pressure over the bubble becomes $\Delta P_w = P_1 - P_2 = L_b(dP/dx)$, where L_b is the bubble length along the flow direction. Furthermore, the difference in capillary pressure over the bubble is $\Delta P_c = 2\sigma_w(1/a_2 - 1/a_1)$, where σ_w is the surface tension of water and a_1 and a_2 is the aperture upstream and downstream the bubble, respectively. Using the above-mentioned equality between ΔP_c and ΔP_w that is required for bubble trapping, the length L_b of a trapped bubble may be expressed as a function of the apertures a_1 and a_2:

$$L_b = 2\sigma_w \left(\frac{dP}{dx}\right)^{-1} \left(\frac{1}{a_2} - \frac{1}{a_1}\right) \tag{1}$$

In the following, we consider a log-normally distributed fracture aperture a. Then $1/a$ will also follow a log-normal distribution that can be used for determining a probability density function (pdf) for ($1/a_2 - 1/a_1$) and, through Equation (1), for L_b ($f(L_b)$). The pdf $f(L_b)$ expresses the probability of a bubble length L_b to occur in the fracture due to capillary trapping under the given gradient (dP/dx).

Figure 4-15(a) shows a schematic graph of a derived pdf $f(L_b)$ for uncorrelated a_1 and a_2. A constraint for the physically possible lengths of trapped bubbles (Figure 4-14) is that the length L_b must be greater than the local aperture value. Spherical bubbles, for instance, would otherwise be too small to connect both opposite fracture surfaces. Assuming small fluctuations in a one may formulate this constraint as $L_b \geq \langle a \rangle$ (with the minimum bubble

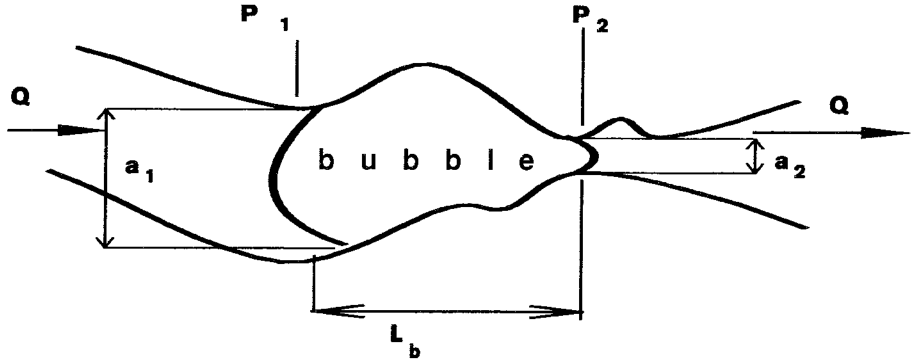


Figure 4-14. Gas bubble in a variable aperture fracture.

length $L_{b,min}$= <a>), where <a> is the mean aperture. At this stage, the pdf $f(L_b)$ and the above expression for $L_{b,min}$ is not only valid for degassing applications, but is generally relevant for gas bubble trapping between two rough surfaces. For degassing applications, we can add the constraint that $L_b \leq X_{low}$ (with the maximum bubble length $L_{b,max}=X_{low}$), where X_{low} is the low-pressure zone extent (read: the extent of the zone where pressures are lower than the bubble pressure under water saturated conditions).

The shaded area between the vertical lines in Figure 4-15(a) thus represents the probability for bubbles with lengths between $L_{b,min}$ and $L_{b,max}$ to get trapped in the fracture. The effect of an increased pressure gradient (dP/dx) on bubble trapping is illustrated in Figure 4-15(b), where $f(L_b)$ was calculated for the same fracture as shown in Figure 4-15(a), but with (dP/dx) being four times as high as that in Figure 4-15(a). The probability of bubble trapping decreases with increasing pressure gradients, and Figure 4-15(b) shows that for this higher gradient, the relevant probability area below $f(L_b)$ is close to zero, which implies that bubble trapping is not likely to occur.

A derived pdf for L_b based on fracture aperture statistics and maximum hydraulic gradient for the laboratory degassing experiment in an Äspö fracture replica (Jarsjö and Geller, 1996) is shown in Figure 4-15(c). The $L_{b,min}$-value (equalling the mean fracture aperture <a>) was $7.8 \cdot 10^{-5}$ metres (which is indicated by the vertical line to the left of the shaded area in Figure 4-15(c), and the $L_{b,max}$-value was 0.058 metres, which is outside the range of the graph of Figure 4-15(c). Figure 4-15(c) thus shows a high probability of bubble trapping in this case, which is in agreement with the experimental observations of an immobile gas phase development by Jarsjö and Geller (1996).

The presented methodology of calculating a probability for bubble trapping as the area below the probability density function $f(L_b)$ between the limits $L_{b,min}$ and $L_{b,max}$ provides a tool for comparative analysis of the possibility of an immobile gas phase development due to degassing in different fractures.

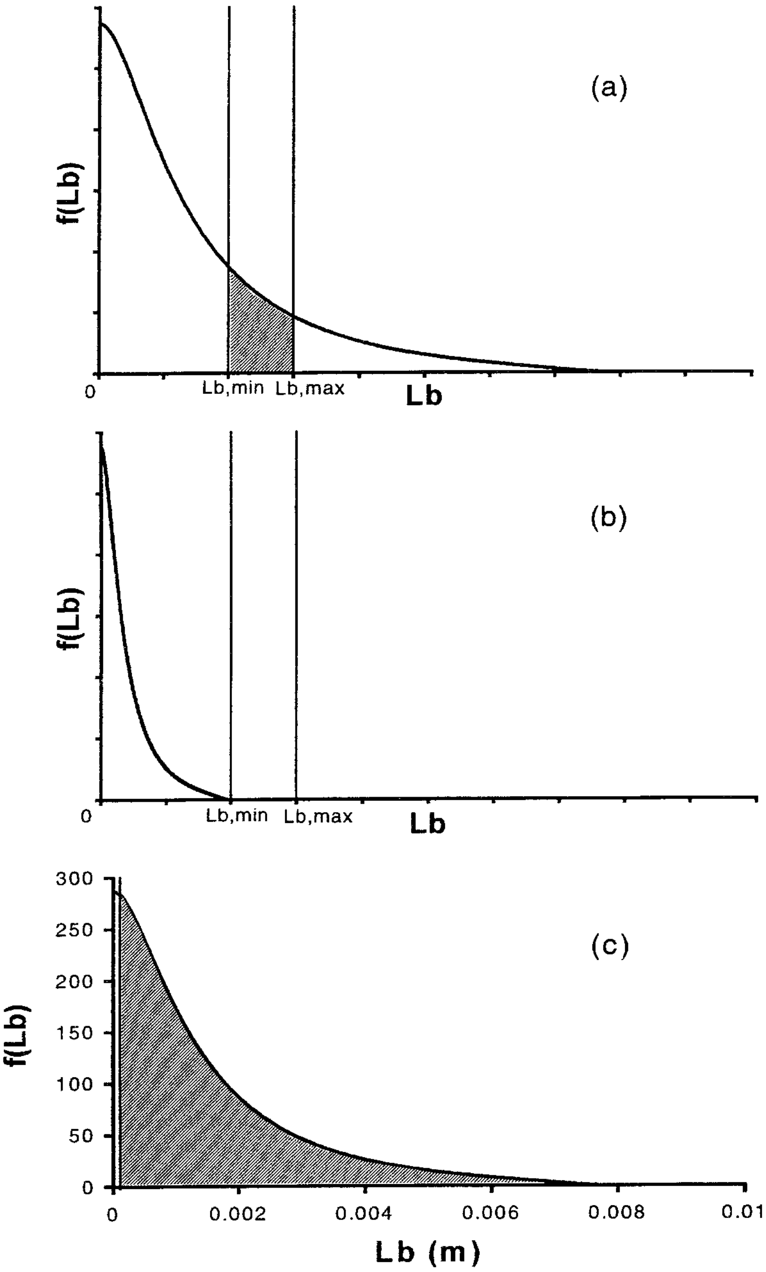


Figure 4-15. *(a) Schematic graph of the derived probability density function $f(L_b)$. (b) The probability density function $f(L_b)$ for the same fracture as in (a), but with the pressure gradient being four times the gradient of (a). (c) A derived pdf $f(L_b)$ based on fracture aperture statistics and the maximum hydraulic gradient from laboratory measurements.*

(II) Bubble pressure (P_b) – saturation (S) – relative transmissivity (T_{rel}) relations

The model (II) $P_b - S$ and $P_b - T_{rel}$ relations are based on the assumption that the gas is trapped in the fracture, and hence not advected with the water, which is an assumption that is relevant for fractures with high model (I) probability areas. We furthermore assume that the pressure of the developed gas phase is equal to, or less than, the bubble pressure of the water. The latter assumption implies that gas will not exist in tighter parts of the fracture, where the local gas phase pressure due to capillary effects would exceed the bubble pressure, even though the corresponding local water pressure may be lower than the bubble pressure. Hence, gas will only exist in apertures that are equal to (or greater than) a critical aperture, hereby denoted cut-off aperture (a_c), where the pressure of the developed gas phase is equal to the bubble pressure of the water.

The a_c-value will vary in space because spatial water pressure differences occur under flow, and in addition to the capillary pressure, the water pressure determines the pressure of the gas phase. For radial flow geometry, an analytical expression for a_c as a function of both the radial distance from the well (or the outlet hole) and the bubble pressure [$a_c(r, P_b)$] was derived; the prevailing water pressures at the fracture boundaries were also explicitly accounted for. The P_b - S relation for a log-normal fracture aperture probability density function ($f_{\ln}(a)$), was then obtained through the calculation of the ratio between the gas-filled fracture volume (i.e., the fracture volume where the aperture a is greater than the local $a_c(r, P_b)$-value) and the total fracture volume (see Figure 4-16):

$$S(P_b) = \frac{\int_0^{2\pi} \int_{r_w}^{R} r \int_{a_c(r,P_b)}^{\infty} a f_{\ln}(a)\, da\, dr\, d\theta}{\int_0^{2\pi} \int_{r_w}^{R} r \int_0^{\infty} a f_{\ln}(a)\, da\, dr\, d\theta} \qquad (2)$$

where r_w is the radius of the well (or outlet hole) and R is the radius of the fracture.

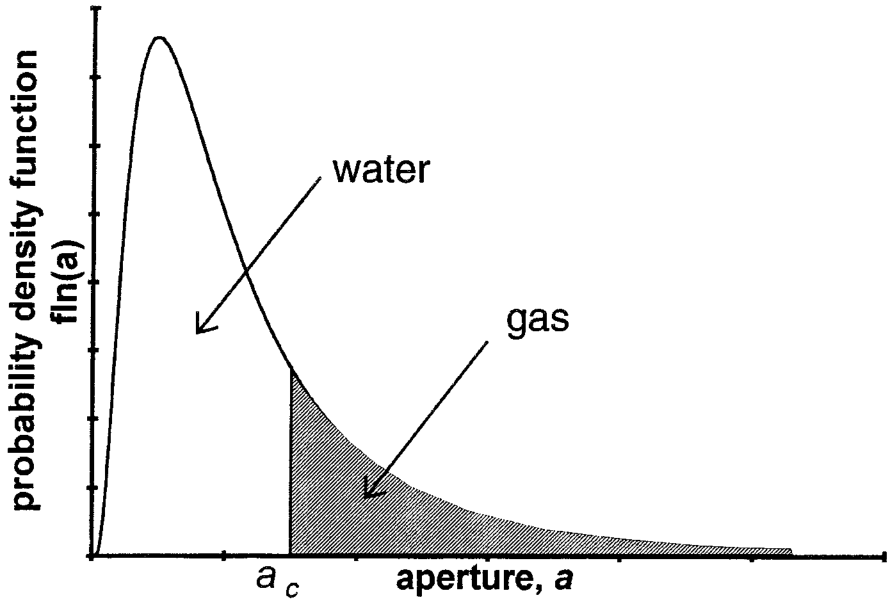


Figure 4-16. *Gas and water filled parts of the fracture for a lognormal fracture aperture distribution according to the cut-off aperture assumption.*

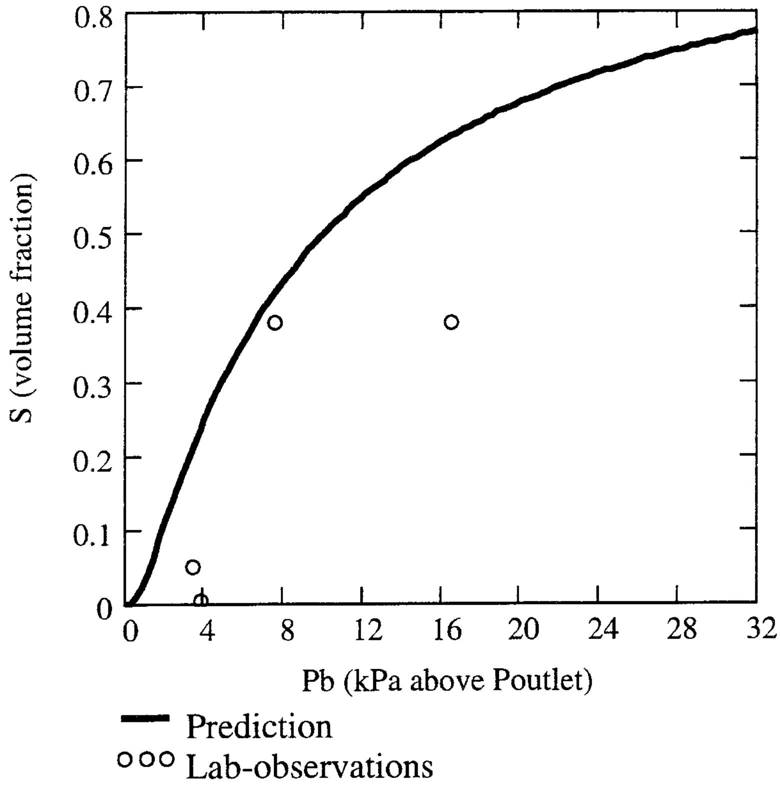


Figure 4-17. *Prediction and observed relations between bubble pressure and volumetric gas saturation.*

The $S(P_b)$-prediction by Equation (2) is in Figure 4-18 compared with laboratory observations of the relation between P_b and S (circles in Figure 4-17), obtained through radial flow degassing experiments in a rock fracture replica (Jarsjö and Geller, 1996). The fracture used in the experiments had a log-normal aperture probability density function $f_{\ln}(a)$, characterized by a geometric mean value (a_G) of 0.078 mm and a standard deviation (of ln a) of 0.84. For the sake of simplicity, the bubble pressure in Figure 4-17 is expressed in kPa above the outlet pressure (that equalled the atmospheric pressure).
In the $S(P_b)$-prediction (Figure 4-18), it was assumed that the water pressure at the outer boundary of the fracture equalled the bubble pressure, which was the case for the two experiments conducted with $P_b \approx 4$ kPa and the experiment conducted with $P_b = 7.5$ kPa. However, in the experiment conducted with $P_b = 16.5$ kPa, the pressure at the outer fracture boundary was considerably lower than the bubble pressure. Therefore, the water was degassed to a certain degree already before entering the fracture, which may have contributed to the fact that the observed fracture gas saturation (S) for a P_b-value of 16.5 kPa was not higher than the observed S-value for a P_b-value of 7.5 kPa (Figure 4-17). The experimental observation point at 16.5 kPa is thus not directly comparable with the other experimental observation points or the prediction.

Figure 4-17 shows that the experimental observations of S for P_b-values equalling 4 kPa and 7.5 kPa fall relatively close to the predicted S-values. It may also be noted that the slope of the predicted $P_b - S$ relation is less steep for higher P_b-values, which is also indicated by the experimentally obtained relation, although the relevance of the measurement point at P_b equalling 16.5 kPa is uncertain due to differences in prevailing boundary conditions, as mentioned above.

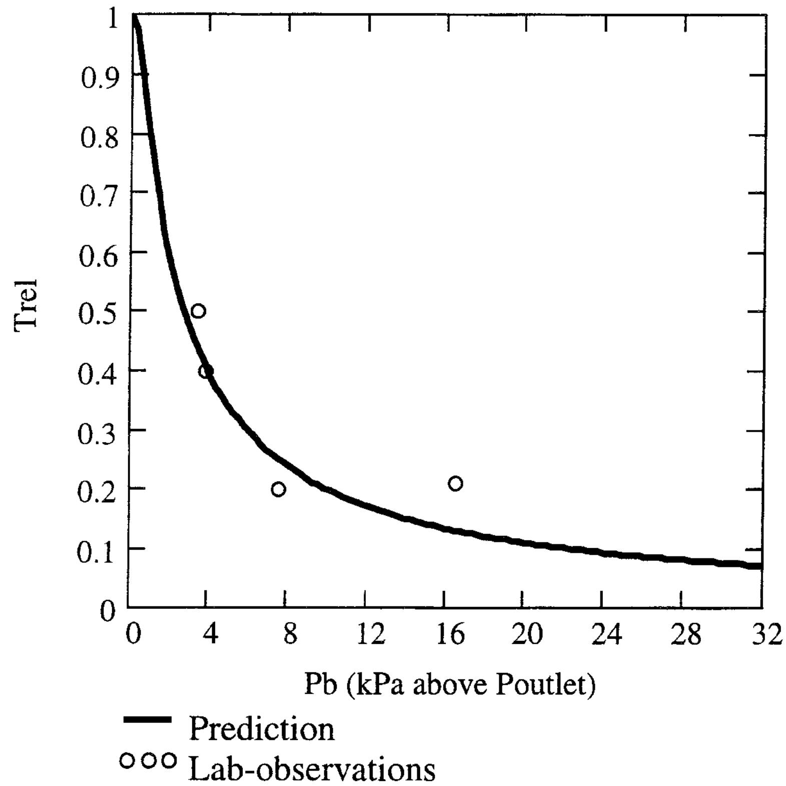


Figure 4-18. Predicted and observed relations between bubble pressure and relative transmissivity.

An expression for the relative transmissivity as a function of the bubble pressure, $T_{rel}(P_b)$ (analogous to Equation (2) for $S(P_b)$), was obtained by assuming that the cubic law holds locally, i.e., that the local transmissivity is proportional to the local fracture aperture value raised to the third power. We hereby define T_{rel} as the ratio between the water transmissivity under degassing (unsaturated) conditions and the saturated transmissivity. Figure 4-18 shows that the relative transmissivity predictions are consistent with the experimental observations of relative transmissivity by Jarsjö and Geller (1996).

Images of the steady-state gas distribution under degassing conditions from the laboratory experiments (Jarsjö and Geller, 1996) support the hypothesis that there is a critical aperture below which a developed gas phase no longer exists, which is consistent with the assumption used for the derivation of Equation (2). However, these images furthermore suggest that the gas phase is not necessarily continuous in the wide-aperture regions, i.e., there may be regions that are water-filled although the aperture of the region is greater than the critical aperture. In contrast, Equation (2) is based on the assumption that all apertures that are greater than the critical cut-off aperture are filled with gas (see Figure 4-16). A more detailed analysis of the impact of various gas-water occupancy assumptions on the modelling results will be reported shortly (March, 1998), along with an analysis of the influence of possible gas re-dissolution due to water pressure increases caused by the locally reduced transmissivities.

Final reporting of the contributions by KTH – Water Resources Engineering to the degassing and two phase flow project will appear in the SKB Technical Report series (March, 1998).

4.6.3 Laboratory Experiments

The two-phase laboratory flow studies consisted of single and two phase flow experiments on (1) two sets (both fabricated and natural fracture planes) of small scale fracture samples (the fracture planes were nominally about 200 mm wide and 300 mm in length), (2) one large scale (approximately 2 m by 2 m) fabricated fracture surface, (3) plastic replicas of part of this fabricated fracture surface and the small scale fabricated fracture surface and (4) numerical simulations of the resulting experimental data. The first set of small-scale samples consisted of one fabricated and one induced fracture plane. The second set of small-scale samples consisted of two cores contained sections of the natural fracture from the pilot resin experimental site at Äspö.

Small Scale Samples

The first step in this laboratory program was to conduct a preliminary suite of experiments on the limestone sample, that contained a sandblasted sawcut surface, and on the concrete sample, that was fabricated using a woven geotextile to imprint the "fracture" surface with a uniform roughness. Testing of these first two samples was followed by the full suite of both single phase and two phase experiments, including gas invasion, gas injection and degassing, on the two natural samples from Äspö, followed by tracer tests.

The geometry of the fracture pore space is assumed to have a major impact on degassing within natural fractures. For the small scale samples, the fracture pore space, at the stress conditions at which the last set of degassing experiments were conducted, was impregnated with resin. These fracture planes, measuring approximately 200 mm by 290 mm, were sectioned perpendicular to the fracture plane on 10 mm spacing and the resin filled fracture cross-section was photographed under a microscope and the enlarged images were digitised. The second quarter status report provided the aperture distribution data, aperture geostatistics and the location along each mapped profile of the contact between the adjoining fracture walls for the second Äspö sample.

The aperture contour map provided with the second quarter status report highlighted the pocketed nature of the apertures over the fracture plane and the lack of any continuous or interlinked large apertures or channels. All of the flow and degassing experiments were conducted under linear flow conditions, parallel to the length of the fracture. If the large apertures that form a fairly continuous bridge across the middle of the fracture plane where filled with gas bubbles, fluid flow would be restricted to the small apertures that form only a small part of the aperture field in this fracture plane. It was assumed that this pore space structure would be very effective in reducing the transmissivity of the fracture plane and this was certainly consistent with the large reductions in transmissivity that were measured during the degassing experiments on this sample.

In order to relate the experimental results to existing flow and transport models, both single phase and two-phase flow, it was important to confirm that the measured pore space could be used to represent the single-phase flow field. Previous efforts have not shown a very good match between the flowrates computed using the measured pore space and the flowrates measured in the experimental program. The problem appears to be related to how the pore space and the contact areas are characterized. The fracture plane contains two aperture populations: open or resin filled pore spaces and contact areas (zero apertures). If the contact areas are completely ignored, the aperture values will be overestimated. On the other hand, if all the contact areas are included by random superpositioning, the spatial continuity of the connected pore space will be overestimated.

We used the GSLIB geostatistics package to determine the variograms for the fracture pore space in which the contact areas were assumed to be areas of zero aperture or less than one micrometre. The block kriged data for the aperture and contact areas were used to generate a flow and transport model of this fracture plane at both the 5 mm, 1.5 mm and 1 mm grid scale. The flowrates computed using the 5 mm data underestimated the measured flows. However, the agreement between the measured and computed flowrates was within a few percentage points when the 1.5 mm block grid data were used. This example demonstrated that the measured pore space can be used to simulate the flow and transport properties of specified fracture planes and to examine the role of fracture pore space in determining the impact of degassing on fracture transmissivity.

Plastic Replicas

Three fracture replica models, two approximately 290 mm by 290 mm and a third approximately 180 mm by 290 mm in size, were completed at Sandia in 1997. The fracture replicas recreated the geometry of the large-scale experiments and permitted linear as well as radial flow experiments with a number of manometer ports in the fracture plane. In addition, the fracture replicas provided an experimental configuration and sample size that was similar to that of the small-scale samples.

The transparent fracture models, created using the geotextile-imprinted surface, produced a highly conductive permeable fracture plane, similar to the large physical model. This high conductivity produces high fluid velocities within the fracture plane, even at low pressure gradients and even under confining pressures of 1.8 bars. Higher confining pressures could not be used since the fracture replicas generally exhibit significant creep effects at the higher confining pressures, leading to a continuous decrease in fracture transmissivity, making it difficult to establish steady state conditions for the degassing experiments.

A series of qualitative experiments showed that, for the low pressure gradients generated under linear flow conditions, gas bubbles were generated over much of the fracture plane when the inlet pressure dropped below the bubble pressure. Gas bubbles that formed by degassing generally had a low residence time within the fracture plane. Difficulty was encountered in maintaining the fracture inlet fluid pressures above the bubble pressure for the gas-saturated fluid. However, when the fluid pressures at the inlet were dropped below the bubble pressure the bubbles entering the fracture plane appeared to promote widespread bubble generation within the fracture plane. These bubble clusters tended to have a periodic stability, that is they would grow and then after a sufficient area of the fracture plane had been filled with gas, the bubble clusters would migrate rapidly in the direction of flow. Under convergent flow conditions, the area around the central borehole was swept clear by the fluid acceleration. The size of this area around the borehole increased with increasing fluid pressure gradient. The inertial forces due to the high fluid velocities easily overcame the viscous forces and the low trapping forces provided by the uniform nature of the pore space roughness.

Since the surface roughness of these fracture replicas are thought to represent a very uniform pore space, that has a low gas bubble trapping capacity, it was considered important to quantify the mean apertures, the aperture fields at different confining pressures and image the pattern of gas bubble migration through the aperture plane under different flow geometries and pressure gradients. These quantitative measurements were completed at Sandia National Laboratories with extensive assistance being provided by Sandia staff and scientists. The mean aperture, based on dye measurements, under 4 psi confinement pressure was 0.26 mm. The fracture replica showed only small changes in aperture for confinement pressures of up to 24 psi. To provide direct measurements of the aperture the replica was injected with resin under 24 psi confinement pressure at the end of the flow experiments.

For these quantitative experiments, CO_2 gas saturated water was introduced into the fracture plane to examine how the separation of the gas phase from a gas-saturated water in a rough fracture affects the transmissivity of a fracture plane. Variables of interest in these experiments were the bubble trapping capacity that the fracture roughness creates, the magnitude of the hydraulic gradient, the drop in the fluid pressure relative to the bubble pressure of the gas and the fluid flowrate. In addition, these experiments were designed to determine (1) if the rate at which the separate gas phase forms for a given set of boundary and flow conditions and (2) whether or not a specific threshold build-up of gas bubbles, in the area of the fracture plane that is filled with the gas phase for a corresponding change in the local fluid pressures, are controlling factors in the impact that the gas phase has on the fracture transmissivity.

These quantitative experiments confirmed the short residence times of the fluid within the fracture plane for fractures with very uniform roughness. The high flowrate swept all of the small bubbles out of the system before the pore blocking bubbles could evolve. Therefore, it is practically impossible to develop large bubble nucleation inside the fracture plane, if the inlet pressure was maintained above CO_2 saturation pressure. In order to enhance the gas phase evolution, inlet pressures have to be reduced below saturation pressure (about 0.5 psi below) and a large volume of gas saturated water is needed so that the flow experiment can be maintained for a longer period of time. In order to observe the sweeping effect, bubbles had to be introduced into the fracture plane by lowering the inlet pressure even more, so that they started to evolve at the edge of the fracture. Much lower fracture transmissivities and much rougher fracture surfaces with a highly variable pore space are needed to produce pressure drops and induce degassing within the fracture plane at the gas saturations and sample sizes used in these experiments.

Large Scale Model

Low flowrate tests (0.5 to 4 L/min) were completed on the large scale physical model (LPM) at 1.0 MPa of normal stress to better define the flowrate versus pressure head relationship for the low end of the measured flowrates. While the withdrawal tests could be conducted at low flowrates, as low as 0.2 L/min, for both single phase and two-phase flow, the pressure drops required to produce degassing could only be achieved at higher flowrates (about 8 L/min). Hence, to produce significant degassing in the large scale model, the fracture plane has to reconstructed to produce a well mated but rough fracture surface with a lower fracture transmissivity.

The final work on this study includes the completion of the flow modelling to determine the changes in transmissivity required to reproduce the changes in hydraulic gradient and flowrates for both single phase flow and two phase flow under both linear and convergent flow conditions.

4.7 Hydrochemical stability

4.7.1 Background

The chemical properties of the groundwater affect the canister and buffer stability and the dissolution and transport of radionuclides. It is therefore important to assess 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 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 slabs of 0–100, 100–1,000, 1,000–10,000 and 10,000–100,000 years after closing of the repository.
- To develop a methodology to describe the 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 has the capability to decode mixing in the groundwater system. Identified end-members or reference waters are mixed in proportions to describe all other observation points. The conceptual assumption behind this concept is that the varying hydraulic conditions of the past have caused the complex mixing pattern presently observed. Mass balance calculations are then made to explain the difference between the ideal mixing and the observations.

4.7.4 EQUIP

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. Results of the SKB contribution to the first project year are:

Work package 1: Selection of the study site

The study site selected for the Swedish EQUIP study is the Äspö Hard Rock Laboratory (HRL). This site is well documented concerning geology, hydrogeology and hydrochemistry, see Rhén et al., 1997.

Fracture samples from drill cores, reaching a maximum depth of 1700 m, mainly from the pre-investigation phase have been selected for the EQUIP study.

Work package 2: Review climate & hydrology:

Not only climatic variations but also eustatic (changes in sea level) and glacio-isostatic movements have changed the hydrogeological and hydrochemical conditions significantly in the coastal areas in the Baltic Sea region.

A compilation of the Late Pleistocene and Holocene (the last 130 000 years) climate and hydrology with focus on the conditions at Äspö has been compiled by Andersson (1998). The Holocene climate and different stages of the Baltic sea are relatively well constrained, whereas the knowledge about the situation during the Eemian interglacial and the Weichsel glaciation is poor.

The most important events which hopefully can be traced in the fracture calcites are given below, based on the literature review by Anderson, (1998) and references therein.

During the last interglacial (the Eemian, 130 to 117 ka BP) the climate was warmer and more humid. The sea level in the Eemian Baltic basin was much higher, probably as a result of the depression of the crust caused by the Saale glaciation. It is suggested that during the Eemian, the Baltic basin was connected both with the North Sea in southwest and the Arctic Sea in northeast. This means that the Eemian is the most recent period when the Baltic basin (and the Äspö area) could possibly have experienced marine oxygen-18 and Cl values.

During the Weichsel glaciation the ice sheet had its centre in the Scandinavian mountains and northern Scandinavia. The Middle Weichselian is characterized by fluctuations, melting and re-advances. Äspö was probably not glaciated until the middle or latter part of the Middle Weichselian. The maximum extension of the Weichselian ice sheet occurred around 20 to 18 ka BP and after that the deglaciation started. The Äspö area was deglaciated at ca 12,500 ka BP. Huge quantities of glacial meltwater was drained into the Baltic basin. As a results of eustatic changes and glacial rebound the post-glacial Baltic basin had contact with the sea during the periods; the Yoldia 10.3–9.5 ka BP and Litorina-present 8.0–0 ka BP, whereas fresh water stages are represented by the Baltic Ice Lake 13.0–10.3 ka BP and the Ancylus Lake (9.5–8.0 ka BP). The Äspö area was situated below sea or lake level until ca 3,000 years ago.

Variations in $\delta^{18}O$ and Cl values during the different time periods are summarised in Figure 4-19 (Andersson 1998).

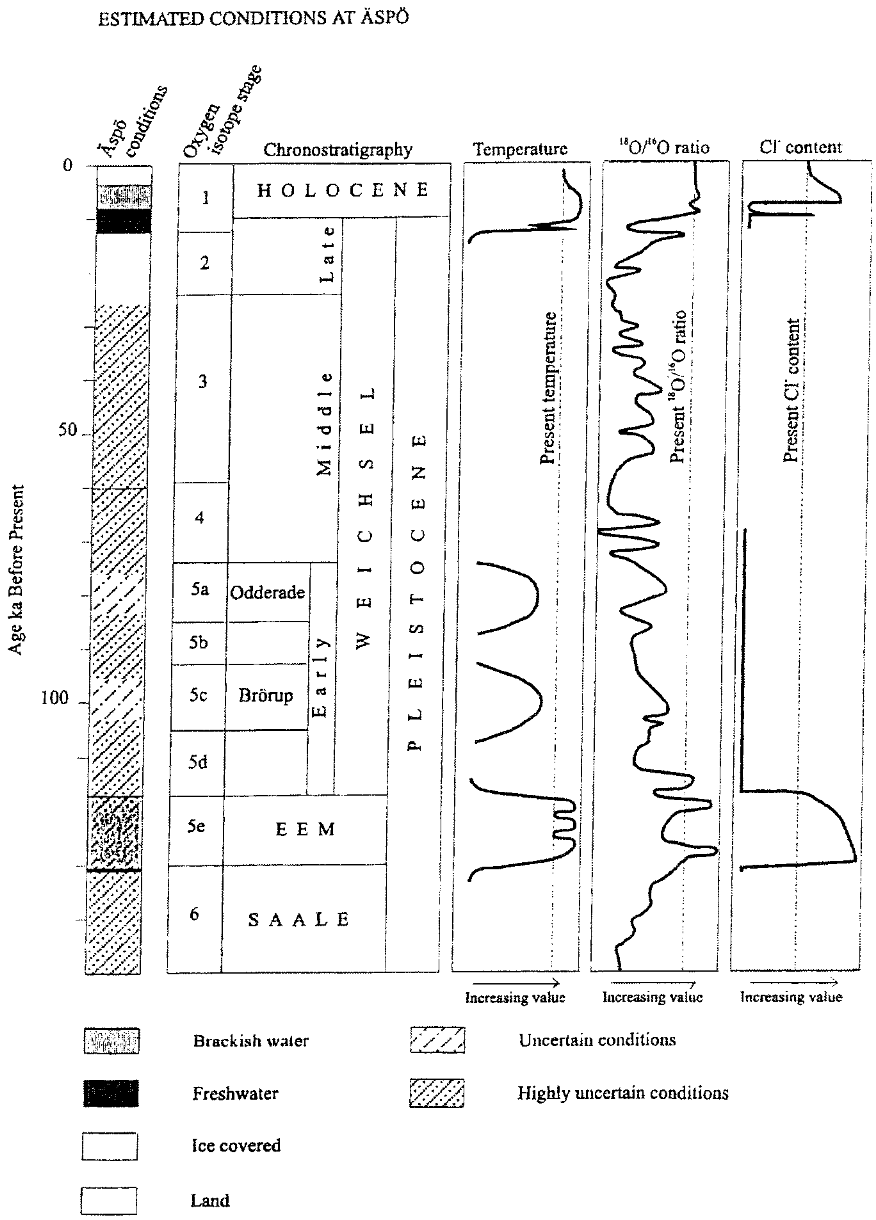


Figure 4-19. *An outline of estimated conditions at Äspö 150 ka BP to present.*

Work packages 3 and 4: Assemble hydrogeological and geochemical data and establish conceptual models for palaeohydrology

The hydrogeological and hydrochemical interpretations are based on measurements from a large number of boreholes: Boreholes drilled from the surface during the preinvestigation phase reaching depth of 1,700 m, boreholes drilled from the tunnel mainly penetrating depth down to 550 m, and percussion boreholes drilled from the surface reaching depth of ca 100 m.

More than 400 groundwater analyses, including main elements and environmental isotopes are available. The hydrogeochemical information has been decoded and the evolution of the groundwater chemistry and the post-glacial hydrogeological evolution of the Äspö area are presented in the proceedings of the second Äspö International Geochemistry Workshop, 6–7 June, 1995, ICR 97-04 (Laaksoharju & Wallin (eds) 1997) and summarised in TR 97-06 (Rhén et al., 1997).

Chemical components and environmental isotopes have been used in multivariate plots in order to distinguish different groundwater components. The information from the multivariate plots together with additional stable and radiogenic isotope data have been used to determine the origin of the components (end-members) distinguished. Modelling and interpretation of the groundwater chemistry showed that several events have contributed to the present distribution and composition of the groundwater:

- Meteoric water of present climate and cool climate (probably glacial meltwater).
- Baltic Sea water; present and probably ancient.
- Brine-type water.

The modelling shows that mixing, together with bacteria mediated reactions (e.g. sulphur or iron reduction), ion exchange, and calcite precipitation/dissolution explains the groundwater chemistry at Äspö.

The following evolution has been outlined by Laaksoharju & Wallin (1997): Glacial meltwater, (possibly from several glaciations) has, due to high hydraulic heads caused by the ice cap, been in-mixed to considerable depth with a saline water of brine type. Later, Baltic seawater has been introduced by density turnover. Subsequently when Äspö rose above the sea level, meteoric water has been recharged and in-mixed with the Baltic Sea- and glacial-brine waters.

Work package 5: Calculate potential impacts of palaeohydroevents

A modelling of the groundwater flow of the Äspö area during the postglacial (10,000 year) period has been carried out by Svensson (in manuscript). The objective of the study was to make a first attempt to simulate the groundwater composition (with respect to origin) below the island of Äspö. The model is based on variations in groundwater flow and salinity and the statement that that the water composition at 500 metres is determined by the conditions prevailing after the latest glaciation (last 10,000 years). In this first attempt neither groundwater mixing nor chemical reactions are accounted for. The average hydraulic conductivities used for the "rock mass" are given as decreasing stepwise each 200 metres, going from $1.3 \cdot 10^{-7}$ (m/s) to $4.7 \cdot 10^{-8}$(m/s) at >600 m depth.

The results indicate very dynamic situations with rapidly changing groundwater compositions. It appears that at a depth of 450 m at Äspö, brackish Yoldia and later Litorina water, has totally replaced glacial melt water. The model shows meteoric and brine water to be the only groundwater components present today (Svensson, in manuscript).

When comparing the modelled water composition with the measured oxygen-18 and Cl values it is obvious that the origin of the groundwater includes several components in addition to brine and present meteoric (cf. above WP 3 and 4). It can thus be concluded that mixing is a very important process and is certainly governed by the large variations in hydraulic conductivity of the fractures not accounted for in this flow simulation.

Work package 6: Sample drill cores for fracture infill studies

The sampling for the EQUIP study is concentrated to the deep vertical surface boreholes that penetrates Äspö and Laxemar. These boreholes were drilled during the preinvestigation phase and the groundwater samples collected in these boreholes are thus not influenced by disturbances caused by the tunnel. Conductive fractures from the sections sampled for groundwater chemistry were collected in addition to some other interesting water bearing structures at Äspö (e.g. fracture zone EW-1 and NNW striking highly conductive fractures). The sampled depths range from 25 to 1,600 metres.

Work package 7: Analyses of minerals

Previous fracture mineral studies at Äspö have shown $\delta^{18}O/\delta^{13}C$ to be very useful for separation of calcites of different origins (cf. WP 9 below). Furthermore co-variation between trace elements and stable isotope ratios has been indicated (Landström and Tullborg, 1995). Therefore sampling of calcite for stable isotope analyses and trace elements (using INAA) have been performed. Small samples from the fracture fillings have been separated, homogenised and sent for isotope/trace element analyses. It has been indicated in earlier work that high Sr values and positive Eu anomalies are indicative of hydrothermal calcites. Only preliminary results are available from the INA but a low temperature origin for the sampled calcites are so far indicated.

Work package 8: Fluid inclusion studies

The possibility of using fluid inclusions to determine the origin of the calcites in respect of formation temperature and composition of the fluid from which it precipitated will be tested. Preliminary results show that possibly three or four out of six samples may have inclusions suitable for analyses.

Work package 9: Isotopic analyses

33 new samples for analyses of stable isotopes from fracture calcite have been collected. The results of these analyses have been plotted together with the earlier results (Tullborg, 1997) in a $\delta^{18}O$ histogram and a $\delta^{18}O/\delta^{13}C$ plot (c.f. Figures 4-20 and 4-21). The sampling has been concentrated to open and water conducting fractures. Generally, the stable oxygen and carbon isotope values show extremely large variations in the calcites from Äspö and Laxemar, from -20 to 0‰ $\delta^{18}O$ and -74 to -2‰ $\delta^{13}C$, reflecting repeated hydrothermal activity and complex past and present hydrological situations. The very low $\delta^{13}C$-values are interpreted as caused by anaerobic degradation of organic matter under closed system conditions.

The large variations in isotopic ratios in the open fractures indicate that these fractures have been water conducting during long periods of time reflecting quite different conditions.

From the $\delta^{18}O$-histogram it is seen that values corresponding to precipitation from modern recharge ($\delta^{18}O$ of -9.5‰ SMOW) and brackish water (Baltic Sea) water or a mixture between these, dominates down to a depth of 350 m. Deeper down a few values corresponding to precipitation from brackish water occur, but below 510 m these are not recorded.

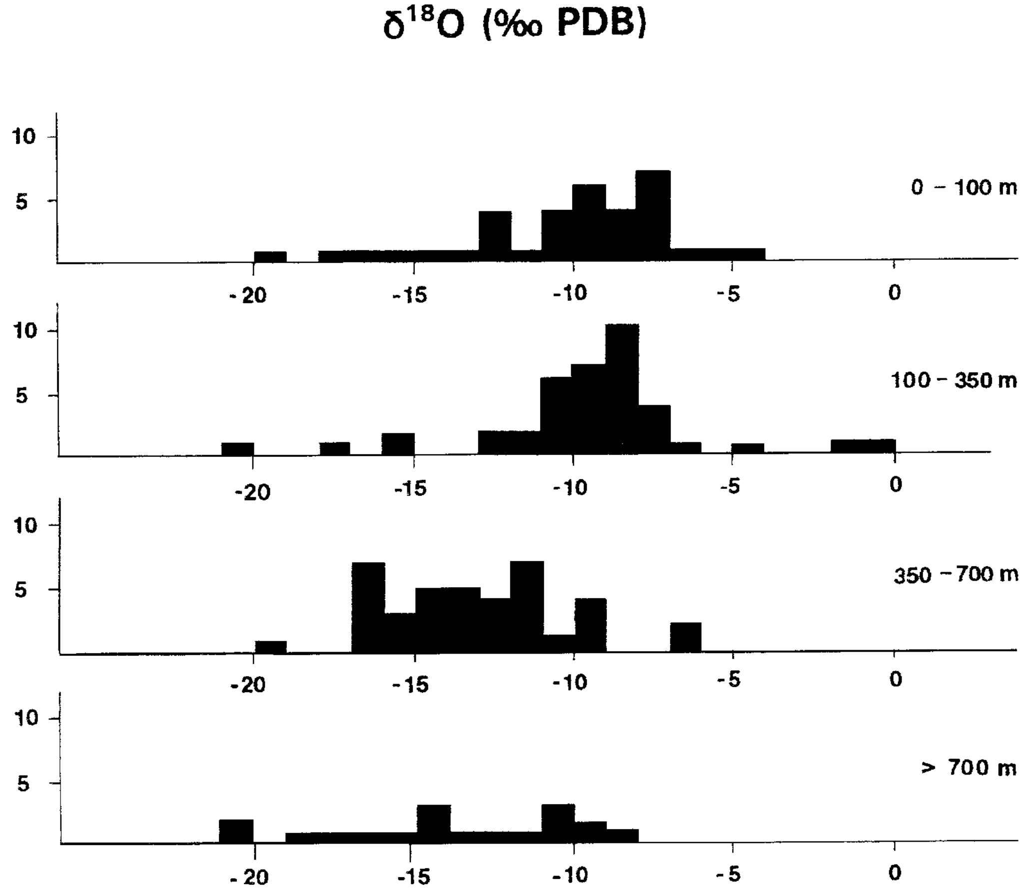


Figure 4-20. $\delta^{18}O$-histogram of fracture calcite from 131 open fractures.

At depths between 350 and 700 m calcite with $\delta^{18}O$-values in the range of -17 to -11‰ dominates. These calcites mostly have $\delta^{13}C$-vaules in the range -16 to -9‰ PDB, which are not the typical values for hydrothermal calcites of the area (-5 to -2‰). These calcites are thus interpreted as potentially low temperature calcites (so far supported by the trace element analyses, c.f. WP 7) and in such a case, assuming prevailing temperatures, they have been formed from a water with $\delta^{18}O$ ranging from -18 to -12‰ SMOW.

At depths below 700 m the isotopic signature is more diffuse and the amounts and frequency of calcite coated fractures appears to be lower. This may indicate 1) more stagnant conditions or 2) that the high salinity of the water prohibit calcite formation/ redistribution.

Calcite precipitated from marine water of oceanic character ($\delta^{18}O$ of approximately 0‰) occurs in a few fractures in the uppermost 300 m. Since the Baltic Sea is not likely to have had water of oceanic signature during the post glacial period, these calcites should be older than this and possibly as youngest from the Eemian (c.f. above).

A few values with extremely low $\delta^{18}O$-values (c. -20‰) and high $\delta^{13}C$ values (-2 to -5‰) are found at all depths. Observations of hydrothermal mineral paragenesis in some of these fractures favour a hydrothermal origin for these calcites.

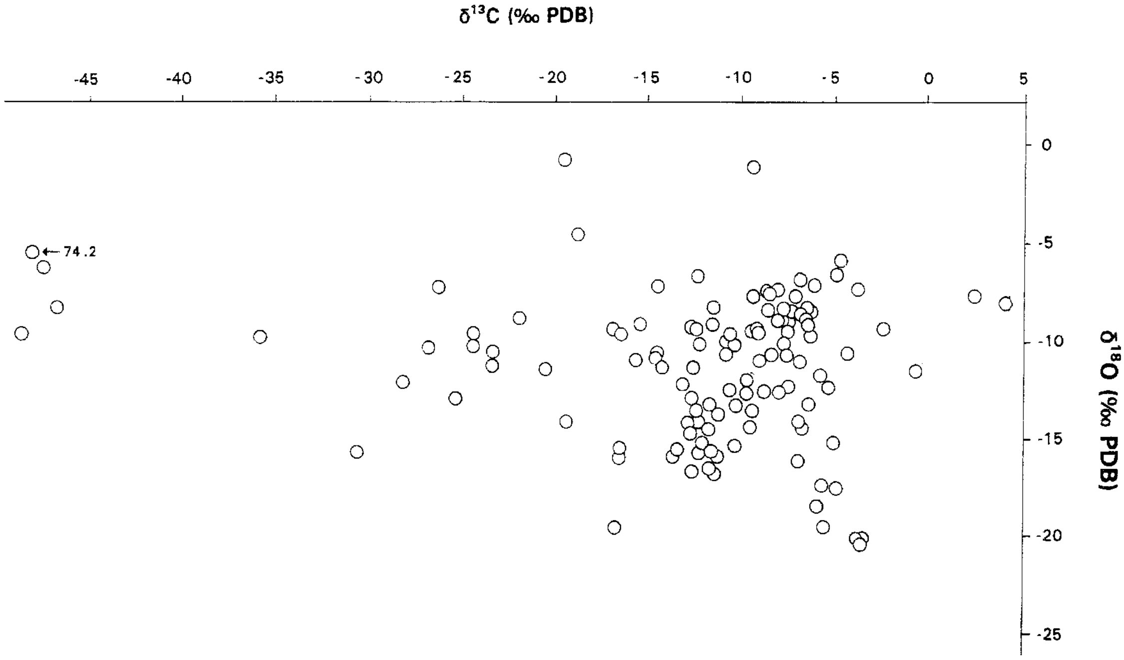


Figure 4-21. $\delta^{18}O$ and $\delta^{13}C$ for fracture calcites from Äspö and Laxemar.

Work package 11 Synthesis

The $\delta^{18}O$ and $\delta^{13}C$ ratios of the fracture calcites show large variations indicating that different events have been recorded in the calcites. Calcites with marine $\delta^{18}O$-values have been detected in a few fractures down to 300 m and values corresponding to brackish water down to 500 m. Values which correspond to temperate and cool climate meteoric water is found at all depths, as well as remnants of calcites with hydrothermal signatures. Looking at the frequencies and depth distributions of the isotopic values, there is a dominance of calcites re-equilibrated with the present groundwater at least to a depth down to 700 metres: water of meteoric and brackish character are most common down to 350 m. In contrast, at depth between 350 m and 700 m calcites in equilibrium with water of lower $\delta^{18}O$ values dominates. The latter may be interpreted as precipitates from a glacial-brine mixture. This depth distribution is in good agreement with the interpretations of the groundwater chemistry prior to the tunnel construction.

4.7.5 Modelling

Task #5 of the Modelling Task Force is a combined modelling of the transient situation during the tunnel construction. The exercise is planned to need the expertise of both groundwater flow and hydrochemistry modelling. At a workshop and start-up meeting for Task #5, held 4–5 September 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. Two coordinators have been appointed to facilitate the modelling work and to chair the Working Group Meetings.

The Modelling Task #5 has started with a workshop where approaches and plans for the modelling were presented and discussed. At the start-up workshop it was agreed that the communication between the modellers was best arranged through working group meetings. The first working group meeting, on initial and boundary conditions, was held at SKB in October.

The second project meeting for hydrochemical stability was held at Posiva 5 December. It was decided to continue the work along plans and previous objectives. The technical discussions were focussed on the results of re-sampling of KLX 02 and the modelling of redox conditions at Posiva's candidate sites, Olkiluoto and Hästholmen.

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

4.8.1 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.

4.8.2 Results

During 1997 the ninth meeting of the Äspö Task Force (TF) was held. It was arranged by ANDRA in Cherbourg, France, in February. In November PNC arranged the tenth Task Force meeting in Kamaishi, Japan.

Issue evaluation table

The Issue Evaluation Table provides valuable help in relating performance assessment as well as characterization key issues to the actual, forthcoming experiments at Äspö (Olsson, 1995). An independent review of the table has been undertaken. In addition the list of Äspö HRL experiments addressing each issue has been updated. An enhanced Issue Evaluation Table has been produced.

Task No 3 – The hydraulic impact of the Äspö tunnel excavation

The evaluation of the modelling work on Task No 3 (the hydraulic impact of the tunnel excavation at Äspö) has been completed. The first part may be regarded as a direct continuation of Task No 1 and addresses how robust are site scale groundwater flow models based essentially on pumping test results and does extrapolation from such models provide reasonable results. The second part uses the data set available up to the first turn of the spiral of the Äspö tunnel for improving the site scale groundwater flow models. Modelling work on Task No 3 conducted by the different organisations is summarised in Table 4-4.

Table 4-4. Organisations and modelling groups of Task No 3, the Äspö tunnel experiment. SKB ICR means the Äspö International Co-operation Report Series.

Organisation	Modelling Team	Representative	Task 3A	Task 3B	Reference
ANDRA	Itasca Consultants	D Billaux	X		Billaux 1995 (in French)
CRIEPI	CRIEPI	Y Tanaka	X	X	SKB ICR 96-07
PNC	Golder Associates	W Dershowitz		X	SKB ICR 97-03
PNC	Hazama Corporation	R Yamashita	X		DRAFT
Posiva	VTT Energy	F Mészáros	X	X	SKB ICR 96-06
SKB	CFE	U Svensson	X	X[2]	SKB HRL PR 25-91-03
UK Nirex	AEA Technology	D Holton	X	X	SKB ICR 97-05

In Task 3A it became evident that important hydraulic connections were missing. These were necessary in order to explain the detailed hydraulic responses to the elevator shaft. The main advantage of Task 3B was that it demonstrated that a detailed analysis of the transient pressure responses due to tunnel construction will provide an improved structural model. Model calibration gave an insight into the features and their connectivity; however, a successful calibration exercise is very time consuming.

The use of tunnel drawdown information vs. borehole information during pumping tests has been addressed. Obviously, the tunnel drawdown experiment provides a lot more information, but on the other hand it is less well controlled. It is useful for site characterization to model the tunnel drawdown effects, but again this requires substantial work.

The evaluation report has been published (Gustafson et al., 1997) and provides much more information on this exercise.

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

The TRUE-1 tracer test programme is described in detail in Section 4.3. The tests discussed (RC-1 and DP-1 to 4) were chosen as predictive modelling tasks for the Äspö Task Force groups. The predictive modelling exercises for Task No 4C and 4D were presented in interim reports, (Ström, 1996) and (Ström, 1997a). Seven modelling groups participated. The complementary tests (RC-2, DP-5–DP-6) have not been the subject of any predictive modelling.

Concerning Task No 4C, a preliminary comparison between model predictions made by the Äspö Task Force and the experimental results, shows that most modelling teams predicted breakthrough from all four injections, although some teams predicted distinctly lower mass recoveries from the two injections which *in-situ* did not produce a breakthrough. The breakthrough times predicted by the modelling teams are also in accordance with those observed in the experimental results.

Concerning the modelling of Task No 4D, it seems there are larger differences among the predictions when compared to the predictions of Task No 4C. This fact will be further investigated within the evaluation process that is now on-going.

Each modelling group will also present its study in an Äspö ICR report. The individual reports of Tasks 4C and 4D will be published in the Äspö ICR series early 1998. The evaluation of Tasks 4C and 4D will be completed during 1998.

Task No 4E – predictive modelling of reactive tracer tests part of TRUE-1

The STT-1 sorbing tracer test was performed in a radially converging flow geometry with injection in borehole KXTT4 and pumping in borehole KXTT3, see Section 4.3. The test is performed at a pumping rate of 0.4 l/min. The test was started in mid July 1997 with the injection of two conservative (Uranine and HTO) and six weakly/ moderately sorbing tracers (^{22}Na, ^{85}Sr, ^{86}Rb, ^{47}Ca, ^{133}Ba, ^{137}Cs).

The breakthrough of Cs is very weak, less than 1 % after 100 hours and about 15 % after 1500 hours. In addition, a new complementary injection (STT-1b) will be performed in late November in KXTT1:R2.

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.

The following subtasks have been identified:

Task 4E:I	Prediction of sorbing tracer test STT-1 based on preliminary tracer tests and reported diffusion and sorption data from the laboratory.
Task 4E:II	Evaluation of tracer tests with sorbing tracers.
Task 4E:III	Prediction of complementary sorbing tracer test STT-1b. The models utilised should be the same, i.e. there should be no updating of the structural model implemented nor calibration on available experimental results from STT-1.

At the 10th Task Force meeting, eight different modelling groups presented predictive modelling results for the performed tests with sorbing tracers STT-1, (Ström, 1997b). No evaluation of the performed modelling has been initiated so far. The compilation provided by the Proceedings is the starting point for the evaluation process.

The Task 4E exercise will be extended by additional predictions of sorbing tracers test STT-1b. Predictive modelling results will be discussed at the next TF meeting.

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 task definition has been successively refined during 1997. 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.

Initially, it is very important to clearly define performance measures and for Task 5 these have been worked out in connection with modelling workshops. Two Task 5 workshops were arranged during 1997. The second workshop (first working group meeting on initial and boundary conditions) in late October detailed the data deliveries. Two batches of data have been planned for.

The next Modelling Group meeting on Task 5 is planned for March 1998.

The next TF meeting will be arranged by SKB on September 1–3, 1998, at Äspö.

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 characterization, 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 Prototype repository

5.2.1 Background

Many aspects of the repository concept 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, 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 quantify the processes which take 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 idea of establishing a Prototype Repository at Äspö HRL has developed over a long time. More recent program planning, including the introduction of other large-scale experiments efforts at Äspö, have further clarified the role of such an experiment in the overall development of the deep repository program. As a result, the Prototype Repository is focused on testing and demonstrating the system function of the KBS-3 concept. Activities aimed at contributing to development and testing of practical engineering measures required 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 projects such as Technology Demonstration and Retrieval Test.

5.2.2 Objectives

The major objectives for the Prototype Repository are:

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

The Prototype Repository should as much as possible simulate a part of a disposal tunnel in the real deep repository, regarding geometry, materials and rock environment. The Prototype Repository is set up to simulate a repository under what can be described as normal conditions, which is essentially the same as the reference design described in SR-95. In the Prototype Repository the heat generation from spent nuclear fuel will be simulated by electrical heaters.

The evolution of the Prototype Repository should be followed for a long period of 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 stage operation of the real deep repository. The Prototype Repository will in this context provide operating experience for 10–15 years longer than have been achieved with deposited canisters containing spent fuel.

5.2.3 Experimental concept

The overall idea is that the Prototype Repository should, to the extent possible, simulate the real deep repository system. This calls for testing in full scale and at relevant depth. Furthermore, test arrangements should be such that artificial disturbance of boundary conditions or processes governing the behaviour of the engineered barriers and the interaction with surrounding rock are kept to minimum. The Prototype Repository will, however, be limited to some extent, with respect to simulate a real deep repository:

- The test site is given and the location in conjunction with certain conditional criteria is therefore limited.
- No handling of spent fuel; the canisters to be used will be equipped with electrical heaters to simulate the heat generating from the spent fuel.

- The Prototype Repository cannot demonstrate long-term safety, since the experiment considered will be extended in time at most tens of years.
- The Prototype Repository cannot demonstrate final handling and installations of components due to practical reasons, such as instrumentation etc.

Different alternatives as regards location and layout of the test have been considered. The test location chosen is the innermost section of the TBM tunnel at 450 m level. In the real deep repository, localisation of the deposition tunnels and canister positions is planned to be determined by a step by step characterization procedure followed by a step by step detailing of the repository layout. Each step is based on data from characterization of the host rock, which contribute to the adjustment of localisation in relation to data as major and minor discontinuities and their orientations, water conditions, magnitude and orientation of rock stresses etc. The site of the Prototype is given and restricted to the inner part of the TBM tunnel. However, methods for characterization of the rock mass at the test site are expected to contribute to the assessment of methods for characterization of the "near-field" rock mass and the canister positions in a real deep repository.

The tentative layout includes six simulated deposition holes with a spacing of about 6 m (Figure 5-1). The Prototype Repository is planned to consist of two sections, which will be separated by temporary plugs, in order to achieve mechanical support to the backfill and to achieve sufficient sealing to enhance the water pressure around the Prototype. The inner section will contain four deposition holes that will be left for long time (more than 10 years). The outer section will contain two deposition holes. The outer test section is planned to be decommissioned after about 5 years. The distance between the deposition holes is determined considering the heat diffusivity of the rock mass and bentonite buffer and the fact that maximum acceptable surface temperature of the canister is 100 °C.

The deposition holes will be mechanically excavated by full-face boring, diameter 1.75 m and to a depth of 8 m. The performance of the boring machine and the boring tech-

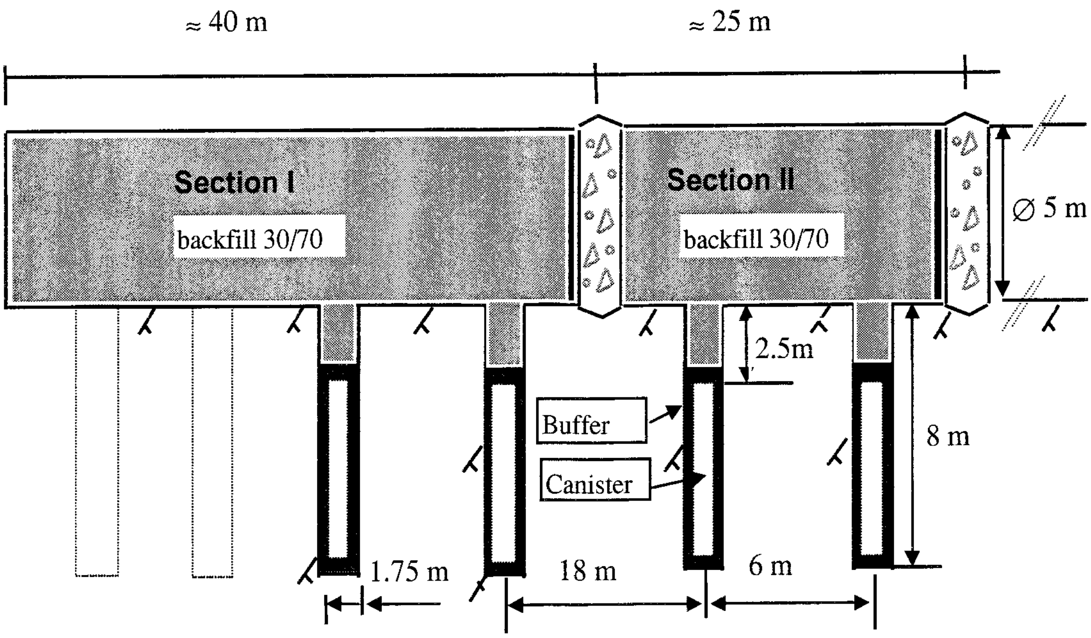


Figure 5-1. Schematic view of the layout of the Prototype Repository (not to scale).

niques will be analysed. Special considerations must be taken to investigate the geometric result, surface roughness and the disturbed zone, i.e. induced fracturing. Rock mechanical consequences as fracturing and strains, due to stress redistribution will be monitored by registration of acoustic emission and strain measurements in holes around selected deposition holes.

The canisters for Boiling Water Reactor fuel assembles (BWR) 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 deposition holes and surrounded by bentonite blocks (Figure 5-2). The plan is that the decay heat will be simulated and the experiment controlled by the power output. However, possibilities to run a temperature-controlled experiment will also be considered.

The buffer will be made of bentonite blocks of highly compacted Na-bentonite. The blocks will have an initial dry density of about 1.74 ton/m^3 and a water ratio of 17%. 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. Different alternatives as regards initial water saturation of the buffer material, block manufacturing etc., are being studied.

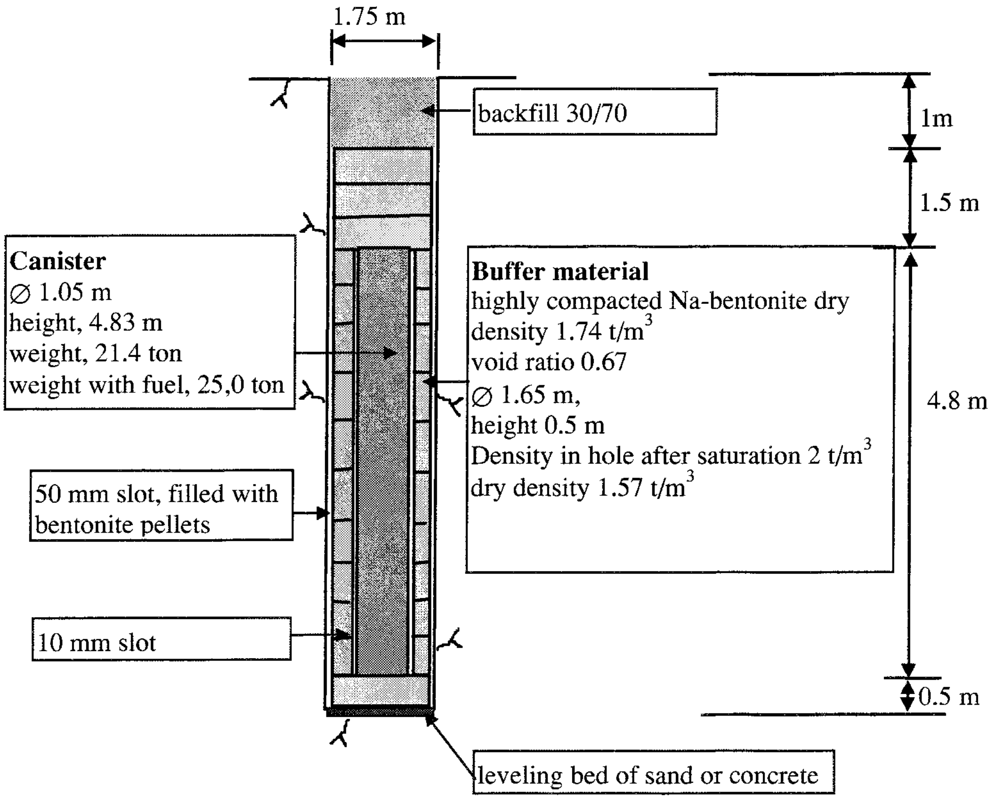


Figure 5-2. *Schematic layout of the deposition hole including canister and buffer (not to scale).*

Instrumentation will be used to monitor important processes and properties in the buffer material, backfill and the near field rock. The intention to minimise disturbances will, however, add restriction to possible monitoring. The function of the engineered barriers is controlled by a number of measurable parameters. The intention is to measure these properties in order to study the processes. Modelling is carried out as integral parts of the tests. Main processes that will be studied include:

- Water uptake and pressure in buffer, backfill and rock.
- Temperature distribution in canister, buffer, backfill and rock.
- Swelling pressure and displacements in buffer and backfill.
- Chemical processes.

Other processes that are of interest in the intended test layout are:

- Stresses and displacements in the near field rock.
- Tracer transport in the buffer.
- Gas transport from the canister.
- Bacterial migration in buffer.

5.2.4 Results

Detailed planning has been continued during 1997, and the layout and the experimental set up of the Prototype Repository continuously updated.

The deposition holes are planned to be excavated during spring 1999. Different options to accomplish the 1.75 m diameter holes have been evaluated and the contractor has been procured. Manufacturing of canisters is proceeding as planned and the design of the electrical heaters and other installations in the canisters are in progress.

The characterization of the rock mass in the area of the Prototype repository in continuously going on. The evaluation of the characterization data obtained in stage 1 (characterisation from the deposition tunnel), has been reported and characterization work stage 2 (exploratory drilling) is in progress. The characterization performed in stage 1 has included:

- Compilation of existing data from basic tunnel mapping (cut off 1 m).
- Laser scanning (profile and image scanning).
- Tunnel radar (Ground Penetrating Radar).
- Water inflow measurements (every 6 m).
- Detailed geological mapping of test section floor.

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. Another main joint set is semi-horizontal joints trending NE. RMR classification range from good to very good.

Laser scanning of the Prototype Repository site provides images of good quality of the walls. However, interpretation of joints from the images proved more difficult than expected. Major fractures were easily detected, but smaller structures proved more difficult to interpret.

Inflow measurements confirm locations of water inflow from standard mapping. The total quantity of inflowing water to the Prototype Repository is about 5 l/minute. Most of this water comes from the inner 20 m of the TBM tunnel.

The characterization according to stage 2, include pilot and exploratory drilling, in situ measurements of thermal properties and in situ rock stress measurements etc. The holes and cores will be investigated in order to establish the thermal, hydraulic, and mechanical conditions for the Prototype Repository.

Up to now three exploratory holes 20–30 m long and 12 pilot holes to a depth of 8 m have been cored, logged and hydraulically tested. The rock quality is generally very good and very small inflows and pressures have been registered in the pilot holes.

In-situ rock stress measurements have been performed by the overcoring method, and the primary stresses obtained were σ_H=26 MPa and strike 11°, σ_h=18 MPa and σ_v=21 MPa.

In-situ measurements of thermal properties have been performed in five different locations in the Prototype Repository.

The scope for 1998 is to further detail the planning, prepare the site and to furnish key components for The Prototype Repository. Major activities planned are:

- Site characterization.
- Scoping calculation and prediction modelling.
- Detail planing of layout, material and monitoring etc.
- Excavation of deposition holes.
- Establish the quality assurance system.

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 put into operation, and the first phase of the program, addressing floor mapping and preliminary geological modeling, was carried out during 1997. Four locations for boring of full scale simulated deposition holes were selected tentatively.

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 will be a test of the integrated function of the backfill material and the near field rock in a deposition tunnel excavated by blasting. It will also be a test of the hydraulic and mechanical functions of a plug. The test is partly a preparation for the Prototype Repository.

In 1997 the preparations have continued and the fieldwork started with supplementary excavation and rock characterization. The test set-up will be made in 1998.

The original ZEDEX tunnel has been prolonged with 16 m. The purpose was to have a larger test section and better options for the location of the plug. The new part of the tunnel was excavated with very careful blasting, in order to have a blast damage of the near field rock which is as small as possible. However, the excavation resulted in a very high inflow of water in the new part. The measured inflow was 5 l/min, which is about 10 times more than could be accepted for practical reasons.

14 holes were drilled into the water bearing fractures in the new part of the tunnel, in order to try to drain the water bearing zones. The drainage decreased the inflow to 2 l/min but it was concluded that this is still too much. The new part will be backfilled but not used for flow testing.

5.4.2 Test layout

The final design of the test has been settled and the test plan approved. Fig 5-3 shows the layout of the test.

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. 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.

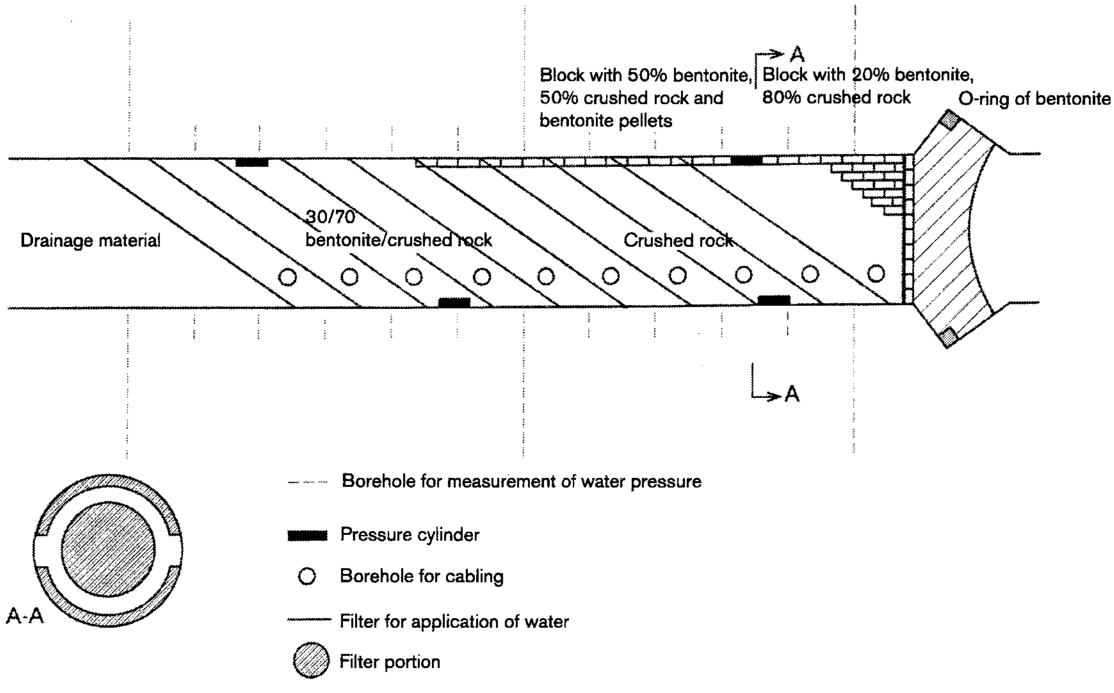


Figure 5-3. An overview of the Backfill and Plug Test.

5.4.3 Results

Characterization

The first step in the characterization of the surrounding rock has been taken. The following investigations have been made:

- Laser measurements of the tunnel geometry.
- Geological mapping.
- Geophysical measurements from the rock surface.
- Water-inflow measurements in 5 m long sections.

Step 1 of the characterization and older measurements have yielded a preliminary model of the rock in the test area.

ENRESA

ENRESA has joined the project. ENRESA will take active part in the following work:

- Test design and planning as participants in joint technical project meetings.
- Instrumentation with installation of in situ hydraulic conductivity measurement devices.
- Modelling with scoping calculations and predictions of the THM processes.

Instrumentation

The instruments for measurement of thermal, hydraulic, and mechanical behaviour of the backfill and rock during the saturation and test phases have been developed and chosen. The following variables and properties will be measured during the test:

- Temperature in the backfill.
- Water ratio of the backfill.
- Water pressure in the backfill and rock.
- Total pressure in the backfill.
- Local hydraulic conductivity of the backfill.

The latter measurement will be made with probes developed and installed by ENRESA.

The cables and tubes for the instruments will be 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. The water pressure in the rock will be measured in boreholes sealed with bentonite packers. The old boreholes that will not be used for any measurements will be sealed mainly with bentonite plugs.

Compaction technique

The new vibrating plate and its carrier have been tested with inclined compaction of the backfill materials in a drift in Äspö HRL. The results showed that the machine worked well also close the walls. However, the problems at the roof remained and a vibrator for compaction close to the roof has been designed and built.

Laboratory tests

Supplementary laboratory tests on backfill material for investigating the influence of salt in the pore water and degree of saturation on the hydraulic conductivity have been made. The results show that the influence of a salt content corresponding to Äspö water is very strong on the hydraulic conductivity of backfill material with 10–30% bentonite. The hydraulic conductivity increases with increasing salt content. The influence increases with decreasing bentonite content and decreasing density but is insignificant in backfill without bentonite. For densities corresponding to 90% Proctor the increase in hydraulic conductivity is a factor 10–100 for backfill with the bentonite content 10–30%.

The results also show that the influence of the degree of saturation on the hydraulic conductivity is very strong. The hydraulic conductivity decreases with decreasing degree of saturation. A preliminary model has been derived from the laboratory tests.

Scoping calculations

Preliminary modelling with scoping calculations has been made using the finite element code ABAQUS.

The hydrology of the rock around the test site has been modelled in 3D at the block scale 200x200x200 m^3. The model has included the Assembly hall, the TBM tunnel and all drifts inside the block. A porous media model is used and so far no fractured zones have been included. The influence of the boundary conditions and a possible skin zone has been investigated. The results show, as expected, that these conditions are important for the magnitude of the water pressure between the drifts.

The water saturation phase between two filter mats in backfill with 30% bentonite has been modelled with a 2D model. The calculations have used the preliminary material models derived from the laboratory tests. The results show that the time until saturation may be up to 10 years if no water pressure is applied in the filter mats.

The water flow tests have been modelled with the same model. The results show that the water flow into the permeable mats will be in the range 0.1–10 l/h at the expected pressure gradients.

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 Results

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. Heaters installed in the canister simulate the heat emission from spent nuclear fuel. The test will be located at the 420-meter level in the laboratory, in an extension of the D-tunnel.

5.6 Long term tests of buffer material (LOT)

5.6.1 Background

Most work concerning smectite clay stability has been made on natural systems in deep shales or in the vicinity of hydrothermal events. The conducted buffer field tests have in different ways deviated from possible Swedish repository conditions, e.g. low ground water salinity (BMT, Stripa), low water pressure (URL), and deviating buffer clay composition and high temperature (French clay, Stripa). Relatively large buffer alteration was noticed in the French tests, both with respect to clay mineralogy, redistribution of easily dissolved species and to the physical properties of the material.

5.6.2 Objectives

The test series aims at validate models and hypotheses concerning long term processes in 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 objectives may be summarised in the following way:

- Produce data for validation of models concerning buffer performance under quasi-steady state conditions after water saturation, e.g. swelling pressure, cation transport and gas penetration.
- Validate existing models concerning buffer degrading processes, e.g. illitization and salt enrichment.
- Study survival, activity and migration of bacteria in the buffer.
- Determine the nature and extent of possible copper corrosion.
- Determine gas penetration pressure and gas conductivity.
- Serve as pilot tests for the planned full-scale test series with respect to clay preparation, instrumentation, data handling and evaluation.

5.6.3 Experimental concept

The testing philosophy is to place prefabricated units of clay blocks surrounding copper tubes in vertical boreholes and to maintain the tube surfaces at defined temperatures. The test series includes 6 test buffer-parcels (Table 5-1) of which 3 will be exposed to standard KBS-3 conditions in order to validate present models of clay buffer performance, and 3 test parcels which will be exposed to adverse conditions in order to validate models for buffer alteration. The buffer-parcels are placed in boreholes with a diameter of 30 cm and a length of around 4 m. The boreholes will be separated from each other by 3–6 m in a representative granitic rock structure containing water-bearing fractures in which the groundwater pressure and salinity are found suitable.

Table 5-1. Specification of the Long-Term Test series.

No	Type	Purpose	T,°C	P_c	time, y
S1	ref	Pilot	90	T	1
S2	ref	LTP	90	T	~ 5
S3	ref	LTP	90	T	~ 20
A1	chem	Ma,C,Se	120<150	T, ([K^+], am, pH)	1
A2	chem	Ma,C,Se	120<150	T, ([K^+], am, pH)	~ 5
A3	high T	LTP-T	120<150	T	~ 5

S = standard conditions
P_c = controlled parameter
LTP = long term performance test
Ma = mineralogical alteration
Se = "salt enrichment"

A = adverse conditions
C = cementation
T = temperature
am = accessory minerals

Temperature, total pressure, water pressure and water content are measured during the heating period. At termination of the tests, the clay will be extracted by overcoring the original borehole in order to minimise redistribution of water before sampling. 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 during 1997

The two pilot heating tests S1 and A1 have been running during the year at temperatures close to 90 and 130°C, respectively. The tests have in principle delivered the expected data concerning temperature, moisture and pressure. Moisture gauges in the S1 parcel, placed halfway between the rock and the central tube, showed that the buffer in this position was fully water saturated after approximately 40 days after test start. Initially, the power was controlled to give a constant temperature in order not to over-heat the clay. In mid March the regulation was changed over to fixed power in order to follow the temperature development under such conditions. Based on the previous recorded power data the power was determined to be 600 W in the S1 parcel and 1000 W in the A1 parcel. A minor increase (2°C and 4°C, respectively) in maximum temperature was thereafter
noticed in both parcels. The temperature distributions at approximately mid test period (April 30) are shown in Figure 5-4. In December the power was decreased in steps and finally reduced to zero in both parcels in order to facilitate the forthcoming uplift and sampling of the parcels.

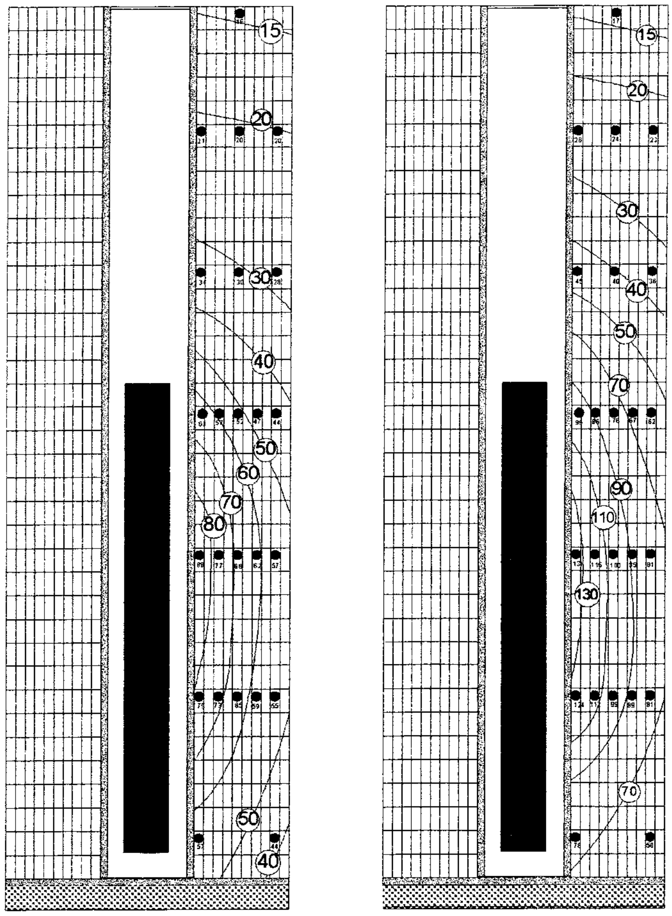


Figure 5-4. Temperature distribution in parcel S1 (left) and A1 (right) April 30, which approximately represents mid test period. Horizontal scale is exaggerated.

The S1 and A1 pilot parcels will be extracted in February and March respectively and physical, mineralogical and microstructural analyses and tests will be made. The planning for the 4 remaining long term test parcels will start in mid April, and drilling of the test holes is planned to begin in May. The emplacement of these parcels is planned to take place 1999.

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 geo-hydraulic 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 Results

Mechanical modelling of excavation depth and fractures in rock caused by tool indentation

An overview of the work conducted in the Division of Mining Engineering, Luleå University of Technology since 1993 has been made. The mechanical excavation was reasonably simplified as an indentation process of the interaction between rigid indenters and rocks. A large number of experiments carried out in the laboratory of Luleå University of Technology based on the mentioned simplification have been presented and fracture systems in rock under indentation have been formulated based on these experiments. The indentation causes crushing and damage of the rock and results in a crushed zone and a cracked zone. The indenter penetrates the rock with a certain depth when the force is over a threshold value relevant to the rock and tool. Outside the cracked zone there are basically three systems of cracks: median cracks, radial cracks, and side cracks. Fully developed radial cracks on each side of the indented area can connect with each other and join with median crack. This forms the so-called radial/median crack system. The influence of the mechanical properties of the rock has been discussed based on the conceptual model presented in SKB PR 44-94-022, and the main factors governing the indentation event have been summarised. The cracked zone is dealt with by an analytical fracture model. The side crack is simulated by applying the boundary element method coupled with fracture mechanics. Functional relationships have been established relating either the indentation depth or the length of radial/median cracks to the various quantities characterizing the physical event, namely the shape and the size of the indenter and the properties of the rock, etc. Results in the form of equations combining the theoretical approach and the experimentally obtained data provide new and more profound understanding of the physical mechanisms of rock indentation process. The conceptual model has, therefore, advanced into calculable formulas and computer codes for predicting the indentation depth, cracked zone, side crack and radial/median crack lengths for different shapes of indenter and various hard rocks with a reasonable accuracy. There is therefore a possibility to make an estimation of the excavation disturbed (or damage) zone (EDZ) in the assessment of nuclear waste repositories by using the results obtained.

Simulation of Rock Indentation Subsurface Cracks and Side Cracks Using Fracture Mechanics and Numerical Methods.

Numerical simulation of rock damage and cracks caused by indentation was reported in 1997. Data from previous indentation experiments carried out in three typical rocks, namely sandstone, marble and granite using hemispherical and truncated indenters were analysed. Cracked zone and side cracks were modelled. The cracked zone was described by a splitting fracture model, which predicted a fan like pattern of fractures. Factors influencing fracture propagation are the indentation stress state and fracture properties of the rock. The stress state was found to be dependent on the total load, indenter shape, indenter size and rock properties. The larger the loading force, the larger the cracked zone. The size and shape of the crushed zone were found to be dependent on the loading force, rock type and indenter geometry. A cavity model was used to describe the expansion of the rock in the crushed zone. As a result large tensile stress developed due to the cavity expansion. The growth of side cracks near the cavity zone was simulated using a fracture model coupled to a boundary element code. Side cracks were found to be driven either by shear or tension, or a combination of these. A deep cavity caused deep and long side cracks. Large cavity expansion allowed the side cracks to develop easily and to propagate upwards.

Influence of heterogeneity

Rocks with different densities of microcracks were examined experimentally by Division of Mining Engineering, Luleå University of Technology. To investigate the fracture mechanisms of rocks composed of heterogeneous inclusions, numerical tests on model samples were performed by using a Rock Failure Process Analysis code, RFPA2D. Heterogeneity was considered for both grains (or inclusions) and the filling materials. The simulation reproduces the main features of mechanical tests on brittle failure of rocks. One example was a compressive test shown in Figure 5-5, where the specimen has a quite large scale of heterogeneity and the rock property parameters, such as strength, Young's modulus and Poisson's ratio, are in random distributions, even within the visible grains. From this figure one could notice that: (1) At the beginning of the deformation process, a few local fractures, mostly around the grain or inclusion boundaries, were initiated and the damage was homogeneously distributed through the sample in a random way: the sample behaved elastically, few acoustic emissions were emitted and little energy was released; (2) Deviations from linear elasticity started to appear as more active fractures propagated, which resulted in more acoustic emissions and energy release; (3) The stress climbed to a peak as the strain started to localise onto an oblique shear zone in an unstable manner. Global failure did not occur until the biggest energy release and the biggest stress drop were observed. It was found that every large increase of acoustic emission and released energy resulted in a large stress drop. An examination of the failure mode showed that the fracture propagated not only going-through the grain boundaries, but also going-through grains, which proves that strong grains can act as crack barriers, whereas weak grains or grain boundaries may enhance the crack growth. Although most of the elements failed in a tensile mode, macroscopic shear band was formed, which agreed well with reported experimental observations. Other tests have been also carried out, such as rock indentation, extension of pre-existing crack under various loading and boundary conditions. These works were carried out by a joint research between Luleå University of Technology and Northern-eastern University in China. Through the preliminary results obtained in this joint investigation it may be conclude that (1) heterogeneity is an important factor which should be taken into consideration in order to understand the detailed process of rock fracture; (2) the main features in crack system and rock fragmentation can be governed by the stress field, which confirms the assumption in previously presented conceptual model.

Preparation of field test and crack observations

In connection with the boring of holes in full deposition hole scale in ÄHRL in 1998, cutters are planned to be instrumented so that the actual pressure these apply to the rock can be measured. In this field study the practical force magnitude under field conditions and the practical loading rate can be studied, which will make it possible to evaluate the present model. Preparations have started with investigations of suitable cutters to instrument.

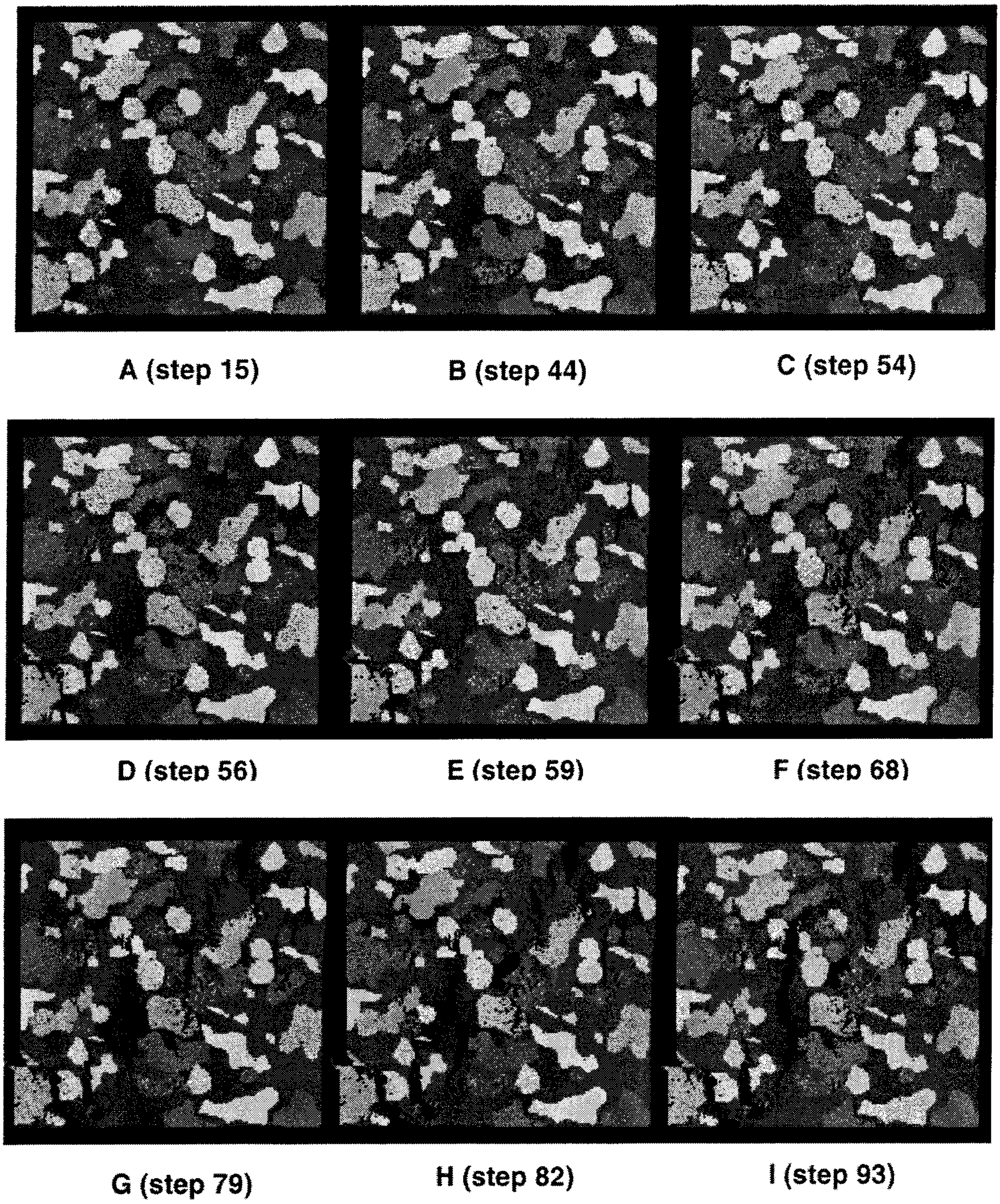


Figure 5-5. Simulated compression test. The specimen has a quite large scale of hetero-geneity. Rock property parameters, such as strength, Young's modulus and Poisson's ratio, are in random distri-butions, even within the visible grains. The figures after "steps" represent loading displacement.

6 Äspö facility operation

6.1 Plant operation

6.1.1 Excavation

Excavation for new experimental sites took place in the beginning of the year. The new tunnels will mainly be used for the Demonstration of technology and Long Term Test of Buffer material projects. When the excavation was completed scaling was made of the whole tunnel.

A new top layer of asphalt was laid on the road in the main access tunnel in the beginning of the summer.

6.1.2 Drainage system

The main undertaking on the drainage system was to change pumps in one of the pits. Today we have the same kind of pumps in all the four main pump pits. This facilitates the maintenance and gives us freedom to change pumps between different pits. We have also made some minor work on the drainage tube as well as mounted safety barriers in unprotected areas.

For the first time since the excavation all the pumps has now been at the workshop for maintenance. No serious stops have occurred.

6.1.3 Ventilation system

In the beginning of the year a lot of ice was formed in the ventilation shaft due to insufficient heating of the inlet air in combination with a lot of water in the shaft. Severe damage took place at the -450 m level and a tube, protecting the water leaking into the upper part of the shaft from continuing downward with the ventilation air, was damaged. Two electrical heaters have now been installed in the heat exchange system for the ventilation air. In case of temperatures below -20°C, this will not be enough but then the speed of the fan will automatically be reduced.

Due to the new experimental tunnels that were completed during the spring additional fans and ventilation tubes have been mounted.

6.1.4 Power supply

Two new transformers have been installed to meet the requirements from the coming experiments. Electric supplies and lights have also been installed in the tunnels that were excavated in the beginning of the year.

6.1.5 The hoist

The guides to the hoist have been adjusted and wheels have been mounted on the cage. This means that the hoist now runs very smoothly. At the end of the year a guarantee inspection took place. Minor modifications have to be done to the control system.

6.1.6 New office

The work with the new office, laboratories and storage started during September. According to the plan all buildings will be ready during spring 1998.

6.1.7 Environment and safety

A new rescue container has been equipped and painted in rescue colours. It will mainly be used at the -450 m level.

All staff have participated in a course how to give first aid.

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 characterization of one of the sites. The licence application for detailed characterization 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

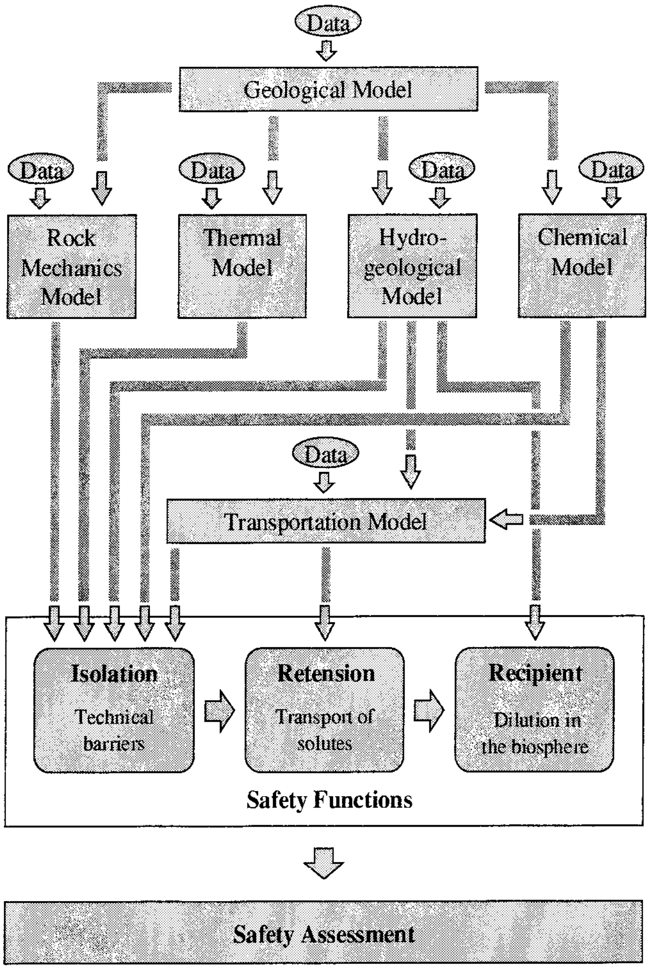


Figure 6-1. *Schematic flow chart describing how information are transferred between different geoscientific models and how these models are used in the safety assessment to be done. The need of different types of input data are shown as balloons marked "Data".*

entry, SKB's Site Characterization 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.

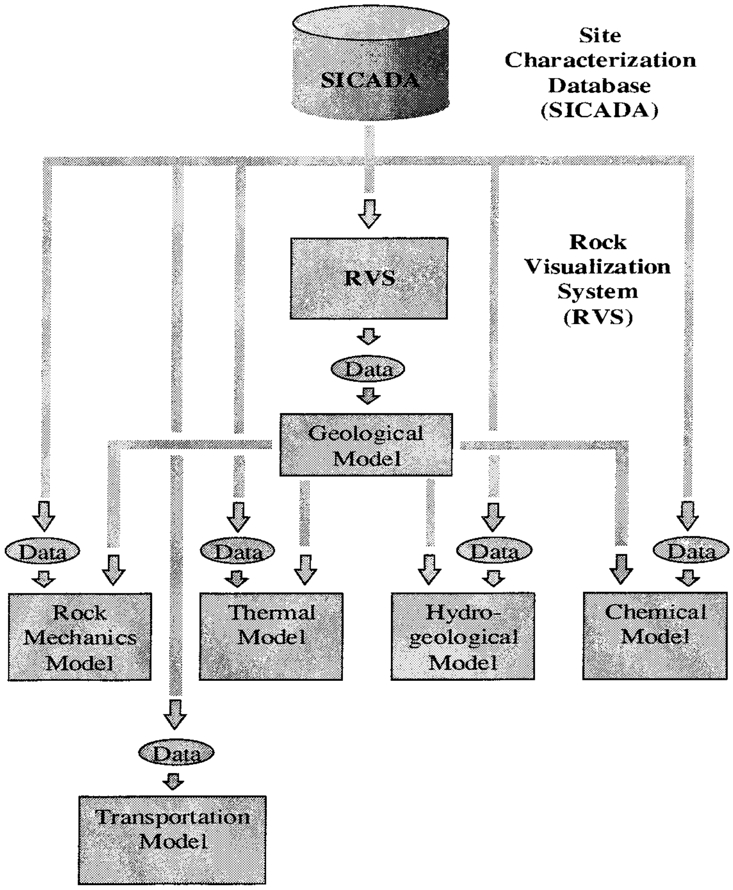


Figure 6-2. Schematic flow chart describing where from data are taken to the different geoscientific models used as a baseline fore the safety assessment to be done. The balloons in Figure 6-1 have been complemented with the origin of data. As indicated SICADA and RVS are highly important tools on the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

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.

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.

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 four levels, viz.:

- Science (Level 1)
- Subject (Level 2)
- Method (Level 3)
- Activity (Level 4)

At present the SICADA data structure contains the sciences engineering, geology, geophysics, geotechnics (introduced during 1997), 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.

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	Level 4 Activity
Engineering	Tunnel excavation etc.	Drill and blast etc.	D&B – Round drilling D&B – Charging D&B – Round D&B – Ventilation etc.
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 1 Water sampling, class 2 Water sampling, class 3 Water sampling, class 4 Water sampling, class 5 etc.
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 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 still 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 data management task during 1997 has been to implement a new database application, SIACAD/WWW-Retriever that finally should replace SICADA/Retriever as well as SICADA/Finder. The new application will be based on the Home Page concept that means that it should be possible to reach SICADA by using a common WEB-browser. Two prototypes have been tested during 1997, but none of them satisfies our requirements. The key issue just now is if the new interface should use the benefits of Java or not. A disadvantage with Java could be performance. A new system specification will be compiled and the programming work is planned to start during 1998.

SICADA/WWW-Retriever will first of all be reachable from SKB's internal home page (SKB's Intranet), but also external users will have time limited access privileges if there is a valid cooperation agreement with SKB.

6.3 Monitoring of groundwater head and flow

6.3.1 Background

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

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

- firstly it is a necessary requirement in the scientific work to establish a baseline of the groundwater head and flow situation as part of the site characterization exercise. That is, a spatial and temporal distribution of groundwater head prevailing under natural conditions (i.e. prior to excavation).
- secondly it is indispensable to have a such a baseline for the various model validation exercises which are implemented for the Construction Phase and the Operational Phase including the comparison of predicted head (prior to excavation) actual head (post excavation)
- thirdly it was conditioned by the water rights court when granting the permission to execute the construction works for the tunnel that a monitoring program should be put in place and that the groundwater head conditions should continue to be monitored until the year 2004 at the above mentioned areas.

A beneficiary spin off of constructing and maintaining the HMS is the competence building that is generated.

The HMS commenced operating in 1987 and has been in use since. The number of boreholes included in the network has gradually increased. The tunnel construction started in October 1990 and the first pressure measurements from tunnel drilled boreholes were included in the HMS in March 1992. To date (31 December 1997) the monitoring network comprises a total of 62 boreholes most of which are equipped with inflatable packers, measuring the pressure by means of pressure transducers. The measured data is relayed to a central computer situated at Äspö village through cables and radiowave transmitters. Once a year the data is transferred to SKB's site characterization database, SICADA. Manual levelling is also obtained from the surface boreholes on a regular basis. Several boreholes have been excluded from measurement while other been included over the years, Figure 6-3.

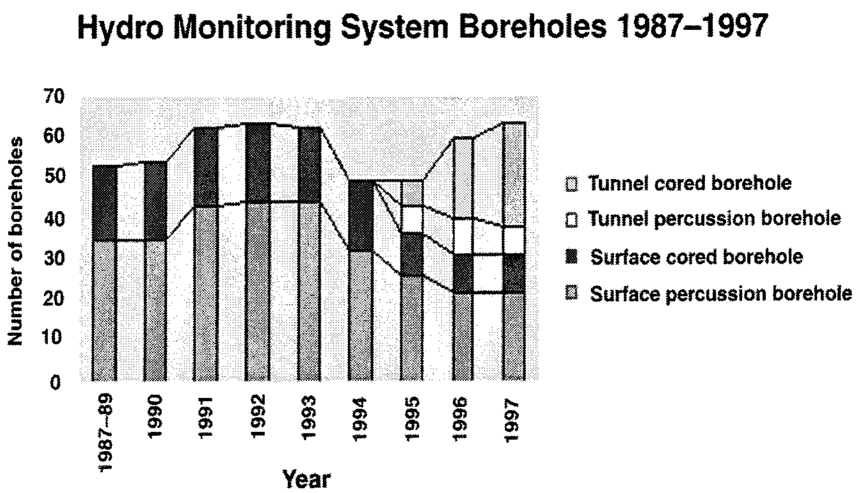


Figure 6-3. Number of boreholes included in HMS 1987–1997.

Water seeping through the tunnel walls is diverted to trenches and further to 21 weirs where the flow is measured.

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

6.3.2 Results

Specifically the data was put to use in different ways, in addition to complying with the water rights court the following was achieved:

I. The monitoring system provided the means to continuously control the groundwater head in a block where tracer experiments are conducted. The head distribution in the block should remain constant throughout the experiment since it forms an initial condition to the problem. Alteration in head gradients during the experiment might complicate the analysis.

II. It has been possible to correlate changes in head caused by the blasting which took place during November 1996 to March 1997. As an example, Figure 6-4 shows the effect of blasting at two different locations on the head in different parts of borehole KXTT4. In this instance the blasting took place at site D and site L. These are situated at the -420 m level at the entrance to the TBM tunnel but on each side of the main tunnel.

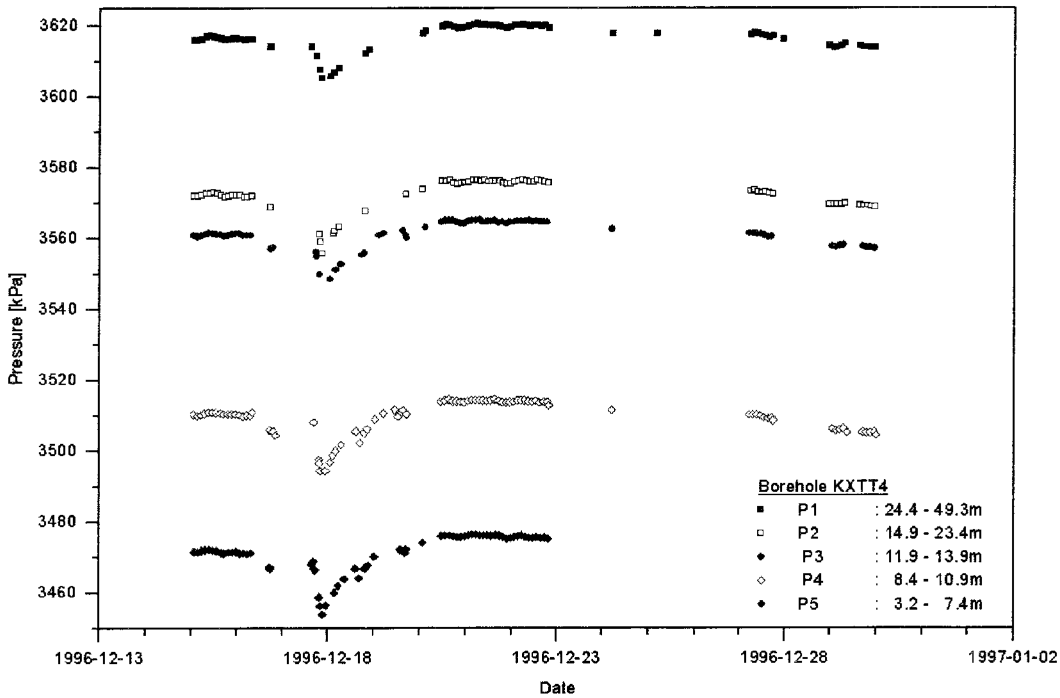


Figure 6-4. Groundwater head changes in different part of borehole KXTT4 due to blasting.

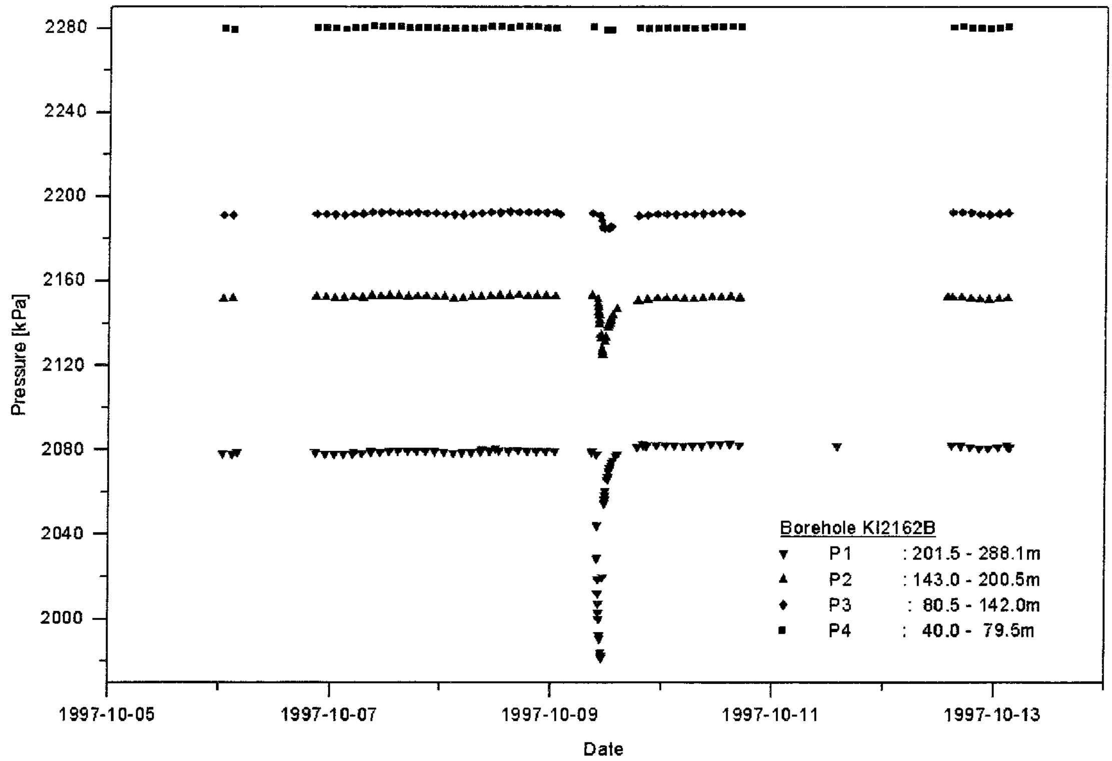


Figure 6-5. *Groundwater head changes in KA2162B due to hydraulic interference testing.*

III. The HMS measured head and salinity provided basic information on the influence of the tunnel drainage on the surrounding environment.

IV. It has been possible to characterize hydraulic features by means of hydraulic interference testing. An example is in Figure 6-5, which shows the response of different parts of borehole KA2162B when flowing KA2598A for one hour. The part of the borehole furthest away from the tunnel face displays the largest amplitude and successively smaller amplitudes the closer to the tunnel face. This type of information forms the basis for the understanding of the fracture/flow system in the rock.

The HMS data will continue to support the various scientific projects undertaken, providing basic data with a spatial and temporal coverage.

During 1998 the monitoring network will be extended with new boreholes drilled in the lower parts of the tunnel. These boreholes are associated with the experiments planned, which will be established and connected to the HMS. Specifically it is anticipated that the TRUE Block Scale project will contribute with 3–4 boreholes and the Prototype Repository project with some boreholes. Possibilities of including boreholes from the southeast part of the tunnel drilled at the lower levels will be investigated.

A review will be undertaken on the requirement and desire to extend the network with additional surface drilled boreholes in order to provide better spatial coverage. Depending on the outcome of the review additional boreholes might be included in the network. These will primarily monitor the groundwater head.

An investigation into the correlation between barometric pressure and the flow in the tunnel will be launched. It must be established whether this correlation is due to natural phenomena or induced by the instruments.

Over the years a large amount of data has been collected. This has been reported on an annual basis, as it also will be in the future. It is, however, planned that a detailed analysis will be undertaken covering the complete time period for which data has been collected with the purpose to put it in its hydrogeological context. As an integrated component of the analysis is the discrimination between intentional and unintentional disturbances, a compilation of works, incidents, accidents and breakdowns during the operation of the tunnel will be commissioned.

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: KAS10, HAS08, HAS20, HAV02, HLX04,

The following boreholes have been renovated HAS15, HAS16, HAS17, HAS18, KAS06, and KAS12.

The computers of the measurement system have been exchanged to PC:s. Also the software has been changed to the operative system Windows NT4.0, with the application software Orchestrator modified to included the measure software.

The new tracer experiment TRUE Block Scale has been instrumented and connected to the HMS.

The pressure reference system in the tunnel has been increased from 3,107m to 3,510 m.

The measurement equipment of PG5 has been moved to the TBM-tunnel (parallel to F-tunnel) to avoid future flooding.

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

6.5 Program for monitoring groundwater chemistry

6.5.1 Background

The groundwater chemical sampling and analyses started within the preconstruction 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 preconstruction 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 a 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.

6.5.2 Objectives

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

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

6.5.3 Results

Groundwater sampling was undertaken on two occasions, in March and October in 1997. In addition to the "monitoring samples" several samples for the different projects were collected. During 1997, the monitoring program has been extended to cover the lower parts of the tunnel. Within the monitoring program 24 sections in 22 boreholes (see Table 6-2) are sampled. Sampling and analyses are performed according to Chemistry Class no 4 and 5 as described in "Manual for Mobile Field Laboratory", SKB MD 431.011-01.

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	Only in October
KAS09	116–150 m	4	
KA1131B		4	Only in October, replaces SA1229A
KA1755A	88–160 m	4	Replaces KAS04
KA2050A		4	Only in October
KA2162B		4	Only in October
KA2511A	139–170 m	4	Only in October
KA2563A	187–196 m	4	Only in October
KI0025F	158–168 m	4	Only in October
KI0025F	86–88 m	4	Only in October
KXTT3	12.42–14.42	4	
KR0012B		4	
KR0013B		4	
KR0015B		4	
SA0813B		4	
SA1009B		4	
SA1229A		4	Only in March
SA1420A		4	
SA1730A		4	
SA2074A		4	
SA2273A		4	
SA2600A		4	
SA2783A		4	
SA2880A		4	
SA3045A		4	

The hydrogeochemistry monitoring program is continuously updated. Adjustments in the monitoring program might be requested from the Task #5 modelling groups.

7 International cooperation

7.1 Current international participation in the Äspö Hard Rock Laboratory

Nine organisations from eight countries are currently 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 Dechets 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.**
- Empresa Nacional de Residuos Radiactivos **ENRESA.**

In each case the cooperation is based on a separate agreement between SKB and the organisation 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 organisation. The ZEDEX project (see 3.2) and the TRUE Block Scale Experiments (see 4.3.3) are examples of such projects.

Specific technical groups so called Task Forces are another form of organising the international work. A Task Force on groundwater flow and solute transport in fractured rock is ongoing (see 4.8).

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

7.2.1 United Kingdom Nirex Limited

United Kingdom Nirex Limited (Nirex) has provided support from AEA Technology to the Äspö Task Force on Modelling Groundwater Flow and Transport, in respect of the

TRUE-1 experiment, and thereafter directly to TRUE-Block Scale Project. In addition Nirex has provided support from Golder Associates (UK) for the ZEDEX experiment.

Äspö Task Force on Modelling Groundwater flow and Transport, TRUE

Background

At the beginning of 1997 Nirex concluded its involvement in the Äspö Task Force on Modelling Groundwater Flow and Transport to refocus its effort on the TRUE-BS. The Task Force modelling work initially involved participating in a series of predictive exercises. The first of these exercises, Task 1, consisted of predictions associated with the LPT2 pump test. Task 3, the tunnel drawdown experiment consisted of predictions of the consequence of construction of the Äspö tunnel. These exercises were published in 1997 in the International Co-operation Report Series (Holton and Milicky, 1997 and Gustafson et l., 1997).

Results

As part of TRUE a series of sub-tasks was defined by the Äspö Task Force. Task 4B consisted of a series of scoping calculations for the first TRUE stage (Holton, 1997). The objective of this work was to assist in the design of the first tracer cycle, TRUE-1.

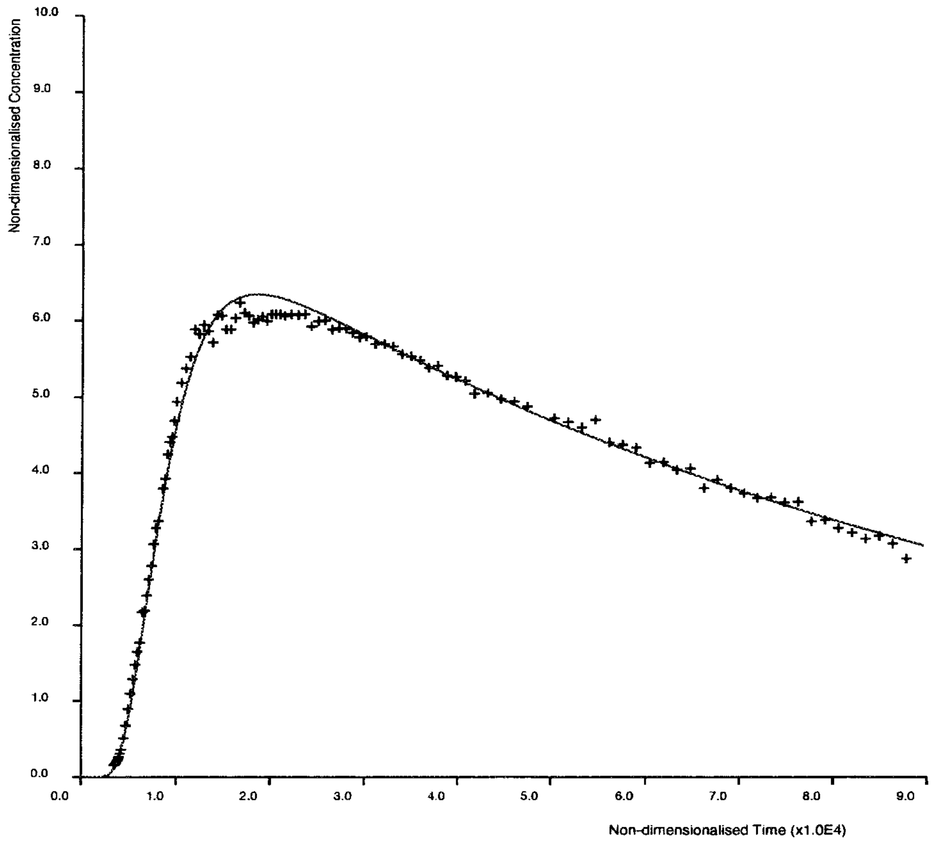


Figure 7-1. Breakthrough curve for the preliminary tracer test performed on Feature A at the TRUE-site. The crosses indicate the experimental results; the full red line indicates the best fit match using a semi-analytic model of a single fracture. This modelling has included the form of the tracer dilution in the injection borehole.

The principal focus of this work was to identify the possible adverse impact of a range of features on the main objectives of TRUE. The approach adopted for Task 4B used a semi-analytical technique to model radial groundwater flow in a single fracture. This work highlighted the importance of taking proper account of the form of the injected tracer pulse. By taking proper account of the injected source pulse a good match can be found to the breakthrough curve observed for the preliminary tracer test, performed at the TRUE-1 site, (Figure 7-1).

The final involvement in the Äspö Task Force involved participation in Task 4C, the predictive modelling of radially converging tracer tests. This used a variable aperture numerical approach, modelled using NAMMU, that included Taylor dispersion. Figure 7-2 (Holton et al. 1997) shows a typical stochastic aperture field with computed pathlines for 100 stochastically generated realisations. The predictions showed reasonable agreement with the results of TRUE-1. However, the work demonstrated the need to have a good understanding of the 'natural' flow conditions (i.e. flow conditions without pumping) and the source zone conditions (i.e. good characterization of how the tracer dilutes in the injection borehole).

TRUE-Block Scale

Results

The contributions made by Nirex in the latter part of 1997 have focused on providing technical and modelling support of the TRUE-Block Scale experiment. TRUE-Block Scale has a key objective of increasing understanding and the ability to predict tracer transport in a fracture network. So far this has involved making some initial estimations of the discrete fracture network parameters and implications for the TRUE-Block Scale, using NAPSAC (Hartley et al. 1996). The conclusions of this work are still at a preliminary stage. In addition, some 3-D modelling has been performed to try to understand the disturbances (drawdown) observed during the drilling of boreholes at the TRUE-Block Scale Site. Three-dimensional visualisation of the responses and a structural model of the site have been used to help understand how these responses fit together.

Early in 1998 the supporting modelling work will focus on preparing for the interference testing, planned for May 1998. It is anticipated that Nirex will continue to contribute to the analysis and predictions of tracer testing in fracture networks as part of the TRUE-Block Scale. This contribution will make use of the programs and modelling capability developed by Nirex to address flow and transport in fracture networks.

ZEDEX

Background

The ZEDEX Project, performed at a depth of the order of 420 metres below ground level, has continued during 1997 with the compilation of a report providing an integrated interpretation of the excavation affected zones around the drifts. Whilst the experimental programme was completed on schedule in July 1996 the data analysis has continued into 1997.

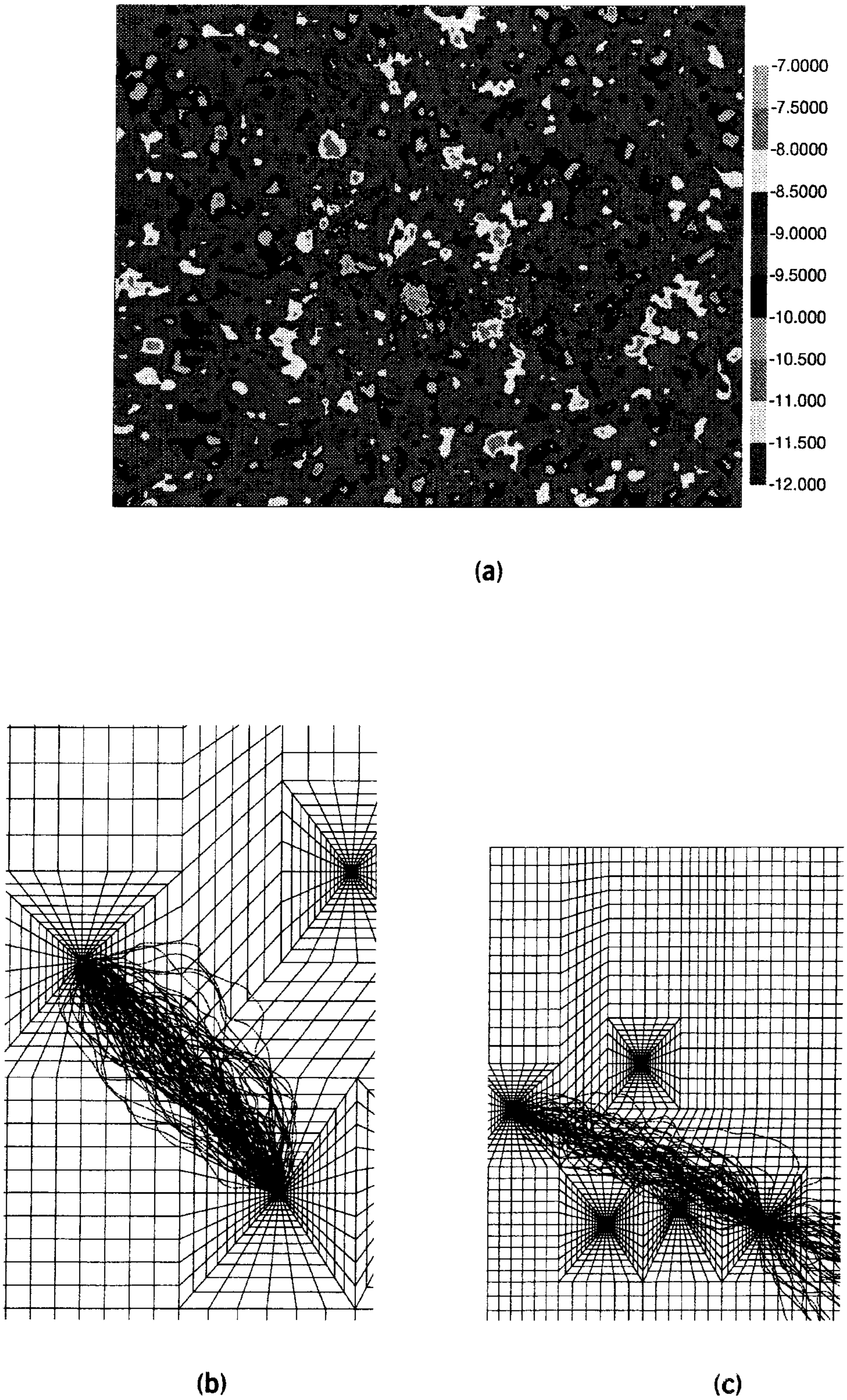


Figure 7-2. (a) Filled contoured aperture distribution for a realisation. (b) Pathline calculations for release from KXTT1 for 100 realisations. (c) Pathline calculations for release from KA3005A for 100 realisations.

Results

During the compilation of the final report it was noted that some discrepancies existed relating to the earlier analysis and interpretation of the hydraulic data acquired from the short radial boreholes drilled in the drift walls after excavation. At the time the earlier analysis was produced (SKB 96-03) it was recognised that the hydrogeological data from the A and C boreholes, drilled around the positions of the drifts were not well understood. Both data sets, from the short radial boreholes and the A and C boreholes, have been re-analysed during 1996–97. The data from the short radial boreholes were re-analysed by Colenco and the data from the A and C boreholes were re-analysed by Golder Associates. Integration of both datasets was undertaken by NAGRA.

At the design and planning stages for the ZEDEX project, the working hypothesis established was that in the near-field 'damage' zone (defined as distances of less than 2.0 metres) disturbance could be reduced by the application of an appropriate excavation method. The hypothesis also predicted that the far-field disturbance (defined as distances greater than 2.0 metres) would be essentially independent of excavation method, as it would be caused by stress redistribution, influenced by discontinuity geometry and the mechanical properties of the rock mass.

The results from the project, whilst generally supporting this, showed that the division into a near field and far field is not appropriate. A more appropriate division recognises a damaged zone closest to the drift wall dominated by changes in rock properties which are mainly irreversible and a disturbed zone, beyond the damaged zone, dominated by changes in stress state and hydraulic head, where changes in rock properties are small and mainly reversible and where there are no or insignificant material property changes.

7.2.2 ENRESA

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 back analysis 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 equalisation ratio of the water pressure depends mainly on the combined non-dimensional variable μT where:

$$\mu T = \frac{Fkt}{f\gamma}$$

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

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

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:

$$F = 4\pi(0.345L)$$

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, m. 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:

$$f = \frac{1}{\mu T}\frac{Fkt}{\gamma_w}$$

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 100mm and the permeability of the backfill 10^{-13} m/s (typical of a bentonite). A value of μT equal to 2 ensures an equalisation 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:

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

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 equalisation 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 m 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 m 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, two water tanks of 10 and 100 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 and development 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 7-3 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

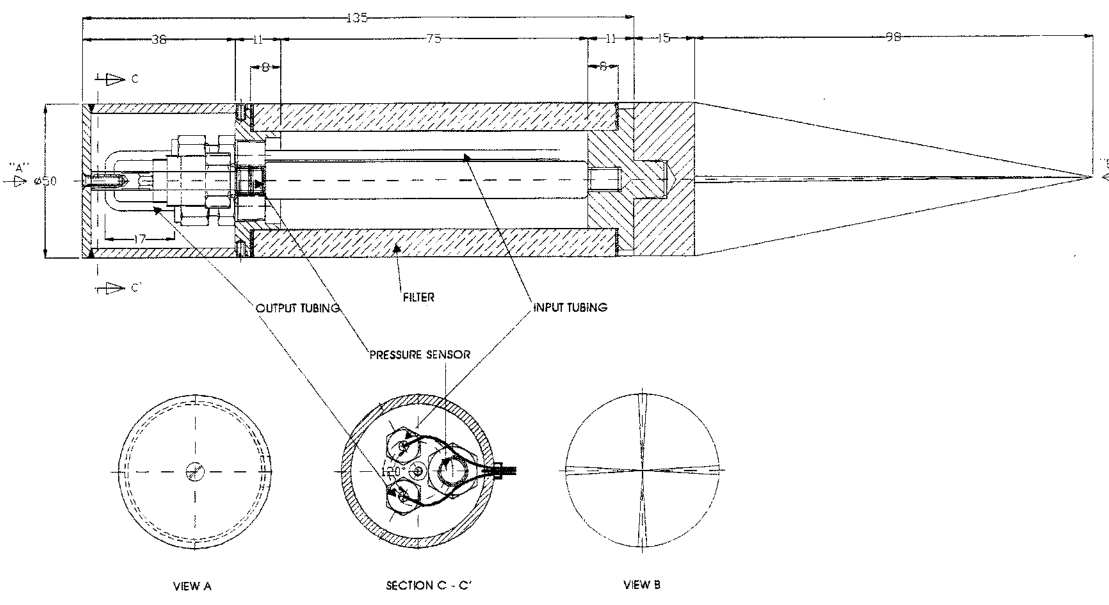


Figure 7-3. DPP sensor.

of the permeability to be measured may be very wide (from 10^{-8} to 10^{-11} m/s), the system has been designed so that the internal volume of the measuring circuit may be easily modified. Also the possibility of measuring the volume (flow) of water transfer to the backfill during the pulse test has been included in the system design, for the case of very permeable media.

Additional equipment and system description

The complete system comprises a number of DPP sensors (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 7-4. 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.

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.

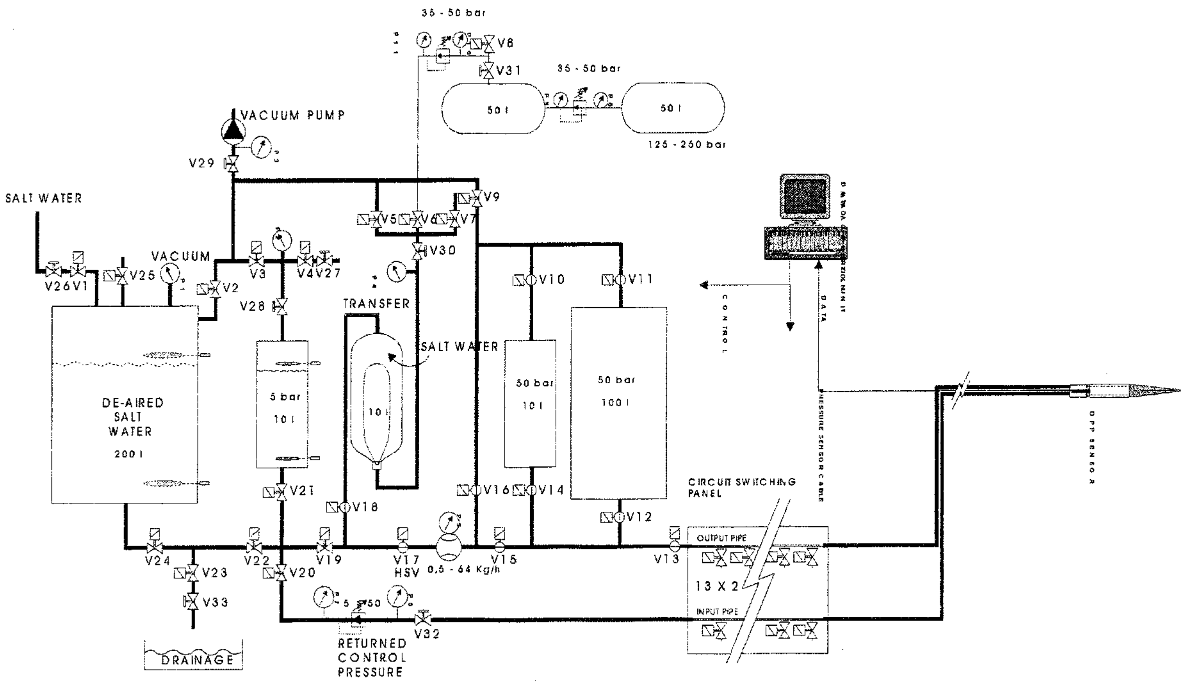


Figure 7-4. Dynamic pore pressure measuring system.

2. A **secondary** circuit, which may use compressed air, 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 de-airing unit for the Äspö salt water to be used in the primary circuits.
- A compressed air unit (air pump), to generate the positive pressure.
- A vacuum pump, to remove air from the primary circuits.
- Auxiliary solenoid valves.
- High speed solenoid "valves, to control pulse generation.
- 2 auxiliary tanks of 10 and 100 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 50 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 7-4). 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

Once the backfill is saturated, the three main tanks are prepared in the following way:

- The return tank is almost empty of water, in a vacuum atmosphere.
- The transfer is full of de-aired salt water and with the pumping balloon deflated.

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 balloon by means of the air pump, and 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. 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 5 bars will be applied to the balloon by means of the air pump, 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 pump tank 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.

Field installation

The total number of sensors is to be determined and the measuring points should be placed within one of the 30/70 backfill sections.

To reduce mechanical damage to the DPP sensors, these will be installed in position after the corresponding 20 cm thick layer has been compacted. Given the composition of the backfill, it may be very difficult to drill or excavate a well-formed hole for DPP sensor insertion after layer compaction. On the other hand, a good contact between the DPP sensor filter and the backfill material is necessary. Based upon all these requirements, the following installation procedure is foreseen (see Figure 7-5):

- STEP 1: Normal compaction of the layer preceding the one in which the measurement is to be accomplished.
- STEP 2: Dummy metal pieces of the same dimensions as the DPP sensors are inserted in the preceding layer at the desired measuring points.
- STEP 3: The measuring layer is compacted with the dummies in place *(NOTE: This operation has to be tested in advance to identify potential practical problems)*.
- STEP 4: Once layer compaction is completed, DPP dummies are extracted using a special tool (only the main body is extracted, the pick remains in place).
- STEP 5: The DPP sensors are introduced in the holes left by the dummies.
- STEP 6: For each DPP sensor, a small slot is excavated in the compacted surface to lay the corresponding tubes and cable and take them to the general tubes & cables conduit.
- STEP 7: The other end of the tubes and cable is connected to the hydraulic/electric control system placed outside the test area.

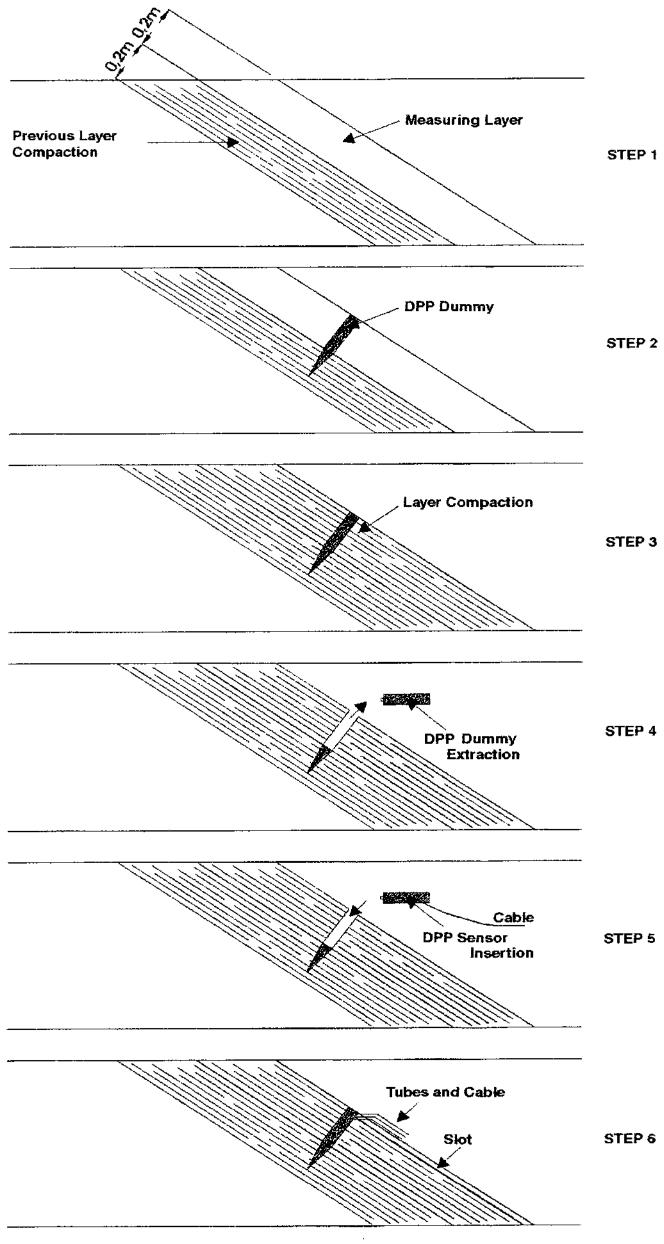


***Figure** 7-5. DPP sensors installation.*

Laboratory calibration

Before installing the sensor in the backfill, laboratory calibrations will be performed, in order to check the correct behaviour of the transducer. To this end, a calibration cell is going to be built early in 1998. A preliminary scheme of this cell is presented in Figure 7-6.

The dummy metal cylinder will be installed before compacting the mixture material in the cell. This is to avoid damage to the actual sensor. The final soil density will be similar to that expected in the field, and compaction energy will be adopted accordingly. After soil compaction, the dummy cylinder will be replaced by the sensor, following a similar procedure as the one described in Figure 7-5, for field installation.

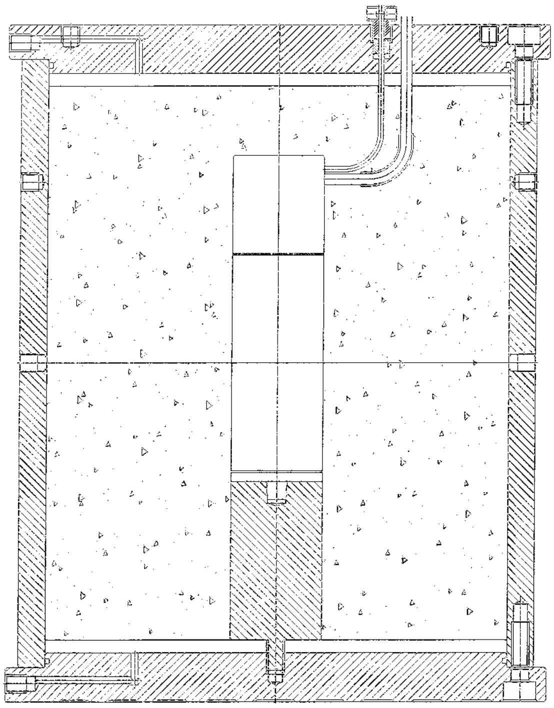


Figure 7-6. Scheme of the calibration cell for the DPP sensor.

Soil saturation can be achieved in the cell by flushing water from its top and bottom, and also from the lateral boundary. This is to assure a short time for hydration, before applying a pulse pore water pressure to the sensor. A global constant head test, producing a water flow between bottom and top boundaries may also be performed. In this way, an independent measurement of the permeability is obtained. Therefore a comparison with both permeability measurements provides a good test for checking and calibrating the sensor. Also, in order to check the suitability of the equipment, some simulations of this test using the computer code described in next paragraph are going to be performed.

Modelling hydration and flow processes in a selected zone

Scoping calculations

The modelling work to be performed by ENRESA refers to a particular slice where the sensors described before are to 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.

The problem to be analysed 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 hydromechanical analysis is necessary. The computations are being carried out using the computer code

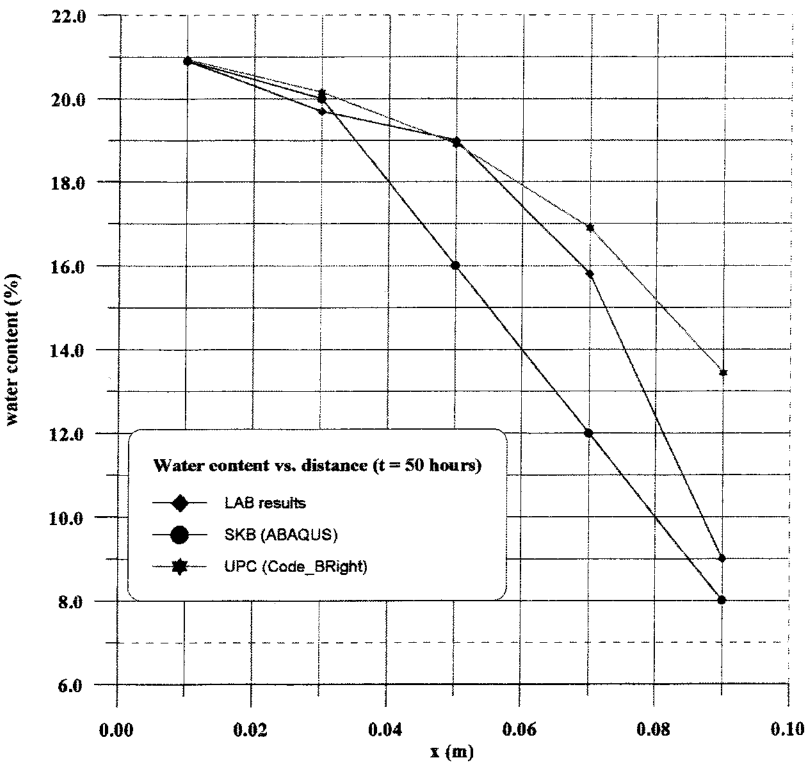


Figure 7-7. Results from ABAQUS (CT) and Code_BRight (UPC) compared with laboratory results (water content vs distance at 50 hours, Case A).

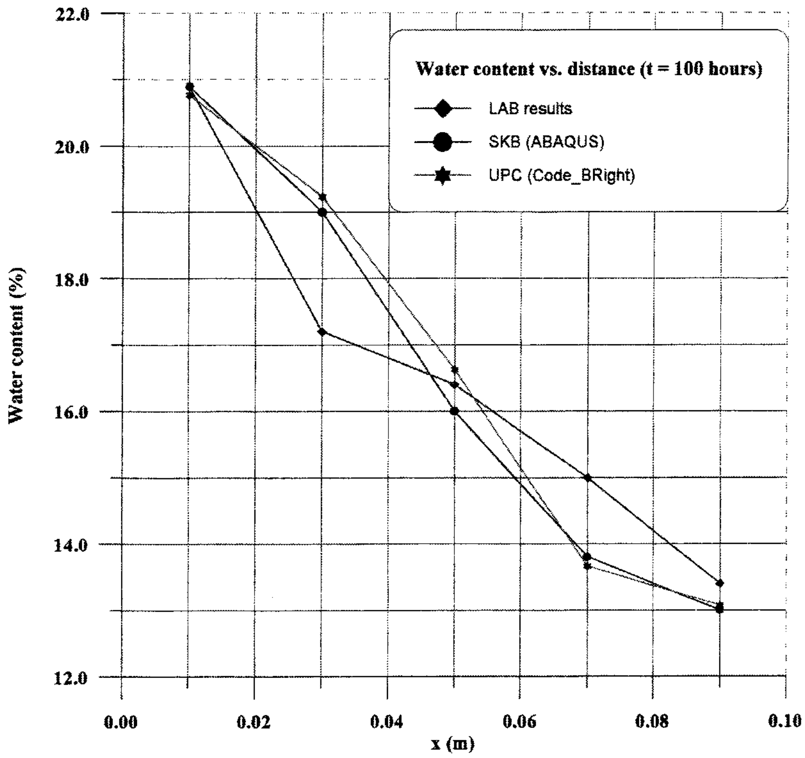


Figure 7-8. Results from ABAQUS (SKB) and Code_BRight (UPC) compared with laboratory results (water content vs distance at 100 hours, Case B).

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. The mechanical behaviour is modelled by an elasto-plastic constitutive model that considers explicitly the effect of deformations due to saturation. Because CODE-BRIGHT is an "in house" development, additional modelling requirements may be accommodated. During 1997, modelling work has been devoted to definition of the problem, to the comparison of codes used by ENRESA and SKB and to the mesh generation work. Some scoping calculations have also been performed.

In order to compare the codes used by SKB (code ABAQUS used by CT) and by ENRESA (CODE_BRIGHT from UPC), a simple case was selected. 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. The test was repeated using two different initial water contents (6.3% – Case A- and 13% – case B-) and a 30/70 backfill mixture. These experiments were used by Clay Technology to obtain tentative parameters for that soil, in particular, saturated permeability, K_{sat}, and "n" in $K_{unsat} = K_{sat} (S_r)^n$ where K_{unsat} is the unsaturated permeability and S_r is the degree of saturation. Other input data, such as the water retention curve and coundary conditions, were provided by Clay Technology to reproduce the experiment using CODE_BRIGHT. The objective of the comparison was not to check code performances, but imply to establish a common framework in order to compare results in the future, when reproducing the full test.

Figures 7-7 and 7-8 present a comparison between experimental data and simulations by CT and UPC using their respective codes. It should be pointed out that a few combinations of parameters give similar results, but for comparison two different sets have been used for each case (A and B), corresponding to CT and UPC approaches.

These sets are the following:

		K_{sat} *(m/s)*	*n*
Case A.	CT parameters	$2. 10^{-10}$	10
	UPC parameters	$3.9\ 10^{-10}$	10
Case B.	CT parameters	$5. 10^{-11}$	10
	UPC parameters	$3.9\ 10^{-11}$	10

Note that, although the material is the same in both cases (only the initial water content is different), the permeabilities obtained are different. Further simulations and comparisons with experimental data are thus required, in order to achieve a reasonable calibration of parameters.

Figure 7-9 presents the basic geometry of the slice used in the scoping calculations performed during 1997. This geometry corresponds to a previous stage in which the final configuration of the test was not totally defined. It includes the backfill as homogeneous material, the EDZ and the surrounding rock. Only the tunnel area is presented in 2D. Plane strain conditions were adopted in these initial simulations.

The analyses presented in this report refer to the saturation phase. In this case one of the purposes of the simulation is to estimate the time required to reach saturation under different initial and boundary conditions. To cope with that, the conditions assumed in

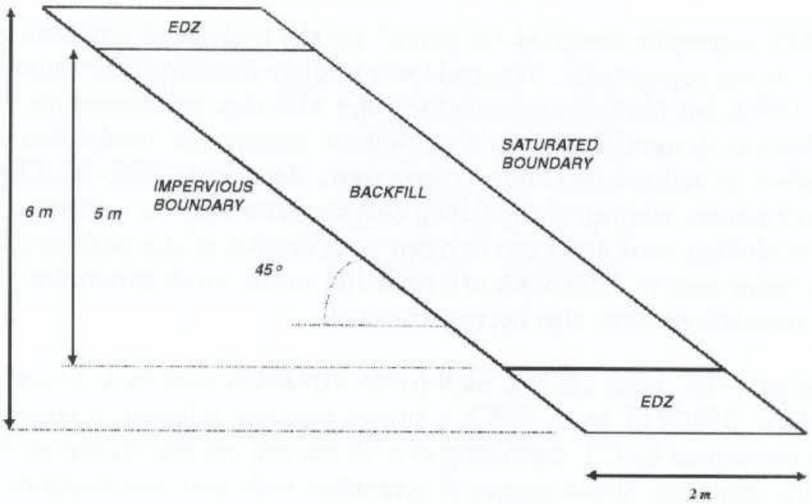


Figure 7-9. Basic geometry used in the analyses (distance in meters).

cases A and B have been applied to that geometry. The slice is considered to be impervious on the left side and saturated (zero pore water pressure) on the right side. A value of zero pore water pressure has also been applied to the surrounding rock as an initial condition.

Figures 7-10 and 7-11 show the contours of degree of saturation for two different times for case A. The evolution of the saturation front is clearly shown. Figures 7-12 and 7-13 present the same situation for case B, which corresponds to an initially wetter material. Both analyses presented here have been performed using the parameters obtained by UPC in the calibration presented above. Figures 7-14 and 7-15 show the variation of the degree of saturation on the tunnel axis for different times, for both cases, A and B. In this way, a better representation of the evolution of the saturation front is obtained.

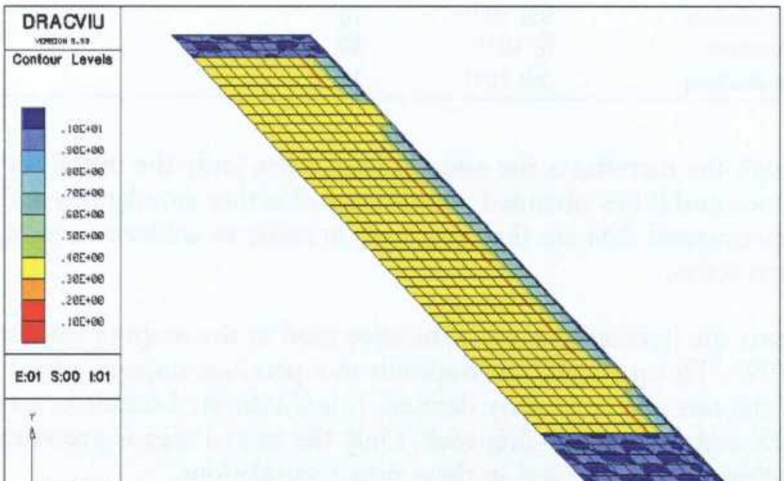


Figure 7-10. Contours of degree of saturation at t = 0 days in the backfill and EDZ zones (Case A, UPC parameters).

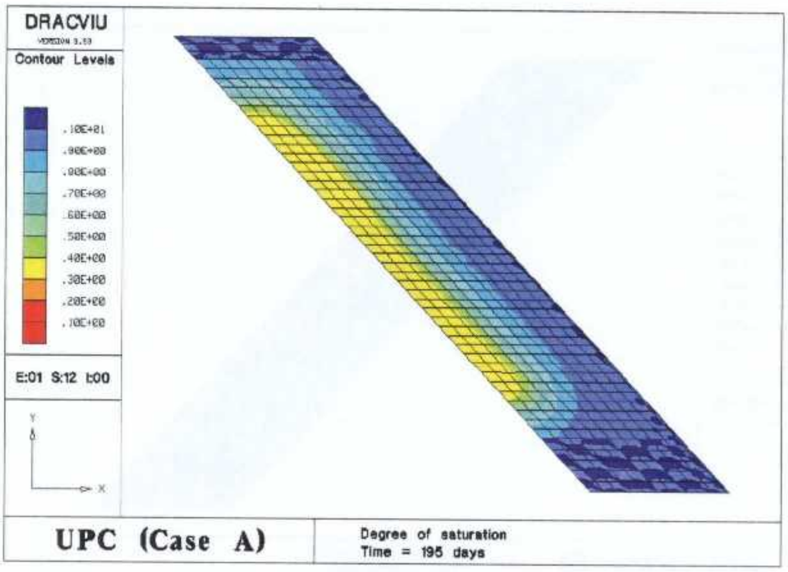


Figure 7-11. Contours of degree of saturation at 195 days in the backfill and EDZ zones (Case A, UPC parameters).

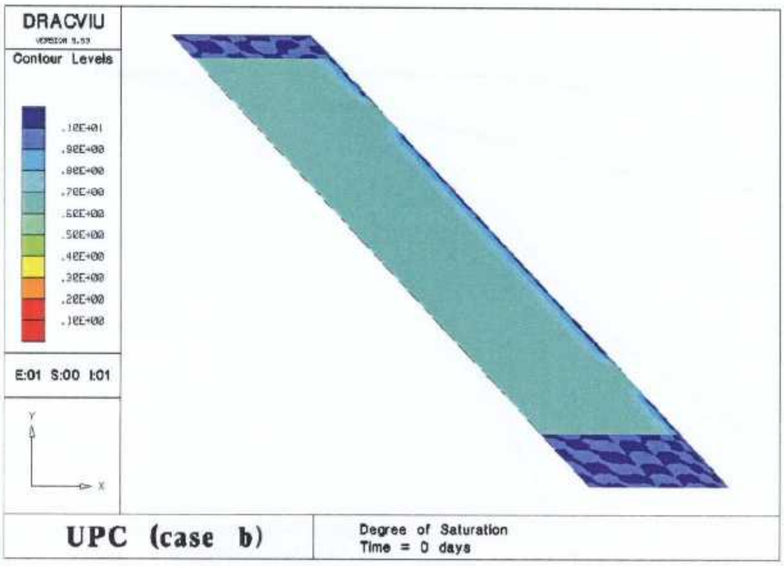


Figure 7-12. Contours of degree of saturation at t = 0 days in the backfill and EDZ zones (Case B, UPC parameters).

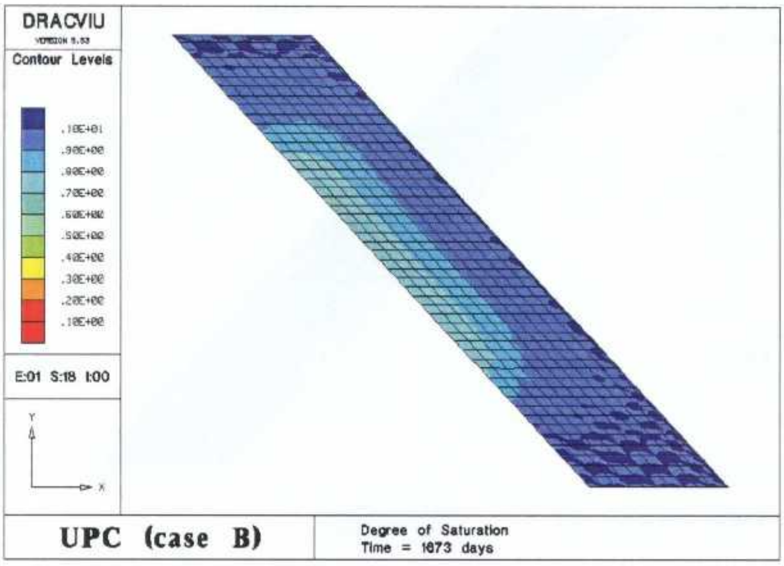


Figure 7-13. *Contours of degree of saturation at 1,673 days in the backfill and EDZ zones (Case B, UPC parameters).*

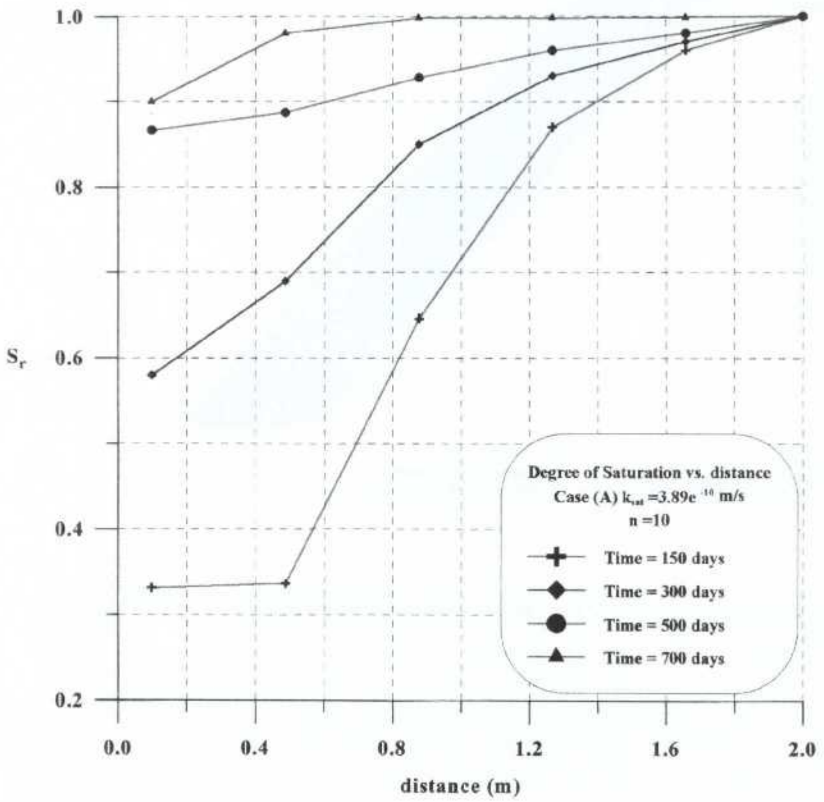


Figure 7-14. *Degree of saturation vs distance for different times (Case A, UPC parameters). Distance 0.0 m corresponds to impervious boundary, and distance 2.0 m corresponds to saturated boundary.*

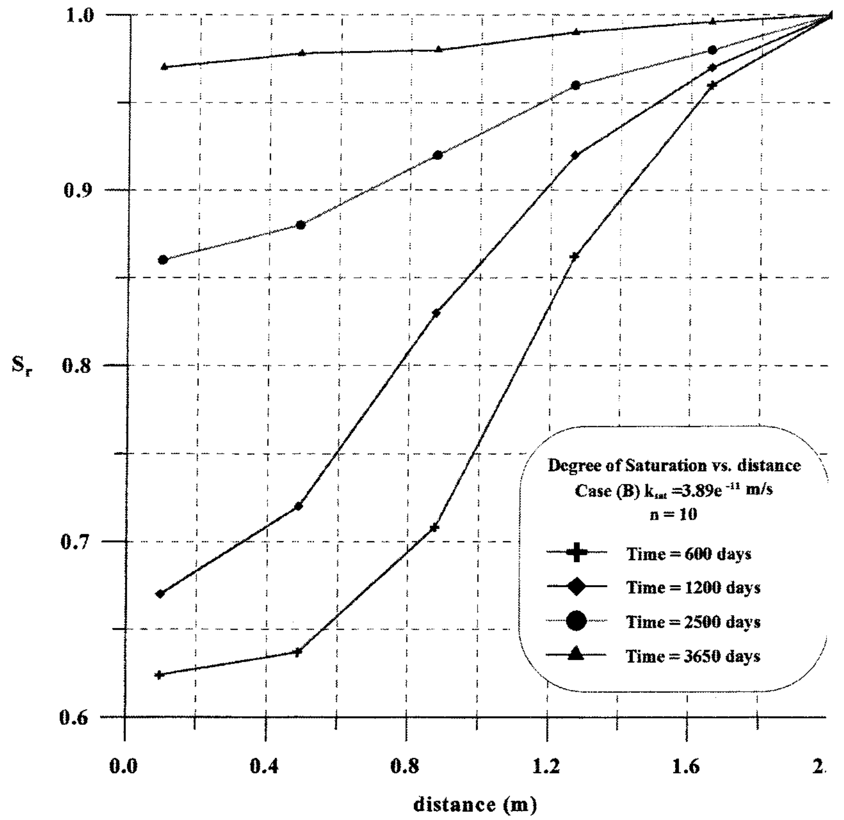


Figure 7-15. *Degree of saturation vs distance for different times (Case B, UPC parameters). Distance 0.0 m corresponds to impervious boundary, and distance.*

These results make it possible to estimate the time required to reach saturation. As the actual test layout remains to be defined, the final scoping calculations will be presented in future reports. Thus the values presented here are simply estimations and correspond to a selection of the cases considered. Here, t_0 refers to the time required to reach 95% of saturation in all nodes of backfill, and t_1 is the time required to reach 99%.

	Case A (w = 6.3%)		Case B (w = 13%)	
	t_0 (years)	t_1 (years)	t_0 (years)	t_1 (years)
CT parameters	3.12	3.67	7.05	8.70
UPC parameters	1.86	2.41	9.51	11.16

The estimations obtained using CT parameters are consistent with the values obtained by CT using the ABAQUS computer code. Some differences between their values and those presented here may correspond, apart from the numerical differences of the code itself, to the way the water retention curve is introduced in the analysis: numerically in ABAQUS and using a mathematical interpolation in CODE_BRIGHT. In spite of the differences, the results obtained are similar and define a common framework in which future comparisons may be made. In particular, more definite scoping calculations when the test is totally defined will be performed, and will be interpreted and compared in detail.

8 Other matters

8.1 Quality assurance

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

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

The overall guiding document for issues relating to management, quality and environment is SKB-HLK (SKB's Handbook for Management and Quality Assurance). A reworking of the SKB quality assurance handbook was undertaken during 1997.

Subject specific manuals, such as economy and personnel administration were finalised. It remains to draft manuals on purchasing and tendering procedures, information technology, project administration environmental issues, registry and information.

All activities of any significance for Äspö HRL shall be documented and archived so that full traceability is achieved and stored safely. A new register for the Äspö HRL was developed emphasising the project management of documents.

The Äspö Handbook cover issues of decision-making, procedural instructions, manuals etc to guide the work as pertaining to quality assurance and environmental issues at the Äspö HRL and to ensure that the operations are covered by the criteria specified in SKB-HLK. A new version of the Äspö Handbook was compiled containing instructions on management and quality assurance for the work undertaken at the Äspö HRL. The Handbook is complemented with instructions available on SKB's intranet.

A new software application for time and resource management in running under MS Project Plan called HRL Plan was customised for project tracking at the Äspö HRL. Project managers are obliged to utilise this software and established routines of reporting to the Äspö HRL management.

During the autumn of 1997 an internal audit was undertaken at the Äspö HRL with regard to procedures relating to safety, health and environment. In spite of some remarks from the auditors the overall impression was good. The Äspö HRL has good prospects, plans and well motivated staff in order to achieve a smooth and functional work in the fields of safety, health and environment.

Additionally, an internal audit was conducted within SKB with regard to purchasing and tendering. Among other things it was noted that the tendering and purchase of larger project are done well. However, the purchase of smaller and medium sized projects are sometimes done with lacking competition. The auditors are also identified a need for further training in the field of purchasing.

SKB is investigating the prerequisites to become certified according to the ISO 9000 and ISO 14001 standards. Furthermore criteria has been proposed for classification of service providers. Providers shall comply with SKB's quality and environmental requirements.

The quality assurance system for the projects shall be improved and become more efficient.

8.2 Public relations and information activities

The task of the information group at Äspö HRL is to provide information to visiting groups about SKB, the Swedish System and the Äspö Hard Rock Laboratory. An average visit takes around two hours and contains introduction and information in a conference room, followed by an underground visit.

The Äspö Day, an open house held in the middle of May, was held traditionally and some 700 visitors took the opportunity to visit the facility. About 400 of these were taken underground to visit the tunnel.

The summer tours for tourists and the general public started the June 30th and went on until August 1st, 1997. It was a co-operation between SKB/Äspö HRL, OKG and Figeholms Taxi. During the five weeks there were 30 groups and 396 visitors visiting the underground facility.

During the year some 5,000 visitors were brought underground. Many of the visits came from abroad, mainly technical staff and/or politicians.

In addition, OKG has brought visitors to the Visitor's Niche located 115 m from the tunnel entrance.

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