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Äspö Hard Rock Laboratory
Annual Report 1996

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ÄSPÖ HARD ROCK LABORATORY

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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.

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 construction of the Äspö Hard Rock Laboratory was finished in 1995. To mark this important milestone in the history of the Äspö Hard Rock Laboratory SKB organized "Äspö 96" as a combined 10-year anniversary and inauguration of the Äspö Hard Rock Laboratory facilities.

The objective of the ZEDEX project is to compare the mechanical disturbance to the rock for excavation by tunnel boring and blasting. 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, which is the hydraulically significant part, 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. During 1996 a series of tracer experiments in radially converging and dipole flow configuration have been performed. These tests have been subject to blind predictions by the Äspö Task Force on groundwater flow and transports of solutes.

A special borehole probe, CHEMLAB, has been designed for different kinds of retention experiments where data can be obtained representative for the in situ properties of groundwater at repository depth. The probe has been delivered and the first tests performed at Äspö.

The Prototype Repository Test is focused on testing and demonstrating repository system function. The Backfill and Plug Test includes tests of backfill materials and emplacement methods and a test of a full scale plug. Planning and preparations for these experiments has continued during 1996. Demonstration of methods for deposition and retrieval of canisters will be made in a new tunnel at the 420 m level.

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 tests holes have been instrumented and the temperature raised to 90 and 130°C, respectively.

Eight organizations from seven 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 1996 ger en översikt av genomförda arbeten och erhållna resultat.

Geovetenskapliga undersökningar på Äspö och närliggande öar påbörjades 1986. Sedan dess har berggrunden undersökts med flera djupa borrhål, omfattande bergarbeten genomförts, en forskarby byggts och parallellt med byggnadsfasen har ett intensivt forskningsarbete pågått. Detta har resulterat i en heltäckande prövning av olika metoder för att undersöka och utvärdera berget inför byggandet av ett djupförvar. Byggandet av Äspölaboratoriet slutfördes i början av 1995. För att markera den viktiga milstolpe som nåtts organiserades "Äspö '96" som ett kombinerat 10-årsjubileum och invigning av Äspölaboratoriet.

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. Under 1996 har en serie spårförsök genomförts, både i radiellt konvergerande och dipolkonfiguration. 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 har levererats till Äspölaboratoriet och de första försöken har genomförts.

Prototypförvaret syftar till att prova och demonstrera den integrerade funktionen hos djupförvarets olika barriärer. Backfill and Plug Test innefattar prov av olika återfyllnadsmaterial och packningsmetoder samt prov av en tunnelplugg i full skala. Planering och förberedelser för dessa experiment har fortsatt under 1996. Demonstration av slutförvarsteknik innefattar prov av deponering och återtag av kapslar. Dessa försök kommer att genomföras i en ny tunnel på 420 m nivån.

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 har fyllts med bentonit och instrumenterats. Temperaturen i hålen har höjts till 90 respektive 130°C.

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

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 construction of the Äspö Hard Rock Laboratory was finished in 1995. To mark this important milestone in the history of the Äspö Hard Rock Laboratory SKB organized "Äspö 96" as a combined 10-year anniversary and inauguration of the Äspö Hard Rock Laboratory facilities. Äspö 96 was attended by about 140 distinguished guests. The Second Äspö International Seminar was held the following day in Stockholm. At the seminar, which was open to interested scientists, the results from the ten years of research at Äspö and the planned work at Äspö HRL was presented and discussed. The seminar was attended by about 120 scientists.

Work on the final reports for this Stage Goal is in progress. There will be 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 will be a report presenting the current model of Äspö based on investigations performed to date. The reports have been reviewed and are currently being updated before they will be submitted for a final review.

Regional and site scale three-dimensional groundwater flow models have been produced for Äspö. The model takes density variations due to varying salinity into account and makes use of a novel algorithm for treating the unsaturated zone. The new algorithm has provided realistic numbers for groundwater recharge. The regional model is used to compute the boundary conditions for the site model.

Stage Goal 2 – Finalize 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 is 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 are also provided by BMBF and Nagra.

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 were completed and reported in 1995. The analysis of results obtained 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, project parties agreed on an extension of the ZEDEX Project including additional data collection, thorough analysis of available data and predictive modeling efforts.

The experiment has been 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 hypothesis set out at the start of the ZEDEX Project was that near-field disturbance (at distance of less than 2 m from the drift wall) could be reduced by the application of an appropriate excavation methods and that far-field disturbance would be independent of the excavation method. The results from the ZEDEX Project show that a division in near-field and far-field is not appropriate. Based on ZEDEX results the following division has been found more appropriate:

- there is a **damaged zone** closest to the drift wall dominated by changes in rock properties which are mainly irreversible and
- there is **disturbed zone** outside the damaged zone dominated by changes in stress state and hydraulic head and where changes in rock properties are small and mainly reversible.

There is of course a gradational change in rock properties and rock stress with distance from the rock wall and there is hence no distinct boundary between the two zones.

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, which is the hydraulically significant part, can be limited through application of appropriate excavation methods. A limited extent of the damaged zone should also make it 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 realization phase of the project started in March 96 and is still in progress. The system will be put into use during spring 97.

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. Detailed characterization has been made of 88 water-conducting fractures that intersect the main access tunnel. 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 and lithified cataclastic shear-zones.

The only striking difference between individual water-conducting features is the internal fault geometry. No other distinguishing criteria (such as lithologic domains, mineralogy of fracture infills, transmissivity etc.) were identified. On the basis of the geometric arrangement of master faults and splay cracks five types of water-conducting features could be distinguished. Both 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 of the same type is in the range of meters to many decameters. The application of the classification scheme is limited to small-scale considerations. For large scale transport, the results indicate that due to a common genetic history, water flow in the underground of Äspö is dominated by one single family of water-conducting features.

A permit to use short-lived radioactive nuclides for the TRUE, Radionuclide retention, and Long Term Tests of Buffer Material experiments has been obtained from the Swedish Radiation Protection Institute (SSI).

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 modeling 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 modeling 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.

During 1996 a series of tracer experiments in radially converging (RC-1) and dipole flow configuration (DP1-DP4) have been performed in the feature selected for testing, Feature A, using conservative fluorescent tracers and metal complexes. These tests have also been subject to blind predictions by the Äspö Task Force. Further, a set of complementary tests have been performed with the objective of providing final support for the planned tests with sorbing tracers.

The radially converging tracer test (RC-1) was initiated in mid January 1996 using a steady flow of 0.2 l/min from a section in borehole KXTT3 where it intersects feature A. Tracer injections were performed in the four surrounding boreholes where they intersected the same feature. The experiment showed breakthrough from the two injection sections in KXTT1 and KXTT4 with mass recoveries of 91 and 97%, respectively. The breakthroughs show little or no effects of processes, i.e. the breakthroughs are simply translations in time of the injection signal. No breakthrough was observed from the remaining two injection sections in KXTT2 and KA3005A, which are located farthest away from the pump hole. A subsequent stepwise increase in the pump flow to 400ml/min and finally 3.4 l/min, enabled breakthrough from the remaining two injection sections, but with very low mass recoveries. A preliminary comparison between model predictions made by the Äspö Task Force and experimental results, shows that most modeling 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 breakthrough. The breakthrough times predicted by the modeling teams are also in accord with those observed in the experimental results.

An experimental plan for the planned tests with sorbing tracers have been prepared. The basic idea is to perform a series of three tracer tests with one truly non-sorbing tracer (tritiated water), and a selection of weakly sorbing (Na, Ca, Sr) and moderately sorbing tracers (Rb, Ba, Cs). The tests will tentatively be performed in a radially converging flow field at Q=400, 200 and 100 ml/min. The test geometry is KXTT1->KXTT3 or KXTT4->KXTT3. During late March and April 1997, site preparations and pre-tests will be carried out. The tests with sorbing tracers are scheduled to start in May and will continue for a duration of three to four months.

The objective of the Resin technology development is to establish a technique by which a description of the pore space of a feature investigated with tracer tests can be mapped by epoxy resin injected into the feature. 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.

At the Pilot Resin site a test of injection techniques and equipment and resins is carried out in-situ in a fracture system close to the drift wall. Site characterization work has been carried out at the site. During August-September 1996 a series of three resin injections were performed. The injection sequence started with injection of dye-labeled water in a given section with all other holes closed. The purpose of the dye was to tag the flow paths participating in groundwater flow, this to enable comparison between the porosity impregnated by the resin. Subsequently, dye-labeled isopropyl alcohol was injected to ensure good wettability and avoidance of fingering effects. Finally injection of dye-labeled resin was performed. The injection periods lasted between 5-7 hours with injection pressures kept between 30-55 bars. Simplistic calculations predict the areal spread of the resin to be in the order of square meter(-s). Subsequent to the injections, ten short 56 mm boreholes have been drilled with the aim of obtaining a picture of the areal spread of resin. More than 50% of the drilled exploratory holes carried resin. Then three 200 mm cores were drilled parallel to three of the exploratory holes. There were problems obtaining intact core samples and a refined drilling technique using a smaller diameter had to be developed.

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. The total duration of the project is approximately four years from the start in July 1996.

During the spring of 96 a structural-hydraulic model of the experimental level and a data set for scoping calculations were compiled. Alternative locations of the target block were considered based on the developed model. A pilot borehole, KA2563A, has been drilled to investigate the properties of the selected experimental volume in the southwestern corner of the laboratory, south of the TBM tunnel. The borehole intersected two water bearing features which produced significant water inflows to the boreholes. The rock volume beyond these features contained no major water bearing features and the rock volume was considered suitable for the planned experiment. Cross-hole seismic measurements and flow logging has been performed to further characterize the block.

The REX project focuses on the reduction of oxygen in a repository after closure due to reactions with rock minerals and microbial activity. A field experiment will be performed where the consumption of oxygen in contact with a fracture surface will be studied. The field study is supported by laboratory experiments to determine oxygen reaction mechanisms and kinetics. Laboratory measurements are in progress and preparation have been made for the field experiment which will start in 1997. Preliminary measurements of dissolved methane and hydrogen in Äspö groundwaters have been performed. They have been combined with the measurements of bacteriological oxygen consumption in Äspö groundwaters. These results show that oxygen may be consumed by methanotrophic bacteria in a closed nuclear waste repository.

Most radionuclides have a strong affinity for adhering to different surfaces, i.e. a high K_d value. Numerical values that can be used in the safety assessments have been arrived at via laboratory measurements. However, it is difficult in the laboratory to simulate the natural groundwater conditions in the rock when it comes to redox status and concentrations of colloids, dissolved gases and organic matter. A special borehole probe, CHEMLAB, has been designed for different kinds of retention 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 construction of the CHEMLAB probe is completed and the probe was delivered to Äspö HRL in April 1996. An inactive test was performed to simulate a typical experiment and get experience on how to operate the probe. Some equipment problems were identified and modifications were subsequently made to the probe. The first experiment with radioactive isotopes was diffusion of ^{131}I and ^{57}Co in bentonite. The experiment started in November but had to be terminated early because a sensor indicated a too high pressure in a flow line. The pumps were automatically stopped. The CHEMLAB probe had to be taken out of the borehole and sent to the manufacturer for service.

The project Degassing of groundwater and two phase flow has been 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.

A degassing and two-phase flow test was conducted at the TRUE resin site. The objectives of the pilot injection-withdrawal tests with gas saturated water were to investigate whether degassing effects can be observed in borehole tests at higher gas contents and lower fracture transmissivities than the gas content and transmissivity of the previously performed pilot test. In the test water with a gas contents of about 17% was injected into the fracture. A flow reduction of 50% was observed when the pressure in the withdrawal hole was reduced to atmospheric. Degassing is considered to be the most likely explanation for this behavior.

Modeling work has shown that degassing effects are limited to a low-pressure zone which has an extent on the order of centimeters for boreholes and on the order of meters for drifts. Trapping of gas bubbles in fractures is strongly dependent on fracture roughness. The analysis indicates that bubbles of up to one centimeter length may be trapped at gradients as high as 10^4, implying that for boreholes and drifts, bubbles may get trapped throughout the low-pressure zone, provided that the extent of this zone is sufficiently large.

Laboratory test on 200 mm diameter core samples showed significant reductions in fracture transmissivity, up to 90%, when a separate gas phase was introduced into the fracture plane. Fracture planes with relatively smooth and tabular apertures recovered their original fracture transmissivities fairly quickly, while the fracture planes that were characterized by a rough or variable aperture required several hours for the fracture transmissivities to return to their original values under single phase flow conditions. A full set of experiments have been completed using the Large Physical Model, an artificial fracture with uniform roughness with a size of about 2 by 2 m. The test results show non-linear effect due to turbulence close to the withdrawal hole and large flow reductions due to two-phase flow effects.

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

The evaluation of the modeling work on Task No 3, the hydraulic impact of the tunnel excavation at Äspö, is on-going. 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 tests results and does extrapolation from such models provide reasonable results. The second part uses the data set available from the period during excavation of the Äspö tunnel for improving the site scale groundwater flow models.

Task No 4 has been the main modeling effort within the Task Force during 1996. The scope of Task 4 has been to perform forward modeling of the radially converging tracer test (RC-1) and of the dipole tracer tests (DP1-4) carried out as part of the TRUE experiments. The model predictions have later been compared with experimental results.

Task 4 constitutes one of the few real blind predictive modeling exercises ever conducted in the field of tracer transport in fractured media. No thorough evaluation of the modeling performed has been done so far but a preliminary analysis of modeling of the RC-1 test show that;

- Quite an impressive amount of modeling work has been performed considering the large amount of data available and the time constraints.
- Comparing the experimental result with the simulations from the eight groups, it is evident that the flow system/boundary conditions are not completely understood.
- The predicted breakthrough times are on the right order of magnitude, in some cases very good, for two out of four tracer tests.

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 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. The field compaction tests made in 1995 showed that a new compaction equipment was required. During 1996 a vibrating plate has been designed and built. The vibrations are produced by the oil hydraulic of the carrier, which will be a small flexible rebuilt digging machine. The vibrating plate is equipped with a complete bottom plate, that is shaped to suite compaction close to the roof and walls with inclined compaction. The plug for the Backfill and Plug Test in the ZEDEX drift has been designed. Laboratory tests on backfill materials have been running and the development and testing of equipment for measuring THM-processes in backfill and buffer materials have continued during 1996.

The Prototype Repository Test is focused on testing and demonstrating repository system function. A full scale prototype including four deposition holes with canisters with electric heaters and highly compacted bentonite will be built and instrumented. The function of the prototype will then be monitored for several years. Certain activities aimed at contributing to development and testing of the practical, engineering measures required to rationally perform the steps of a deposition sequence are also included. Detailed planning of the Prototype Repository has been continued during 1996.

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. The demonstration of deposition technology will be made in a new tunnel south of the ZEDEX drift excavated by drill and blast. Excavation of the new tunnel began in November 1996.

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 and its temperature has successively been increased to 90°C. The second test parcel, A1, was inserted into its borehole in mid November. The temperature in this borehole will be 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. Data concerning temperature, total pressure, pore water pressure and humidity in the two test parcels have been produced during test period and no major divergence from expected values has been found. The swelling pressure of the bentonite was around 4 MPa in both tests and full water saturation has been achieved in all positions equipped with moisture gauges.

The work with modeling the cracks caused by cutters or bits at mechanical excavation in crystalline rocks has continued with studies on the influence of mechanical properties of rock on the indentation depth and crack length. The main factors governing the indentation event have been identified and 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 indentation force, the shape and the size of the indenter and the properties of the rock.

Studies of induced cracks in the TBM tunnel wall in Äspö Hard Rock Laboratory and in borehole wall in the research tunnel at Olkiluoto, Finland has been made. Rocks at these two places are diorite and gneiss respectively. The basic crack types defined by laboratory indentation tests were found in the studied samples but with some variations. For the different excavation methods TBM caused deeper and longer cracks in the walls than was caused by the button cutters of the blind hole boring machine. It is remarkable that only few and short cracks were found in the side walls independent of method. The densely cracked layer is less than 10 mm deep and the subsurface cracks do not penetrate deeper than 10 to 20 mm into the side wall.

Facility operation

The hoist has been taken into operation after it was approved by the authorities in the beginning of 1996. The electrical system of the hoist has been upgraded to assure reliable operation in the wet environment underground. The drainage system has operated well during the year.

A local mobile telephone system has been installed at the Äspö HRL. I works in all tunnels underground, the hoist shaft, the office building, and at the surface up to a few hundred meters away from the office and the tunnel opening.

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 new database, SICADA, developed by SKB which was put into operation in 1995 will be one of SKB's most important database systems. The system has been further developed during 1996 and the following applications currently exist; Diary, Finder, Retriever, Project, and WWW-Retriever. The WWW-Retriever makes it possible to retrieve data from SICADA through SKB's internal home page on SKB's Intranet.

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. A new measuring station has been installed in the tunnel at the 450 meter level.

A new measurement system called Datascan 7000 with the software Orchestrator (MSS-system) has been installed in the tunnel. This system takes care of data from the Long Term Tests of Buffer Performance.

International participation

Eight organizations from seven 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.

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

CONTENTS

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

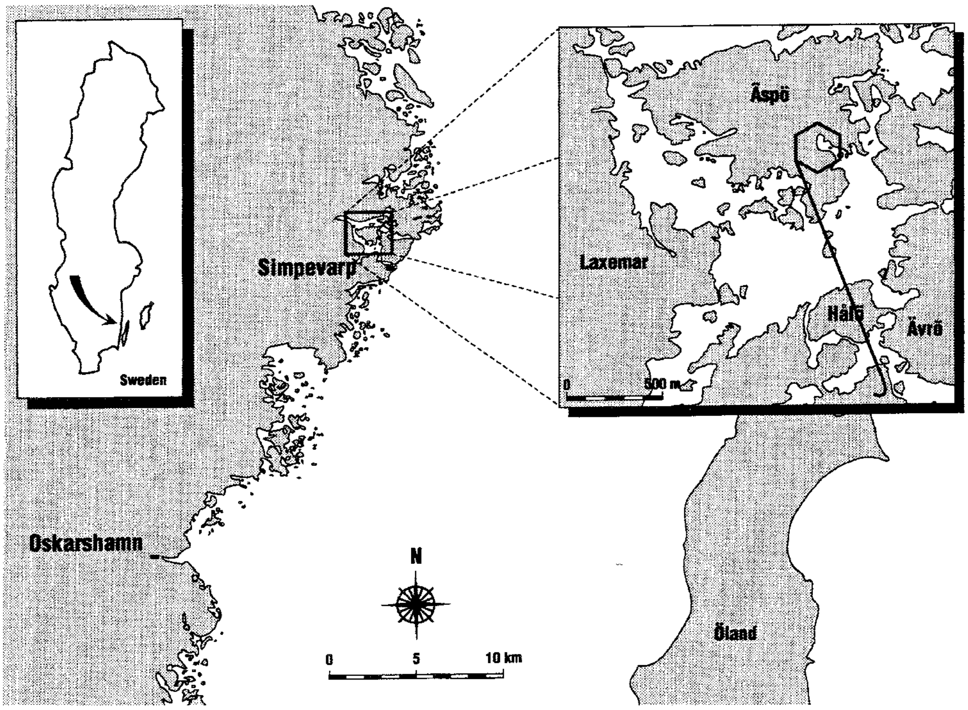


Figure 1-1. Location of the Äspö HRL.

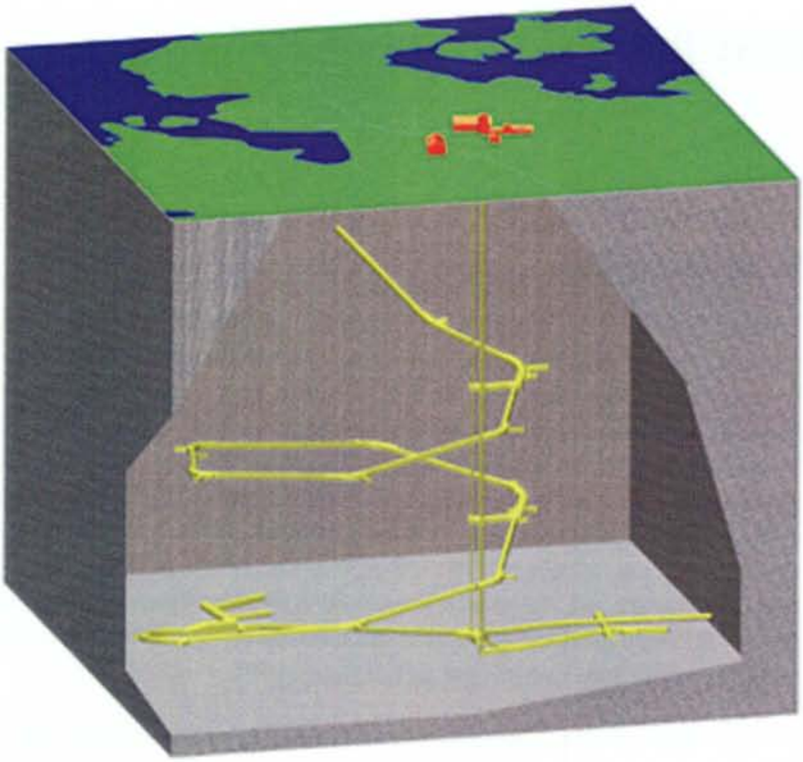


Figure 1-2. *Schematic design of the Äspö HRL. The lower part of the facility has been excavated by a 5 m diameter Tunnel Boring Machine.*

Figure 1-3. *Aerial view of the Äspö Research Village.*

Village is located at the surface on the Äspö Island and it comprises office facilities, storage facilities, and machinery for hoist and ventilation, see Figure 1-3.

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

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

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

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

1.2 ÄSPÖ 96

The Äspö Project began 10 years ago with geoscientific investigations on Äspö and nearby islands. 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 construction of the Äspö Hard Rock Laboratory was finished in 1995. To mark this important milestone in the history of the Äspö Hard Rock Laboratory SKB organized "Äspö 96" as a combined 10-year anniversary and inauguration of the Äspö Hard Rock Laboratory facilities. Äspö 96 was attended by about 140 distinguished guests. The current status of nuclear waste management in Sweden and the role of the Äspö Hard Rock Laboratory for the Swedish and international nuclear waste programs was addressed by Carl-Erik Nyquist, President and CEO Vattenfall AB, Sten Bjurström, President of SKB, Maurice Allegre, Chairman of ANDRA, and Kjell Pettersson, Chairman of Oskarshamn Municipal Council. The Äspö Hard Rock Laboratory was inaugurated by Erik Krönmark, the Governor of Kalmar County. After the ceremony there was a guided tour of the underground facilities showing the current research projects in progress.

The Second Äspö International Seminar was held the following day in Stockholm. At the seminar, which was open to interested scientists, the results from the ten years of research at Äspö and the planned work at Äspö HRL was presented and discussed. The seminar was attended by about 120 scientists.

As part of "Äspö 96" a book, "The Äspö Hard Rock Laboratory – 10 Years of Research", was produced summarizing the results from ten years of research and plans for the future. The book was handed out to the participants of Äspö 96 and

Figure 1-4. *The speakers at Äspö 96, from left to right; Kjell Pettersson, Chairman of Oskarshamn Municipal Council, Erik Krönmark, the Governor of Kalmar County, Carl-Erik Nyquist, President and CEO Vattenfall AB, Maurice Allegre, Chairman of ANDRA, and Sten Bjurström, President of SKB.*

the Second Äspö International Seminar. The book has also been distributed to the individuals and organizations that normally receive SKB's Technical Reports. Additional copies can be obtained from SKB.

1.3 OBJECTIVES

SKB has 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, and

2 Finalize 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.

1.4 ORGANIZATION

A schematic chart of the organization of the Äspö HRL valid from January 1995 is shown in Figure 1-5.

The Äspö Hard Rock Laboratory has so far attracted considerable international interest. As of December 1996 eight foreign organizations were participating in the Äspö HRL in addition to SKB. These organizations were: Atomic Energy of Canada Limited (AECL); Power Reactor & Nuclear Fuel Development Corporation (PNC), Japan; Central Research Institute of Electric Power Industry (CRIEPI),

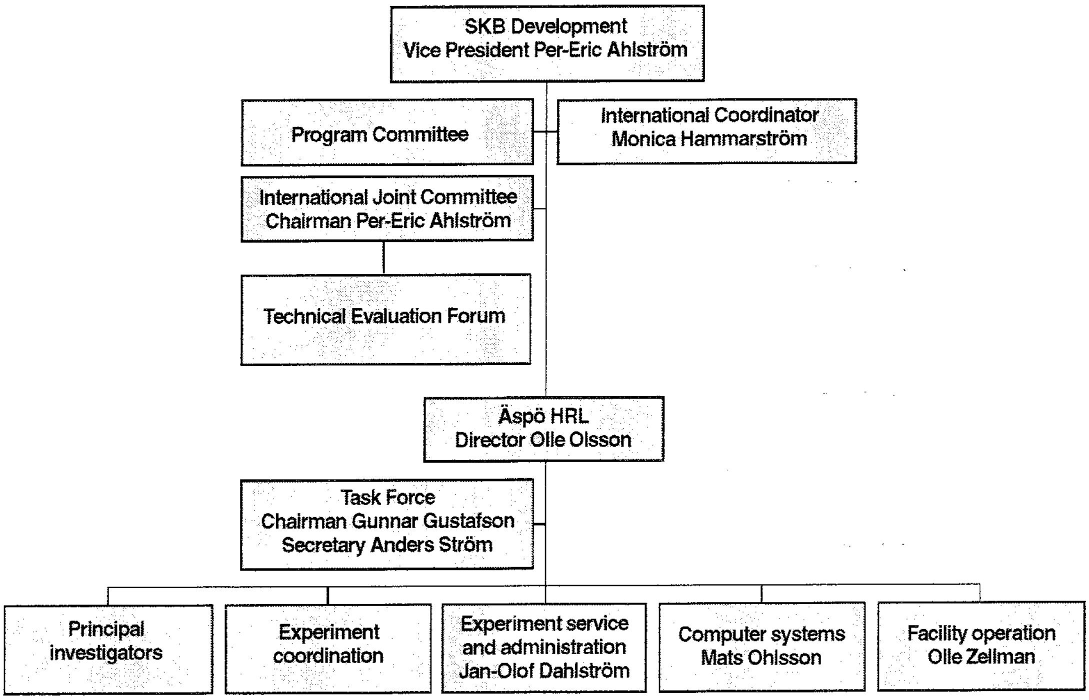


Figure 1-5. Organization of the Äspö Hard Rock Laboratory.

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; and Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie (BMBF), Germany. The agreements with ANDRA and Posiva have been prolonged for another four year period. The agreement with AECL has been prolonged until the end of 1998.

In February 1997 a cooperation agreement was signed with Empresa Nacional de Resuidos Radioactivos (ENRESA), Spain, covering the time period until the end of 2000.

1.4.1 The Program Committee for the Deep Repository

The committee is SKB's internal joint steering/advisory group for the deep repository project and the Äspö HRL. The Program Committee proposes and/or discusses changes in the technical/scientific program and changes in quality, schedule and cost frames. Coordination with SKB's other RD&D also takes place within the SKB Program Committee. Chairman of the Program Committee is Per-Eric Ahlström (March 1997).

1.4.2 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 organizations participating in the Äspö HRL. The TEF meetings are organized to facilitate a broad scientific discussion and review of results obtained and planned work. Technical experts from each participating organization and the IJC delegates participate in the TEF meetings. Chairman of IJC/TEF is Per-Eric Ahlström and secretary is Monica Hammarström (March 1997).

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.

1.4.3 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 organized 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 1996 the staff at the Site Office has consisted of about 15 full time employees.

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

1.4.4 Task Force on modeling of groundwater flow and transport of solutes

The Technical Coordinating Board (TCB) which preceded the IJC established the Task Force on modeling 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 modeling groups are now actively involved in the work. Chairman (March 1997) is Gunnar Gustafson, CTH and secretary Anders Ström, SKB.

1.5 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 organization 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 modeling of groundwater flow and transport of solutes in the planning, design, and evaluation of the flow and transport experiments.

1.6 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 1-6.

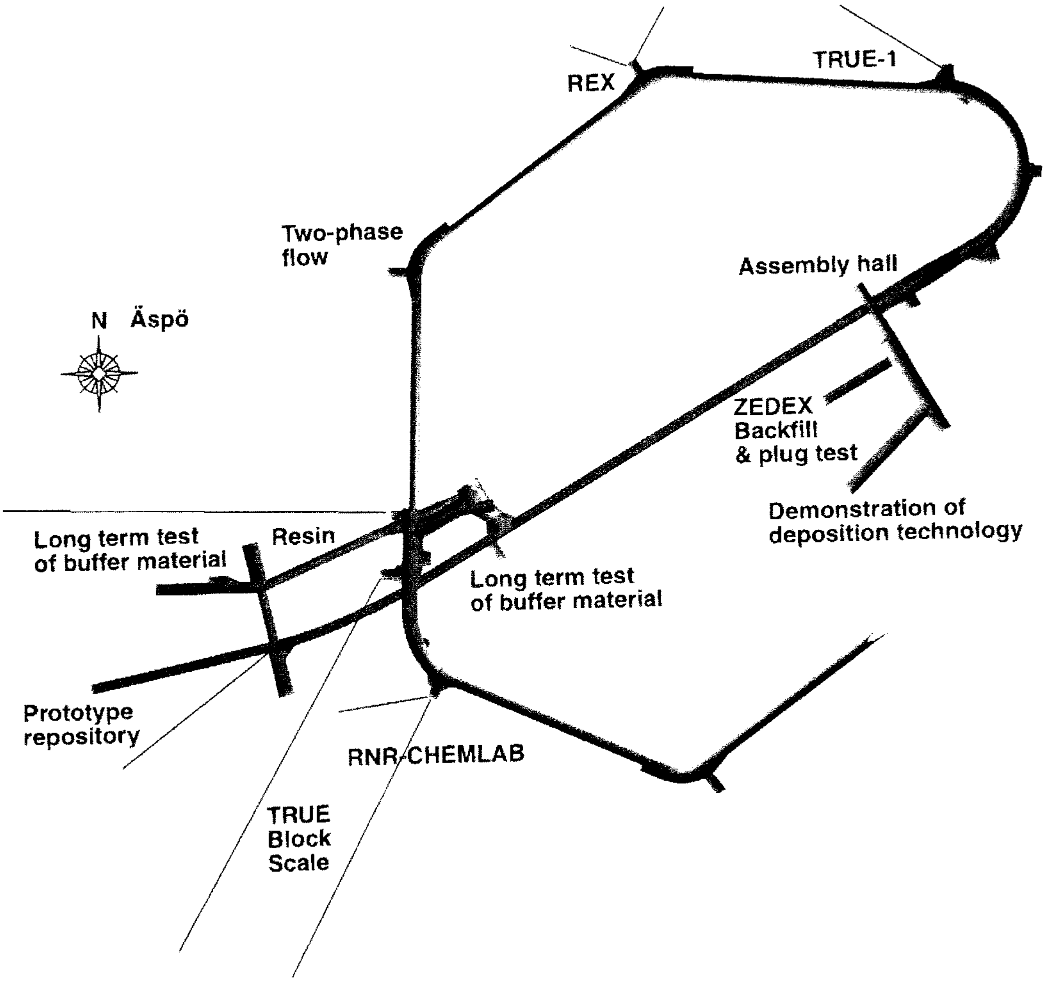


Figure 1-6. *Underground excavations at the 300-450 m levels and current allocation of experimental sites.*

2 VERIFICATION OF PRE-INVESTIGATION METHODS

2.1 GENERAL

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

- show whether a site has suitable geological properties,
- provide data and knowledge concerning the bedrock on the site so that a preliminary emplacement of the repository in a suitable rock volume can be done as a basis for constructability analysis,
- provide the necessary data for a preliminary safety assessment, which shall serve as support for an application under NRL (the Act Concerning the Management of Natural Resources) to carry out detailed site characterization, and
- 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, see Figure 2-1.

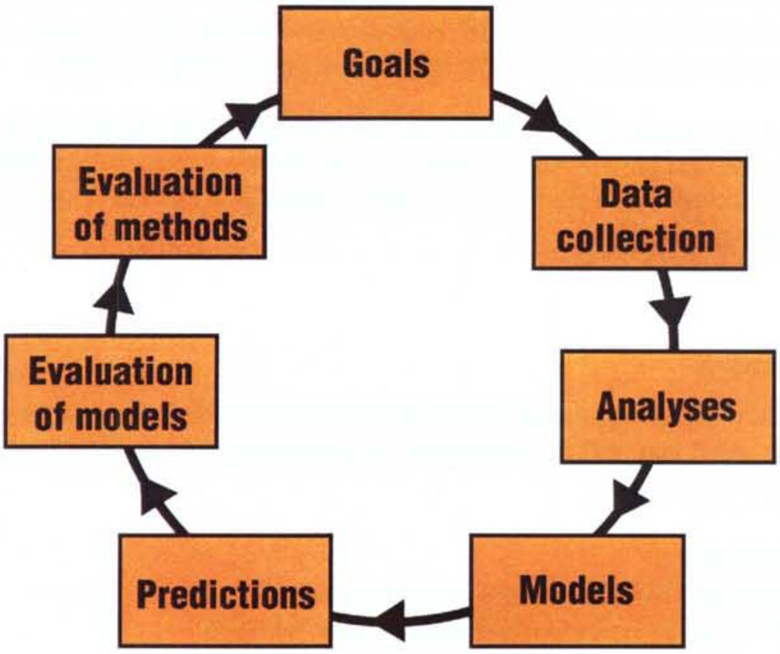


Figure 2-1. The strategy for the verification of the pre-investigation methods.

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.

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:

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.

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 700-2874 m (depth 200 m) has been reported previously.

2.2.2 Results

The work during the period has been focused on compiling of the new model over the Äspö site and the evaluation of pre-investigations. The planned titles for the final reports are:

REPORT 1
Äspö HRL – Geoscientific evaluation 1997/1.
Overview of investigations performed 1986-1995.

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

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.

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.

REPORT 5
Äspö HRL – Geoscientific evaluation 1997/5.
Models based on site characterization 1986-1995.

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 fourth reports will give a detailed description of the comparison between predictions and outcome for tunnel section 700-2875 m, which to a large extent have been presented in 12 Progress Reports. The evaluation will focus on the validity of conceptual models and evaluation methodology used and also the feasibility and robustness of methods and investigation strategy (sequence, amount etc).

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

The reports have all been reviewed at least once.

2.2.3 Planned work

The final draft versions of the reports are planned to be produced mainly during January-February 1997 and the final review performed during spring 1997. The final reporting of "*Verification of Pre-Investigation Methods*" is planned to be completed during summer 1997.

2.3 CODE DEVELOPMENT/MODELLING

2.3.1 Background

As a basis for a good optimization 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 Results

Regional and site scale groundwater flow models – Scope

Late 1996 a regional and a site scale groundwater flow model were set up. Some of the results are presented below. The scope was to make 3D regional and site scale models useful for calculating the natural (undisturbed) groundwater flow and the groundwater flow within the Äspö HRL. Density driven flow dependent of the salinity of the groundwater was to be included. The intention with the regional model was also that the regional model should be used for calculating the boundary conditions for a site model. A stochastic continuum approach was chosen and the code used was PHOENICS. The developed sub-program (for the code PHOENICS) treating the unsaturated zone was also to be used.

The objectives for the regional groundwater flow model was extended because of modelling needs for the SKB project SR 97. Some sensitivity studies will be performed early 1997.

The site scale modelling is intended to give a better model realization of the Äspö site compared to the one used earlier in the project and to be used for estimating boundary conditions for experiments performed in the Äspö HRL.

Process description

The flow was based on the following equations:

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

The dispersion used was proportional to the local darcy velocity. The simulations were steady state.

Geometric framework and parameters

Regional groundwater flow model

The model covers an area of 10 x 10 km^2 and down to a depth of 3 km. The model consists of 360 000 cells and the cells are 100 m cubes below a depth of 200 m. Above 200 m depth in the model the height of the cells decreases and the uppermost cells follow the topography. BFC (Body Fitted Coordinates) net is used. The regional hydraulic conductor domains and hydraulic rock mass domains are defined according to models set up 1996.

Site scale groundwater flow model

The model covers an area of 1.8 x 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, see

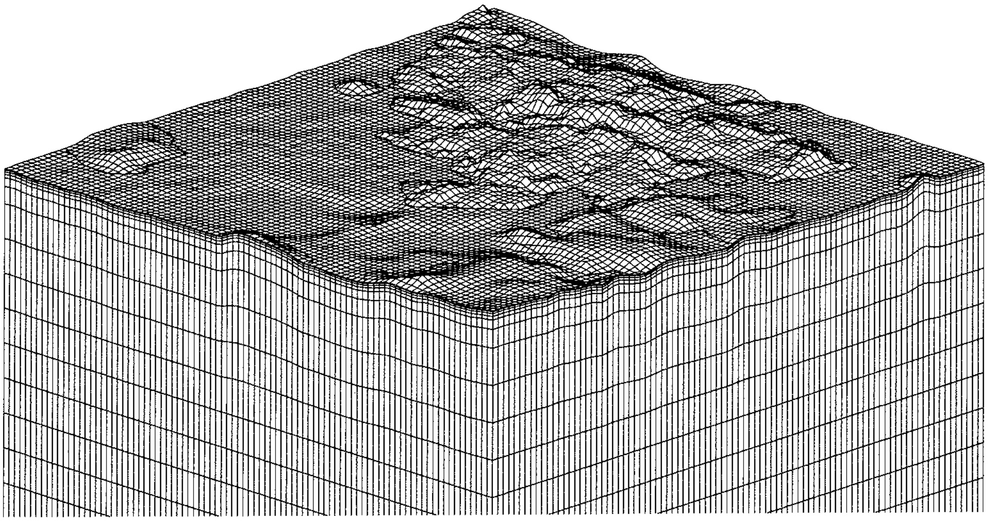


Figure 2-2. *Finite-volume net for the site scale model. View from south-east with Äspö in the centre. (Vertical scale is magnified 10 times).*

Figure 2-2. Above 100 m depth in the model the height of the cells decreases and the uppermost cells follow the topography. BFC (Body Fitted Coordinates) net is used. The hydraulic conductor domains and hydraulic rock mass domains are defined according to models set up 1996.

Material properties

Transmissivities of the hydraulic conductor domains are deterministic and hydraulic rock mass domains are described as stochastic continuum. Properties for the hydraulic rock mass domains are based on the hydraulic tests in 3 m test scale for the site scale but transformed to actual cell size. For the regional model tests in the 100 m test scale were used.

The uppermost cells (close to ground surface) in the model are given constant hydraulic conductivities somewhat higher than the geometric mean hydraulic conductivity for the uppermost zone. This is made in order to make the sub-program treating for the unsaturated zone work properly.

In the regional model two of the main streams are also simulated by assigning high hydraulic conductivity for the uppermost cells in the position where the streams are.

Spatial assignment method

Each hydraulic rock mass domain were given properties as stated for the 1996 model. No correlation between the hydraulic conductivities for the cells are assumed.

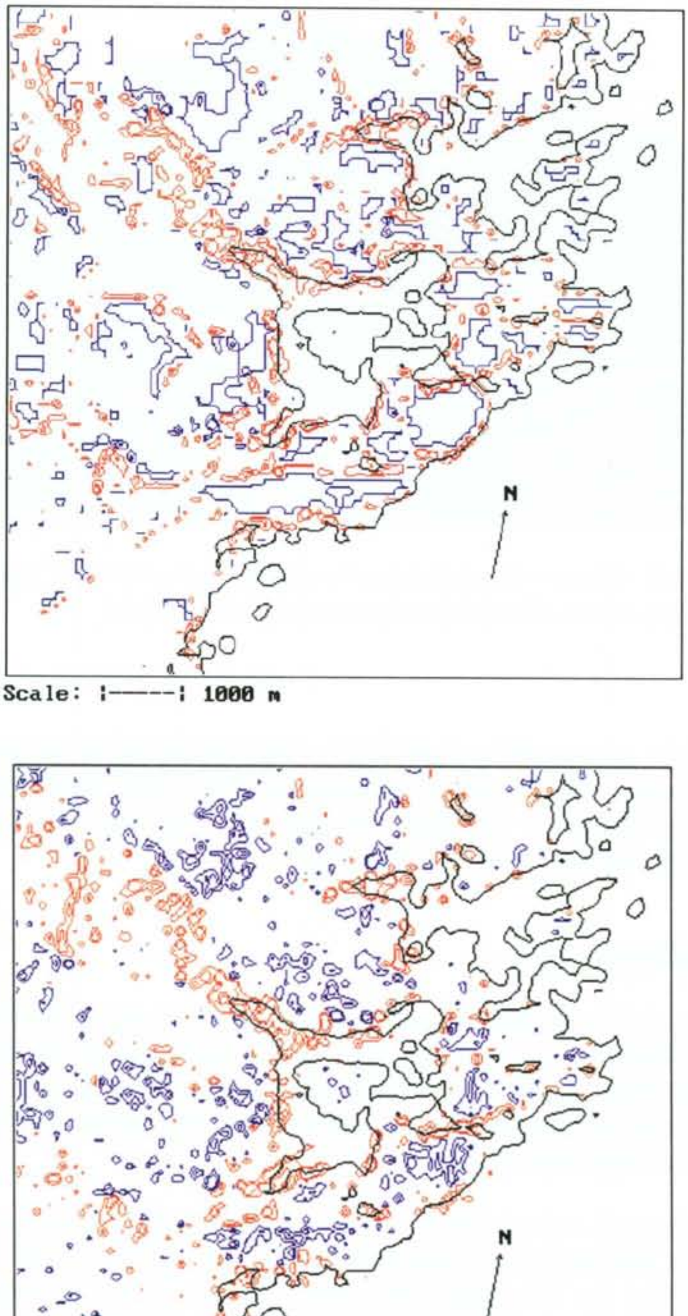


Figure 2-3. *Vertical flow at 3 m (top) and 30 m (bottom) depth. Blue colour indicates downwards and red upwards flow.*
Isoline values: Top: 200 and 400 mm/year.
Bottom: 100 and 200 mm/year.

Boundary conditions

Net recharge was set 200 mm per year for the upper surface not covered by the sea. The sea surface was modelled as constant pressure. Salinity at the sea bottom was set to 6 g/ litre.

For the site model upper boundary, the northern and southern side boundaries were taken from the regional model. It was found difficult to define the coupling between the regional and site scale model due to the different grid sizes. Tests will be performed to find a suitable algorithm.

Regional model –Natural conditions (undisturbed by tunnel)

The results presented are preliminary.

Recharge- and discharge areas

The groundwater flow 3 and 30 m below ground surface is illustrated by the vertical component of the flow shown as isolines in Figure 2-3. The recharge areas are in the situated on the hills and the discharge areas are found in the valleys, as expected.

Horizontal flow

The flow in the uppermost cells are shown in Figure 2-4, the streams can easily be seen in the figure.

Salinity distribution and groundwater fluxes

An east-west vertical section through the model is shown in Figure 2-5. The section intersects the centre of the tunnel spiral at Äspö HRL. As can be seen in the figure there is fresh water down to about 700 to 800 m where the boreholes KLX 01 and 02 are and to about 100 m at Äspö. One can also see that the water from the Laxemar area is discharging mainly close to the coastline.

Site scale model

The results presented are preliminary.

Horizontal flow

The flow in the uppermost cells are shown in Figure 2-6, the streams can easily be seen in the figure. As can be seen the flow pattern on southern Äspö changes when the tunnel is present.

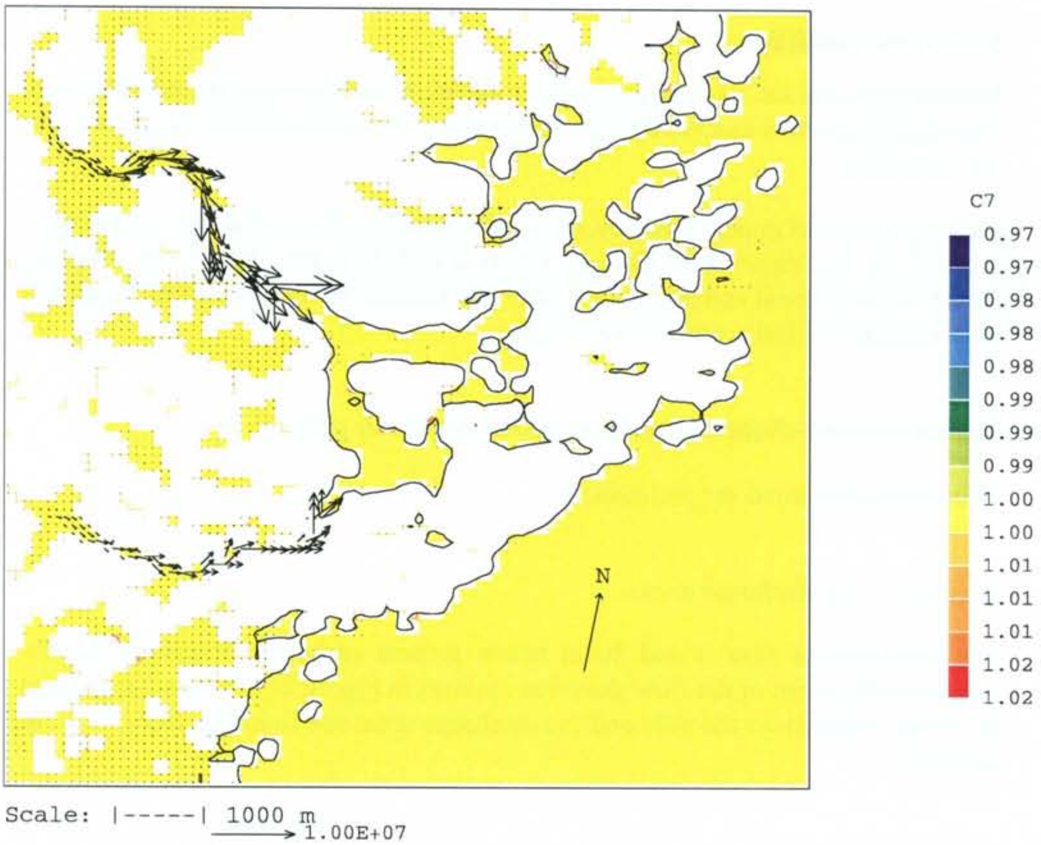


Figure 2-4. *Horizontal flow and saturated areas close to surface. Groundwater flow in the uppermost cells of the model.*

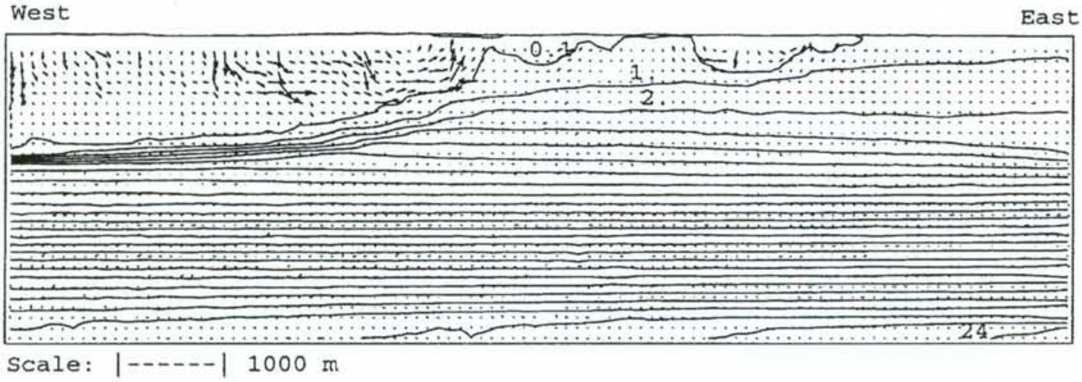
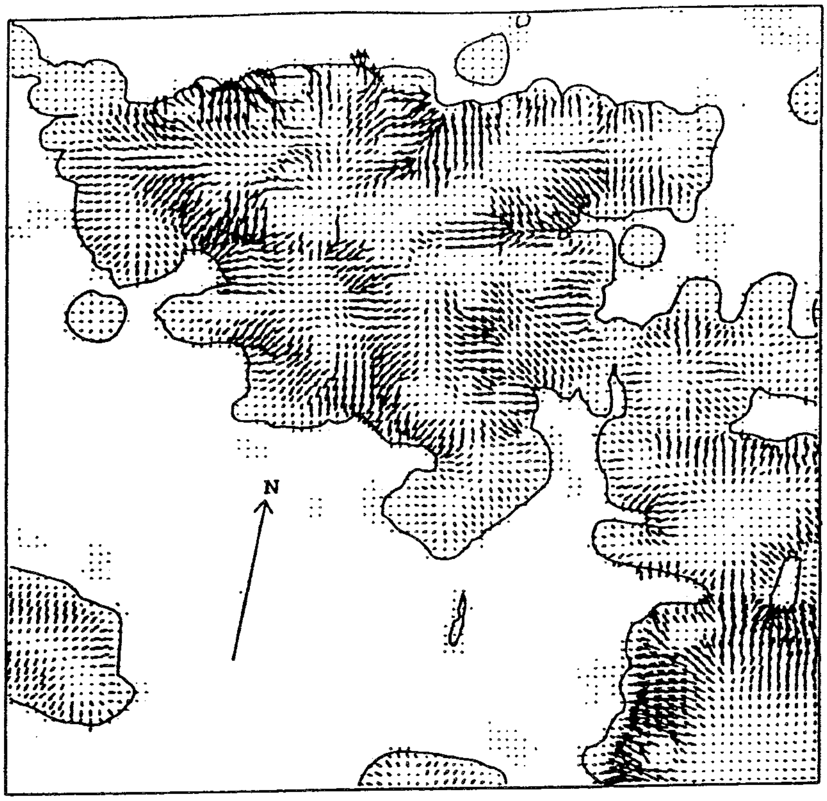


Figure 2-5. *East-west vertical section through the model. The section intersects the centre of the tunnel spiral at Äspö HRL. Salinity given as % (by weight). (Flow from ground to 120 m depth not shown).*



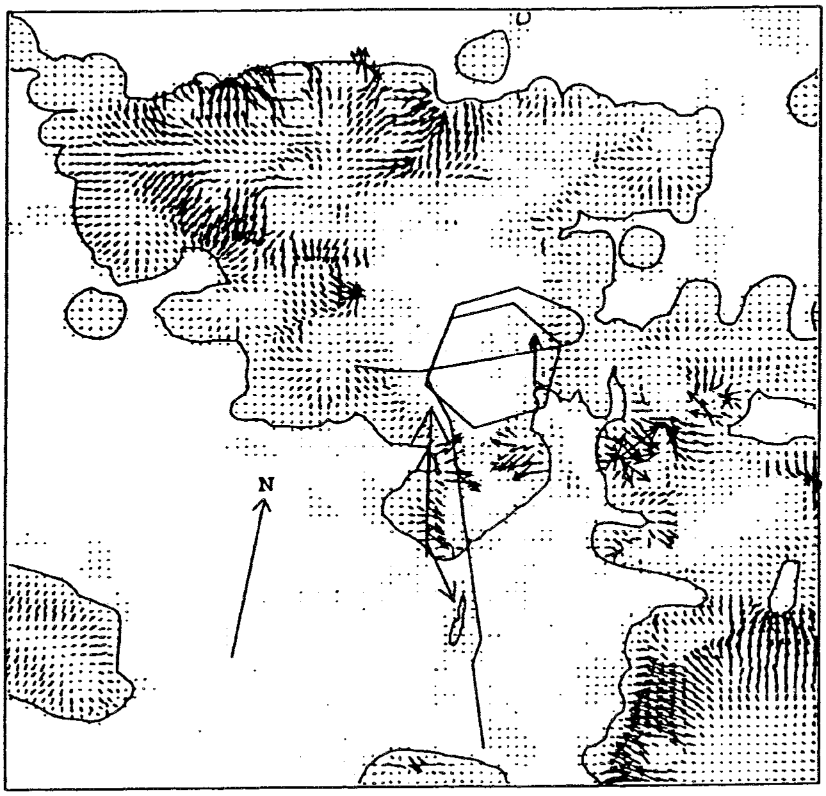


Figure 2-6. *Horizontal flow. Groundwater flow 4 m below ground surface. (A 12 mm long vector in the figure correspond to a flux of* 10^{-6} *m/s).*
Top: *Natural conditions.*
Bottom: *Tunnel face at 3600 m, the complete tunnel.*

2.3.3 Planned work

Regional groundwater flow model

Some sensitivity studies will be made early 1997 and the report is planned to become a Technical Report.

Site scale groundwater flow model

The model will be more thorougly calibrated early 1997 and thereafter the flow-field below Äspö island will be calculated and reported in spring 1997.

Description of code developments made during the re-modelling of Äspö HRL will be included in the reporting of the modelling.

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 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 optimize repository design with respect to engineered barriers and repository layout.

Detailed characterization will facilitate refinement of models 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

The excavation of a tunnel will cause a disturbance in the rock surrounding the tunnel. The character and the magnitude of the disturbance is dependent on to the existence of the air-filled void represented by the tunnel and the method of excavation used to construct the tunnel. The properties of the disturbed zone around excavations are of importance to repository performance in that the zone may provide a preferential pathway for radionuclide transport or may affect the efficiency of plugs placed to seal drifts.

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). 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 were completed and reported in 1995 (Olsson et al., 1996). The analysis of results obtained 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 modeling efforts. Significant in-kind contributions to the project are also provided by BMBF and Nagra.

3.2.2 Objectives

The objectives of ZEDEX are:

- to understand the mechanical behavior 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.

3.2.3 Experimental configuration

The ZEDEX project was performed in conjunction with the change of excavation method from drill & blast to tunnel boring that took place during the summer of 1994. The experiment is expected to provide a better understanding of the EDZ that will contribute to the basis for selecting or optimizing construction methods for a deep repository and its subsequent sealing.

The experiment is 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 Figure 3-1. To get a denser distribution of data points near the drift wall additional short radial boreholes were drilled in 1996. Three rings of more than 8 short radial boreholes each were drilled. Two of the rings were situated in the D&B Drift and one ring in the TBM drift.

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. A drift was then excavated from the end of the assembly hall to access the D&B test drift. The first two rounds in the D&B test drift were not part of the test and were made to reduce the effects of the anomalous stress field caused by the drilling niches and D&B access drift. The following four rounds 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". The shape of the blasted drift

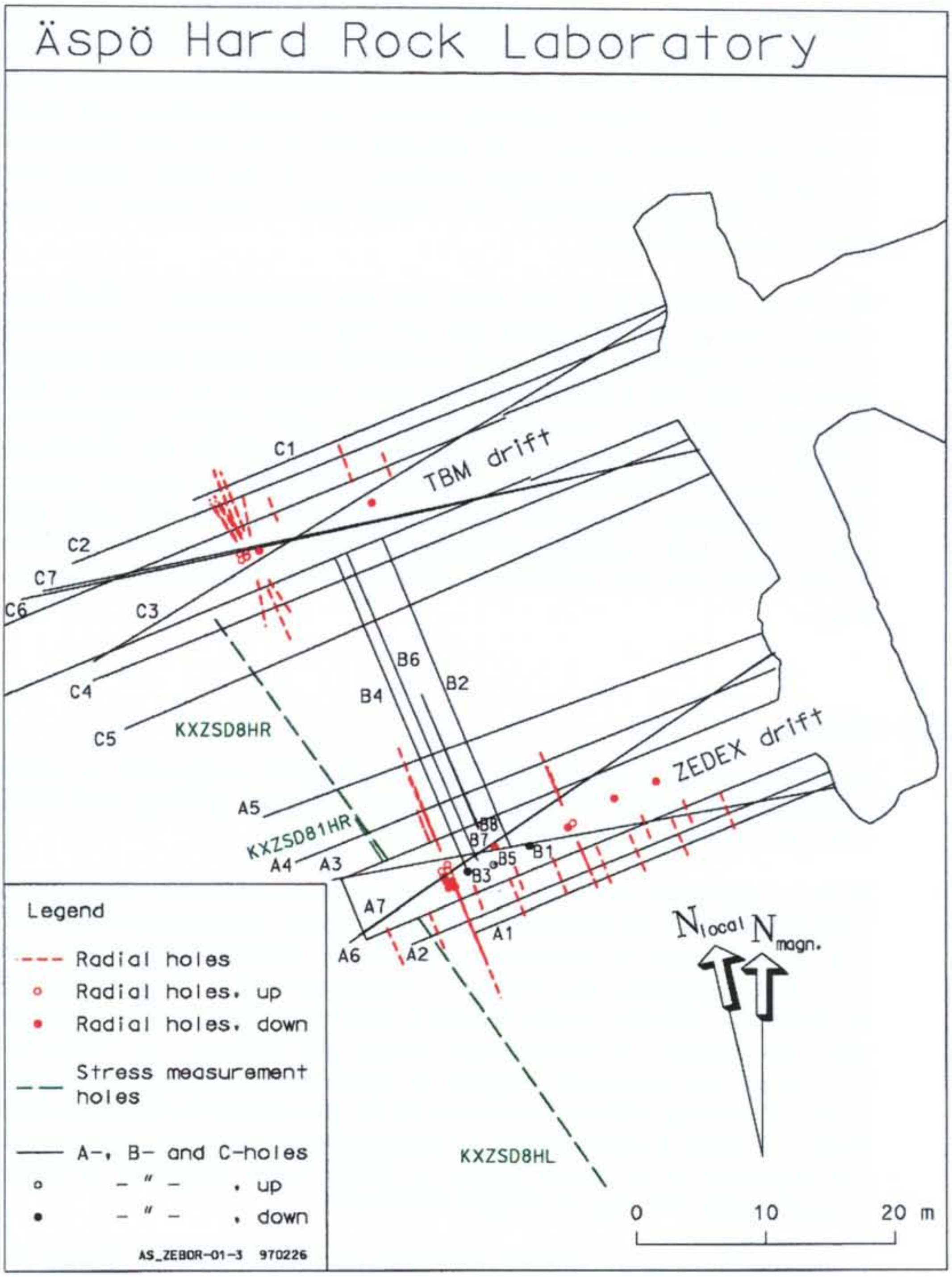


Figure 3-1. *Configuration of test drifts and investigation boreholes for the ZEDEX study.*

was designed to be circular with a flat floor and the diameter (5 m) was designed to be about the same as the TBM drift. A number of boreholes were drilled axially and radially relative to the test drifts to assess the properties and extent of the EDZ. After excavation of the drifts a number of short (3 m) radial boreholes were drilled in each drift to assess the extent of the disturbed zone in the near-field (also termed the "damaged zone"). A set of longer boreholes (>>15 m) was drilled radially from the drift to investigate properties of the disturbed zone, in the far-field, at a larger distance from the drift wall.

The initial conditions in the rock mass have been characterized by several techniques including; tunnel mapping and core logging to determine geotechnical classification factors (Q, RMR), in situ seismic (P- and S-wave) velocity measurements and radar measurements. The rock mass response to excavation has been observed by mapping of induced fractures, multi point borehole extensometers (MPBX) and convergence measurements, laboratory testing on core samples, and by acceleration, vibration, seismic velocity, permeability and acoustic emission (AE) measurements. During the ZEDEX extension additional short radial holes were drilled. High resolution permeability, P- and S-wave interval velocities, seismic tomography and anisotropy measurements have been made in these boreholes.

3.2.4 Results

Geological setting of the ZEDEX test site and initial interpretation of results obtained before, during, and after excavation are presented in Olsson et al. (1996) and in the Äspö HRL Annual Report for 1995.

Stress measurements have been performed in the pillar between the D&B and TBM drifts to study the variation in stress as a function of distance from the tunnel wall. The magnitudes of the stresses measured at the ZEDEX site are significantly lower than the expected values based on an extrapolation of trends seen throughout the Äspö HRL. Previous studies at Äspö in deep boreholes using the same instrument (the Swedish State Power Board triaxial cell, Hallbjörn et al., 1990) have given lower stress magnitudes compared to measurements made off the ramp using CSIRO overcoring methods. The reasons for this discrepancy are not yet resolved. Figure 3-2 shows a comparison of the measured and modeled principal stresses. The magnitude of the model stresses are based on the magnitude of stresses measured some 25 m from the ZEDEX D&B drift.

Analysis of the Acoustic Emission (AE) events that occurred the first 8 hours after excavation have shown that AE-events occur at deviatoric stress levels of 25 MPa. This is well below the typical range of crack-initiation stresses. Source mechanism analysis of AE events showed that the great majority of events could be fit to shear-slip mechanisms. Other mechanisms considered were explosive (crack-opening) events and implosive (crack-closure) events. The partially failed rounds, number 2 and 6, had the highest proportion of implosive events. Much of the activity from these rounds occurred in the blasted but intact volume, which may have cracks initially opened by the blast gases. The implosive events may represent the closure of such cracks.

The AE-event density was approximately a factor of 10 higher for the D&B drift compared to the TBM drift. Figure 3-3 shows the event density as a function of

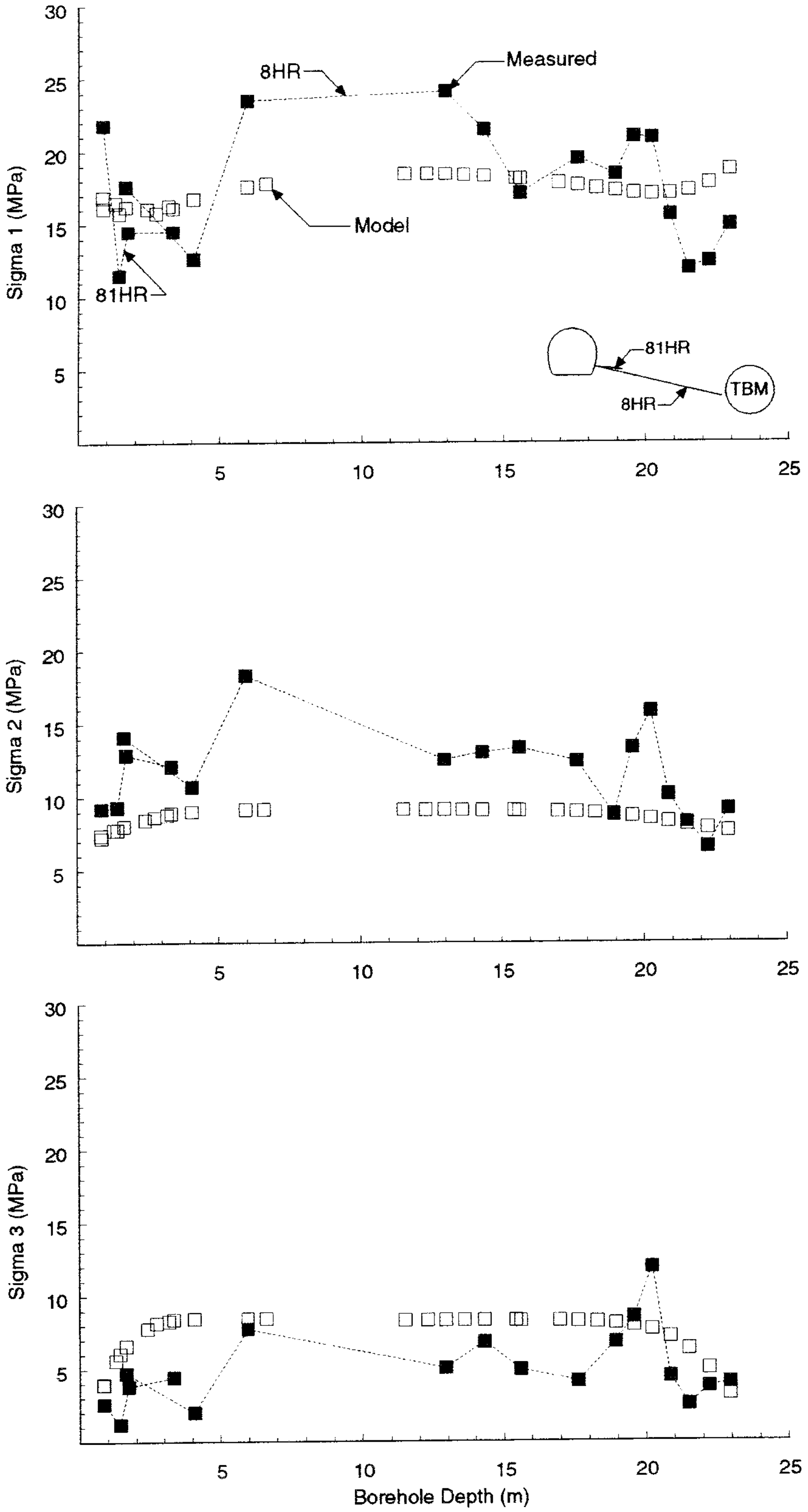


Figure 3-2. Comparison of the measured and predicted principal stress magnitude distribution in the pillar between the TBM and D&B drifts.

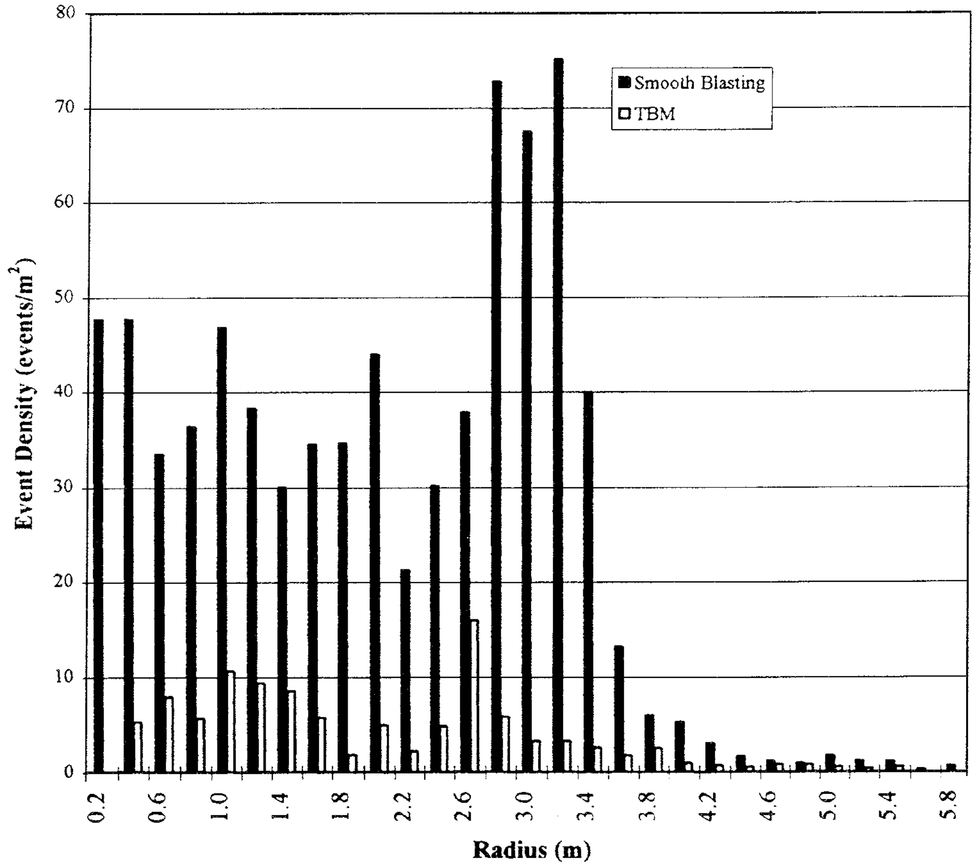


Figure 3-3. *Average AE event density as a function of radial distance from the center of the drift for the TBM drift and rounds 2, 3, and 4 of the D&B drift.*

radius for the TBM and D&B drift. For the TBM drift the majority of AE-events occur at the face, i.e. inside the drift radius of 2.5 m, and within a few tens of centimeters from the drift wall. For the D&B drift the event density is high out to one meter from the drift wall.

Several seismic techniques were used to evaluate the rock properties in the near-field of the ZEDEX test drifts. All seismic methods show low velocities close to the tunnel surfaces. Generally it was found that the low velocity zone is extremely small (less than 10 cm) or even not present in the TBM drift. The D&B drift exhibits a larger low velocity zone with an extent of about 50 cm. Some single holes showed low velocities to a depth of 100 cm. These were located in the floor of the blasted drift. Cross-hole seismic measurements showed a maximum velocity anisotropy of about 15%.

The hypothesis set out at the start of the ZEDEX Project was that near-field disturbance (at distance of less than 2 m from the drift wall) could be reduced by the application of an appropriate excavation methods and that far-field disturbance would be independent of the excavation method. The results from the ZEDEX Project show that a division in near-field and far-field is not appropriate. Based on ZEDEX results the following division has been found more appropriate:

- there is a **damaged zone** closest to the drift wall dominated by changes in rock properties which are mainly irreversible and
- there is **disturbed zone** outside the damaged zone dominated by changes in stress state and hydraulic head and where changes in rock properties are small and mainly reversible.

There is of course a gradational change in rock properties and rock stress with distance from the rock wall and there is hence no distinct boundary between the two zones.

The ZEDEX experiment has been performed in a rock mass with low stresses which has resulted in a mainly elastic behavior and no induced damage 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 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 has been observed up to 1 meter from the drift wall while the corresponding extent for the TBM drift is a few tens of centimeters. Changes in seismic velocity indicate a larger increase in crack density. The dye penetration tests that have been performed in the slots sawed from the drift has shown the extent of macro fracturing, which in the floor of the D&B drift has extended to about 50 cm. The hydraulic measurements performed in the damaged zone has shown little change in permeability of the rock matrix. The larger permeabilities observed have been associated with the induced and pre-existing fractures.

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 current view of the characteristics and extent of the damaged and disturbed zones are shown in Figure 3-4.

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, which is the hydraulically significant part, can be limited through application of appropriate excavation methods. A limited extent the damaged zone 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 in support of an increased permeability in the disturbed zone affected by the stress redistribution caused by the void (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 is 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.

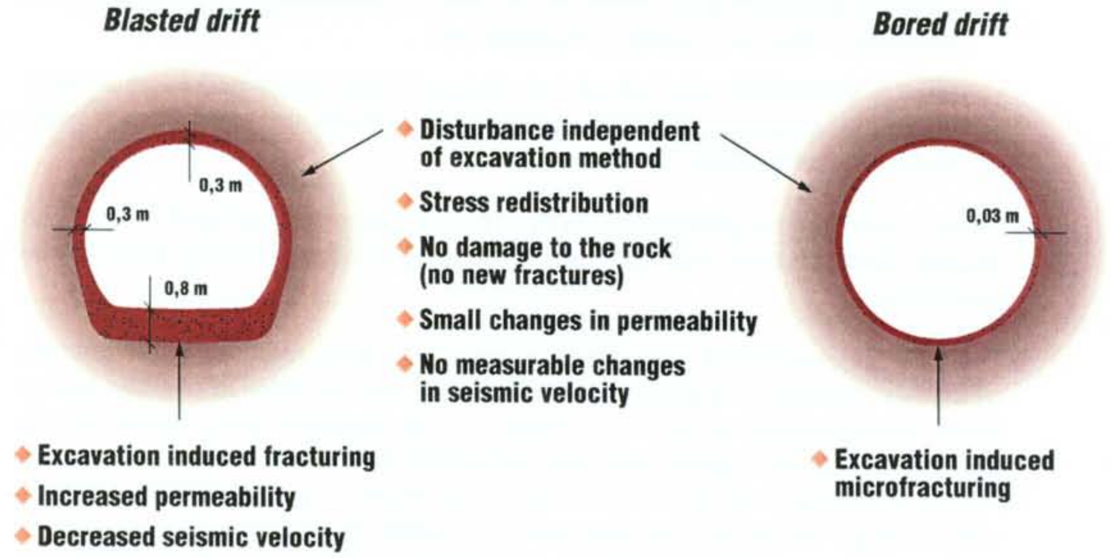


Figure 3-4. *Summary of the main findings of the ZEDEX Project. The extent of the damage zone is significantly greater in the drift excavated by blasting compared to the drift excavated by a tunnel boring machine.*

The ZEDEX Project has been successful, particularly with respect to the mechanical aspects and met the objectives set out for the project.

- A conceptual model and hypotheses were established within the project and these were tested by the data obtained and validated through modeling.
- An integrated suite of measurement techniques were applied and tested for 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 between the damaged and disturbed zones developed around the drifts.
- The interpretation of the data has resulted in the establishment of the boundary between the damaged and disturbed zones. Further it has demonstrated the link between damage and excavation method and has shown that a difference between the two D&B methods, in terms of damage, could not be determined.

3.3 ROCK VISUALIZATION 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 Hard Rock Laboratory 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 visualizing the rock model, based on available site data in SICADA, it is possible to optimize new investigation efforts. During the design of the Deep Repository the rock model will be the basis for optimization of the tunnel layout.

To fulfil above strategy and requirements SKB decided to develop a visualization system in November 1994. Rock Visualization System (RVS) is the name of the running project and the system as well.

The aim is to develop an advanced visualization system, based on a commercially available CAD system, that should be well integrated with SKB's investigation database SICADA and SKB's GIS database.

The Rock Visualization System should be based on the CAD-system MicroStation 95 including MicroStation Modeler and MicroStation QuickVision. MicroStation is a modern and powerful 3D-modelling system developed by Bently Systems Inc in U.S.A, and is running on computers with the most common operating systems as DOS, Windows, Windows 95, Windows NT and UNIX.

Specifications were compiled by the members of the project group (Mats Ohlsson, Ingemar Markström and Ebbe Eriksson) during the spring 1994. The Principal Investigators in the Äspö project and other geoscientific experts in SKB's organization have been involved in defining many of the functions needed in the system.

The project is divided in two phases, viz:

- Systematization phase.
- Realization phase.

The systematization phase was ordered from Arctic Software AB, Luleå, Sweden, in November 1994. The systematization work has been based on the concept of the Yourdon-method. The result of the systematization work, a detailed and extensive system specification, was delivered by Arctic Software AB in December 1995.

3.3.2 Results

The realization phase of the project was ordered from Team uStation AB, Täby, Sweden, in March 1996. Team uStation AB is a small but competent company in the area of advanced visualization. During the autumn 1995 Team uStation AB successfully developed QuickVision together with the head programmers at Bentley Systems, Inc. QuickVision is an advanced MicroStation viewer that can be used to spin rendered models on an ordinary PC and nearly independent of the complexity of the model to be viewed.

The realization of the RVS/Server program, which is needed and should be running on the SICADA database server, has been ordered from ErgoData AB, Göteborg, Sweden. (ErgoData AB has developed SKB's investigation database SICADA.)

The project has been running very smoothly, but at the end of the year Team uStation AB reported that the programming work is more extensive than expected when the fixed price agreement was signed in March 1996. A delay of at least one month (probably two month) has been estimated by Team uStation AB.

New functions and corrected functions are by routine sent to Ingmar Markström at Sydkraft Konsult AB for testing. All tests are documented strictly and all deviations (compared to the system specification) are sent to the programmers by electronic mail without any delay. The contractor always responds directly.

According to the project plan the realization phase is divided in four parts, namely:

1) Planning and mobilization
   1 month; *Running from 1996-03-01 to 1996-03-31*

2) Development of functions with priority 1
   5 month; *Running from 1996-04-01 to 1996-09-30*

3) Development of functions with priority 2 and 3
   3 month; Running from 1996-10-01 to 1996-12-31

4) Documentation and implementation
   1 month; Running from 1997-01-01 to 1997-01-31

The current status is that part one of the realization phase has been completed according to the time schedule, but part two and three are still in progress. The project is delayed about two months, which means that the date of final delivery will occur in April 1997. The plan is to introduce RVS within the TRUE Block Scale Experiment.

3.4 DEVELOPMENT OF HYDRAULIC TESTING SYSTEM FOR USE UNDERGROUND

3.4.1 Background

Hydraulic testing in boreholes drilled from underground is associated with special problems. High water pressures in boreholes, sometimes in combination with large water flow are examples of problems which have been handled in the Äspö HRL project. Limited working space at the borehole site in the tunnel, often in combination with limited available time, and hard environmental conditions are other problems related to underground testing. Therefore, the development of a new hydraulic testing system, fulfilling these requirements and with better practical functionality is underway.

3.4.2 Specification

The development project was started in mid-1995 with writing the design specifications of the system. The system should be designed for operation in ≤ 56 mm boreholes, drilled from tunnels at depths down to 500 m, i.e. at hydrostatic overpressure up to 5 MPa. The following types of hydraulic tests in packed-off sections should be managed:

- Out-flow tests
  - without regulation
  - with constant pressure regulation
  - with constant flow regulation (option).
- Injection tests (at formation hydrostatic pressures ≤ 1 MPa)
  - with constant pressure regulation.
- Pressure build-up (fall-off) tests subsequent following the tests above.

The specification of the pressure and flow monitoring of the system are 6000 kPa with a resolution of 0.01 % and 0.001 to 100 l/min respectively.

The system should be constructed for easy set-up at the borehole. The rig should support hoisting with 33 mm and 20 mm testpipes in vertical, horizontal as well as in inclined boreholes.

3.4.3 Project status

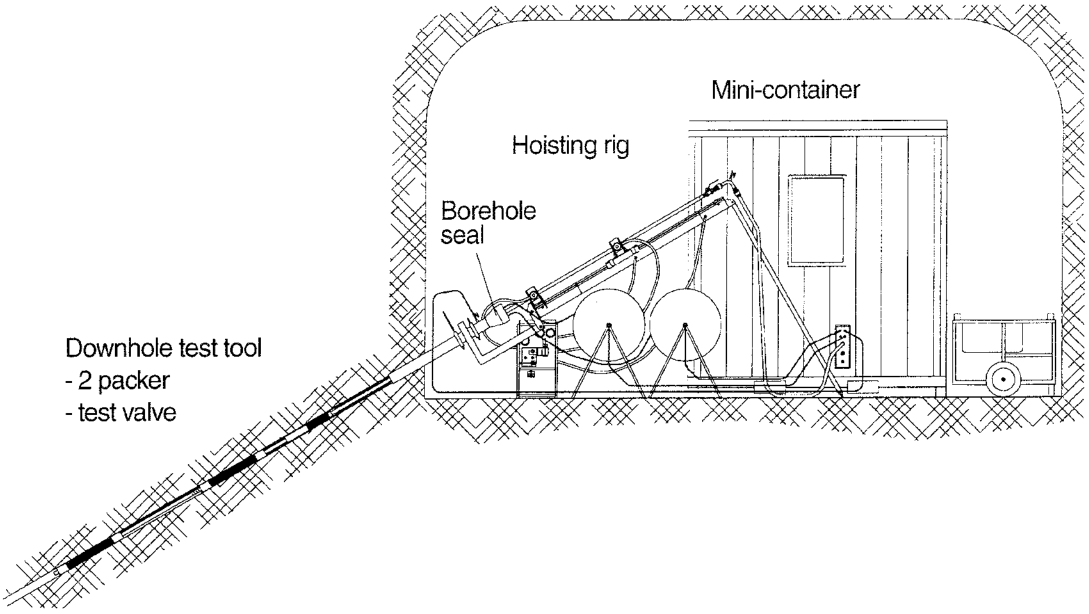
Geosigma was contracted for the construction and manufacturing of the system, excluding the rig which was manufactured by Liw-in Stone. All manufacturing and assembling work is now completed as well as functional tests have been made by the manufacturers. An overview illustration of the system is given in Figure 3-5.

A delivery and acceptance test of the entire system will be performed in March-April 1997. The programme for these test includes tests of system modules at the two manufacturers' workshop and, the most importance, functional tests in boreholes at Äspö.

3.5 UNDERGROUND MEASUREMENT METHODS AND METHODOLOGY

A summary report describing and evaluating the investigation methods and instruments used from underground during the construction phase of the Äspö HRL will be compiled. For all areas of methods, tunnel documentation, drilling, borehole geology, borehole geophysics, hydrogeology, etc., the individual methods and instruments will be described, the accuracies will be discussed and the methods will be judged with regard to feasibility and usefulness. Moreover, needs of further improvements for the methods will also addressed.

A first draft of the report has been written, but much editorial work still has to be done. The descriptive part of the report will include a number of illustrations, photos and diagrams. The evaluation part will include judgements by the principal investigators of the Äspö HRL based on experience from the construction phase.



Interior, system parts

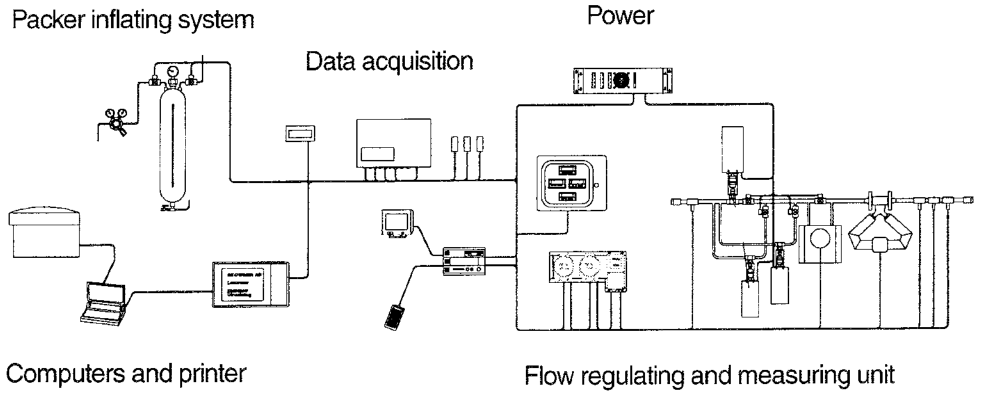


Figure 3-5. The system for Underground Hydraulic Testing (UHT-1).

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 the function of the host rock as a barrier is described by different models.

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 modeling groups work on the same set of field data. The modeling 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 modeling, 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 characterisation and classification also 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 characterisation of fractures with respect to rock type, tectonic evolution, infillings and wallrock alteration,

and by means of this characterisation 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 includes 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 (<1 m, 1-10 m, 10-100 m and >100 m).

4.2.4 Results

An initial classification of the fractures in the Äspö HRL tunnel indicated two classes, simple and complex. The results of the initial characterisation and preliminary classification has been reported in Progress Report 25-95-03. The full characterization of a large number of water conducting features has also been completed and reported in ICR 97-01. Main findings are:

The preliminary characterization stage indicated that on an observation scale of meters to decametres, all water-conducting features are related to faults. The fault geometries are consistent with the mechanic principles of fault nucleation, propagation and linkage derived by Martel & Pollard (1989). This model characterizes the anatomy of faults as interconnected systems of shear fractures (master faults) and tensile fractures (splay cracks).

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.

Fault geometries or any other parameters are indistinguishable in the Småland granite and in the Äspö diorite. Fracture frequencies are higher in the Fine-grained granite, and other fault characteristics contributing to the transport properties (e.g. lithologic units, mineralogy, distribution of pore-spaces) are also different. However, Fine-grained granite was never observed to be the dominating host rock of any of the features because it occurs as small intrusive bodies or dykes whose sizes are measured in meters to a few decametres. It is concluded that because (within the database of 88 water-conducting features) this rock type does not host faults over more than a few meters, it is not relevant for the larger-scale transport properties of the faults.

In the review process of this report, it was pointed out that the possibility exists that large bodies of Fine-grained granite could exist even if they were not observed in the part of the tunnel system on which this report is based. It is a topic of planned future investigations to explore and characterize faults hosted by Fine-grained granite.

The only striking difference between individual water-conducting features is the internal fault geometry, while no other distinguishing criteria (such as the arrangement of lithologic domains, mineralogy of fracture infills, transmissivity etc.) were identified and probably do not exist. 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 geometries.
Type 5 – parallel fault zones with long connecting splays.

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 large-scale 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 water-conducting features.

Conceptual models of the fault geometry are derived on the basis of the field database and laboratory analyses of mineralogy, porosity and pore-space distribu-

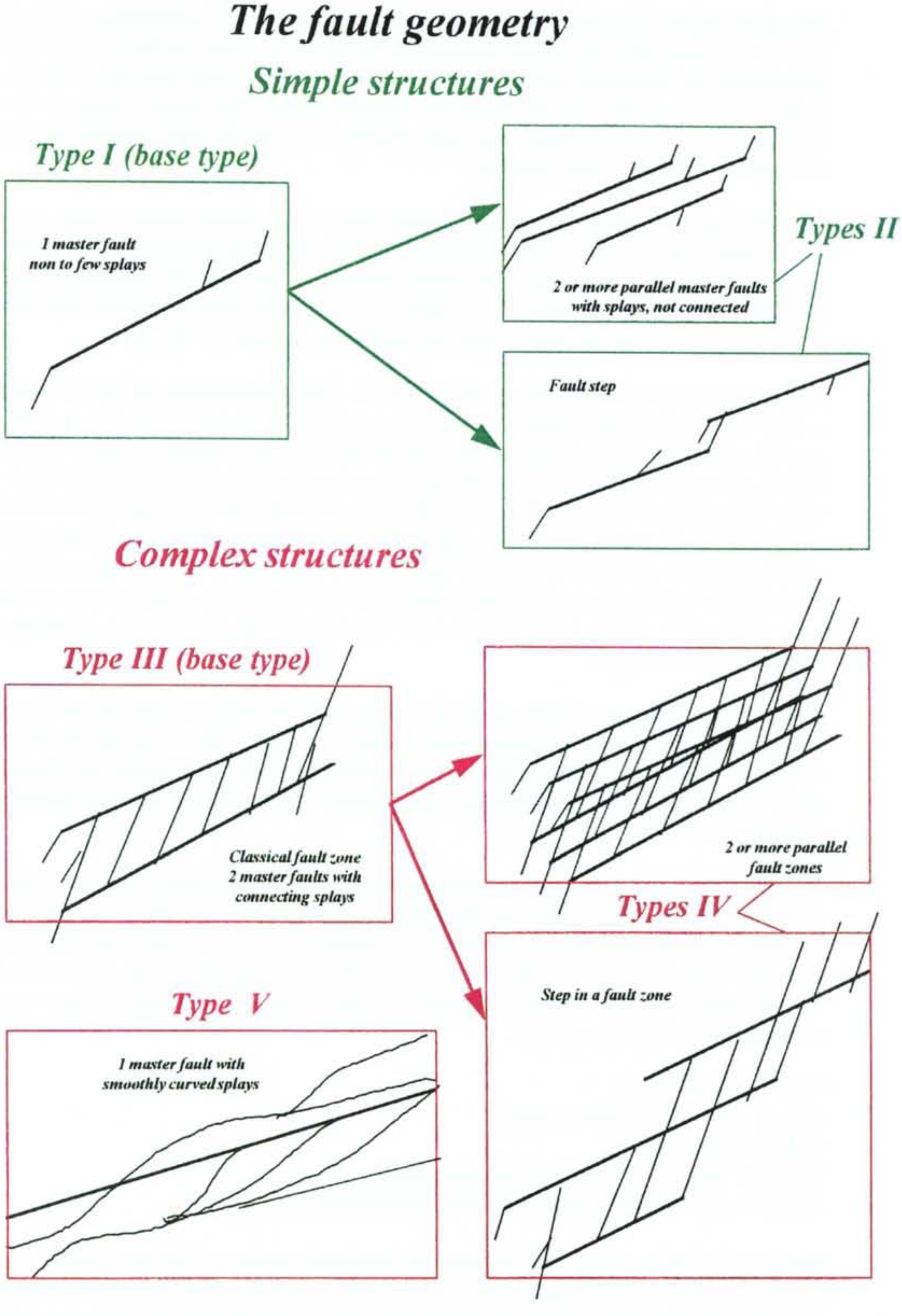


Figure 4-1. *The five different fracture types identified by the FCC project.*

tion. Flow within faults occurs within the master faults and/or in the splay cracks. The lithologic domains adjacent to the flow porosity are

- fault gouge/breccia,
- lithified cataclasite,
- fracture coating,
- mylonite (altered or unaltered),
- granite (altered or unaltered).

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.

4.2.5 Planned work

The plans for finalising the work follow along two lines. One line is to use the knowledge of the two previous phases to describe flow paths from the laboratory up to surface and to estimate the proportion of different fracture classes in these flowpaths. The radionuclide retardation properties of the different fracture classes will be included. The second line is to practically check the concept against the data and knowledge obtained from the TRUE tracer experiment and to describe the TRUE I site volume based on the FCC classification. A final check of the consistency of the work is to run a groundwater flow model based on a fracture network where the different fracture classes are included. This consistency check is, however, outside the present scope of the project. A final report on the project scheduled to the end of 1997.

4.3 PERMIT TO USE RADIONUCLIDES IN EXPERIMENTS

The Swedish Radiation Protection Institute (SSI) gave SKB a permit to use short-lived nuclides in three different type of experiments, the projects Radionuclide retention, TRUE and Long Term Test of Buffer Materials. The permit is valid up to 1998-12-31 and includes the nuclides which are planned to be used in this time period. The nuclides and the amount to be used in the different experiments are listed in Table 4-1.

In addition to the limitations given by the maximum activity, there is also a limitation put by the highest dose rate which should not exceed 2μ Sv/h at the fenced boundary of the experimental sites.

Table 4-1. Isotopes to be used in experiments.

TRUE		
Isotope	Halflife	Max inj. act. *
^{3}H	12.3 y	30000
^{14}C	5730 y	900
^{22}Na	2.602 y	63
^{24}Na	14.96 h	41
^{35}S	87.5 d	4000
^{36}Cl	$3 \cdot 10^{5}$ y	60
^{37}Ar	35.0 d	500000
^{42}K	12.36 h	500
^{43}K	22.2 h	100
^{45}Ca	163 d	600
^{47}Ca	4.54 d	100
^{51}Cr	27.7 d	4000
^{82}Br	35.34 h	50
^{85}Kr	10.76 y	50
^{86}Rb	18.7 d	200
^{85}Sr	64.9 d	70
^{89}Sr	50.5 d	200
^{90}Sr	28.5 y	10
^{95}Tc	60 d	200
^{99m}Tc	6 h	1000
^{99}Tc	$2.1 \cdot 10^{5}$ y	1000
^{111}In	2.81 d	300
^{114m}In	49.5 d	100
^{125}I	60.14 d	10
^{131}I	8.02 d	10
^{133}Xe	5.25 d	200
^{131}Cs	9.69 d	8000
^{134}Cs	2.06 y	30
^{137}Cs	30.17 y	40
^{131}Ba	11.5 d	300
^{133}Ba	10.5 y	300
^{147}Nd	10.98 d	400
^{153}Sm	46.75 h	600
^{152}Eu	13.33 y	100
^{155}Eu	4.96 y	1000
^{153}Gd	241.6 d	2000
^{159}Gd	18.56 h	1000
^{160}Tb	72.1 d	100
^{161}Tb	6.9 d	600
^{159}Dy	144.4 d	5000
^{166}Ho	26.8 h	300
^{169}Yb	32.0 d	600
^{175}Yb	4.2 d	1000
^{177}Lu	6.71 d	800
^{186}Re	3.78 d	700
^{234}Th	24.1 d	100
^{233}Pa	27.0 d	500
^{237}U	6.75 d	600
^{239}Np	2.355 d	600

CHEMLAB		
Isotope	Halflife	Max activity
^{57}Co	271.8 d	<0.1 MBq in each experiment
^{85}Sr	64.9 d	
^{99}Tc	$2.1 \cdot 10^{5}$ y	
^{125}I	60.14 d	
^{134}Cs	2.06 y	

LOT		
Isotope	Halflife	Max acitivity
^{57}Co	271.8 d	<1 MBq in each experiment
^{134}Cs	2.06 y	

* Max injected activity allowed in each injection (in MBq)

4.4 TRACER RETENTION UNDERSTANDING EXPERIMENTS

4.4.1 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 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 analyzed 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 conceptualize and parametrize an experimental site on a detailed scale (L=5 m) using non-reactive tracers in a simple test geometry.
- To improve tracer test methodologies for non-reactive tracer tests on a detailed scale.
- To develop and test a technology for injection of epoxy resin on a detailed scale and to develop and test techniques for excavation (drilling) of injected volumes, and
- 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 tracer experiments during the First Tracer test cycle. This has implied a prolongation of the First TRUE stage with another year, with reactive tracer tests to be performed late 1996.

Due to the development of new underground openings during the 4th quarter of 1996 through the first quarter of 1997, the tests with sorbing tracers have been postponed until May 1997. The time table for conclusion of TRUE-1 have been postponed accordingly with final reporting scheduled to be finished by June 1998.

Results

TRUE-1 characterization

One new component in the descriptive model of the TRUE-1 site is a hydraulically internally well connected zone, Zone NW-2' , which has been identified during a

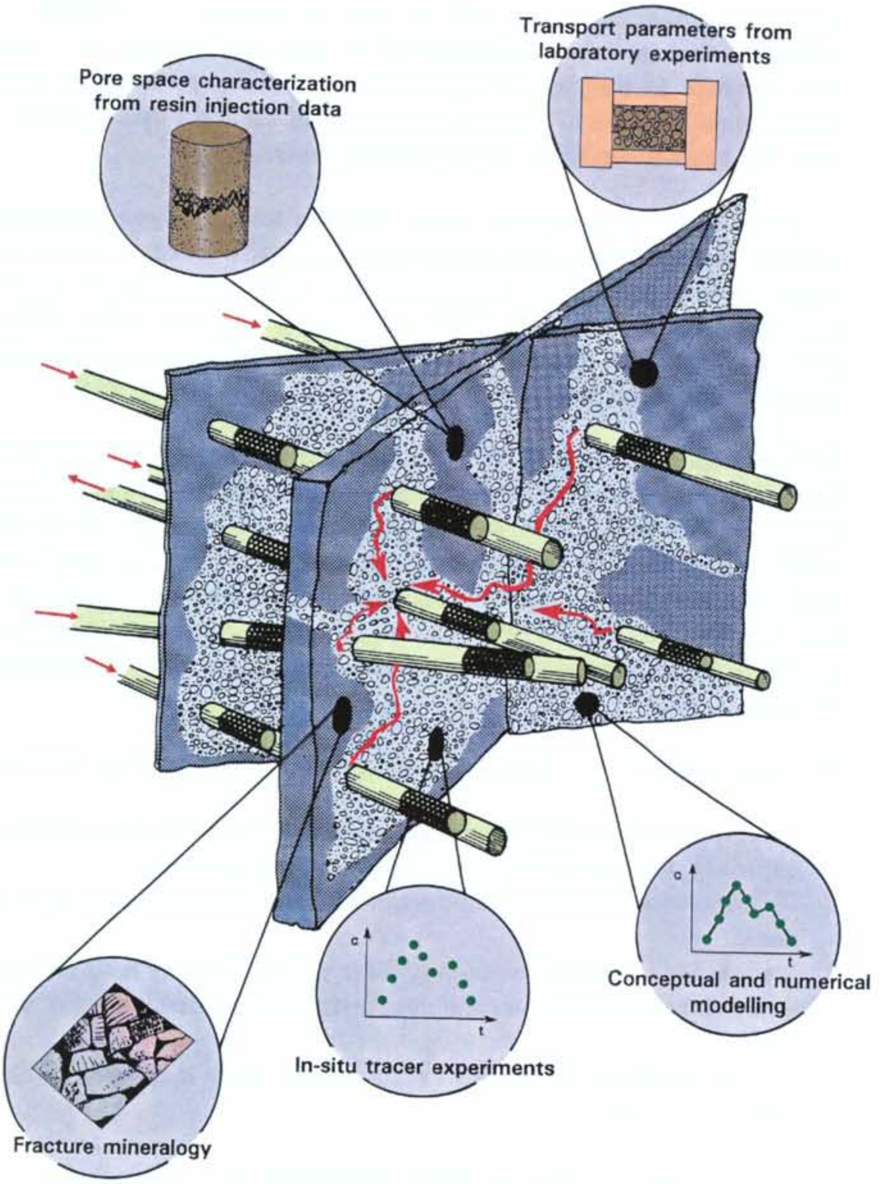


Figure 4-2. Principal outline and components of the TRUE-1 experiment.

revisitation of the interference test results. The zone is located immediately east of Feature A, is structurally less well defined, and is interpreted to be made up of at least three individual features, c.f Figure 4-3. Interference tests performed in the zone (test #8 in KXTT4:P2) show distinct responses in Feature A. Reciprocally, tests performed in Feature A show secondary responses in sections containing zone NW-2'. In light of the finding of NW-2', the pseudo-spherical flow dimension noted in studies of pressure derivatives can be interpreted such that the hydraulic system made up of Feature A and NW-2' constitutes a leaky aquifer system, cf. Winberg et al., (1996). The interference tests have consequently been reinterpreted using type curves for a leaky aquifer model. Transmissivities evaluated for Feature A range from $6 \cdot 10^{-8} - 6 \cdot 10^{-6}$ m^2/s with a leakage coefficient between K'/b' =

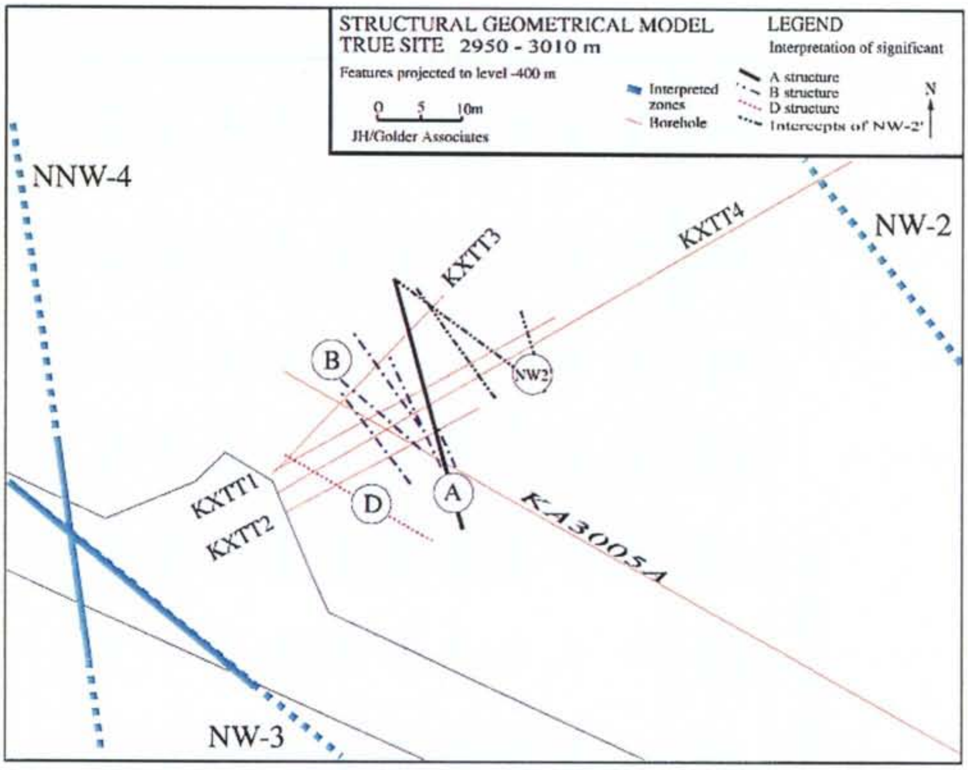


Figure 4-3. *Structural-geological model of the TRUE-1 site. Horizontal section at Z=-400 masl showing bounding minor fracture zones and identified features.*

$4 \cdot 10^{-10} - 6 \cdot 10^{-8}$ s^{-1}. The transmissivity of zone NW-2' has been evaluated to range between $10^{-6} - 10^{-5}$ m^2/s.

In addition detailed structural-geological mapping of the entire cores from KXTT1-KXTT4 and KA3005A, have been performed within the framework of collaboration between TRUE and FCC, c.f. Section 4.2.

A comprehensive groundwater chemical analysis campaign has been performed on waters collected from the TRUE-1 site. Analysis have been made in accordance with Äspö HRL Class 5 analyses (Ca, Fe, Co, Cr, Sb, Rb, Cs, Ba, Sr, Zr, Hf, Th, U, Sc, Eu, Tb, Yb and Ce (INAA), U and Th isotopes with α-spectroscopy, ^{226}Ra and ^{222}Rn) in all sections (N=5) containing Feature A, in Feature B (N=2), Zone NW-2' (N=1), NW-3 (N=1) and NNW-4 (N=1). Complementary analyses have been made of La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Rb, Cs, Tl, Ba, Re, Sc, Y, In, U and Th using ICP-MS.

Some of the more important components used in an assessment of the origin of the groundwaters sampled at the TRUE-1 site are listed in Table 4-2. The groundwaters are found to belong to the saline ([Cl] > 5000 mg/l) and brackish ([Cl] = 1000–5000 mg/l) groundwater types. The TRUE-1 groundwaters plot close to the meteoric water line which indicate that the sampled waters originate from an open system. Multivariate mixing calculations (Laaksoharju and Skårman, 1995) using TRUE-1 data has shown that Features A, B and NW-2' show similar and stable mixing portions resulting from mixing of glacial, marine and meteoric groundwaters. The water composition found in NW-3 and NNW-4 result from mixing of brine, glacial and meteoric groundwaters. The latter waters show lower tritium

Table 4-2. TRUE-1 – Listing of some important chemical constituents used in the assessment of the origin of groudwaters.

TRUE label	Section	Feature	Sample	Date	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	HCO_3 (mg/l)	Cl (mg/l)	SO_4 (mg/l)	^3H (TU)	^2H ‰ (SMOW)	^{18}O ‰ (SMOW)
KXTT1:R2	L=15.00-16.00	A	2341	960410	1768.9	14.06	1285.5	81.4	91	5084.0	343.25	16	-76.9	-10.2
KXTT2:R2	L=14.55-15.55	A	2348	960412	1754.3	13.79	1263.3	80.8	91	5119.4	357.71	22	-78.4	-10.2
KXTT3:R2	L=12.42-14.42	A	2343	960410	1775.9	14.33	1301.1	82.3	92	5091.1	347.00	24	-78.4	-10.2
KXTT4:R3	L=11.92-13.92	A	2345	960411	1763.7	14.16	1253.8	81.5	98	5013.1	343.00	18	-78.6	-10.1
KA3005A:R3	L=44.78-45.78	A	2344	960411	1730.0	13.63	1191.4	82.5	93	4878.3	350.60	30	-75.5	-10.0
KXTT2:R3	L=11.55-13.55	B	2347	960411	1632.2	11.60	963.7	79.7	124	4389.1	326.92	39	-68.4	-9.3
KXTT3:R3	L=8.92-11.42	B	2346	960411	1621.3	12.14	947.3	79.9	130	4296.9	295.1	20	-73.4	-9.3
KXTT4:R2	L=14.92-23.42	NW-2'	2340	960409	1731.7	14.08	1191.8	83.2	106	4920.9	329.82	25	-77.0	-9.9
KA3067A:P4	L=6.55-27.05	NW-3	2342	960410	2374.3	12.72	2705.6	49.3	10	8584.9	426.3	14	-95.2	-13.0
SA2880A	L=11.92-13.92	NNW-4	2349	960422	3156.4	13.64	4378.1	41.1	22	12956.3	625.3	17	-87.7	-12.3

values which are in accord with the lower portion of meteoric water shown by the mixing calculations.

The results will be used as a base for selecting tracers for the tests with sorbing tracers planned for TRUE-1.

TRUE-1 tracer test programme

During 1996 a series of tracer experiments in radially converging (RC-1) and dipole flow configuration (DP1-DP4) have been performed in Feature A using conservative fluorescent tracers and metal complexes. These tests have also been subject to blind predictions by the Äspö Task Force, cf. Section 4.7. Further, a set of complementary tests have been performed with the objective of providing final support for the planned tests with sorbing tracers.

Table 4-3. Summary of performed conservative tracer tests during 1995-1996.

TEST	GEOMETRY	TRACER(S)	RECOVERY
DILUTION #1	-	Uranine	–
PTT-1	T1→ T3 (Q=870 ml/min)	Uranine	95%
RC-1	T1→ T3 (Q=200 ml/min), successively increased to 400 and 3000 ml/min)	Uranine Gd-DTPA	93% 53%
	T2→T3	Rhodamine WT Eu-DTPA	0 0
	T4→ T3	Amino G Acid Ho-DTPA	100% 44%
	KA3005A→ T3	Eosin Y Tb-DTPA	0 0
DP-1	T1→ T3 (Q=10:100 ml/min)	Uranine Gd-DTPA	88% 90%
DP-2	T2→ T1 (Q=10:35 ml/min)	Amino G Acid	56%
DP-3	T2→ T1 (Q=3.5:35 ml/min)	Uranine	45%
DP-4	T2→ T4 (Q=10:50 ml/min)	Amino G Acid	30%
RC-2	T1→ T4 (Q=100 ml/min)	Uranine	5%
DP-5	T4→ T3 (Q=10:100 ml/min)	Amino G Acid	28%
DP-6	T4→ T3 (Q=10:200 ml/min)	Uranine	70%

The objectives of the performed tests were specifically to;

- test transport connectivity within Feature A (RC-1),
- test flow heterogeneity within Feature A (DP1-DP4),
- determine and compare transport parameters for selected conservative tracers (RC-1, DP1-DP4),
- test techniques, tracers and equipment for injection and sampling of tracers in low-transmissive rocks (RC-1, DP1-DP4),
- test alternative high mass recover flow paths for the planned tests with sorbing tracers using radially converging and dipole flow fields (RC-2, DP5-DP6),

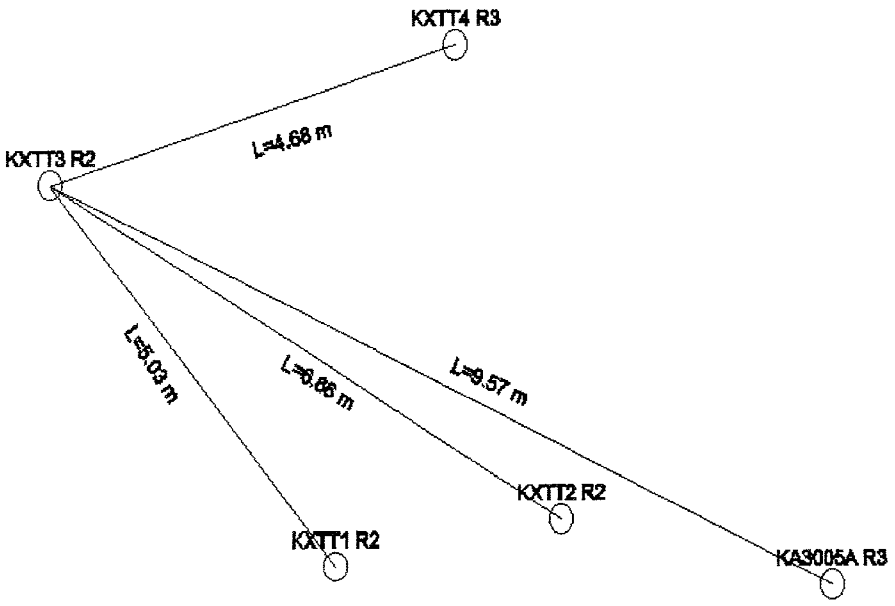


Figure 4-4. *Borehole intersections with Feature A visualized in the plane of the feature. Distances given in metres.*

- test of finite pulse injection scheme to improve identification of processes (RC-2).

Table 4-3 and Figure 4-4 summarize the performed tracer tests, the respective geometries used and tracers used in the experiments.

The radially converging tracer test (RC-1) was initiated in mid January 1996 by establishing a steady flow of 0.2 l/min in section KXTT3:R2, After about a week two tracer injections were performed in KXTT1:R2 and KXTT4:R3, cf. Figure 4-4. Subsequently, a second set of tracer injections were introduced in KXTT2:R2 and KA3005A:3.

The experiment showed breakthrough from the two injection sections in KXTT1 and KXTT4 with mass recoveries of 91 and 97%, respectively, (Andersson, 1996). The breakthroughs show little or no effects of processes, ie. the breakthroughs are simply translations in time of the injection signal. No breakthrough was observed from the remaining two injection sections in KXTT2 and KA3005A, which are located farthest away from the pump hole, and which also are located closest to the tunnel. A subsequent stepwise increase in the pump flow to 400 ml/min and finally 3.4 l/min, enabled breakthrough from the remaining two injection sections, but with very low mass recoveries. A preliminary comparison between model predictions made by the Äspö Task Force and 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 breakthrough. The SKB TRUE Project team predicted breakthrough for all four injections at the initial pump rate, cf. Selroos and Cvetkovic, in prep. Figure 4-5 shows that the agreement between predicted and experimental breakthrough is quite good. The breakthrough times predicted by the modelling teams are also in accord with those observed in the experimental results.

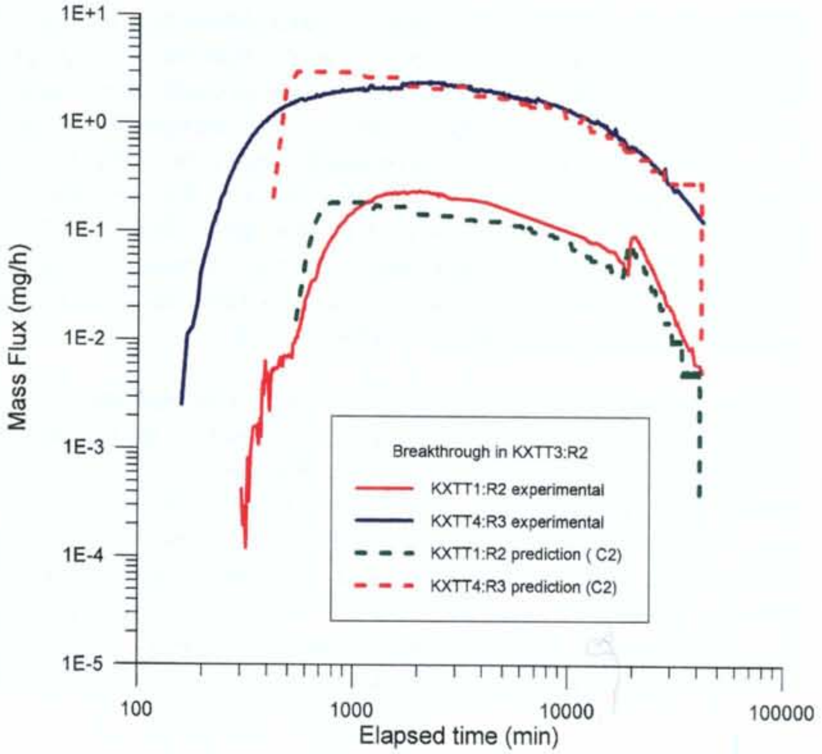


Figure 4-5. *Tracer breakthrough during TRUE-1 RC-1. Comparison between predictions (ensemble results) made by the SKB TRUE Project team and the corresponding experimental results (log-log representation).*

The latter can to a large extent be explained by the calibration of transmissivity and flow porosity against the performed preliminary tracer tests, one of which utilized a flow path successfully tested in RC-1. From the predictions, performance measures have been calculated for breakthrough time t_5, t_{50}, t_{95}, defined as the time when 5, 50, and 95% of the mass has been recovered. Table 4-4 compares the prediction results of the TRUE team with the experimental results. Most modelling teams overpredicted the drawdown in the injection sections resulting from the pumping, which show that the confined aquifer representations commonly used do not reflect the leaky aquifer behaviour attributed to Feature A.

Table 4-4. TRUE-1 RC-1. Comparison between predictions of travle time made by the SKB TRUE team and experimental results. Predictions conditioned on measured transmissivities and *in-situ* steady state head data (natural and induced flow conditions).

Injection section	t_5 (hours)	t_{50} (hours)	t_{95} (hours)
KXTT1:R2 Prediction	19.6	150.2	463.5
KXTT1 R2 Experimental	25.5	154	488
KXTT4:R3 Prediction	16.5	151.9	592.5
KXTT4:R3 Experimental	20.9	156	560

Subsequent to the RC-1 test, a series of four dipole experiments (DP1-DP4) have been performed, Andersson et al. (in prep). Performed scopings of the planned dipole tests in Feature A highlighted the need to establish unequal strength dipoles to ensure sufficient mass recovery. The relative strengths of the performed tests are indicated in Table 4-3. The experimental results show that the recovery is lower than RC-1 for the flow path KXTT1:R2->KXTT3:R2. The breakthrough curve for this test is shown in Figure 4-6. The flow paths KXTT2:R2->KXTT1:R2 and KXTT2:R2->KXTT4:R3 show low recoveries. A basic preliminary evaluation in 2D using SUTRA (inverse mode) yields consistent values of hydraulic conductivity, flow porosity and dispersivity (D/v=0.2-0.5m).

In September 1996 three complementary tests were performed to assist in locating the planned test with sorbing tracers, Andersson et al. (in prep). The RC-2 test showed that the flow path KXTT1:R2-> KXTT4:R3 is not suited for further study due to low mass recovery. The test of finite pulse injection showed that the procedure employed worked, but could be made more efficient. The tests in dipole configuration, DP5 and DP6, showed that tracer losses occur in the flow field between KXTT4:R3 and KXTT3:R2. In order to ascertain a high mass recovery the relative dipole strength (injection/pumping) needs to be less than 1:20. The breakthrough curve for uranine for diple test DP6, cf. Table 4-3, is shown in Figure 4-7.

An experimental plan for the planned tests with sorbing tracers have been prepared (Andersson et al., 1997). This plan was presented and reviewed at a TRUE-1 Review meeting in January 1997. The basic idea is to perform a series of three tracer tests with one truly non-sorbing tracer (tritiated water), and a selection of weakly sorbing (Na, Ca, Sr) and moderately sorbing tracers (Rb, Ba, Cs). The tests will tentatively be performed in a radially converging flow field at Q=400, 200 and 100 ml/min. The test geometry is KXTT1->KXTT3 or KXTT4->KXTT3. The input function will be monitored in-line using a portable HPGe detector. Analysis of the collected water samples will be performed at the newly established BASLAB at the CLAB facility. During late March and April 1997, site preparations and pre-tests will be carried out. The tests with sorbing tracers are scheduled to start in May and will continue for a duration of three to four months.

Pilot Resin Injection Experiment

The objective of the Resin technology development is to establish a technique by which a description of the pore space of a feature investigated with tracer tests can be mapped by epoxy resin injected into the feature. 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. In addition, the collected data is important for further development of the conceptual understanding of fracture void space.

At the Pilot Resin site a test of injection techniques and equipment and resins is carried out in-situ in a fracture system close to the drift wall. Site characterization work has been carried out at the site (in the F-tunnel) with the objective of constructing a structural-hydraulic model of the identified fracture and its immediate surroundings. Ten short characterization boreholes were drilled on the identified feature. The collected drill cores have been logged and photographed. The holes have been surveyed and logged with a borehole TV camera. In addition flow

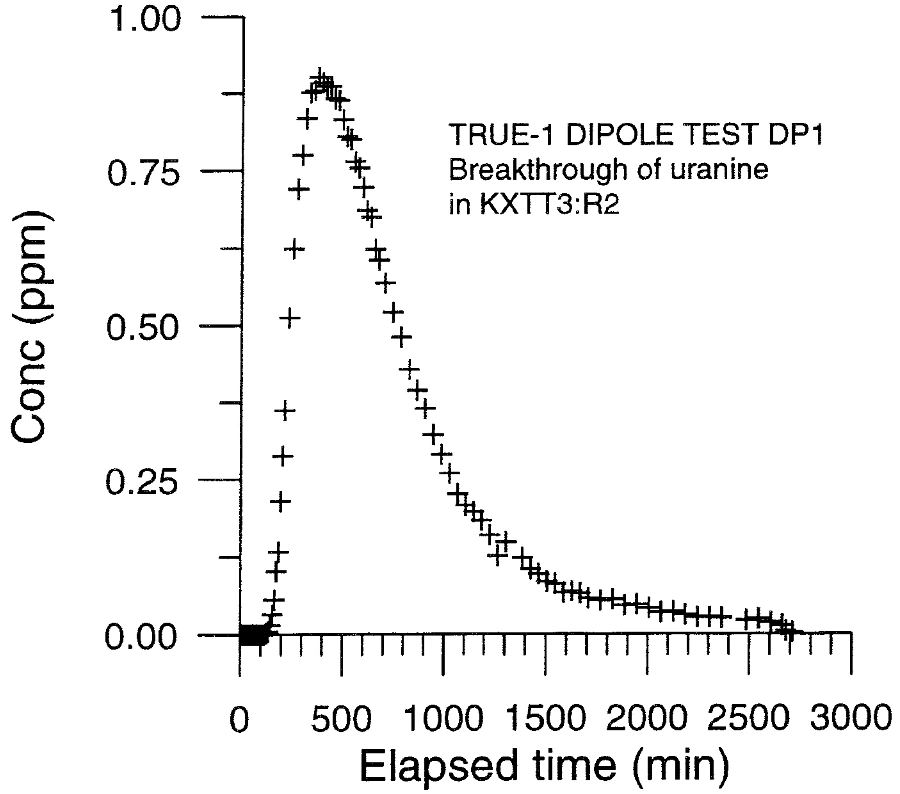


Figure 4-6. Breakthrough curve for uranine for TRUE-1 dipole test DP-1.

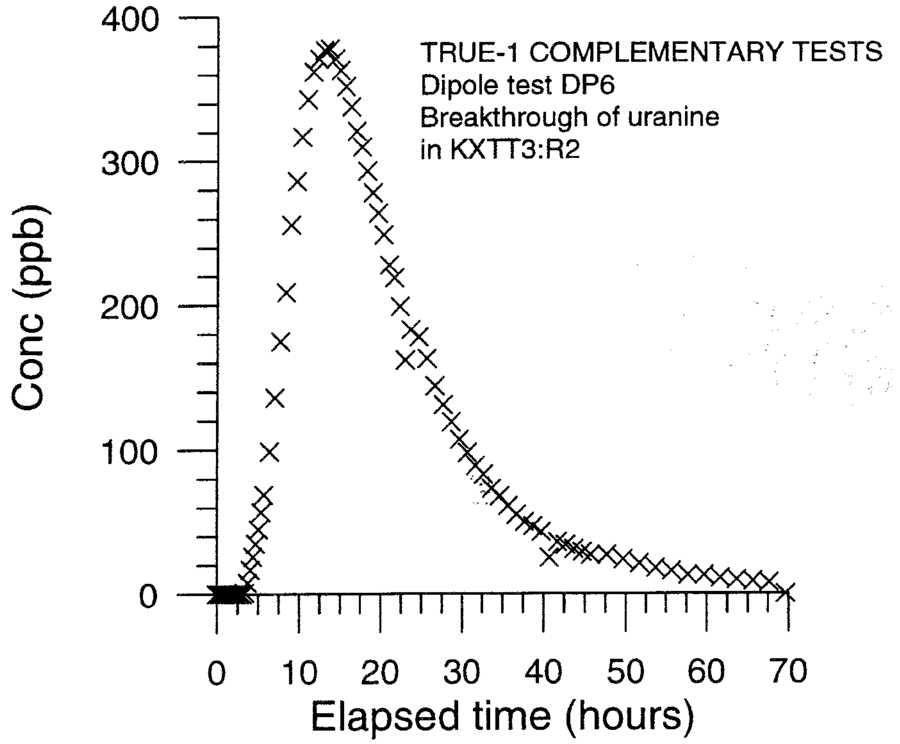


Figure 4-7. Breakthrough curve for uranine for TRUE-1 dipole test DP-6.

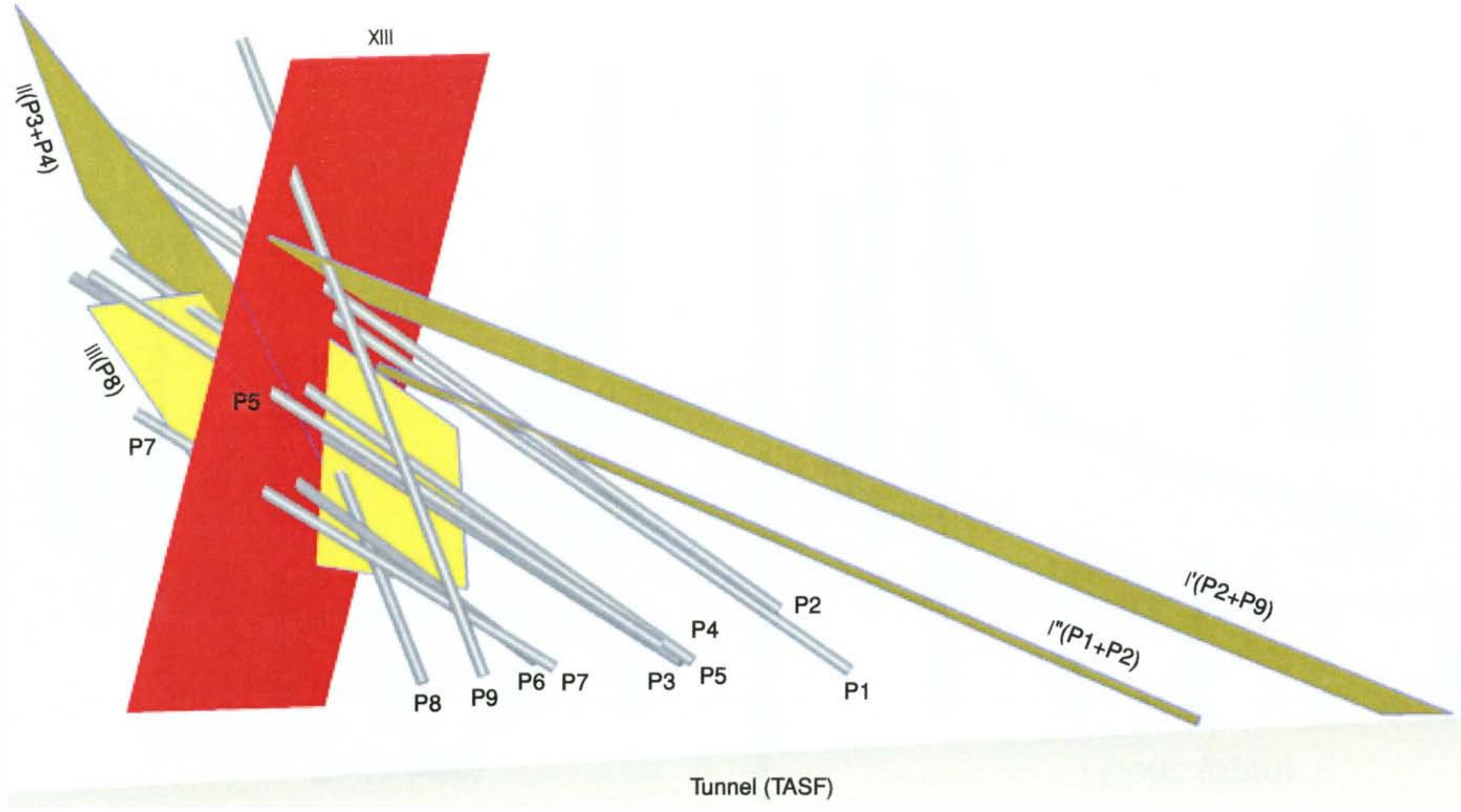


Figure 4-8. *Horizontal section through the 3D CAD model of the Pilot Resin Injection site in the F-tunnel.*

logging using a single packer and short time interference tests has been performed with the aim of identifying the conductive parts of the boreholes and hydraulic connectivity within the instrumented array. The recorded inflows from the interesting parts of the holes range from 0.01-0.08 l/min.

The characterization data collected at the Pilot Resin site have been integrated and compiled in a 3D CAD model. The analysis indicated that the original fracture which was targeted by the boreholes indeed is not the only conductive feature responsible for the noted inflows and connectivity. The conductive fracture planes I' and I" are trending northwest and connect boreholes KXTP1-KXTP2 and KXTT2-KXTP9, respectively, c.f. Figure 4-8. A third fracture plane, II, connects boreholes KXTP3 and KXTP4. All four planes intersect the original target fracture, which is denoted XIII. The performed interference tests showed interconnectivity between KXTP1, KXTP2 and KXTP9, which is also sustained by a tracer test under natural gradient performed with injection in KXTP2, which yielded breakthrough in KXTP1 and KXTP9. A similar injection of tracer in KXTP3 did not yield breakthrough in KXTP4 or in any other borehole.

During August-September 1996 a series of three resin injections were performed. The injection sequence started with injection of dye-labelled water in a given section with all other holes closed. The purpose of the dye (Rhodamine B) is to tag the flow paths participating in groundwater flow, this to enable comparison between the porosity impregnated by the resin. Subsequently, dye-labelled isopropyl alcohol was injected to ensure good wettability and avoidance of fingering effects. Finally injection of dye-labelled resin was performed. Different colours were used for each of the three injections, green, red and blue. The ambient pressures in the borehole sections prior to the activity ranged from 18 to 20 bars. Injections have been made in KXTP7 (V=300 ml), KXTP3 (V=2000 ml) and in KXTP1 (V=1500 ml). A fourth injection in KXTP2 did not succeed due to packer failure in the hole. The injection periods lasted between 5-7 hours with injection pressures kept between 30-55 bars. Simplistic calculations predict the aerial spread of the resin to be in the order of square metre(-s).

Subsequent to the injections, ten short 56 mm boreholes have been drilled with the aim of obtaining a picture of the aerial spread of resin. The cores have been logged with regards to lithology and structural characteristics of fractures associated with either coloured dye or resin occurrence. More than 50% of the drilled exploratory holes carried resin. The cores were intentionally opened up such that resin occurrence could be mapped. In most cases the resin had a somewhat flakey occurrence with poor bonding to the fracture surfaces. Using these observations as guide, three 200 mm cores were drilled parallel to three of the exploratory holes. The holes were drilled centred on 36 mm pilot holes were a 20 mm bolt with a bottom expander anchor was used to keep the core together axially. The employed technique did not suffice to maintain the cohesion of the core segments. The main influence is attributed to the dead weight of the core (approx. 75 kg/m) which in the case of a horizontal borehole, and the mismatch between the pilot hole diameter and the steel rod, enabled severe erosion of resin impregnated fractures.

In order to remediate the sampling, a technique using 146 mm triple tube drilling and 36 mm pilot hole and anchor bolt was used. The anchor bolt was in this case cemented in using epoxy resin with a different colour. The technique used showed significantly improved performance with regard to overall integrity of the core. However, since the outer diameter of the core is 102 mm, improved cohesion of the core is traded for reduced surface area (pore space data). It should also be noted that indications of combined effects of poor drilling advance due to the increased cutting area in combination with stress relief (core discing) has been noted in the case of the latter technique.

The plans for 1997 include logging of the large diameter cores and planning and execution of the analysis of pore space and reporting of the Pilot Resin experiment. The results of the Pilot Resin experiment will constitute the basis for planning of the resin injection in Feature A at the TRUE-1 site.

4.4.2 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 batch sorption and through diffusion measurements have been conducted on site specific material from Feature A, which is presently being investigated in the TRUE-1 experiments, cf. Section 4.4.1.

Rock samples have been sent to the University of Helsinki for studies of the porosity and porosity distribution with the ^{14}C-MMA impregnation method. The results are presently under evaluation.

Comparative gas diffusion tests of some rock specimens have been performed at the University of Jyväskylä.

Evaluation and integration of laboratory data for use in scoping calculations for the planned tests with sorbing tracers in Feature A has been performed. Data on porosity, matrix diffusion, matrix sorption and surface sorption have been calculated/estimated for the tracers proposed to be used in the tests.

Experimental

Batch sorption experiments on material from Feature A

For the batch part of these experiment, both the sorption and desorption measurements have been performed. The tracers that were used were $^{82}Br^-$, $^{131}I^-$, $^{186}ReO_4$-, ^{169}Yb-EDTA, ^{160}Tb-DTPA, ^{177}Lu-DOTA, Uranine, Amino G Acid and Rhodamine WT (non-sorbing tracers) together with $^{22}Na^+$, $^{47}Ca^{2+}$, $^{86}Rb^+$, $^{85}Sr^{2+}$, $^{137}Cs^+$ and $^{133}Ba^{2+}$ (sorbing tracers). Gamma-spectrometric measurements of all collected samples have been conducted and the spectra have been evaluated in order to determine the amount of sorption that occurred for the different tracers.

Through diffusion experiments on core material from Feature A

A preliminary evaluation of the through diffusion in the diffusion cell with site specific material has been performed. Samples on the low concentration side of the diffusion cell have been measured using γ-spectrometry, and the spectras have been evaluated in order to determine the accumulated amount of activity. HTO was measured by liquid scintillation counting. Samples were also collected for measurements of the fluorescent dyes. Sampling is continued for the sorbing tracers that has not decayed, i.e. $^{22}Na^{+}$, $^{85}Sr^{2+}$, $^{133}Ba^{2+}$ and $^{137}Cs^{+}$.

Results

Through diffusion and batch sorption experiments on generic Äspö material

Diffusion experiments with tritiated water ($H^{3}HO$, HTO), sodium ($^{22}Na^{+}$), strontium ($^{85}Sr^{2+}$) calcium ($^{45}Ca^{2+}$), rubidium ($^{86}Rb^{+}$), cesium ($^{137}Cs^{+}$) and barium ($^{133}Ba^{2+}$), have been performed. Sampling of all cells is finished except for $^{137}Cs^{+}$ and $^{133}Ba^{2+}$ for which monitoring continues. Breakthrough has occurred of $^{137}Cs^{+}$ on the target side of the 1 cm diffusion cell containing fine-grained granite and $^{133}Ba^{+}$ in the 1 cm Äspö-diorite, respectively. At this point only a very limited number of measurements have been performed and no diffusivity calculations have therefore been made for these experiments.

The evaluated diffusivities and rock capacity factors for all diffusion cells are presented in Table 4-5. The K_d values for Na, Ca and Sr obtained from the diffusion measurements were calculated using HTO in each diffusion cell in order to determine the porosity of each sample. A diffusion-based K_d was then obtained from the definition of the rock capacity factor, $\alpha = \varepsilon + K_d\rho$.

A comparison of the K_d values obtained from sorption experiments and diffusion experiments is presented in Table 4-6. Earlier results have shown that K_d values decrease with increasing size fraction. The largest size fraction, 2-4 mm, is the most representative when comparing the K_d values obtained in batch experiments with the K_d values obtained in the diffusion experiments. Possibly, this is due to the fact that the largest fraction consists of whole mineral grains, whereas the smaller fractions consists of crushed grains with increased surface areas. The surface areas measured by BET gas adsorption show a factor 10 larger surface area for the smallest fractions compared to the largest fraction. It should be noted that the batch K_d values even for the largest size fraction are considerably higher than the diffusion K_d values. This can probably be explained by the effects of crushing, which creates new surfaces and may increase the accessibility for pores that may not be representative for the intact rock material.

The results of diffusion and batch sorption experiments with Na^{+}, Ca^{2+} and Sr^{2+} have been summarised in a paper was presented at the Materials Research Society (MRS) fall meeting in Boston, USA (Johansson et al., in press).

From the basis of the batch and diffusion experiments with Na, Ca and Sr it can be concluded that:

Table 4-5. Evaluated effective diffusivities (D_e), rock capacity factors (α), sorption coefficients (K_d) and rock formation factors (F), for Äspö diorite (Äd) and fine-grained granite (Fgg).

Cell nr	Nuclide	Rock type	Cell size (cm)	D_e *) (m^2/s)	α (1)	K_d (m^3/kg)	$F_{(HTO)}$ (1)	$F_{(sorb)}$ (1)	$F_{(sorb)}/F_{(HTO)}$ (1)
1	HTO	Fgg	1	1.0±0.01E-13	4.7±0.3E-03		4.3E-05		
	Na-22			6.4±0.01E-14	1.1±0.02E-02	2.6±0.2E-06		4.8E-05	1.13
2	HTO	Fgg	2	7.5±0.12E-14	4.4±0.3E-03		3.1E-05		
	Na-22			6.0±0.1E-14	1.3±0.01E-02	3.2±0.2E-06		4.5E-05	1.44
3	HTO	Äd	1	1.4±0.01E-13	4.4±0.3E-03		6.0E-05		
	Na-22			7.8±0.1E-14	8.5±0.2E-03	1.5±0.2E-06		5.9E-05	0.98
4	HTO	Äd	2	1.2±0.01E-13	4.3±0.2E-03		5.1E-05		
	Na-22			7.3±0.1E-14	1.1±0.02E-02	2.3±0.2E-06		5.5E-05	1.08
5	HTO	Äd	4	3.2±0.12E-14	8.6±0.8E-04		1.3E-05		
	Na-22			1.3±0.1E-14	2.1±0.01E-03	4.6±0.3E-07		9.9E-06	0.75
6	Na-22	Fgg	4	6.2±0.1E-14	7.0±0.1E-03			4.7E-05	
7	Na-22	Äd	4	1.6±0.1E-14	2.4±0.03E-03			1.2E-05	
8	HTO	Fgg	1	1.2±0.03E-13	3.4±1.0E-03		5.1E-05		
	Sr-85			3.5±0.1E-14	2.5±0.02E-02	8.2±0.5E-06		4.5E-05	0.88
9	HTO	Fgg	2	6.2±0.35E-14	2.4±0.5E-03		2.6E-05		
	Sr-85			7.9±0.3E-15	4.4±0.05E-03	7.5±2.0E-07		9.9E-06	0.39
10	HTO	Äd	1	1.9±0.03E-13	9.8±1.1E-03		8.1E-05		
	Sr-85			6.3±0.1E-14	2.9±0.03E-02	6.9±0.5E-06		7.9E-05	0.98
11	HTO	Äd	2	1.4±0.07E-13	5.3±0.9E-03		5.7E-05		
	Sr-85			2.8±0.1E-14	1.2±0.01E-02	2.5±0.4E-06		3.6E-05	0.63
14	HTO	Fgg	1	4.0±0.08E-13	8.6±2.6E-03		1.7E-04		
	Ca-45			1.4±0.03E-13	1.8±0.1E-02	3.6±1.5E-06		1.8E-04	1.06
15	HTO	Äd	1	1.2±0.03E-13	5.5±1.2E-03		5.2E-05		
	Ca-45			4.3±0.1E-14	2.1±0.1E-02	5.5±0.8E-06		5.4E-05	1.05
16	HTO	Fgg	2	2.2±0.07E-13	5.3±0.8E-03		9.2E-05		
	Ca-45			7.3±0.12E-14	1.4±0.08E-02	3.5±E0.6-06		9.3E-05	1.00
17	HTO	Äd	2	8.5±0.48E-14	1.9±0.5E-03		3.6E-05		
	Ca-45			3.2±0.01E-14	1.5±0.08E-02	4.9±0.5E-06		4.1E-05	1.15
18	HTO	Fgg	1	6.8±0.12E-14	1.2±0.3E-03		2.8E-05		
19	HTO	Äd	1	9.6±0.18E-14	3.5±1.0E-03		4.0E-05		
20	HTO	Fgg	2	4.3±0.21E-14	8.9±1.8E-04		1.8E-05		
21	HTO	Äd	2	9.3±0.56E-14	2.2±0.5E-03		3.9E-05		
22	HTO	Fgg	1	1.8±0.03E-13	4.1±1.3E-03		7.5E-05		
23	HTO	Äd	1	1.4±0.01E-13	2.1±0.5E-03		5.7E-05		
24	HTO	Fgg	2	5.1±0.25E-14	1.1±0.3E-03		2.1E-05		
25	HTO	Äd	2	1.0±0.05E-13	3.2±0.6E-03		4.2E-05		
26	HTO	Fgg	1	7.2±0.12E-14	4.9±0.6E-03		3.0E-05		
27	HTO	Äd	1	1.4±0.05E-13	7.7±2.3E-03		5.9E-05		

‘) Errors are given as one standard deviation

Table 4-6. K_d values evaluated from the 2-4 mm size fraction and average diffusion K_d for Na^+, Ca^{2+} and Sr^{2+}. For rock type notations, cf. Table 4-5.

Tracer	Rock type	K_d, largest size fraction (m^3/kg)	K_d, diff. exp (m^3/kg)
Na^+	Äd	6.6±0.6E-6	1.4±0.6E-6
	Fgg	4.0±0.5E-6	2.9±0.4E-6
Ca^{2+}	Äd	3.8±1E-5	5.2±1.3E-6
	Fgg	1±0.3E-5	3.6±1.5E-6
Sr^{2+}	Äd	3.4±0.8E-5	4.7±0.8E-6
	Fgg	1.3±0.5E-5	4.5±0.6E-6

- Prediction of K_d, for weakly, ion exchangeable sorbing tracers in laboratory diffusion experiments, based on laboratory batch experiments, may overestimate the matrix diffusion related K_d if small size fractions are used. The comparisons show that large size fractions are the most representative for estimating the K_d in bulk rock samples. This is attributed to the fact that these fractions consist of primarily of polymineralic grains.
- The observed differences in D_e between HTO and Na^+, Ca^{2+} or Sr^{2+} are attributed to differences in water diffusivity, Dw. No influences of the material properties on D_e have been observed.
- There is a tendency of decreasing D_e and α with increasing cell length, indicating that the transport porosity (and the storage porosity) decreases with increasing cell lengths. It is probable that the shorter samples overestimates the D_e and α since the length of the samples are of the same size as the scale of heterogeneity of the samples.

Experiments on site-specific material from Feature A

In the diffusion part of this experiment, breakthrough have been observed for $^{82}Br^-$, $^{131}I^-$, $^{186}ReO_4$-, ^{169}Yb-EDTA, ^{160}Tb-DTPA, ^{177}Lu-DOTA, $^{22}Na^+$, $^{85}Sr^{2+}$ and $^{45}Ca^{2+}$. Minor traces of $^{137}Cs^+$ and $^{133}Ba^{2+}$ have also been detected, cf. Figure 4-9. A preliminary evaluation of the diffusion results shows that HTO has a diffusivity of approximately $3 \cdot 10^{-14}$ m^2/s and that the porosity of the sample is 0.1%. The diffusivity and porosity shown by the iodide (I^-) and bromide (Br^-) is much lower than expected, which indicates the effect of anion exclusion. This is to be expected since the material has a very low porosity.

Unfortunately, in the metal complex part of these experiments and the experiment involving sorption on borehole equipment, it appears that only a part of the metal ions used (Yb, Tb and Lu) were actually complexed with the complexing agent (EDTA, DTPA and DOTA). The reason for this is not fully understood and is presently being investigated further.

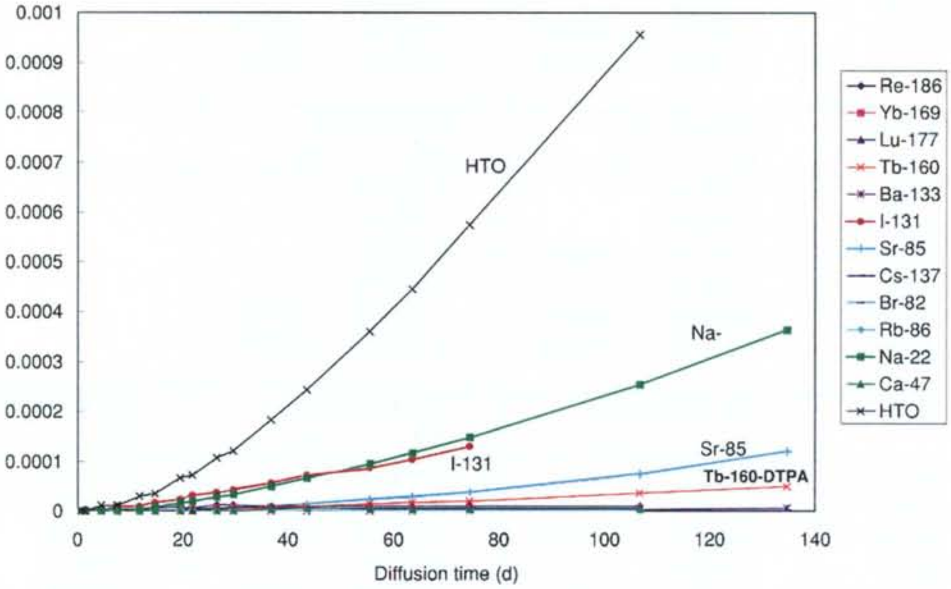


Figure 4-9. *Diffusion cell with site specific material from Feature A. Breakthrough curves for different tracers. Scaled ratio of concentration vs. diffusion time.*

The results of the batch experiments are presented in Tables 4-7 and 4-8. Evaluation of the results is in progress. Preliminary observations from the batch experiments indicate small differences in sorption capacity between the fresh material, altered granite or the mylonite. For the more strongly sorbing Cs, there is an indication of decreased sorption strength with increased degree of alteration, which may be due to the degradation of biotite, which is known to sorb Cs strongly.

The planned work for 1997 include continued measurements of diffusion in the Cs- and Ba-cells, reporting of the experiments on generic Äspö material and continued analysis of the diffusion cell with site-specific material from Feature A. The porosity distribution of the Sr cells will be examined by the ^{14}C—MMA method in collaboration with the University of Helsinki. A selection of cells will be measured with electrical resistivity measurements and gas diffusion for the purpose of comparison of methods.

Table 4-7. Site-specific material from Feature A. K_d values evaluated for Äspö diorite, mylonite and altered granite.

K_d values evaluated for slightly sorbing tracers. The solid phases used are Feature A specific materials (mylonites and altered granites) together with some generic materials (Äspö Diorite and Granite). The solid material was crushed and sieved and the 1-2 mm fraction was used for this experiment. The synthetic groundwater that was used had the same composition as the Feature A groundwater. 8.5 ml of synthetic groundwater was contacted to 2 g of solid material. This table show the K_d-values obtained from measuring the losses of tracers in the liquid phase and calculating the K_d from the mass balance, "sorption-K_d". The values presented are given for a contact time of 9 days.

Tracer	Äspö Diorite		FGG	
	Kd	+/-	Kd	+/-
Na-22	< 2.80E-05		< 1.23E-05	
Ca-47	< 4.40E-05		< 4.76E-04	
Rb-86	1.42E-03	3.49E-04	< 5.93E-04	
Sr-85	< 2.25E-04		< 1.04E-04	
Cs-137	1.40E-02	1.16E-03	1.61E-03	1.99E-04
Ba-133	1.19E-03	1.17E-04	6.28E-04	1.25E-04

Tracer	Mylonite T2		Mylonite T4	
	Kd	+/-	Kd	+/-
Na-22	< 2.19E-04		< 3.11E-04	
Ca-47	< 5.32E-04		< 7.11E-04	
Rb-86	2.05E-03	4.30E-04	< 5.39E-04	
Sr-85	< 2.62E-04		< 1.66E-04	
Cs-137	8.00E-03	5.62E-04	1.18E-03	1.89E-04
Ba-133	1.31E-03	1.31E-04	3.72E-04	1.26E-04

Tracer	Alt. Granite T2		Alt. Granite T3		Alt. Granite T4	
	Kd	+/-	Kd	+/-	Kd	+/-
Na-22	< 1.19E-04		< 6.02E-05		< 1.50E-04	
Ca-47	< 6.16E-05		< 6.32E-04		< 3.12E-04	
Rb-86	8.89E-04	3.72E-04	3.78E-04	3.13E-04	< 5.15E-04	
Sr-85	< 3.54E-05		< 9.36E-05		< 3.93E-04	
Cs-137	1.10E-02	9.63E-04	3.14E-03	2.25E-04	1.46E-03	1.97E-04
Ba-133	1.16E-03	1.38E-04	1.81E-03	1.37E-04	4.11E-04	1.24E-04

Table 4-8. Site-specific material from Feature A. Desorption K_d values for Äspö diorite, mylonite and altered granite

The K_d-values for the slightly sorbing tracers on different feature A material, see previous table for experimental details. This K_d-values are desorption K_d, i.e., After a contact time of 9 days, the tracer spiked water was removed and new non-spiked synthetic groundwater was contacted to the solid phase. The K_d was thus from the ratio of the desorbed tracer concentration versus the concentration of tracers which were not sorbed in the spiked water.

Tracer	**Äspö Diorite**		**FGG**			
	K_d	+/-	K_d	+/-		
Na-22	3.78E-06	7.06E-08	5.98E-06	9.14E-08		
Ca-47	5.42E-05	3.62E-06	< 2.20E-05			
Rb-86	5.88E-04	1.14E-05	2.52E-04	6.09E-06		
Sr-85	1.08E-04	1.71E-06	3.05E-05	6.19E-07		
Cs-137	1.40E-03	7.15E-06	4.84E-04	4.87E-06		
Ba-133	7.45E-04	5.43E-06	4.51E-04	3.81E-06		
Tracer	**Mylonite T2**		**Mylonite T4**			
	K_d	+/-	K_d	+/-		
Na-22	6.83E-06	9.34E-08	2.55E-06	6.91E-08		
Ca-47	2.68E-05	1.80E-06	1.71E-05	1.86E-06		
Rb-86	5.06E-04	9.46E-06	1.30E-04	3.32E-06		
Sr-85	5.01E-05	8.12E-07	2.65E-05	5.41E-07		
Cs-137	1.06E-03	6.43E-06	4.00E-04	4.30E-06		
Ba-133	4.99E-04	3.66E-06	2.25E-04	2.04E-06		
Tracer	**Alt. Granite T2**		**Alt. Granite T3**		**Alt. Granite T4**	
	K_d	+/-	K_d	+/-	K_d	+/-
Na-22	2.94E-06	7.18E-08	4.39E-06	9.18E-08	1.11E-06	6.24E-08
Ca-47	2.72E-05	2.42E-06	< 4.94E-05		<2.01E-05	
Rb-86	4.43E-04	9.84E-06	3.86E-04	8.63E-06	1.28E-04	3.24E-06
Sr-85	4.15E-05	7.80E-07	9.03E-05	1.51E-06	1.04E-05	2.69E-07
Cs-137	1.24E-03	7.71E-06	9.35E-04	7.17E-06	3.54E-04	3.59E-06
Ba-133	7.19E-04	5.69E-06	8.88E-04	5.98E-06	1.97E-04	1.70E-06

"<" indicates the measurement limit of the experiments.

4.4.3 TRUE Block Scale

Background

Initiated in April 1996, work has been in progress to define and launch the TRUE Block Scale Experiment. This subproject of TRUE broadens the perspective to transport processes in a network of fractures and a spatial scale between 10 and 50 m. The specific objectives of the TRUE Block Scale Project are to (Winberg, 1997).

1) increase understanding and the ability to predict tracer transport in a fracture network,

2) assess the importance of tracer retention mechanisms (diffusion and sorption) in a fracture network,

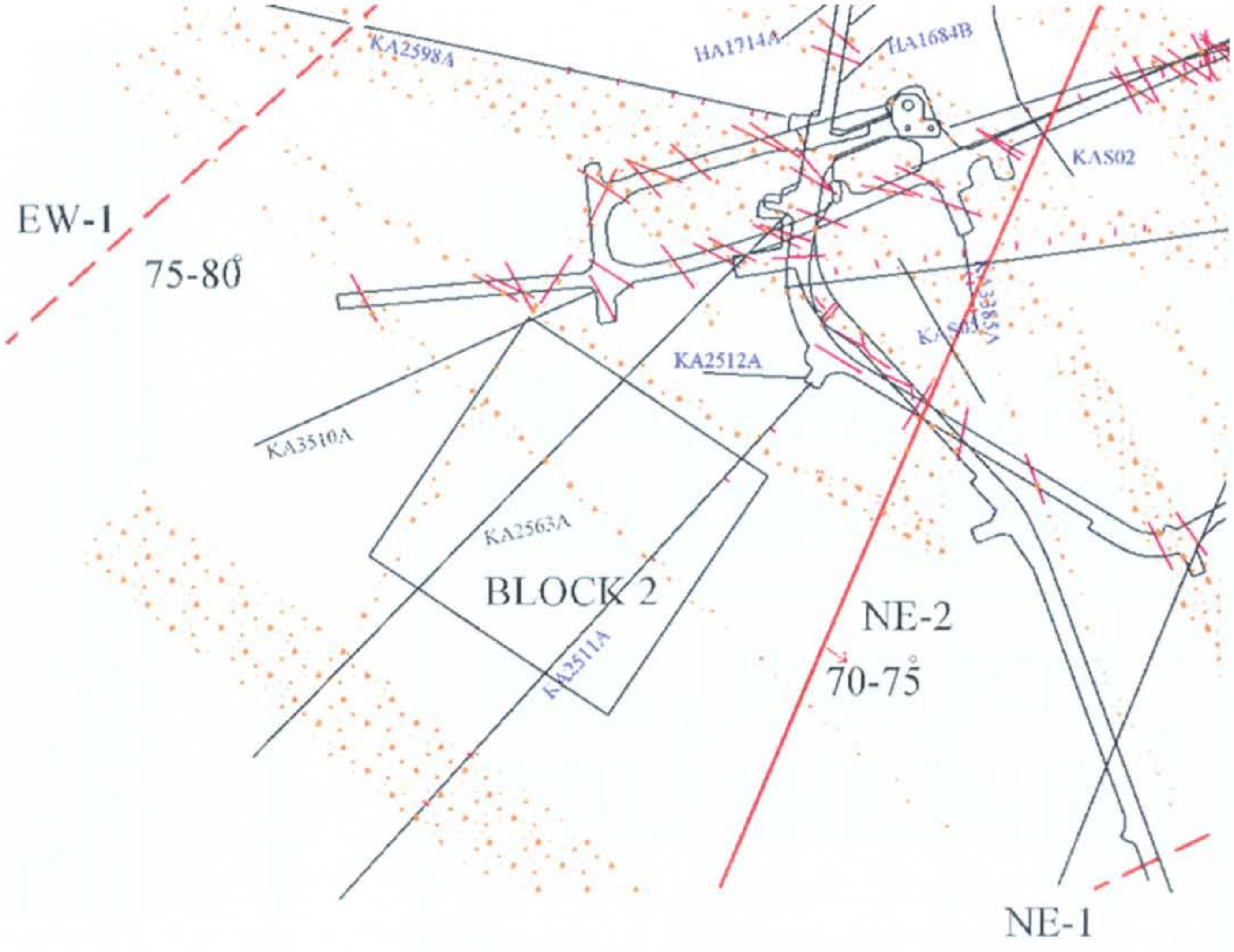


Figure 4-10. Location of TRUE Blocks Scale site (Block 2) in the Äspö HRL. Traces of boreholes and interpreted fracture zones (dotted red) projected onto an horizontal plane at Z=-400 masl).

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. The project is divided into a five different stages;

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

The total duration of the project is approximately four years with a scheduled start in July 1996.

The project is organized as a multi-partite project involving ANDRA, Nirex, Posiva and SKB.

Results

Scoping calculation stage

During the spring of 1996 a scoping data set has been compiled and the structural-hydraulic model of the experimental level (Z≈-450 masl). On the basis of the developed model alternative block positions were considered. Finally the alternative 2, cf. Figure 4-10, was selected mainly because it provides a possibility to access the block both from the TBM region (Z~-450 masl) and from the spiral tunnel. A 56 mm pilot borehole, KA2563A was drilled from the spiral tunnel (Z~-340 masl) transecting the block diagonally at approximately 42 degree angle.

A second borehole, KA3510A, drilled from the TBM part of the tunnel, is a 76 mm hole drilled 30 degrees down with the dual purposes of acting as a monitoring hole for TRUE Block Scale and the Prototype Repository project, the latter to be located in the inner portion of the TBM tunnel. Table 4-9 condensates the data on the two holes.

On the basis of the updated model three NW fracture zones were projected to be intersected by borehole KA2563A. The estimated location of these zones were overall found to concur with in-situ observations in the borehole. However, the

Table 4-9. Geometrical data for the pilot borehole KA2563A drilled into the proposed experimental volume for the TRUE Block Scale Experiment and borehole KA3510A.

Borehole	Eastings (m)	Northings (m)	Elevation (masl)	Azimuth[1] (deg)	Inclination (deg)	Length (m)
KA2563A	2025.6	7271.5	-340.8	237.2	-42.5	362.43
KA3510A	1953.8	7260.9	-448.7	255.3	-30.2	150.06

[1] Azimuth related to Äspö Local North.

magnitude of the inflow in these features was found to be significantly different than that observed in the neighboring KA2511A (Q=25-45 l/min). One of the inflows in KA2563A at L= 105 m amounted to more than 700 l/min. As a consequence, the zones with high inflows were subject to focused cement grouting using a single packer tool in order to facilitate continued characterization in the holes. In total, close to 4 m^3 of cement slurry was injected in KA2563A and KA3510A. Prior to all cement injections, a pressure build-up test was performed over a section length from the collar to the present total drill hole length. These tests showed that the transmissivity of the grouted sections in KA2563A were in the order of 10^{-5} m^2/s. Due to poor seal at the collar of KA3510A the test performed in this hole was not possible to interpret. The location of major inflows in KA2563A, interpreted transmissivities and a list of grouted intervals and grout consumption consumption is given in Table 4-10 and 4-11.

Table 4-10. Location of major inflows along KA2563A, recorded inflows and estimated transmissivity for the flowing section from performed pressure build-up test.

Location of major inflow (m)	Flow rate (l/min)	Transmissivity (m^2/s)
92-96	40-55	$1.3 \cdot 10^{-5}$
102-105	>700	$3.0 \cdot 10^{-5}$
153	100	$5.0 \cdot 10^{-5}$

Table 4-11. Grouted sections along KA2563A, grouted mass of cement (M) and cement slurry volume (V) and calculated vct number for the cement grout.

Grouted section (m)	Cement mass M (kg)	Slurry volume V(m^3)	vct number
90-99	350	462	10
89-105	250	168	08
100-105	1000	1120	08
145-156	200	224	08
142-156	350	392	08

Following completion of the drilling, the following characterization methods have been utilized in the two boreholes;

- Acoustic flow meter (UCM).
- Borehole TV (BIPS).
- Borehole radar using directional antenna.
- Core logging (Petrocore).
- Borehole deviation (Maxibor/Fotobor).
- Double packer flow logging has been performed in 5m and 1m sections in selected intervals between 155 and 280 m.
- A crosshole seismic investigation has been performed between KA2511A (source positions with 5m interdistance) and KA2563A (receiver positions with 1 m interdistance from L=0-350 m).

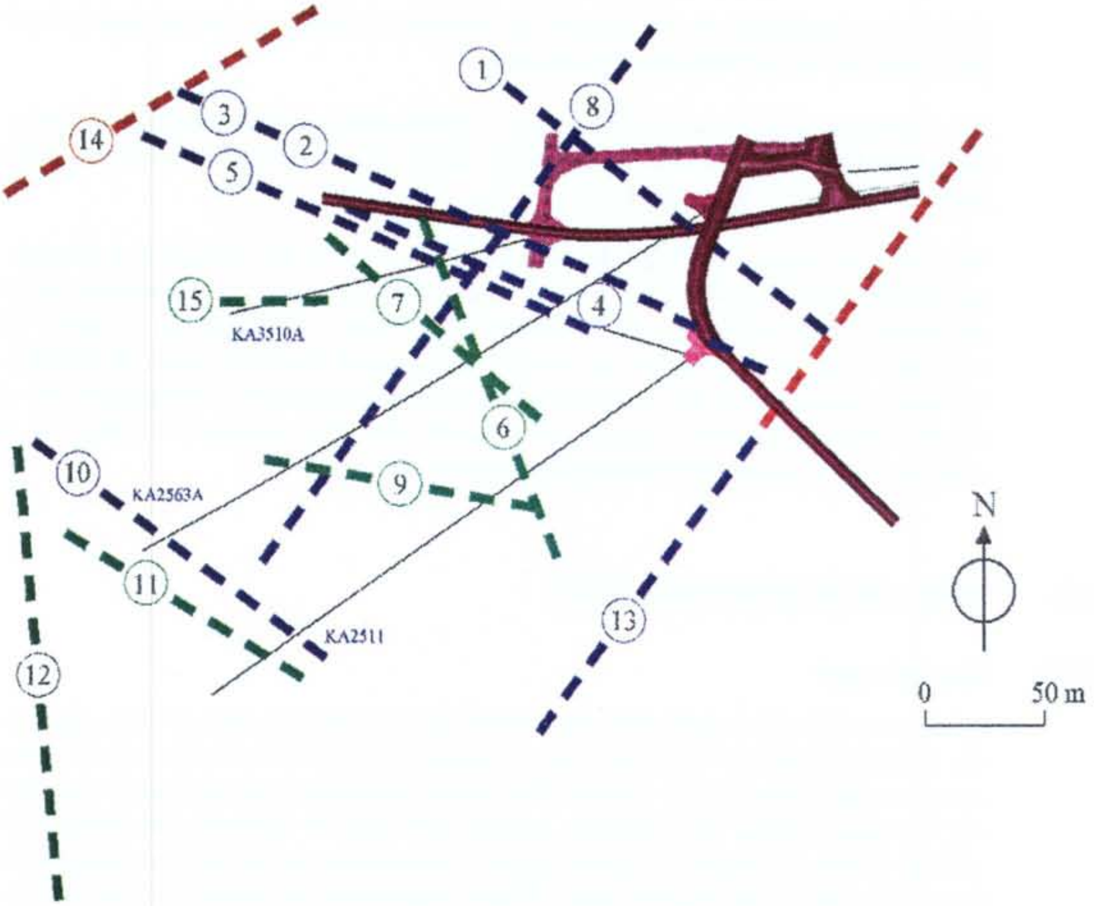


Figure 4-11. *Horizontal section through structural-hydraulic model updated with characterization data collected in KA2511A, KA2563A and KA3510A. Red = certain, blue = probable, green = possible. Numbering refers to internal labelling of fracture zones, eg. Zone #13 = NE-2 and zone #14 = EW-1.*

Using the scoping data set and preliminary characterization results, scoping calculations on feasibility (time/distances, recovery, matrix diffusion, heat as a tracer) and equipment needs were performed. During a scoping calculation workshop in Stockholm, Oct. 16-17 the results of the performed characterization were presented and discussed. In addition, the results of the scoping calculations were presented. The conclusion of the workshop was that the available characterization results do not disqualify the selected block. The grouted portions can be avoided, ie. the that parts of the block delimited by Z<-450 masl and beyond L=160 m in KA2563A are of interest. Scoping results indicate that conservative tracer tests over distances considered yield reasonable time scales. Heat as a tracer is only possible to use over distances in the order of metres. Tests with sorbing tracers are also only realistic over shorter distances. For successful characterization and subsequent tracer tests, the components of the studied fracture network should have a transmissivity on the order of $5 \cdot 10^{-8}$ to $5 \cdot 10^{-7}$ m^2/s.

During the evaluation of the crosshole seismic measurements the inverted seismic velocities were found to differ from previous results obtained from single hole measurements in KA2511A. This resulted in close scrutiny of the applied measurement and processing procedures. This reassessment of borehole deviation data (borehole coordinates in 3D space) has resulted in delay of the evaluation and interpretation of the characterization data.

The characterization data has been used to update the previously developed structural-hydraulic model of the TRUE Block Scale site. A horizontal section of this model is shown in Figure 4-11.

The activities during 1997 are devoted to carrying out of the Preliminary Characterization Stage. This involves drilling, characterization and instrumentation of an additional three boreholes drilled through the block. Subsequently a series of crosshole tests will be carried out in the instrumented borehole array. In parallel, the data coming out of the characterization will be successively integrated into a discrete fracture network model. This model will also constitute a basis for a successively developing/evolving experimental design.

4.5 THE REX EXPERIMENT

4.5.1 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) has been planned to focus on the question of oxygen that is trapped in the tunnels when the repository is closed. Questions regarding the role of oxygen in this context are:

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

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

The objectives of the experiment are:

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

The initial test plan has undergone a peer-review procedure and a revised version has been prepared. Oxygen transport within a groundwater flow in a fracture between two boreholes is no longer part of the planned experiments. The emphasis of the project is instead on a field experiment involving motionless groundwater in contact with a fracture surface. Additional field data (hydrochemical and bacteriological) are required to establish the boundary conditions for the experiments. The field study will be supported by laboratory experiments to determine oxygen reaction mechanisms and kinetics (both for inorganic and microbially mediated processes).

4.5.2 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, funded by PNC, Japan); Centre d'Etudes Nucléaires Cadarache (France, funded by ANDRA, France); 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. Additional samples have been collected from the Äspö tunnel wall and they will be used to continue the testing program for this laboratory system.

Preliminary measurements of dissolved methane and hydrogen in Äspö groundwaters have been performed. They have been combined with the measurements of bacteriological oxygen consumption in Äspö groundwaters. 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.

The drilling where the REX field experiment will take place has been completed. This new borehole is called KA2861A. A single fracture at 8.81 m from the tunnel wall was sampled, and the drillcore has been sent to CEA (Cadarache, France) where a replica of the field experiment will be performed during 1997.

4.5.3 Planned work

The new borehole, KA2861A will be characterised, both hydraulically and chemically. The equipment necessary for the field test will be set-up and tested. Measuring devices will be designed, and tested both in the laboratory and in the field prior to the experiment in this 200 mm borehole. 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 experiments will be supported by analysis of groundwater samples: dissolved chemical (including gaseous) components, as well as bacteria, and microbial oxygen demand. Furthermore, fracture surface samples will be characterized for their mineralogy and attached bacteria. Complete gas analysis of Äspö groundwaters will be performed on SELECT boreholes. They will be used to establish a quantitative model to predict the bacteriological oxygen consumption in a closed nuclear waste repository.

A borehole will be drilled using the "triple tubing" technique in order to collect samples from the NW-3 fracture zone. The material will be distributed between several of the REX participants for immediate characterisation and laboratory testing.

Laboratory tests during 1997 will define the capacity of minerals (with and without added bacteria) to consume oxygen. Minerals, rock samples and bacteria previously extracted from the Äspö site will be used.

Models of oxygen consumption satisfactory for both laboratory and field experiments will be developed. These chemical-rate models for oxygen consumption will be modified as necessary so that they may be used in the performance assessment of a nuclear waste repository.

4.6 RADIONUCLIDE RETENTION

4.6.1 Background

The retention of radionuclides in the rock is the most effective protection mechanism if the engineering barriers have failed. The retention is mainly caused by the chemical properties of the radionuclides themselves and the chemical composition of the groundwater. The water conducting fractures and the groundwater flow has an influence too but are less important for strongly sorbing radionuclides.

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. The sorption could well be irreversible and thus the migration of the nuclides will stop as soon as the source term is depleted.

It is of great value to demonstrate the validity of laboratory results in situ, where the natural contents of colloids, of organic matter, of bacteria etc. are present because laboratory experiments have difficulties to simulate these conditions. The CHEMLAB probe, see Figure 4-12, has therefore been designed to conduct validation experiments in situ at undisturbed natural conditions.

4.6.2 Objectives

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

- To validate the radionuclide retardation data which have been measured in laboratories at simulated in situ conditions.
- To demonstrate that the laboratory data are reliable and correct for in situ conditions.
- To decrease the uncertainty in the retardation properties of the relevant radionuclides.

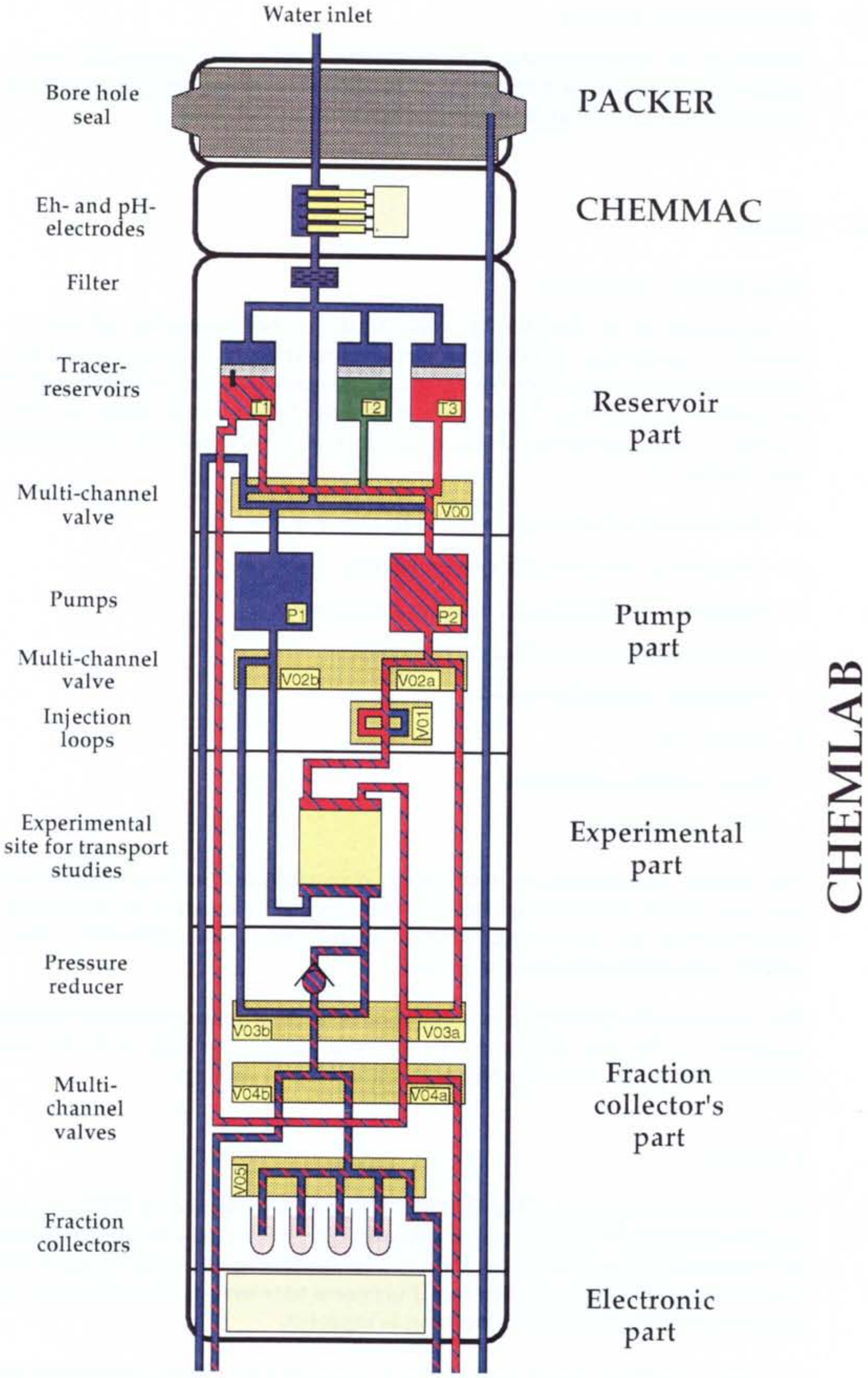


Figure 4-12. Schematic illustration of the CHEMLAB probe.

4.6.3 Experimental concept

CHEMLAB is a borehole laboratory built into a probe, where migration experiments will be carried out under ambient conditions regarding pressure, temperature and formation groundwater from the surrounding rock mass.

4.6.4 Results

Experimental programme

A programme for the CHEMLAB experiments has been compiled and also reviewed by the foreign organizations participating in the Äspö project. The programme, progress report HRL-97-01, gives the rationale, objectives and scope of the planned experiments. None of them is described in detail, since the final planning is made successively as the experiments are to be conducted. The planned experiments are:

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

The different experiments are listed in an increasing order of complexity which does not reflect the time sequence in which they are planned to be conducted. Never-the-less, the simpler experiments are the ones to be conducted at first, starting with the diffusion in bentonite.

The selection of radionuclides to be included in the experiments are based on their abundance in the spent fuel, and their potential danger. The Table 4-12 lists the selected nuclides grouped into low, medium and highly sorbing.

CHEMLAB

The construction work for the CHEMLAB probe was started in 1991 and the manufacturing in 1994. This was completed during 1996, and the equipment was delivered to Äspö in April. At the delivery a detailed check was made to ensure that the product fulfilled the specifications. Functional tests were conducted in order to ensure that the equipment was operating as expected.

An inactive test was carried out in order to simulate a typical experiment and get experiences on how to operate the probe with radionuclides. This was needed to make an application for a licence from the Swedish Radiation Protection Institute, SSI. This was the first time all the functions of the probe were tested under real operational conditions in a borehole. The test was conducted in borehole KA2512A which is located in a niche at the tunnel position 2512 m at approximately 335 m

Table 4-12. Radionuclides selected to be used in the CHEMLAB experiments, grouped into low, medium or strongly sorbing in different chemical environments.

Chemical conditions	**Low sorption** $K_d < 0.01\ kg/m^3$	**Medium sorption** $0.01 < K_d < 0.1\ kg/m^3$	**High sorpt.** $K_d > 0.1$
Oxidizing groundwater	I^-, TcO_4^-	Sr^{2+}, Ni^{2+}, NpO_2^+	Cs^+, Am(III) Pu
Reducing non-saline groundwater	I^-	Sr^{2+}, Ni^{2+}	Cs^+, Tc(IV) Pu, NP(IV) Am(III)
Reducing saline groundwater	I^-, Sr^{2+}, Ni^{2+}	Cs^+	Tc(IV) Np(IV) Am(III), Pu

depth right below the Äspö Research Village. The borehole is almost horizontal with a dip of only 2^o, and a length of 37 m.

From a mechanical point of view it was necessary to make some modifications due to the high pressure of the groundwater in the borehole. A strong lock had to be placed at the end of the borehole in order to keep the probe in place while the packer was inflated. In the large diameter, 101 mm, borehole the force on the probe was calculated to 3500 kg. Also the connections between the five parts of CHEMLAB were made stronger in order to resist the force. A new handling equipment was also developed by which the CHEMLAB parts could be connected and inserted into the borehole.

The flow created by the pumps was not as stable as expected. A modification on the flow lines solved the problem. It was also necessary to mount a by-pass line through which air, remaining in the system when it was installed in the borehole, could be washed out by the borehole water.

The first experiment with radioactive isotopes was diffusion of ^{131}I and ^{57}Co in bentonite. The experiment started in November but had to be terminated early because a sensor indicated a too high pressure in a flow line. The pumps were automatically stopped. Re-starting of the pumps did not give a better function. The CHEMLAB probe had to be taken out of the borehole and sent to the manufacturer for service.

BASLAB

A radiological laboratory, BASLAB, has been established in the CLAB interim storage facility. The laboratory is used for the preparation of the CHEMLAB probe and for the handling of short-lived nuclides to be used in tracer tests. During 1996 BASLAB was only used for the preparation of CHEMLAB before and after the experiment with iodine and cobalt. The operation at BASLAB is regulated by the permissions and rules of the CLAB facility.

4.6.5 Planned work

The first experiment which was terminated in December will be restarted as soon as the CHEMLAB is returned from the service. In order to gain some of the time lost in the first run, the other two runs will be started as soon as possible after the previous one has been completed. Theoretically it is possible to finish the bentonite diffusion experiments in 1997.

Presently the CHEMLAB is manually operated via a control panel in the gallery. A computerized control and monitoring programme is planned to be developed and installed during 1997.

The spent fuel and actinide speciation experiments will probably need a second CHEMLAB system. In order to have the new probe ready in 1999 it will be necessary to start the construction work in 1997. The layout and function together with the costs of such a tool will be assessed during the first part of 1997.

4.7 DEGASSING AND TWO-PHASE FLOW

4.7.1 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. During 1996 there has been two main activities; 1) an *in situ* test of degassing in a fracture and modeling for design of additional field tests performed by Water Resources Engineering at the Royal Institute of Technology and 2) laboratory experiments performed by Fracflow Consultants, St. Johns, Newfoundland.

4.7.2 Field experiments and modeling

Field results

A degassing and two-phase flow test was conducted at the TRUE resin site, between April 15 and May 15, 1996 (Jarsjö and Destouni, 1997a). The pilot hole test (PHT), conducted in December 1994 (Geller and Jarsjö, 1995), provided inconclusive evidence regarding degassing in borehole tests, and therefore it was valuable to conduct another preliminary degassing test under different boundary conditions. The objectives of the pilot injection-withdrawal tests with gas saturated water (PIWT) were to investigate whether degassing effects can be observed in borehole tests at higher gas contents and lower fracture transmissivities than the gas content and transmissivity of the PHT, and to investigate whether the presence of the drift, and its effect of lowering the pressures around nearby boreholes, is of importance for the occurrence of degassing effects in boreholes.

The resin site is situated approximately 450 metres below sea level and includes nine boreholes (denoted P1-P9 in the following text) that intersect a system of fractures between 1 and 4 meters from the drift wall. The borehole pressures at no-flow conditions are lower than the expected background pressure due to the presence of the drift.

The PIWT basically consisted of similar series of constant pressure tests (CPTs) and pressure recovery tests (PRTs) as the PHT. However, since the natural gas content of the resin site was relatively low (1-2% v/v evolved gas on-site), the gas content was increased by: i) injection of N_2-saturated water (with a volumetric N_2-content of about 17% at STP); and ii) lowering of borehole pressures below atmospheric pressure (to approximately 20 kPa abs.), releasing the main part of the gases that are dissolved in water at atmospheric pressure. (Water in equilibrium with N_2 at atmospheric pressure contains an amount of dissolved N_2 corresponding to 1.5% v/v, re-calculated to STP-conditions.)

Single-well injection-withdrawal tests with gas saturated water were conducted in boreholes P2 and P4. In borehole P8, the degassing test sequence was performed using a dipole-configuration, where gas saturated water was injected in P4 at the same time as the actual tests were conducted in P8. The different phases of the dipole test sequence is shown in Figure 4-13. The borehole pressure of the test hole is elevated above the normal, shut-in borehole pressure (P_0 in Figure 4-13) throughout the dipole test sequence (except during the CPT at atmospheric pressure) due to the injection at relatively high pressures in the nearby injection hole. During phase (1), initial CPTs and a PRT were conducted in order determine the borehole pressure – borehole inflow relation at single phase conditions, see Figure 4-13. During phase (2), pressures were lowered to atmospheric pressures and degassing effects could be evaluated from the expected drop in flowrate at two-phase flow conditions. During phase (3), repeat CPTs and PRTs were performed to measure plausible hysteresis effects, due to slow re-saturation of the gas phase, in the borehole pressure – borehole inflow rate relation. Each tick mark on the time axis in Figure 4-13 represent approximately 8 hours.

The gas content in the outflowing water for the single-well injection – withdrawal tests was not significantly elevated, since the injection water was diluted to a great degree already at the start of the withdrawal phase. In contrast, the dipole test

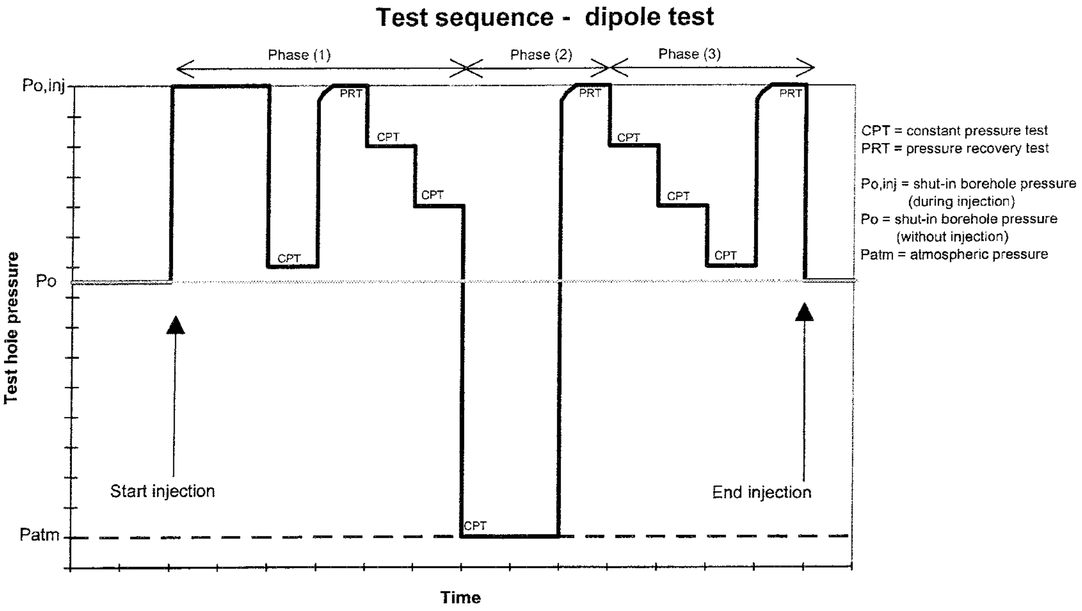


Figure 4-13. *Schematic diagram of the dipole test sequence.*

configuration ensured significantly elevated gas contents in the test hole for a period of 48 hours.

The relation between borehole pressure and steady-state flowrate obtained for the single-well tests in boreholes P2 and P4 indicated that degassing does not cause flow reduction for radial borehole inflow at evolved gas contents of 1.5 to 2.5%, which is in agreement with the findings of the pilot hole test and laboratory tests (Geller and Jarsjö, 1995; Jarsjö and Geller, 1996).

The dipole test in borehole P8 exhibited a linear relation between steady-state flowrate and borehole pressure before lowering the borehole pressure down to atmospheric pressure, as shown by the phase (1) CPTs in Figure 4-14. When lowering the borehole pressure significantly below the N_2-bubble pressure down to atmospheric pressure, the evolved gas content was approximately 15% and the resulting outflow was about 40% lower than the value expected from the linear borehole pressure – flowrate relation obtained through the phase (1) CPTs. Furthermore, the difference in slope between the pressure – flowrate relation obtained through the phase (1) CPTs and the corresponding relation obtained through the phase (3) CPTs (Figure 4-14) imply a 50% reduction in transmissivity after lowering the borehole pressure to atmospheric pressure. Degassing is considered to be the most likely explanation for this behaviour.

The dipole test phase (3) CPTs at higher borehole pressures (Figure 4-14) showed that the low transmissivities remained throughout the testing, indicating that the re-dissolution of the gas phase is slower than the formation of the gas phase. After the end of the dipole testing, a few additional single-well outflow tests were performed in the dipole test hole. The last outflow test, performed twenty-two days after well-shut in, indicated that the borehole outflow still was lower at that time.

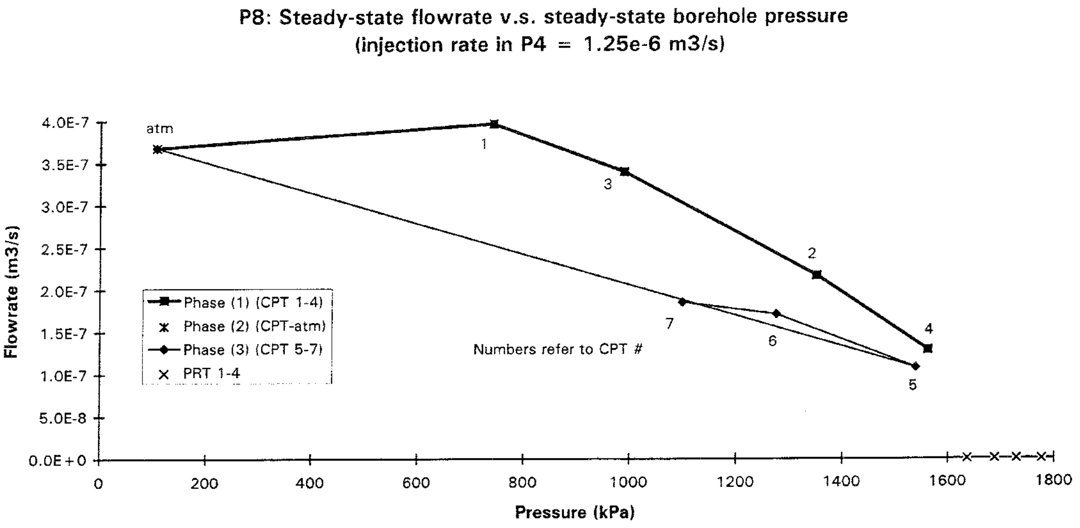


Figure 4-14. Steady-state flowrate versus drawdown for the dipole test conducted in boreholes P4/ P8.

Modelling results

A systematic analysis of the relative importance of various conditions that may affect pressure gradients in the vicinity of a borehole/ drift was performed using numerical methods and relatively simple, analytical solutions (Jarsjö and Destouni, 1997b). The main objectives were to determine under which conditions degassing and bubble trapping can possibly occur, and to investigate the difference in the possibility of degassing occurrence between borehole conditions (small well radius) and drift conditions similar to those in Stripa (large well radius), where groundwater degassing effects are hypothesised to have occurred (Olsson, 1992). The modelling primarily concerned flow in homogenous fractures. The influence of far field boundary conditions, borehole/ drift radius, borehole/ fracture orientation and background pressures on the local pressure field was determined. In addition, the relative influence of pressure gradients, transmissivity and fracture aperture distribution on the maximum possible bubble size that can be trapped in the low-pressure zone of a fracture due to capillary forces was investigated.

The extent of the zone where degassing possibly can occur is limited to the low-pressure zone (i.e., the zone where the pressure of the water is lower than the bubble pressure of the gas). For radial inflow to boreholes and drifts, the low-pressure zone is situated in the nearest vicinity of the borehole/ drift, due to steep gradients caused by the converging flow.

The numerical simulations and the analytical solutions showed that the extent of the low-pressure zone is primarily depending on the well diameter and to some extent the background pressure, whereas the fracture orientation and the range of plausible values of the well radius of influence are less important for the extent of the low-pressure zone.

For gas contents in the water of 1-2%, the extent of the low-pressure zone is on the order of centimetres from a borehole wall, whereas the extent of the low-pressure zone is of the order of decimetres for gas contents of 10-15%, as shown in Figure 4-15. The corresponding extents for a drift are up to a metre for a gas content of

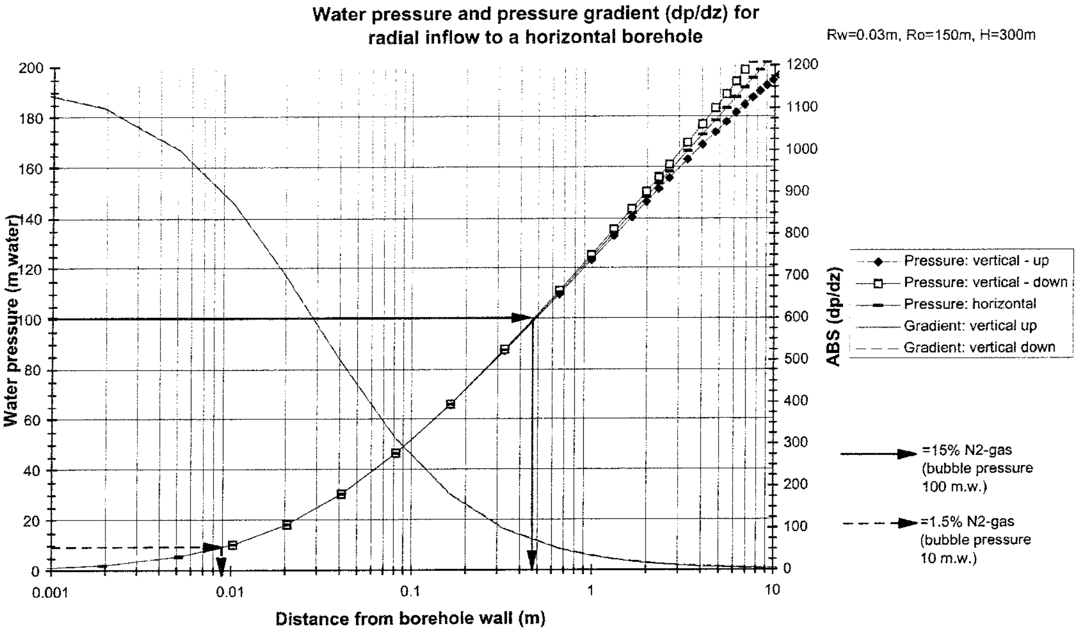


Figure 4-15. Pressure and gradient in the vicinity of a horizontal borehole with a radius of 0.03 metres for a pressure head H at the boundary of 300 m and a radius of influence R0 of 150 m.

1-2% and tens of metres for a gas content of 10-15%. This implies that degassing is not likely to occur in borehole tests at lower gas contents (1-2%), because the extent of the low-pressure zone is so small. In contrast, drifts are surrounded by a much larger low-pressure zone under the same boundary conditions and, therefore, it is plausible that degassing causes significant inflow reductions for this case. Furthermore, it is plausible that degassing occurs in borehole tests at higher gas contents (10-15%), which was also indicated by the pilot injection – withdrawal field tests (Jarsjö and Destouni, 1997a), where degassing is believed to be the most likely cause for a 50% decrease in fracture transmissivity at an evolved gas content of 15%.

Gas bubbles will get trapped in the fracture if the capillary forces that act on the bubble are greater than the local pressure difference over the bubble length in the fracture plane. A derived analytical expression shows that the maximum possible bubble length that can be trapped in the low-pressure zone of a fracture is weakly related to average fracture aperture properties, quantified through the fracture transmissivity, and strongly related to the relative deviations in fracture aperture, quantified through a fracture roughness factor. Using laboratory data on the aperture distribution for rock fractures from Äspö and Stripa (Jarsjö and Geller, 1996), the derived analytical expression suggests that bubbles of up to one centimetre length may be trapped at gradients of 10^4, implying that for both boreholes and drifts, bubbles may get trapped throughout the low-pressure zone, provided that the extent of this zone is sufficiently large.

Planned work

During 1997, the KTH-WRE two-phase flow contribution will be focused on numerical modelling. Based on the results from laboratory and field degassing experiments (Geller and Jarsjö, 1995; Jarsjö and Geller, 1996; Jarsjö and Destouni, 1997a), relevant model approaches will be identified and tested.

The first step will be to perform numerical experiments using Stripa and Äspö fracture aperture data from the laboratory experiments of Jarsjö and Geller (1996). Hereby, the detailed pressures and pressure gradients for single-phase flow in the heterogeneous fractures will be determined and compared with corresponding results for homogenous fractures (see Jarsjö and Destouni, 1997b).

The relative influence of gas bubble pressures on the one hand, and pressure gradients on the other hand, on the developed, steady-state gas saturations will then be investigated for the different fracture aperture distributions. The relevance of hypothetical relations yielding the gas saturation, derived from various equilibrium assumptions, will be tested using the laboratory data and the results from the initial numerical experiments. Since the field aperture distribution of rock fractures at Äspö HRL will be determined through the TRUE resin injection programme, the obtained relations yielding the gas saturation may in the future also provide a basis for the quantification of the steady-state gas distribution under field conditions.

Furthermore, the effect of a developed two-phase flow zone on the total outflow will be addressed. The simulations will be carried out using the fracture aperture data from Jarsjö and Geller (1996). The approach in the numerical modelling will be to locally reduce conductivity values in the low pressure region according to relevant unsaturated conductivity relations, and study the effect of this conductivity reduction on the resulting outflow and pressure field. For model validation, the numerical results on the conductivity reduction will be compared with the conductivity reductions obtained in the laboratory experiments under degassing conditions.

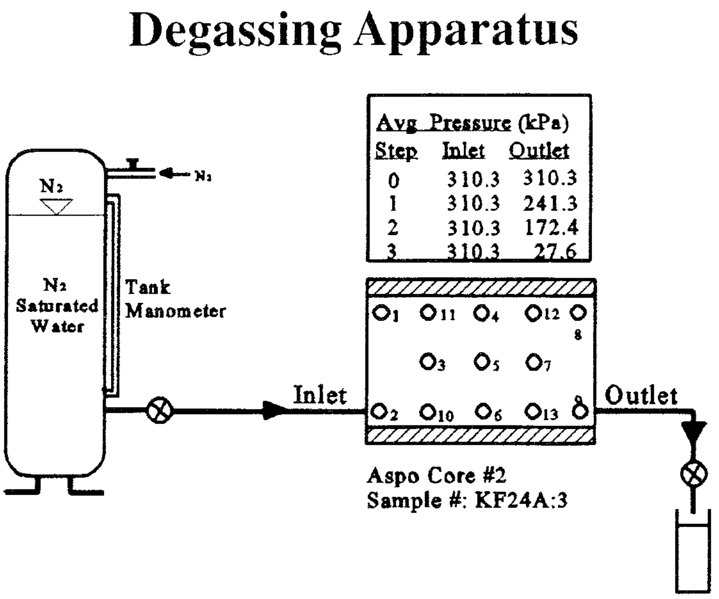
4.7.3 Laboratory experiments

The two-phase flow laboratory studies consist 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 are nominally about 200 mm wide and 300 mm in length), (2) one large scale (approximately 2 m by 2 m) fabricated fracture surface (Large Physical Model), (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 containing sections of a natural fracture plane from the pilot resin experiment site at Äspö.

The first set of samples, a sandblasted sawcut in a limestone sample and a fabricated surface (using a woven geotextile to imprint the "fracture" surface with a uniform roughness) in a concrete sample, were subjected to a limited test program of air invasion, air injection and degassing experiments at different stress levels. Based on these initial experimental results, the air invasion experiments were modified and a new system was prepared that enabled a full suite of degassing experiments to be completed. The full suite of both single phase and two phase experiments, including gas invasion, gas injection and degassing, were then completed on the two natural fracture samples from Äspö, followed by tracer tests at peak normal stress and resin impregnation of the fracture. In addition to determining the effects of a separate gas phase on fracture transmissivity, as a function of roughness, aperture distribution, contact area, stress and sample size, the time required to recover the original fracture transmissivities, after gas had invaded fracture planes, either during degassing or when fully developed two phase flow conditions had been established, was measured. All of the small scale samples showed significant reductions in fracture transmissivity when a separate gas phase was introduced into the fracture plane. Fracture planes with relatively smooth and tabular apertures recovered their original fracture transmissivities fairly quickly, while the fracture planes that were characterized by a rough or variable aperture required several hours for the fracture transmissivities to return to their original values under single phase flow conditions.

Each of the two Äspö cores were subjected to several cycles of loading and unloading normal stress. Both samples showed the typical logarithmic relationship between normal stress and transmissivity as well as the hysteresis between the loading and unloading cycles. While both gas invasion and gas injection experiments were completed on the two Äspö samples at a number of different stress levels, the main focus was on conducting degassing experiments where the volume of evolved gas could be changed by conducting the degassing experiments with different pressure gradients across the sample. The apparatus (Figure 4-16) that was used for the degassing experiments was modelled after the system used at Äspö for the field experiments. This system consists of a 120 litre galvanized tank in which the selected gas was bubbled through a bed of brass shot and marbles, a fluidized bed concept, while a gas cap was maintained at the top of the tank at a pressure that was above the bubble pressure for that particular gas concentration. Saturation at the required percentages of gas normally required about 24 hours. Percentages of gas, by volume, that would evolve at different pressure steps were determined by flowing the gas saturated water through a clear Plexiglas test unit, at different pressure gradients, and measuring the volume of gas that evolved at each pressure step.

Figure 4-16 shows a schematic of the degassing apparatus, the location of the pressure ports/manometers in the fracture plane and the average inlet and outlet water pressures for each part of the degassing experiment. In the first step, i.e. Step 0, the outlet pressure was decreased by only 5 to 10 kPa below the inlet pressure, but still above the bubble pressure, and approximately 10 pore and system volumes of gas saturated water were allowed to flow through the fracture plane to ensure that the fracture plane was completed filled with the gas saturated water. Then the outlet pressure was decreased to three different levels and approximately 15 to 20 litres of gas saturated water were allowed to flow through the fracture plane at each pressure step. Figures 4-17, 4-18 and 4-19 show the preliminary transmissivity changes with time for three of the degassing experiments, at 1 MPa, 5 MPa and 10 MPa of normal stress for the second Äspö sample. Note that the single phase fracture transmissivity decreases with these three increases in normal stress. Thus, the three degassing experiments were conducted at different fracture transmissivities. At each normal stress level, the three main pressure steps produced degassing at different flowrates and hence at different fluid velocities. Also, at all three stress levels, degassing reduced fracture transmissivity by approximately 75% to 90% or to between 10 and 25% of the original measured fracture transmissivities. We believe that these results, while preliminary, do show degassing has a major impact on the transmissivity of these two fractures.



Step	Inlet	Outlet
0	310.3	310.3
1	310.3	241.3
2	310.3	172.4
3	310.3	27.6

Figure 4-16. Schematic of degassing apparatus and the distribution of manometer ports within the fracture plane, including the average inlet and outlet fluid pressures for each degassing step.

A full set of experiments were completed using the Large Physical Model, with the 50 mm diameter borehole, at 1.0 MPa of normal stress. In these experiments with the Large Physical Model, the goal was to measure, under full scale flow conditions, the relative contributions to the reduction in fracture transmissivities that are produced by two-regime (laminar-turbulent) flow versus two-phase (gas-liquid) flow (due to degassing). Pressure heads, or drawdowns, measured along several profiles through the central borehole indicate the increase in the non-linear nature of the head loss under single phase flow with increasing flow rate for 0.5 MPa, and 1.0 MPa of normal stress. All of the experiments show the non-linear nature of the head loss as one approaches the borehole under convergent flow conditions, as shown by deviations from a straight line with increasing flow rate, indicating a transition from laminar to non-laminar or turbulence conditions.

Once the non-linear flow regime had been established, raw gas was added to the water being injected into the fracture plane. At a normal stress of 1.0 MPa, two different experiments with single phase flow rates of 5.64 L/min and 15.4 L/min, respectively, with boundary pressure heads of 5.229 m and 6.481 m, respectively, were conducted. Once stable flow rates had been achieved, 2.5% gas by volume, referenced to the single phase flow rate, was added to the injection flow conduit. For the lower flow rate case, adding the gas to the injection conduit decreased the flow rate from 5.64 L/min to 0.18 L/min (a decrease of 97%) with a corresponding decrease in the pressure heads on the boundary from 5.229 m to 4.934 m (a decrease of less than 6%). For the high flow rate case, the impact was much less dramatic, the flow rates decreased from 15.4 L/min to 13.39 L/min and the boundary pressure heads increased from 6.481 m to 6.826 m. The pressure head data for all of the single and two phase flow tests clearly indicate both the non-linear nature of the flow rate versus pressure head curves as well as the difference in the flow rates for the single and two phase flows.

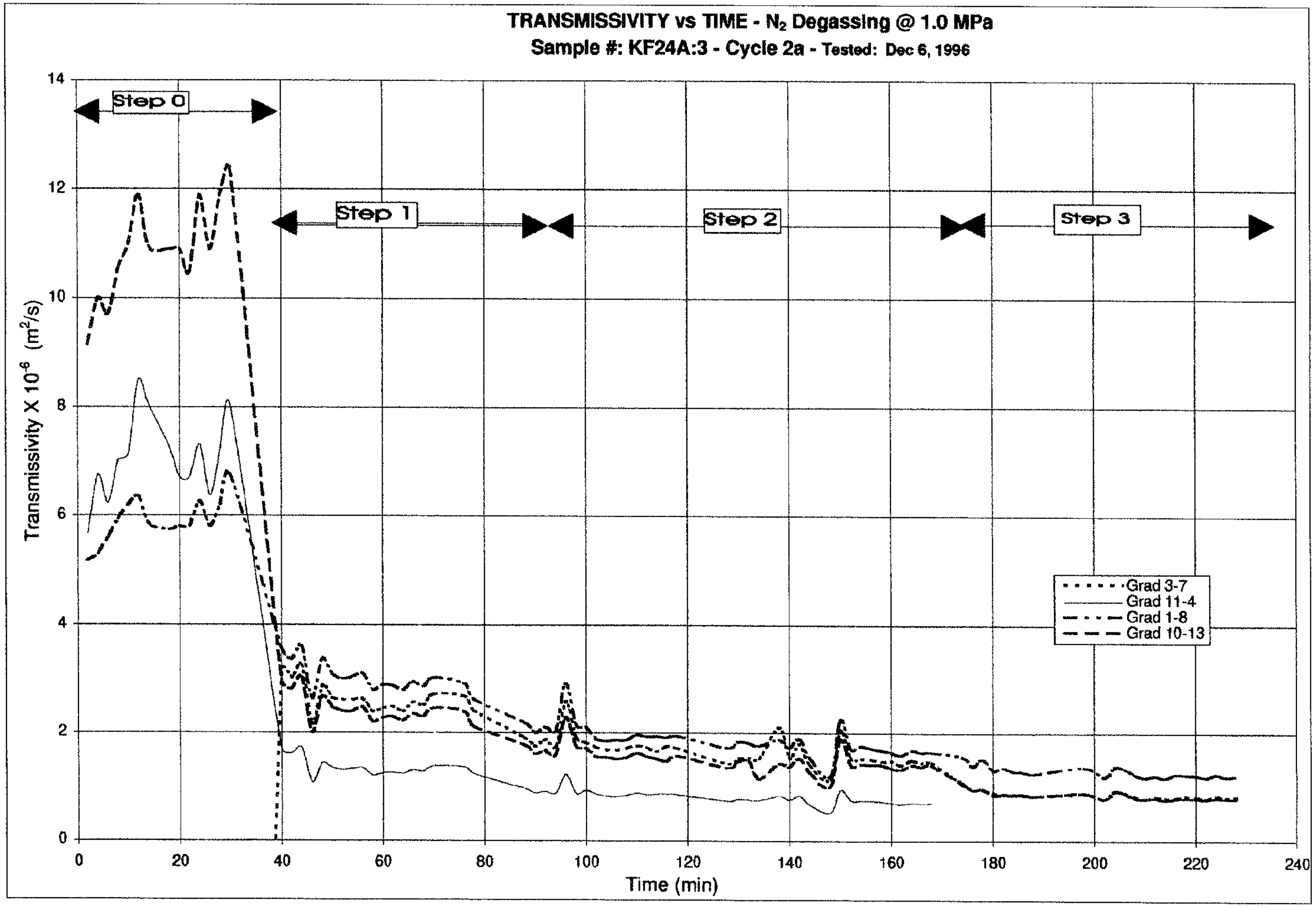


Figure 4-17. *Changes in fracture transmissivity with time for the initial flooding step and the three degassing steps at 1.0 MPa of normal stress.*

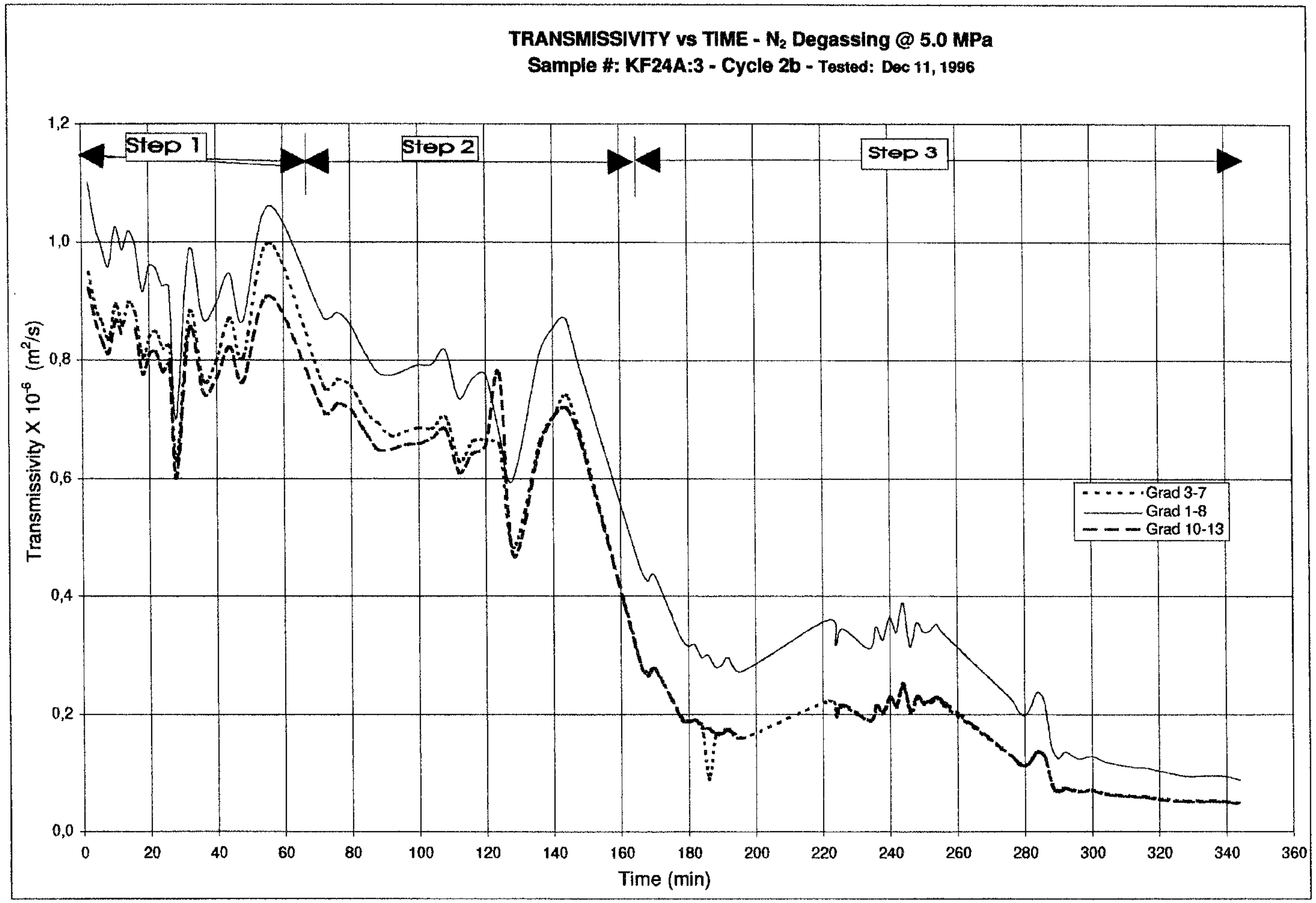


Figure 4-18. *Changes in fracture transmissivity with time for the three degassing steps at 5.0 MPa of normal stress.*

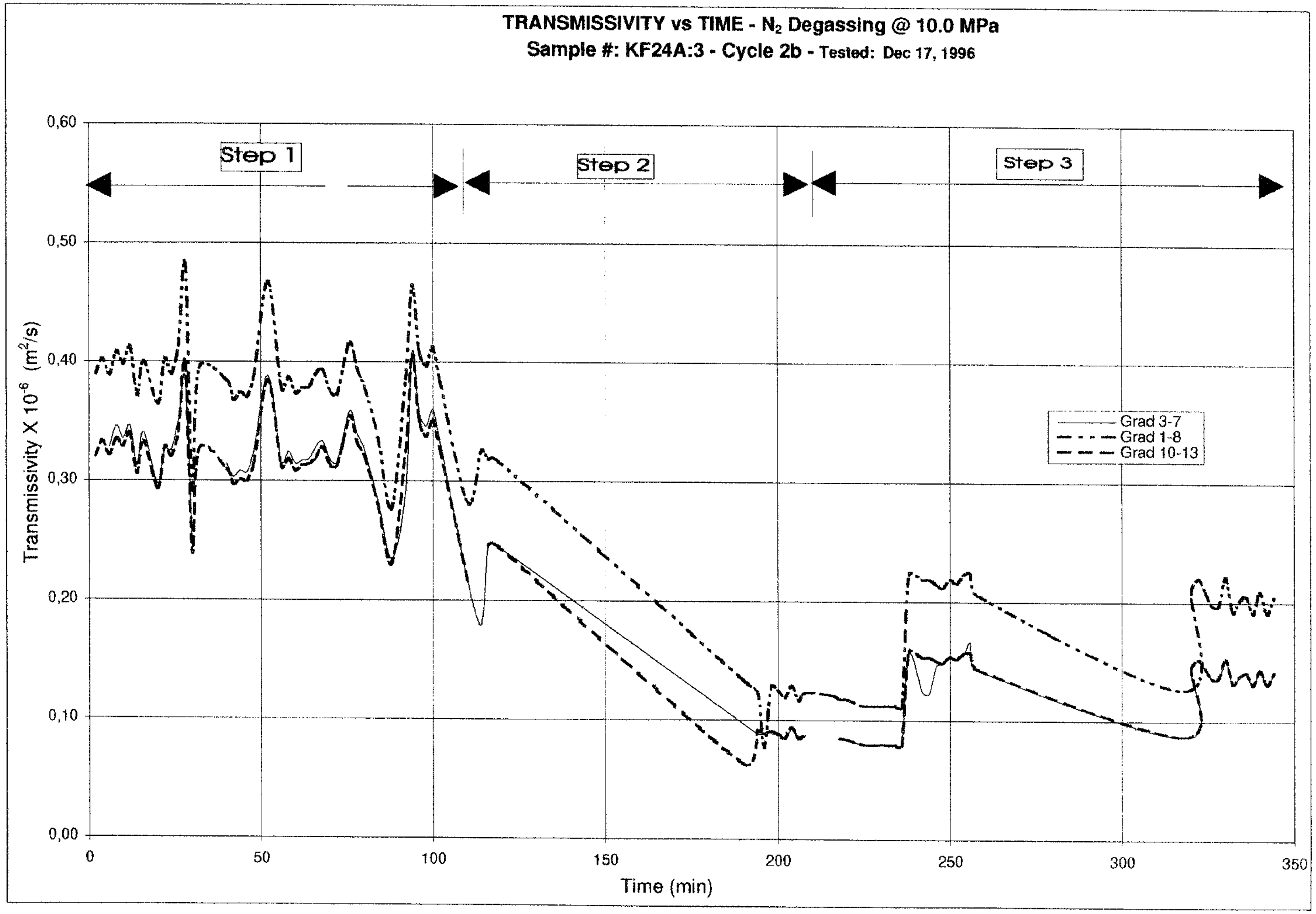


Figure 4-19. *Changes in fracture transmissivity with time for the three degassing steps at 10.0 MPa of normal stress.*

Plastic replicas (two approximately 290 mm by 290 mm and a third replica approximately 290 mm by 180 mm) of the fabricated fracture used in the Large Physical Model were fabricated in 1996 at Sandia National Laboratory. The initial tests on the fracture replica model, conducted at Sandia, consisted of measuring the aperture distribution, by comparing clear and dyed water images, at two different normal stresses. The aperture distribution models were successfully calculated and the basic distribution parameters will be compared to a direct measurement by injecting a second model with a resin and then sectioning the model. These preliminary experiments showed that the gas/water interface exhibited very little interfingering, suggesting that the fracture plane was fabricated with a uniform fracture surface roughness. This permits the final degassing experiments in this series of experiments to be conducted in fracture planes in which relative roughness can be quantified and controlled.

A series of preliminary multiphase numerical models were completed to evaluate the effectiveness of the three gas/liquid tests in characterising the two-phase flow characteristics of the rough fracture planes. These preliminary multiphase simulations show that the pore structure of the fracture plane in the model has to be included and one has to account for the differences in the saturation concepts for fractures versus porous media and the trapping mechanism in fractures with variable apertures.

4.7.4 Future plans

The data from all of the small scale degassing experiments will be analysed, and the pore structure of the last Äspö sample will analysed using a 10 mm profile spacing. Additionally two phase flow experiments at low flows (1 to 4 L/min) at the 1.0 MPa normal stress level will be completed to better define the flow rate versus pressure head relationship at the low flowrates. Based on this, once the low flowrates have been examined, the current borehole will be over-cored to increase its diameter, and then a complete suite of single and two-phase flow experiments will be conducted over the desired flowrate range. The plan is then to further increase the borehole to a third size, and repeat the testing. At this third and final borehole diameter, the normal stress will be increased to 5 MPa to examine the effects of an even larger stress on the fracture plane. At the higher stress levels, the smaller fracture apertures should produce larger pressure drops, more degassing effects and a greater difference between the single and two phase flow results. Final degassing experiments will be conducted on the fracture replicas at Sandia National Laboratory.

4.8 RESULTS FROM WORK IN THE TASK FORCE ON MODELLING OF GROUNDWATER FLOW AND TRANSPORT

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 nine 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.
Task No 2:	Scoping calculations for a number of planned experiments at the Äspö site.
Task No 3:	The hydraulic impact of the Äspö tunnel excavation.
Task No 4:	TRUE – The Tracer Retention and Understanding Experiment, 1st stage. Non-reactive and reactive tracer tests.

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

General

During 1996 the eighth meeting of the Äspö Task Force (TF) was held. It was arranged by SKB in Hultsfred close to the Äspö site.

The Issue Evaluation Table provides valuable help in relating performance assessment as well as characterisation key issues to the actual, forthcoming experiments at Äspö, SKB ICR 95-06. An independent review of the table has been undertaken. This included among other things reviewing the formulation of each issue, comments on the information presently included in the table and addition of the most appropriate international references on each issue. An enhanced Issue Evaluation Table is available.

Task No 3

The evaluation of the modelling work on Task No 3 (the hydraulic impact of the tunnel excavation at Äspö) is on-going. 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 tests 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 4-13.

Task No 4

Task No 4 has been the main modelling effort within the Task Force during 1996 and the subtasks are defined in Table 4-14.

Table 4-13. 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	Billaux	X		DRAFT in French
CRIEPI	CRIEPI	Tanaka		X	SKB ICR 96-07
PNC	Golder Associates	Dershowitz		X	FINAL DRAFT
PNC	Hazama Corporation	Yamashita	X[1]		FIRST DRAFT
Posiva	VTT Energy	Mészáros	X	X	SKB ICR 96-06
SKB	CFE	Svensson	X[2]	X[2]	SKB HRL PR 25-91-03
UK Nirex	AEA Technology	Holton	X[1]	X	FINAL DRAFT

[1] Due to several reasons these modelling studies are not 3A as originally meant. Actually, a partly updated geological structural model has been utilised.

[2] This exercise was not performed within the framework of the Äspö Task Force. The modelling was part of the Äspö Project.

Table 4-14. Definition of the different parts of the Modelling Task related to the non-reactive tracer tests performed at the TRUE-1 site presently in focus within the Task Force group.

Modelling Task	Definition/Scope
4A	To perform modelling in support of the development of a descriptive structural model of the test site
4B	To perform modelling in support of experimental design
4C	To perform forward modelling of the radially converging tracer test (RC-1) and later to compare model output with experimental results
4D	To perform forward modelling of the dipole tracer tests (DP1-4) and later to compare model output with experimental results

During the spring of 1996, data was distributed to the modelling groups of Task No 4C. This included among other things a descriptive structural-hydraulic models on block and detailed scales of the TRUE-1 site, complementary information for the radially converging tracer experiment in terms of flow and injection concentrations, discrete fracture network analyses of data from the characterisation of the TRUE-1 site, performance measures and presentation formats.

The predictive modelling for Task No 4C has been presented in an interim report, SKB HRL PR 96-23. The work constitutes one of the few real blind predictive modelling exercises ever conducted in the field of tracer transport in fractured media. It was considered important by the Äspö Modelling Task Force to present the results of all predictive modelling efforts in one single summary report. This is the first piece of information for the evaluation process of the TRUE-1 modelling that is to come within the Task Force. The report is based on the contributions from the Modelling Groups.

No evaluation of the modelling performed has been done so far but it is clear that:

- Quite an impressive amount of modelling work has been performed considering the large amount of data available and the time constraints.
- Comparing the experimental result with the simulations from the eight groups, it is evident that the flow system/boundary conditions are not completely understood.
- The predicted breakthrough times are in the right order of magnitude, in some cases very good, for two out of four tracer tests.
- Predictive modelling of the four non-reactive dipole tracer tests defined as Task No 4D is now on-going.

Other activities

A proposal on a Task No 5 has been prepared by SKB. It concerns coupling between hydrochemistry and hydrogeology.

4.8.3 Planned work

The proposal on an updated Issue Evaluation Table will be presented to the Task Force group.

All remaining modelling work on Task No 3 is expected to be reported in the ICR-series. The evaluation of the modelling work will result in a DRAFT version distributed in time for the Task Force meeting early February 1997.

The predictive modelling exercise of Task No 4D, the dipole experiments DP1 to DP4, will be the main issue for the modellers during the beginning of 1997. Predictive modelling results are to be presented at the next TF meeting.

Tasks 4C and 4D will be reported by each group in the Äspö ICR series.

A modelling Task No 5 will be initiated.

The next TF meeting will be arranged by ANDRA on February 4-6, 1997, in Cherbourg France.

5 DEMONSTRATION OF TECHNOLOGY FOR AND FUNCTION OF IMPORTANT PARTS OF THE REPOSITORY SYSTEM

5.1 GENERAL

The safety of a repository is determined by:

- the properties of the site,
- the design of the barriers,
- the quality in design, construction and operation of the deep repository.

A KBS-3-type deep repository is supposed to hold about 4500 canisters in rock caverns at a depth of about 500 m. The different barriers (canister, buffer, rock) work together to isolate the waste. Backfilling and plugging of tunnels, shafts and boreholes limits the flow of groundwater via the potential flow paths opened up by the construction and investigation work, thereby making it more difficult for corrodants and any escaping radionuclides to be transported up to or away from them.

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. A major project within this Stage Goal is the design and construction of a prototype repository built to simulate the function of the engineered barriers at full scale. Tests will be made of different steps in the deposition sequence and these tests will provide the basis for development of a quality assurance system for the deep repository. Tests will be made of different backfill materials and technology will be developed for backfilling and plugging of tunnels. In addition, experiments are performed to study the interaction between the engineered barriers and the host rock, in some cases for long periods of time.

5.2 BACKFILL AND PLUG TEST

5.2.1 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 mechanic functions of a plug and be the basis for the design of the plugs in the *Prototype Test*. The Test Plan has been discussed and changed during 1996.

During 1996 supporting tests and preparations have been made. The field compaction tests, performed in 1995, have been reported and a new compaction equipment has been designed and built. The plug for the *Backfill and Plug Test* in the ZEDEX drift has been designed. Laboratory tests on backfill materials have been running and the development and testing of equipment for measuring THM-processes in backfill and buffer materials have continued during 1996.

5.2.2 Results

The field compaction tests made in 1995 showed that a new compaction equipment was required. During 1996 a vibrating plate has been designed and built. The vibrations are produced by the oil hydraulic of the carrier, which will be a small flexible rebuilt digging machine. The vibrating plate is equipped with a complete bottom plate, that is shaped to suite compaction close to the roof and walls with inclined compaction.

The instrument development and testing have been largely focused on instruments for measuring negative pore pressure in water unsaturated buffer and backfill materials. The main purpose of these instruments is to measure the saturation process in the field tests. Four different transducers, that work according to different principles have been tested. They work at different pressure ranges and have different advantages. The transducers are tested under both laboratory and field conditions.

The plug for the backfill in the ZEDEX drift has been designed. It will be made of arch-shaped reinforced concrete with a 1.5 m deep slot in the rock. The inner part of the slot will have an O-ring of highly compacted bentonite blocks for preventing leakage along the concrete/rock interface. The plug will be built in two sequences in order to delay the emplacement of the bentonite blocks until just before the final concrete casting.

Laboratory tests on water-unsaturated backfill materials have been performed during 1996. These tests are used for modelling the hydraulic properties and will be used for calculation and evaluation of the water saturation process.

Preliminary calculations of the water saturation phase have been performed. they show that the time until saturation may be several years for backfill with a high bentonite content. Calculations of the flow testing after saturation have also been made. They show that the plug is important for reaching a high pressure in the backfill if there is a permeable disturbed zone and that the natural gradients in the backfill may be very high during the test sequence. The calculations also show that the flow rate is large enough to be measurable.

5.3 DEVELOPMENT OF A PROTOTYPE REPOSITORY

5.3.1 Background

Many aspects related to the performance of a repository have been tested in a number of laboratory- and in-situ tests. Models have been developed that are able to describe and predict the behavior of both components of the repository, and of the entire system. Ongoing and planned experiments at Äspö HRL will contribute additional knowledge on important parameters and processes. There is a strong need, however, to test and demonstrate the integrated function of the system components, in full scale and under conditions comparable to those in a real repository. In other words, development work has reached the stage when it is appropriate to construct and evaluate a prototype of the intended system.

The idea of establishing a prototype repository at Äspö HRL have developed over a long time. More recent program planning, including the introduction of other large-scale experimental efforts at Äspö, have further clarified to role of such an experiment in the overall development of the deep repository program. As a result, the Prototype Repository Test is focused on testing and demonstrating repository system function. Certain activities aimed at contributing to development and testing of the practical, engineering measures required to rationally perform the steps of a deposition sequence are also included. Efforts in this direction are however limited, since these matters are addressed in other projects.

The concrete, technical planning of the Prototype Repository Test is at an early stage.

5.3.2 Objectives

The objectives of the Prototype Repository Test are:

- To demonstrate the integrated function of full-scale prototype of the repository system.
- To provide a full scale reference for testing and scrutiny of models, experiments and assumptions.
- To develop, test and demonstrate appropriate engineering standards and quality assurance methods.
- To demonstrate technology for monitoring of the repository system.

In addition to these major objectives, it is envisaged that the test will contribute to the process of developing and testing equipment and procedures required to perform the deposition sequence in practice.

5.3.3 Experimental concept

The overall idea is that the experiment should, to the extent possible, simulate the real repository system. This calls for testing in full scale and at relevant depth. Furthermore, test arrangements should be such that artificial disturbances of boundary conditions or processes governing the behavior of the engineered barriers and the interaction with surrounding rock are kept to a minimum.

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

- The difference in time frame. Realistically, the experiments considered can be extended in time to at most a few tens of years. The long-term safety of a repository can therefore not be demonstrated.
- No spent fuel, or any other form of nuclear waste, will be used. Canisters equipped with electrical heaters will be used to simulate encapsulated spent fuel.

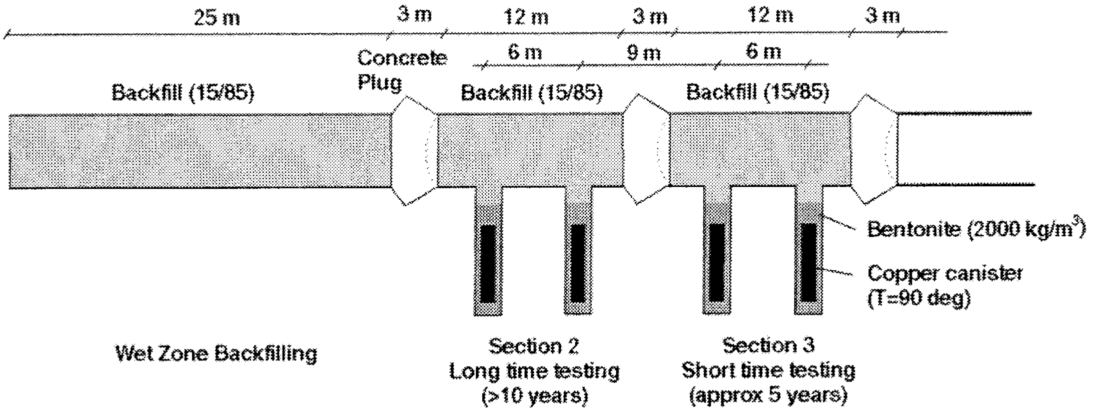


Figure 5-1. *Tentative layout of the Prototype Repository.*

Different alternatives as regards location and layout of the test have been considered. The test location chosen is the innermost section of the TBM drilled tunnel at 450 m level. The tentative layout involves four simulated deposition holes with a spacing of 6 m, see Figure 5-1. Canisters, with dimensions and weight according to the current plans for the deep repository and with heaters to simulate the thermal energy output from the waste, will be positioned in the holes and surrounded by bentonite buffer material. Different alternatives as regards initial water saturation of the buffer material, block manufacturing etc., are being studied. The tunnel will be backfilled. It is expected that the Backfill, Plug and Retrieval Test will provide important know-how with respect to backfilling technology to be applied.

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

Operation time for the experiment is envisaged to be at least 5 years. Decisions as to when to stop and de-commission the test will be influenced by several factors, including performance of monitoring instrumentation, results successively gained and also the overall progress of the deep repository project. It is possible that operation and monitoring of at least the inner test section will be continued for a significantly longer time period than 5 years.

Instrumentation will be used to monitor important processes and parameters in the buffer material, backfill and surrounding near-field rock. The intention to minimize disturbance will however add restrictions to the monitoring possibilities.

Processes that will be studied include:

- Water uptake.
- Temperature distribution.

- Swelling pressure and other mechanical phenomena (e.g. displacements) in buffer and backfill.
- Chemical processes.

Other processes that are of interest, but that are more difficult to assess experimentally given the intended test layout, are:

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

A fifth test hole, located outside the backfilled tunnel section and primarily devoted to the study of these processes, is tentatively being considered.

5.3.4 Results

Detailed planning of the Prototype Repository has been continued during 1996. The drilling of the deposition holes and the manufacturing of the canisters have been identified as the critical items for proceeding with the project according to the planned schedule.

Specifications for drilling of the deposition holes have been compiled and sent out to several contractors together with a request for tenders. Their responses are expected in the beginning of February 97.

It has been decided that canisters produced within SKB's program for development of canisters for the deep repository will be used in the Prototype Repository. Minor modifications will be made to the standard design in order to use electrical heaters and be able to feed them with electric power.

5.3.5 Planned work

Early-stage planning for the test, including preparation of a test plan and establishment of a project organization, have been initiated. It is envisaged that this work can be completed during spring 1997. The scope for 1997 is to further detail the planning, prepare the site and to furnish key components of the for test. Major activities planned are:

- Site characterization.
- Procurement and testing of monitoring instrumentation.
- Canister design and manufacturing.
- Drilling of deposition holes.
- Manufacturing of bentonite blocks.
- Development of quality assurance plans.

In addition various supporting activities will be initiated. Backfilling, plugging and start of the monitoring period are planned to commence late 1998.

5.4 DEMONSTRATION OF REPOSITORY TECHNOLOGY

5.4.1 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 program. 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 program 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 organized as a project under the Facilities Division. Development of equipment for handling and deposition of canisters will be the responsibility of the Deep Repository Division 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.

5.4.2 Objectives

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.

5.4.3 Experimental concept

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. The demonstration will include handling and deposition of canisters and bentonite buffer in 4-6 full size holes. The procedures that are expected to be tested and demonstrated are:

- draining of canister holes,
- buffer emplacement in the holes,
- deposition of canister,
- emplacement of buffer on top of the canister,
- filling the slot between the buffer and the borehole wall,
- filling the top of the deposition holes with backfill.

5.4.4 Results

The project was initiated during 1996 and so far most efforts have been devoted to planning the work and producing a Test Plan. The preliminary planning revealed that additional underground space was required for performing the intended activities. Hence, plans were made for excavation of additional drifts in the Äspö HRL. It was decided that demonstration of the repository technology would be performed in a new drift south of and nearly parallel to the ZEDEX D&B drift at the 420 m level below the surface. The excavation work began in November 96.

5.4.5 Planned work

The excavation of the test drift for demonstration will be completed in March 97. Then ventilation and electricity will be installed in the test drift as part of the preparations for the demonstration activities. Drilling of deposition holes is planned for 1998.

Drilling of deposition holes for test of retrieval will be made at the 450 m level during the autumn of 97. Canister and buffer emplacement will be made during 1998.

An exhibition will be set up adjacent to the demonstration test drift to inform about the different steps in deposition of spent nuclear fuel.

5.5 LONG TERM TESTS OF BUFFER MATERIAL

5.5.1 Background

Results from laboratory studies concerning bentonite clay stability have been used in order to produce models for alteration reactions and for the kinetics of the reactions. Natural soil systems in deep shales or in the vicinity of hydrothermal events have been used to validate these models. A number of buffer field tests have been made, but several of these have in different ways deviated from expected Swedish repository conditions, e.g. limited access to ground water, low ground water salinity, high temperatures or deviating buffer clay composition, and no tests so far have been made deliberately for validation of alteration models. These previous field tests have in general shown insignificant changes in the buffer, except for a high temperature test series in which relatively large buffer alteration was noticed, both with respect to clay mineralogy, redistribution of easily dissolved species and to the physical properties of the material.

5.5.2 Objectives

The present field test series aims to validate models of clay 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 will be studied.

5.5.3 Experimental concept

The testing philosophy is to place prefabricated units of bentonite blocks surrounding a copper tube in a vertical borehole and to maintain the tube surface at a defined temperature. The test series includes 6 such test parcels (Table 5-1) of which 3 will be exposed to standard KBS-3 conditions, mainly in order to study buffer performance, and 3 test parcels which will be exposed to adverse conditions mainly in order to validate models for buffer alteration. The parcels will be placed in boreholes in a representative granitic rock structure containing water-bearing fractures. The boreholes will have a diameter of 30 cm and a length of around 4 m.

Table 5-1. Specification of the Long Term Performance test series.

No	Type	Purpose	T,°C	Pc	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
Pc = controlled parameter
LTP = long term performance test
Ma = mineralogical alteration
Se = “salt enrichment”

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

5.5.4 Results

Two test holes were drilled in May, and subsequent flow and pressure tests indicated that the holes were suitable for the two opening 1 year tests. The preparation and testing of the parcel components were made in laboratory environment and the final mounting of bentonite blocks and installation of the gauges were made at the test site. The S1 test parcel was transported, assembled and emplaced in the test hole at Äspö during the second week in October, see Figure 5-2. The temperature was increased in steps of 10 to 15°C until the final temperature of 90°C arrived at. After some minor introductory regulating problems at low temperatures, the final temperature is kept well within the accuracy demand. In principle, the A1 test parcel was emplaced in the same way as the S1 parcel in mid November. The maximum temperature in the A1 parcel has been increased to 130°C. Data concerning temperature, total pressure, pore water pressure and humidity in the two test parcels have been produced during test period and no major divergence from expected values has been found. Figure 5-3 shows the temperature distribution in parcel S1 at the end of December. The swelling pressure of the bentonite was around 4 MPa in both tests and full water saturation has been achieved in all positions equipped with moisture gauges.

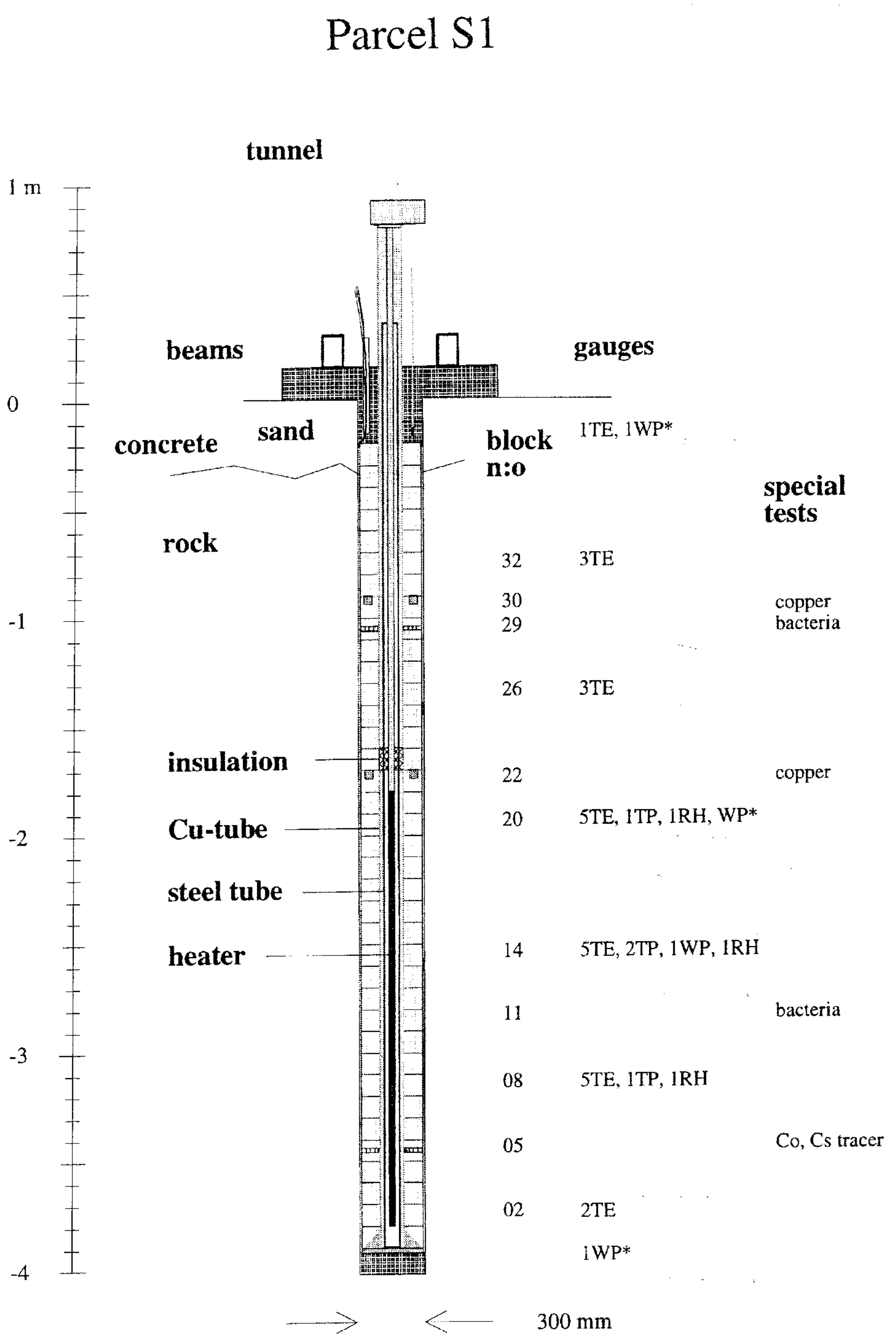


Figure 5-2. *Final layout of test parcel S1. TE denotes temperature gauges, WP water pressure gauges, TP total pressure gauges, RH relative humidity gauges. The figures show the number of gauges at each level.*

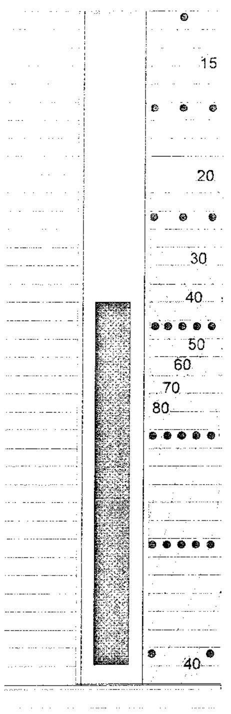


Figure 5-3. *Principle drawing of parcel S1 showing thermocouple location (dots) and isotherms for the conditions at December 31. The horizontal scale is exaggerated four times compared to the vertical scale.*

5.5.5 Planned work

Temperature, total pressure and water pressure will be measured during the entire heating period. A workshop will be held in September 1997 in order to discuss predictions and termination techniques. The termination of the A1 and S1 tests is planned to take place in November/December 1997. Subsequent chemical, mineralogical and physical testing will be performed by which the following conditions and properties will be determined at strategic positions in the buffer:

- water distribution,
- element distribution (ICP/AES, SEM, (STEM)),
- pore-water composition (ICP/AES, titration),
- smectite/illite ratio, (XRD),
- cation exchange capacity, CEC (wet chemistry),
- swelling capacity (oedometer tests),
- swelling pressure (oedometer & triaxial tests),
- hydraulic conductivity (oedometer tests),
- clay structure (SEM, TEM)
- shear strength (triaxial test).

Planning for the four following long term tests will start during 1997 and the emplacement is planned to take place during the fall 1998.

5.6 CRACKS CAUSED BY TBM EXCAVATION

5.6.1 Background

The deep repository for spent fuel consist 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 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.

5.6.2 Modelling of cracks caused by mechanical tools

Formulation of models for indentation depth and crack length

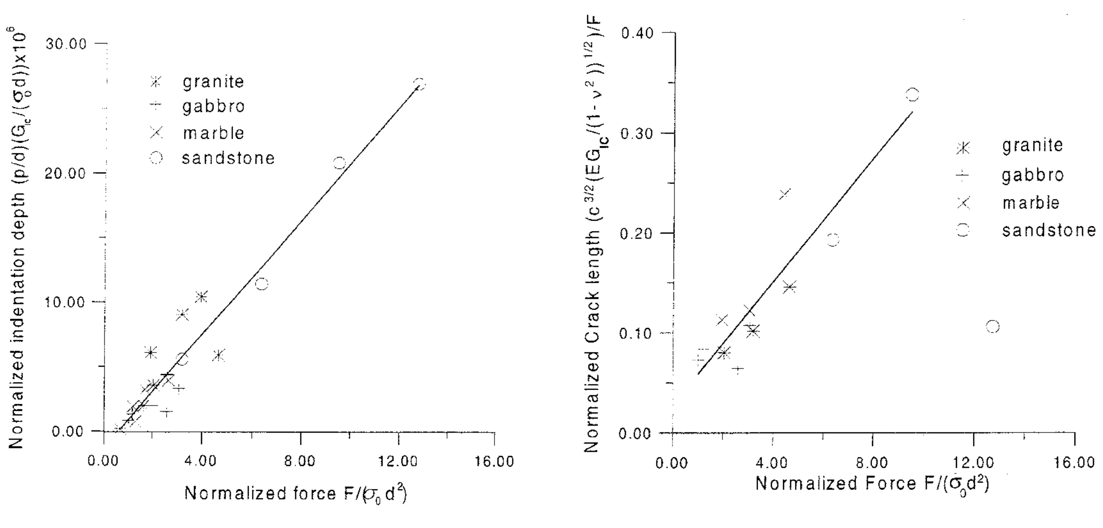
The work with modelling the cracks caused by cutters or bits at mechanical excavation in crystalline rocks has continued with studies on the influence of mechanical properties of rock on the indentation depth and crack length. The main factors governing the indentation event have been identified and functional relationships have been established relating either the indentation depth or the length of radial/median cracks to the various quantities characterising the physical event, namely the indentation force, the shape and the size of the indenter and the properties of the rock. Some typical results for the hemispherical indenter are shown in Figure 5-4. These equations can serve for general use for various rocks with different diameter of the three indenter types, namely, hemispherical, cylindrical and truncated indenters. The analysis provides also a profound understanding of the physical mechanisms of rock indentation phenomena.

Combination of similarity methods and neural network method

A combined approach involving similarity methods and a neural network has been suggested. The similarity methods offer deep physical understanding of the problem of cracking under mechanical excavation and hence to establish quantitative interrelationships between the most important parameters governing the process. Through incorporation of a neural network model, more factors are taken into consideration and as a result the accuracy of predicted tool penetration is improved.

Investigation of model parameter influence on numerical simulation of side cracks

In the numerical modelling of cracks caused by mechanical excavation, some model parameters are introduced in the calculation. The parameters include critical energy release rate, parameters describing the crushed rock and the positions of

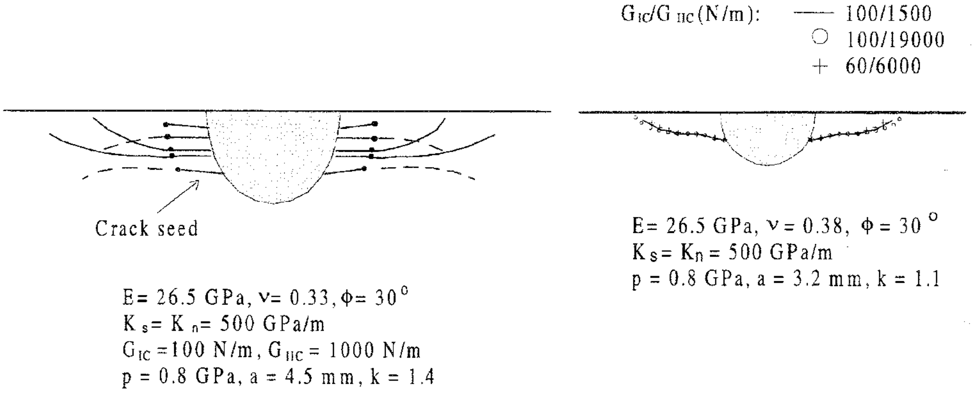


a) Normalised indentation force-penetration relation

b) Normalised indentation force-crack length relation

Figure 5-4. *Functional relationships for the hemispherical indenter.*

initial cracks. They are determined through both experiments and calibrations. The boundary element method and fracture model provide a convenient tool for studying the problem, but the model parameters have to be determined based on experimental facts in order to provide quantitative predictions of the crack development. For instance, see Figure 5-5a, the initial crack positions cause different development trajectories below the indenter. The crack seeds, which have least resistance and follow roughly the side crack patterns as observed in the experiments, are chosen in the simulation. The critical energy release rates affect mainly the loading stresses or indentation load for driving the cracks and have no significant influence on the crack trajectory, see Figure 5-5b.



a) Effect of initial crack positions

b) Effect of critical energy release rate

Figure 5-5. *Effects of some model parameters on simulation of side cracks caused by tool indentation.*

5.6.3 Laboratory indentation test and crack observations

Observations of field cracks

Discrimination of field cracks in the TBM tunnel wall in Äspö Hard Rock Laboratory and in borehole wall in the research tunnel at Olkiluoto, Finland has been made. Rocks at these two places are diorite and gneiss respectively. The basic crack types defined by laboratory indentation tests were found in the studied samples but with some variations. For the different excavation methods TBM caused deeper and longer cracks in the walls than was caused by the button cutters of the blind hole boring machine, see Figure 5-6. It is remarkable that only few and short cracks were found in the side walls independent of method. The densely cracked layer is less than 10 mm deep and the subsurface cracks do not penetrate deeper than 10 to 20 mm into the side wall.

Laboratory indentation tests and crack observations

Some laboratory indentations test have been conducted with the objective of calibrating the actual TBM load and crack development. Core samples of granite and diorite from Äspö were casted in steel rings and indented by truncated indenters with contact diameters of 6.8 and 12 mm respectively. Different levels of load were applied to the samples. The rock samples were then taken out of the confinement rings and sectioned into thin slices. They were treated by fluorescence for crack discrimination and photographing.

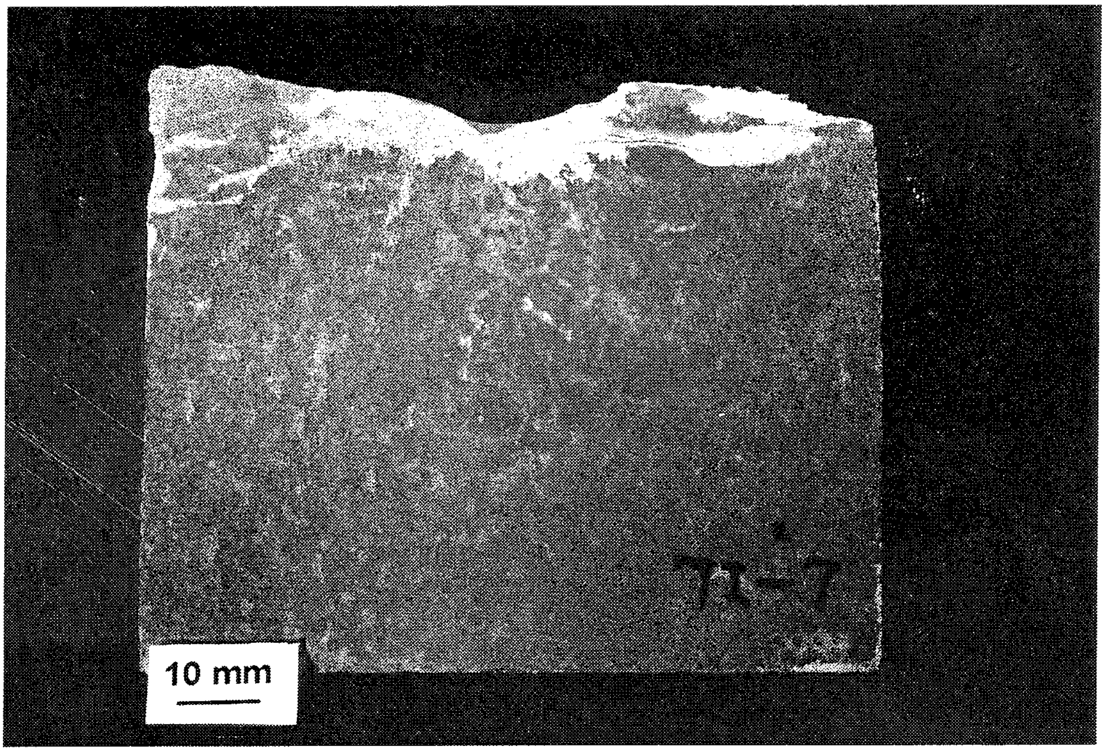
Laboratory indentation tests on samples with pre-existing cracks

For studying the influence of pre-existing fractures on the indentation induced cracks, the same rock types as used in the above indentation tests were heat-treated at 450^0 C for three hours to produce artificial microcracks. The indentations tests were then performed using the same type of indenter as mentioned above. The crack pattern induced by indentation remains the same in both heated and non-heated rock samples. However, the load necessary for producing chips in the heated rock is much lower than that in the non-heated rock. The crack lengths in the heated rock are much shorter than in the non-heated rock samples, see Figure 5-7.

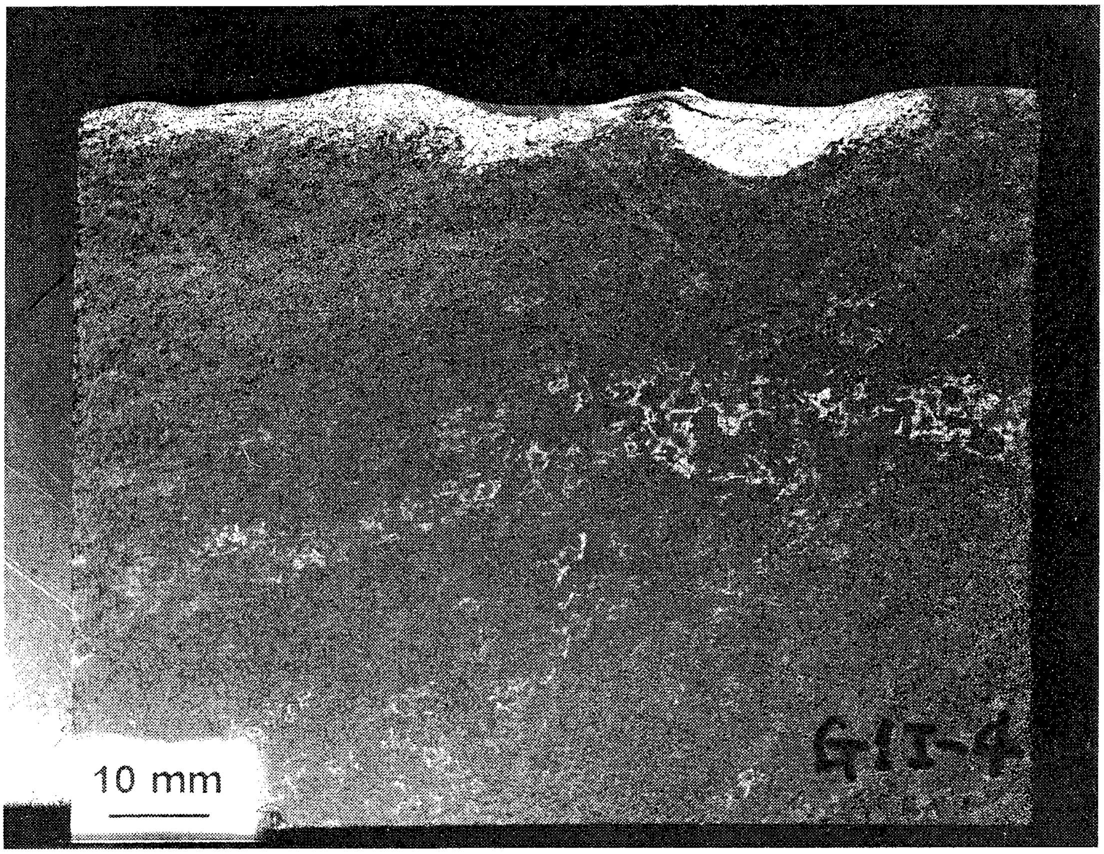
5.6.4 Planned work

Verification tests in the laboratory and supplementary development of the Indentation Crack Model. The verification work consists of comparison of the crack distribution observed in the samples taken from the experimental deposition holes bored in POSIVA's Research Tunnel at Olkiluoto and in samples taken from the TBM tunnel in the Äspö Hard Rock Laboratory with the Indentation Crack Model. Indentation tests have also been made in the undisturbed parts of the samples in order to establish the basic rock properties of the samples including the influence of pre-existing micro-cracks. The comparison is made by means of numerical and analytical methods as well as by neural network fitting.

Verification tests in the Äspö Hard Rock Laboratory. During the boring of simulated deposition holes data are collected regarding boring parameters and rock properties. The planning and preparation starts early in 1997. Data collection as well as analysis and reporting will last into 1998.

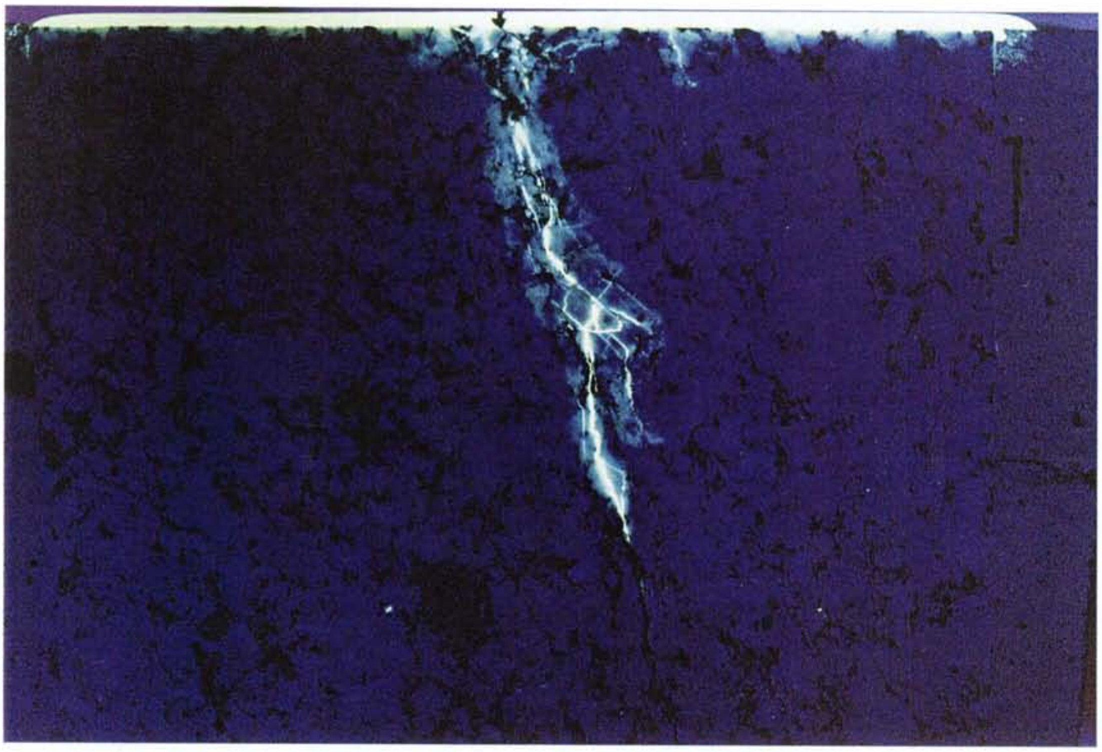


a) Cracks in the wall of TBM tunnel in Äspö.

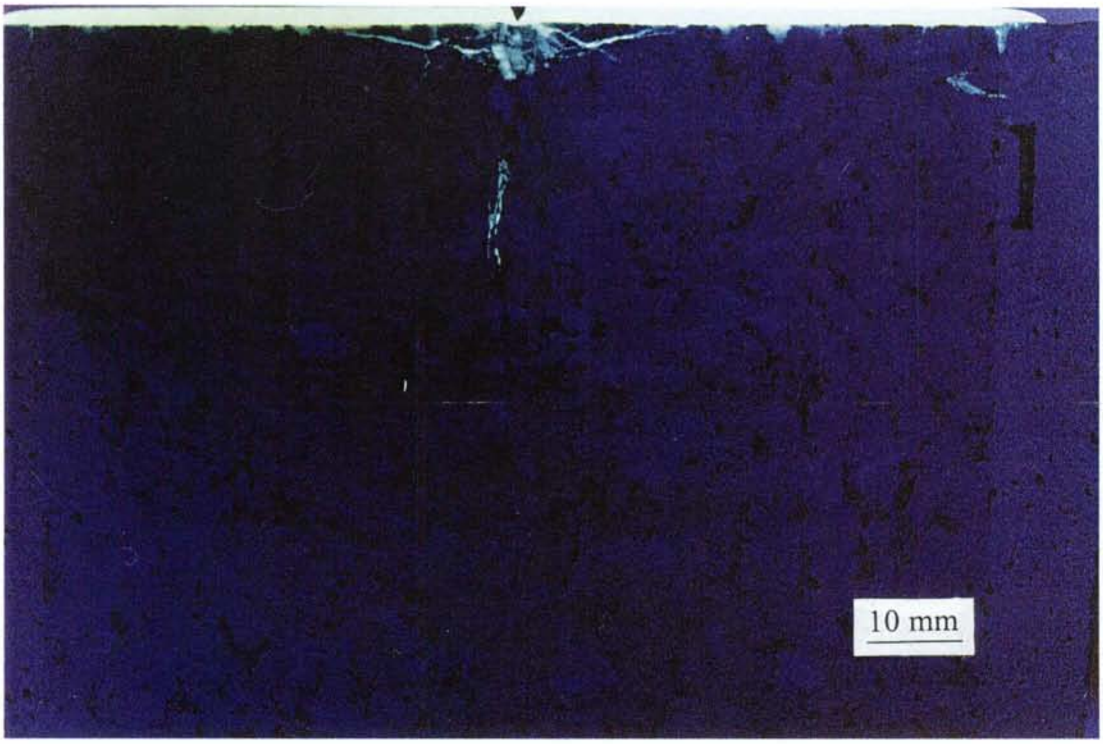


b) Cracks in the borehole wall in Olkiluoto, Finland.

Figure 5-6. *Cracks observed from samples taken in the fields.*



a) Center view of indented diorite sample subject to heat treatment.



b) Center view of indented diorite sample without heat treatment.

Figure 5-7. *Indentation cracks in heated and unheated diorite taken from Äspö.*

6 ÄSPÖ FACILITY OPERATION

6.1 THE ÄSPÖ HRL FACILITY

The hoist was taken into operation and approved by the authorities in the beginning of the year. Net was mounted at the landings to prevent falling material from the shaft to cause any damage on personnel or installations at the landings. The electrical system on the landings was redesigned and shifted to achieve a more reliable function considering to the wet environment. A hoist specialist was engaged to look on the guiders. The joints between the guiders were too big and the size of guiders differed. A tender to adjust the guiders has been accepted and the work will start in the beginning of 1997.

The drainage system has operated well during the year. An extra pump has been purchased in case of pump failure. Planning of a number of smaller activities to increase the safety started during the autumn.

A water collector was installed in front of the outlet fan. This was made to reduce the amount of water coming into the ventilation building. At the end of the year some problems with ice was detected in the inlet shaft due to cold temperatures outside. The heat exchanger was out of operation due to the ongoing excavations.

The increasing research activities have led to a demand for more electricity. Some new installations have been done and more are planned for the future. Planning for a change of most of the tunnel lights and many power outlets has been performed. The problems are mainly caused by the salt water leaking into the tunnel.

Sooner than expected selected scaling was needed and reinforcement with bolts and net was done in some areas.

Two different fire alarm systems have been tested underground. One of them did not meet the requirements. In the beginning of next year installation of one system will take place on every landing.

A cord-less telephone system has been installed. It works underground as well as on the surface a few hundred meters away from the office. No doubt this was the best safety improvement during the year.

All personnel have had the opportunity to refresh their knowledge on how to use a fire extinguisher and the safety representatives have gone through a special education to raise the quality in their work.

6.2 DATA MANAGEMENT AND DATA SYSTEMS

6.2.1 Background

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 at a site.

The first investigation database, GEOTAB, was already set up by SKB during the eighties. The aim by setting up this database was to preserve all data from the KBS-3 investigations and the preinvestigations at Äspö. In 1995 GEOTAB was replaced by SICADA (Site Characterization Database system), but all data in were successfully moved to the SICADA system.

SICADA is and will be one of SKB's most important database systems. The database should efficiently serve planned investigation activities at the future candidate sites as well as the experiments at Äspö HRL.

Three user applications/programs are available, 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. (Looks like the former GEOTAB-application).

The **SICADA/Diary** application is used to log activities and capture data from the work at a typical investigation site. This application is mainly working on the activity log table in the SICADA system. Activities in the log can be added, modified or deleted. By focusing an activity in the log it is possible to show additional information connected or fetch the investigation data associated with the activity.

The activity log table is an activity diary and all selected activities are shown chronologically by default, but it is also possible to display them chronologically for each object (borehole etc.) that corresponds to the current search criteria specified by the user.

All data rows have an unique activity identifier. This identifier uniquely connects measured data with only ***one*** activity in the activity log table. All data rows also have a time stamp and an user identification code to show and control when data was inserted into the table and who did the input.

The **SICADA/Finder** data retrieval application is used to view data. It is possible to get printed table reports, reports to file and view data on the screen. When working with SICADA/Finder it is possible to retrieve data from one table or join two tables and then retrieve the result. Search conditions can be set on any column in selected table(s) without knowing anything about the tricky SQL-language that is used by the application in the background.

The **SICADA/Retriever** application is a classic text terminal program that is useful for the long distance user who is connected to the network by using a serial modem line. Data are fetched by using the hierarchy model. As an example the investigation data from an interference test is fetched by specifying the following main search criteria:

Science:	Hydrology
Subject:	Pumping tests
Method:	Interference test

6.2.2 Results

As planned two new SICADA applications have been developed and delivered by Ergodata AB, namely:

- SICADA/Project.
- SICADA/WWW-Retriever.

Both applications are just now tested and evaluated by the Database Administrator. The role as Database Administrator is held by Ebbe Eriksson.

SICADA/Project is an application that should be used by project leaders and project coordinators when they want to know the progress of the data registration work within a certain project. When using the application a set of data is extracted from SICADA and automatically saved in a file compatible with Microsofts planning program MS/Project.

SICADA/WWW-Retriever will be accessible 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.

6.2.3 Planned work

During 1997 the following main activities are planned:

- Complete the tests of SICADA/Project.
- Release of SICADA/Project Version 1.0.
- Complete the tests of SICADA/WWW-Retriever.
- Release of SICADA/WWW-Retriever Version 1.0.
- Improve the documentation of the SICADA data model, but also the documentation in general.
- Reorganization of the positional information (coordinates etc.) in SICADA.
- Planning and realization of a system administrative tool for configuration and maintenance of the data exchange interface between SICADA and RVS.

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 location of the surface drilled boreholes which were monitored during 1996 is shown on Figure 6-1 while the tunnel drilled boreholes are seen in Figure 6-2.

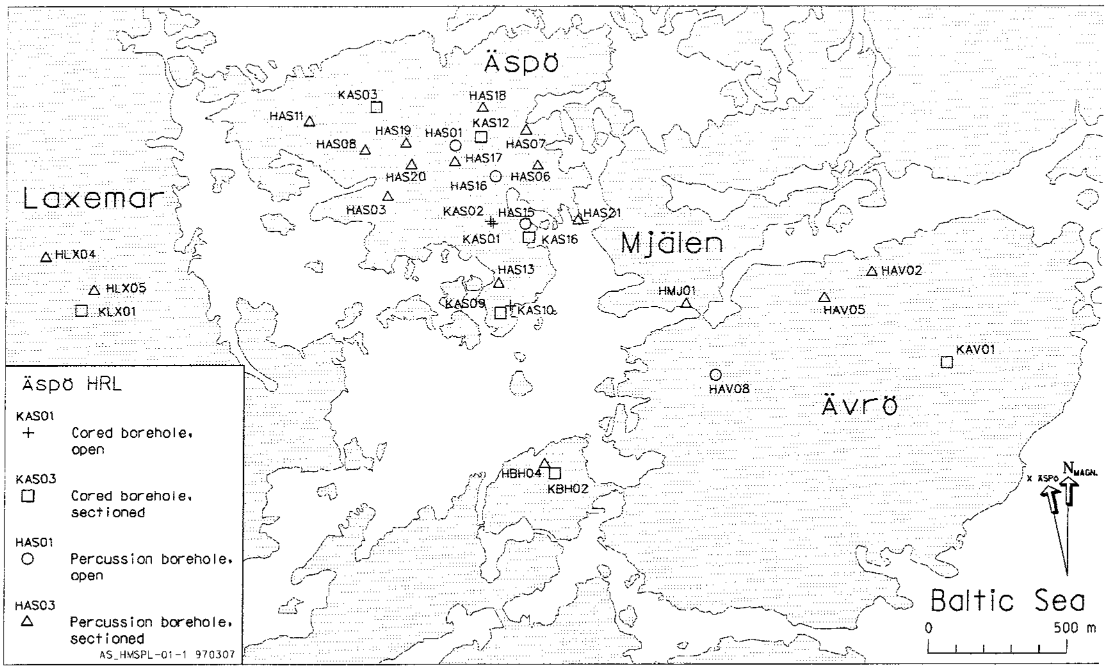


Figure 6-1. Surface drilled boreholes included during the 1996 monitoring.

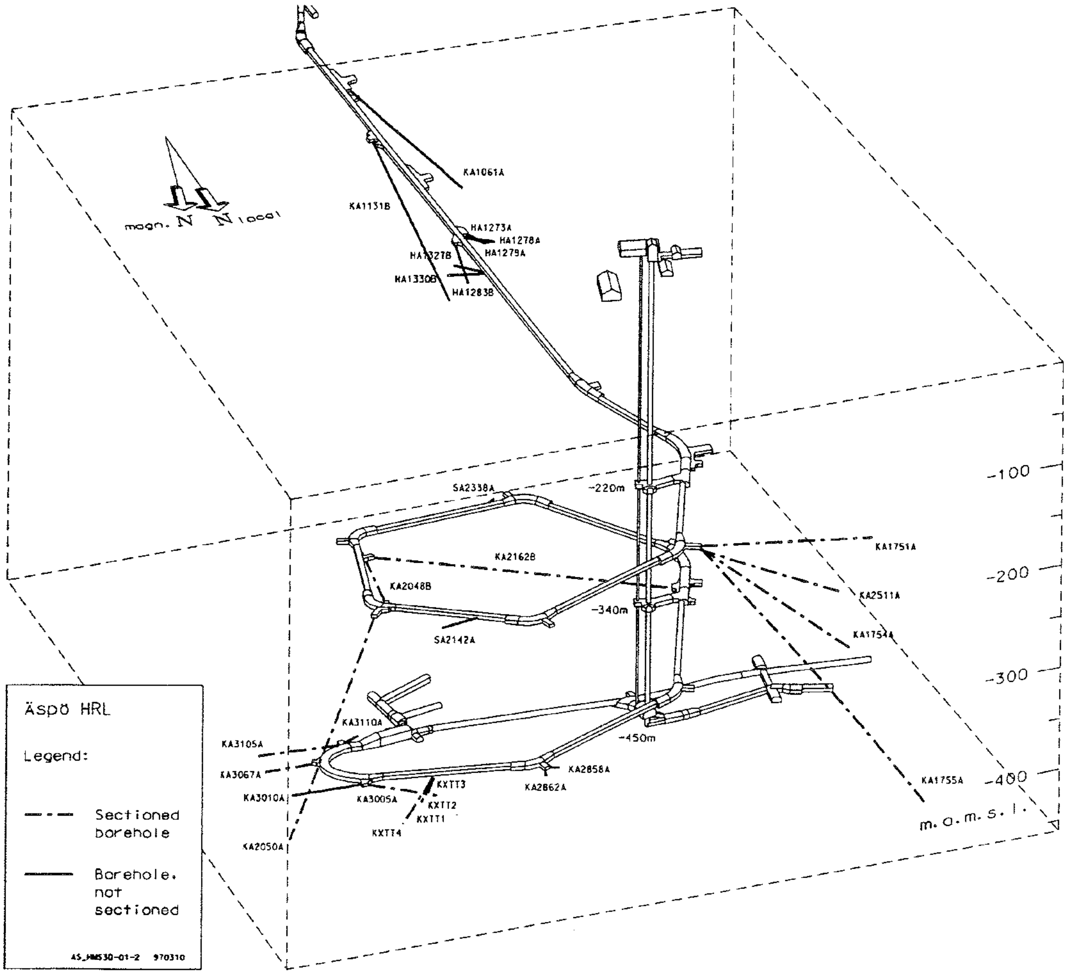


Figure 6-2. Tunnel drilled boreholes included during the 1996 monitoring.

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 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 1996) the monitoring network comprises a total of 60 boreholes, see Figure 6-3, 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 are also obtained from the surface boreholes on a regular basis. Several boreholes have been excluded from measurement while other been included over the years.

Water seeping through the tunnel walls is diverted to trenches and further to 21 weirs where the flow is measured. Air temperature, air humidity and wind velocity

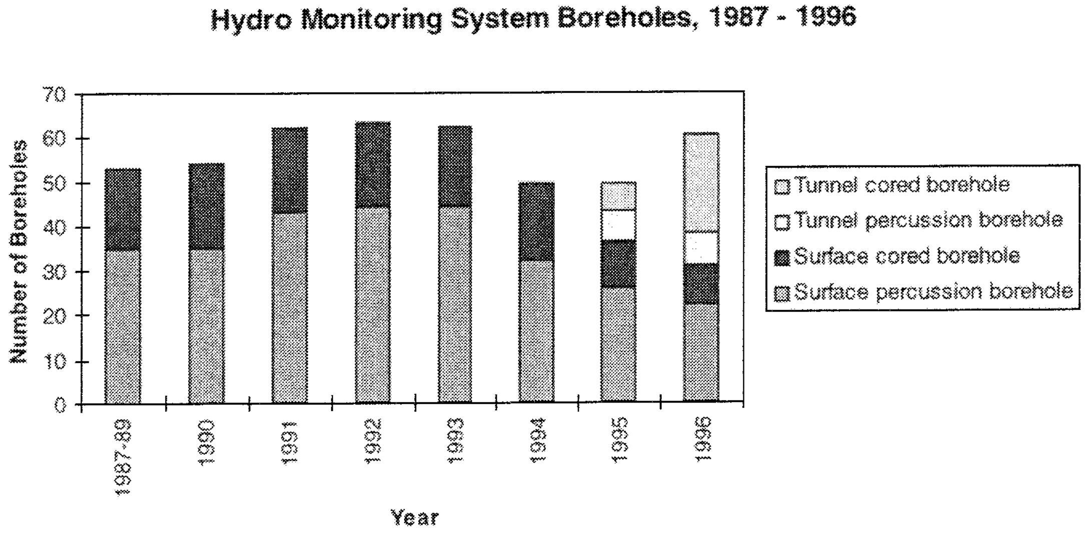


Figure 6-3. Number of boreholes included in HMS 1987-1996.

were measured in order to calculate the humidity transport. However, these measurements terminated in 1995.

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

Throughout 1996 the pumping of water flowing into the tunnel has been fairly constant at 0.0285 m^3/s (2479 $m^3/24$ h). The measurements for the calculation of the transport of humidity in and out of the tunnel was discontinued in 1995 during which the net outflow varied between 5 and -11 $m^3/24$ h. Before the ventilation began through the shafts the outflow varied between 3 and 5 $m^3/24$ h.

The drawdown of the head resulting from the pumping of groundwater appear to affect most parts of Äspö. Figure 6-4 shows the drawdown situation in the upper 150 m as of 31-12-1996. The greatest drawdown of about 95 m is found toward the southern part of the tunnel spiral.

The drawdown in the northern and northwestern parts are more moderately affected, just up to 5 m. It is also seen that the groundwater head gradients in the south are such that the sea water is flowing toward the tunnel spiral. The electrical conductivity of the groundwater in the tunnel is measured at eight locations along the tunnel. It increases from about 700 mS/m at 95 m depth to about 2000 mS/m at 449 m depth. This can be compared to the electrical conductivity of the Baltic Sea around Äspö which is about 1100 mS/m. Pertinent data to the electrical conductivity of the tunnel water is summarized in Table 6-1.

The HMS data has been utilized in studies concerning the three dimensional groundwater distribution around the tunnel, for example reports ICR 96-07 and ICR 96-06, and it formed the basis for the simulation of pressure and salinity field at Äspö, for example report ICR 95-01.

Table 6-1. Electrical conductivity of tunnel water measured during 1996.

Dept of measuring point (mbgl)	Measurement section tunnel entrance (m)	Electrical conductivity (mS/m)	Comments
95	0 – 682	760	
220	1372 – 1584	400 – 700	Great variability
225	Elevator & Ventilation shaft, 0 – 213 m	1000	
334	2357 – 2496	1300	
340	Elevator shaft, 220 - 333 m	1600 – 1400	Large variability
419	2994 – 3179	1250 – 1100	
449	3179 – 3426	2000 – 1550	
449	3426 – 3600	2000 – 1600	
Baltic Sea		1100	

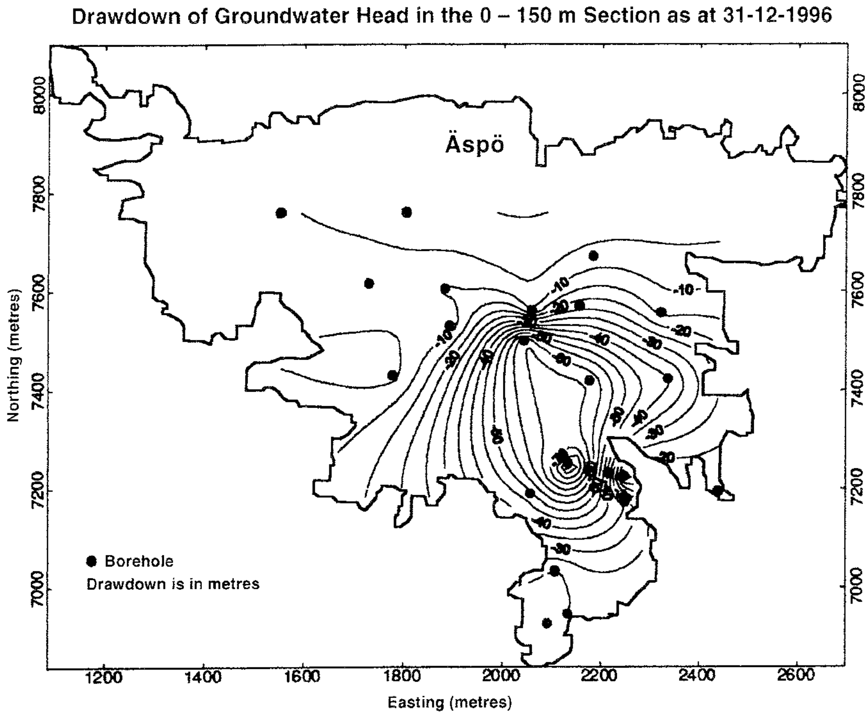


Figure 6-4. Groundwater head drawdown in the upper 150 m as at 31-12-1996.

6.3.3 Future work

The HMS data will continue to support the various scientific projects undertaken, providing basic data which is distributed in space and time.

A major report comparing the predicted hydrogeological situation after excavation with what was actually encountered is underway, with planned completion during 1997.

New measurements in the tunnel, associated with the experiments planned, will be established and connected to the HMS.

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 New results

A new measuring station, station D has been installed in the tunnel at the level -450. The new station will take care of data from weirs in PG5.

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

Maintenance of the measurement equipment in the borehole of the surface (e.g. changing of pressure transducers in the boreholes) has been done in the summer.

Half of the equipment in KAS06 has got stuck in the borehole. The borehole is closed since January 1996. (In January 1997 we will try to recover the equipment in the borehole).

The new measurement system called Datascan 7000 with the software Orchestrator (MSS-system) has been installed in the tunnel. This system will take care of data from the Long Term Tests of Buffer performance and is planned to be in operation until October 1997. There is about one hundred measured channels in the LOT-project.

6.4.3 Planned work

Additional boreholes on the surface will be taken out of operation or going to be renovated according to the hydro monitoring program for 1997.

Take out of operation: KAS10, HAS08, HAS20, HAV02, HLXO4, KAS02.

Renovation: KAS07, HAS15, HAS16, HAS17, HAS18,KAS06, KAS12.

Calibration of the weirs in the tunnel will be done in January 1997.

During 1997 the projects True Block Scale and Backfill test are planned to start. The projects measurement points are going to be connected to a measurement system. (Type of system is not decided yet).

6.5 MONITORING OF GROUNDWATER CHEMISTRY

6.5.1 Background

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

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

After completion of the construction work a few of the time series boreholes were selected for continuous monitoring together with a few boreholes drilled from the surface.

During the pre-construction investigations ten shallow percussion boreholes and thirteen deep coredrilled holes 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 at more than two occasions.

6.5.2 Objectives

The groundwater chemistry monitoring program aims to sufficiently cover the hydrochemical conditions with respect to time and space within the Äspö HRL. This program should provide information for telling where, within the rock mass, the hydrochemical changes take place and at what time stationary conditions have been established.

The objectives are:

- To provide the data necessary to check that the pre-investigation and the construction hase models are valid.
- To have the possibility to see if, and when the groundwater chemistry is changing.

6.5.3 Scope

The sampling is performed twice every year, in spring and in autumn, and comprises boreholes and sections sampled as listed in Table 6-2. Sampling and analyses are performed according to Chemistry Class no 4 as described in "About Sampling and Analyses of Groundwater in SKB Projects". Defined within the on-going evaluation and reporting of pre-investigation and construction phase data.

6.5.4 Planned work for 1997

The monitoring in the tunnel and surface boreholes will be supplemented with sampling for some additional isotope analyses as well. The isotope analyses are planned to be taken only from a few of the monitoring points where results from earlier investigation should be checked. Presently sulphur-34 and carbon 14 are included.

The hydrochemistry monitoring programme is continuously updated.

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

Idcode	Secup/seclow	Class no	Comment
KAS03	533-626 m	4	
KAS09	116-150 m	4	
KA1755A	88-160 m	4	Replaces KAS04
KR0012B		4	
KR0013B		4	
KR0015B		4	
SA0813B		4	
SA1009B		4	
SA1229A		4	
SA1420A		4	
SA1730A		4	
SA2074A		4	
SA2273A		4	
SA2600A		4	
SA2783A		4	
SA2880A		4	
SA3045A		4	

6.6 PUBLIC RELATIONS AND INFORMATION ACTIVITIES

The Äspö Day, an open house in the beginning of June, was held traditionally and some 500 visitors took the opportunity to visit the facility.

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

In addition, OKG has brought about 5 000 visitors to the Visitor's Niche located 115 m from the tunnel entrance.

7 INTERNATIONAL COOPERATION

7.1 CURRENT INTERNATIONAL PARTICIPATION IN THE ÄSPÖ HARD ROCK LABORATORY

Eight organizations from seven 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.**

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

Multilateral projects are established on specific subjects within the Äspö HRL programme. These projects are governed by specific agreements under the bilateral agreements between SKB and each participating organisation. The ZEDEX project which is described in section 3.2 is one example of such a project. The work on the TRUE Block Scale Experiments within the TRUE Programme was outlined during 1996 and will be performed as a multilateral project.

Specific technical groups so called Task Forces is another form of organizing the international work. A Task Force on groundwater flow, radionuclide transport and rock is ongoing (see section 4.8).

Due to the budget situation in the US, the USDOE terminated the participation on April 30 1996. A new Finnish company, Posiva Oy, was formed by TVO and IVO in 1996 for the management of high level waste in Finland. Hence the bilateral agreement between TVO and SKB was transferred to Posiva Oy.

7.2 SUMMARY OF WORK BY PARTICIPATING ORGANIZATIONS

7.2.1 Posiva

Introduction

Posiva was founded in 1995 by Teollisuuden Voima Oy (TVO) and Imatran Voima Oy (IVO) to manage the final disposal of their spent nuclear fuel. The agreement on the Joint Project between TVO and SKB was shifted to Posiva as the company started its operations in 1996.

The work within Joint Project of this agreement comprised three main areas

- flow and transport modelling,
- hydrochemical modelling,
- in-situ measurements and modelling conceptual.

The work within this agreement was concluded and the agreement between Posiva and SKB was signed in June 1996. The new agreement includes the same areas as before but as an extension to the earlier contract the participation to SKB's planned prototype repository has been agreed, as well as, demonstration of important parts of repository system at VLJ-research tunnel at Olkiluoto in Finland.

Later in 1996 Posiva agreed to participate in TBS (TRUE Block Scale) experiment together with Nirex, ANDRA and SKB.

Task Force on Modelling Groundwater Flow and Transport and True

In the context of the Äspö Task Force on Modelling of Groundwater flow and transport of solutes calculations have been made for Task 4C, the predictive modelling of the radially converging tracer tests and dipole tests in a few meter scale. These tests are part of the TRUE series of tracer tests. Two different approaches were used for predictions of the radially converging test; the same approaches are used for the dipole test predictions, which will be presented at the Task Force meeting in Cherbourg in February 1997.

In the year 1996 VTT Energy has participated in the Äspö TRUE project on behalf of Posiva by doing scoping calculations and predictions for the detailed scale experiments RC-1. Calculations have been based on both numerical varying aperture approach and analytic generalised Taylor dispersion approach. The results showed reasonable good agreement with the measured ones but it should be remembered that it was possible to calibrate the flow porosity against a preliminary test.

When comparing the results an inconsistency between the pumping flow rates used in the preliminary test and the actual test and with the corresponding draw downs was observed but could not be explained. This brings to some extent uncertainty into the estimation of the flow field on which the tracer test and its modelling is based on. SKB has published the experimental results and predictions of all participants in a common report.

VTT Energy have also participated in the planning of the TRUE Block Scale Experiment. The scoping calculations for the experimental design were made using the finite element flow model FEFLOW. Towards to the end of the year site scale calculations using the equivalent porous medium approach and Task 3 model of the Äspö spiral were initiated. The calculations aimed at getting an overall view of the present day hydraulic situation around the Äspö tunnel and spiral and to deliver boundary conditions for a more detailed modelling around the planned Block Scale Test area. The calculations showed a gradient at the test area that is 5 to 10 times as high as the observed one. A strong tunnel skin effect could explain the discrepancy but it is important to consider to what extent low head values can be transferred into the rock along the open borehole sections around the 1 metre packers. The reporting of these scoping calculations are in progress.

Hydrochemistry

Posiva's modelling group (participants from VTT and IVO) took part in finalising the reporting on the modelling done in accordance with task plan for integrating hydrochemical mixing reaction models with hydrogeological flow models (Laaksoharju & Wallin 1997). The task was part of the scope of the 2nd International Geochemistry Workshop held on June 6-7, 1995 at the Äspö Hard Rock Laboratory (HRL). The aim was to improve the understanding of groundwater flow and evolution in the geological past and facilitate the coupling between the hydrochemistry and the hydrogeology models. The modelling exercise of Posiva's group comprises combined chemical mass balance and flow modelling of the Redox Zone which is a vertical hydraulically-conductive fracture zone intersected at a depth of 70 metres by the access tunnel of HRL. This provided an opportunity to study geochemical changes resulting from non-saline water inflow into a crystalline bedrock aquifer as anticipated during construction and operation of a deep repository for spent nuclear fuel. The modelling exercise focused on what reactions and processes, in addition to flow and mixing, are needed in order to explain the behaviour of main ions and trace elements in the groundwater. The calculated mixing proportions of different groundwater types were used in calibrating the flow model. The integration of geochemistry with flow modelling is considered encouraging in producing additional information of the heterogeneity of flow paths. The results of chemical evolution can be a valuable tool for palaeohydrological simulations corresponding to long term tracer tests.

One part of the task was also to follow the research of palaeohydrochemistry process identification. Thereupon Posiva's modelling group also participated in the Workshop on Glaciation and Hydrogeology in Stockholm 17-19th April 1996, where the studies of Äspö formed an essential part. Posiva's modelling group gave a presentation on the palaeohydrogeochemical interpretation of the Olkiluoto site (Pitkänen & Snellman 1996), the results of which are in accordance with the interpretation of the Äspö site. At both sites the isotope composition and hydrochemistry in the upper part of the bedrock seem to contain a well developed profile of climatic changes since the Weichselian. Below this a preglacial strongly saline groundwater (brine) is located.

Testing of important parts of repository system

In addition to the joint project at Äspö HRL between Posiva and SKB, the parties have agreed to perform supporting work for development of disposal technology. Description of the tasks carried out in 1996 is as follows.

Characterisation of excavation disturbance around Full-scale experimental deposition holes.

The properties of the disturbed zone around the deposition holes and the properties of the interface between the bentonite barrier and rock have effect on the migration of radionuclides through the disturbed zone, possible flow of gases released from a waste canister and saturation of bentonite buffer. The properties of the disturbed zone are to some extent dependent on tool and machine factors of deposition hole boring and can therefore be modified. The research on the disturbed zone around full-scale deposition holes is aimed to promote the understanding of the properties of the disturbed zone and the means to control them.

Complementary samples were taken from the disturbed zone in the experimental deposition holes at Olkiluoto. The disk samples for the conductivity and diffusivity measurements with Helium-gas were prepared. The disturbed surface of the samples was sealed with gel-time adjusted epoxy sealant. The first results from the 14CPMMA study of the disturbed zone were obtained. The study was focused to give information of the properties of disturbance in different types of rock and to improve the accuracy of the estimated correlation between boring machine parameters and disturbance extent. The preliminary results show clear differences in the disturbed zone between different types of rock.

In situ failure test

The strength and deformation properties of rock are dependent on the heterogeneity, anisotropy, scale of the sample and the loading geometry. When the behaviour of rock is modelled numerically the result depends on the strength and deformation properties of the rock and the modelling method used. An in situ failure test has been planned to be carried out in the research tunnel at Olkiluoto to study the strength of rock and failure in real conditions and in a larger scale than usually in laboratory. The study is focused to evaluate and promote the present understanding of the rock failure and the numerical modelling of such processes.

The in situ failure test has been modelled in 3-D using FLAC3D program and the preliminary shape of the test geometry was modified according to the results. The results have given a rough estimate of the maximum stresses during the test and location of possible failures. The pressure development capacity of the swelling material was tested and pressures up to about 70 MPa were achieved, which suggests that the technique works. The rock samples of two sizes and three different orientations have been tested at present. The results imply that the orientation has significant effect on the uniaxial compressive strength. The sample size, loading rate and saturation degree of the samples had also influence on the strength according to preliminary results.

7.2.2 PNC

TASK FORCE

Background

PNC has been aparticipating in the Äspö Task Force from the beginning of it. Masahiro Uchida who represents PNC and Bill Dershowitz as a modeler from Golder Associates participated in the 8th Äspö Task Force meeting.

New results

Task-3:
Pressure response history due to shaft excavation was reviewed. Characteristics of these responses are as follows:

- Stepwise quick responses tend to occur along a single planar feature striking NW.
- Gradual but significant responses tend to occur to the north, while regional lowering tends to occur to the south.
- Some regional lowering are observed within 100 meters from the Äspö underground workings, indicating that these locations are hydraulically isolated due to the local fracture systems.

These results are included in an ICR Report.

Task-4C:
PNC/Golder team presented prediction of RC-1 Tracer Experiment of TRUE-1 using three approaches, Moench's analytical solution, SEEP/W, and FracMan. An emphasis was placed to use various boundary conditions. Four kinds of boundary conditions were examined and all except for hydrostatistic boundary condition were able to predict the poor tracer recovery.

Planned work

Task-4 (Task-4D)
Prediction for the Dipole Tracer test is underway and the results will be presented at the 9th Äspö Task Force meeting.

TRUE

Background

PNC currently participate in the TRUE project only through the Äspö Task Force. Bill Dershowitz participated in TRUE-BS Workshop held during October 16-17, 1996.

New Results

As described in the "Task Force".

Planned work

Participation for the TRUE-BS experiment is under discussion.

REX

Background

PNC currently participates in the REX project as a PNC/BGS team. Hidekazu Yoshida of Tono Geoscience Center, PNC participated in the Rex technical meetings held at Äspö in April and at BGS, UK in November, 1996.

In April a preliminary field observation has been carried out in order to select appropriate fractures for REX experiment.

Our activities consist of laboratory mineralogical observations of drill cores from Äspö, as well as laboratory batch tests for understanding of microbial effects on rock/water interaction using Äspö groundwater bacteria(s)-inoculated and rocks/minerals in an (+ anaerobic) atmosphere with H_2 + CO_2 + N_2 at 30 degrees C.

New results

All naturally open fractures in the REX boreholes, referred as "Potentially Flowing Features (PFFs)", were successfully distinguished from drilling induced fractures on the basis of petrographic criteria; principally morphological evidence for core-scale interconnectivity and the presence of mineralization that can be attributed to (recent) fluid movements.

The result of the mineralogical observations of drill cores with SEM, EPMA and so on revealed a high porosity zone adjacent to a fracture surface, corrosion of albite, micro-cracking of quartz, and crystals growing into open pore-space, and calcite and sulphide (mostly pyrite) on the fracture surface. The calcite have little iron contents (0.2%). Minerals on the fracture surfaces are coated with a very thin dendritic layer of a clay-type mineral. Detailed mineralogy of two boreholes are presented in a PNC/BGS collaboration report.

The microbial study gave an interesting result that the inoculated sulphate reducing bacteria (SRB) had a noticeable effect on groundwater compositions (Fe, Mn increase and S decrease), even though SRB population decreased markedly from the start of the experiments. Iron reducing bacteria (IRB) gave a striking contrast to the SRB. IRB had no effect on hydrochemistry but showed initial population increase followed by its obvious decrease at the end of the experiment period of three weeks.

Planned work

The results of PNC/BGS work will be compiled by the end of February and will be presented at the next project meeting scheduled on June 16 and 17, 1997. Research plan for the year 1997 is under discussion.

ZEDEX

Background

PNC is participating in the ZEDEX project by sending Mr. H. Matsui as a peer reviewer.

During the period concerned Mr. Matsui reviewed technical notes on the results of the experiments and he attended the 13th project meeting.

Planned work

The final project meeting held in this coming March will be attended by Mr. Matsui.

Knowledges from PNS's EDZ (Excavation Damaged Zone) Experiments being conducted at the Kamaishi Mine will be incorporated and compared with those from ZEDEX to have better understanding of the nature of the "Disturbed Zone" in granitic rocks.

Earthquake study at the Kamaishi mine

Background

The study on the effects of seismisity on ground motion at deep underground, hydraulics and hydrochemistry being conducted at the Kamaishi Mine has been chosen as one of the PNC/SKB collaboration issues. SKB sent Dr. Christopher Juhlin of Uppsala University to Kamaishi to review the data obtained so far in April, 1995 and November, 1996.

68 earthquakes have been recorded during 1996 then in the 7 years since the initiation of the study at the Kamaishi Mine in February, 1990 to the end of December, 1996, 315 earthquakes have been observed there.

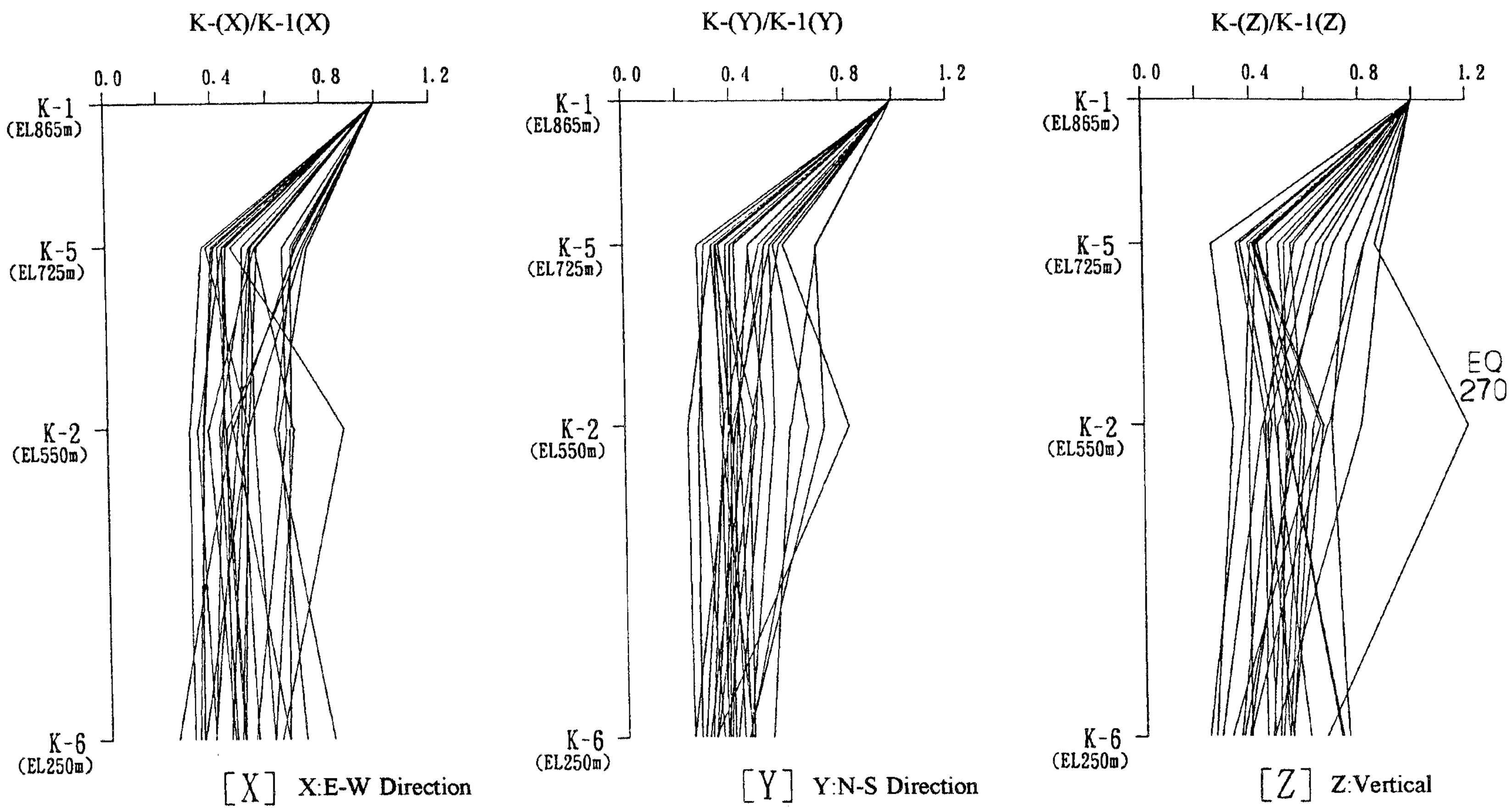
New Results

SKB sent Dr. Christopher Juhlin of Uppsala University to Kamaishi to review the data obtained so far in November, 1996.

The largest earthquake, which occurred south-east of the site on February 17, had a magnitude of M=4.2 and a maximum acceleration at the site of 19.49 gal. The earthquake which gave the largest acceleration of 48.26 occurred on June 5. At the earthquake No. 270, it was recorded a smaller on-surface acceleration than that at underground, see Figure 7-1. No clear explanations have been given so far.

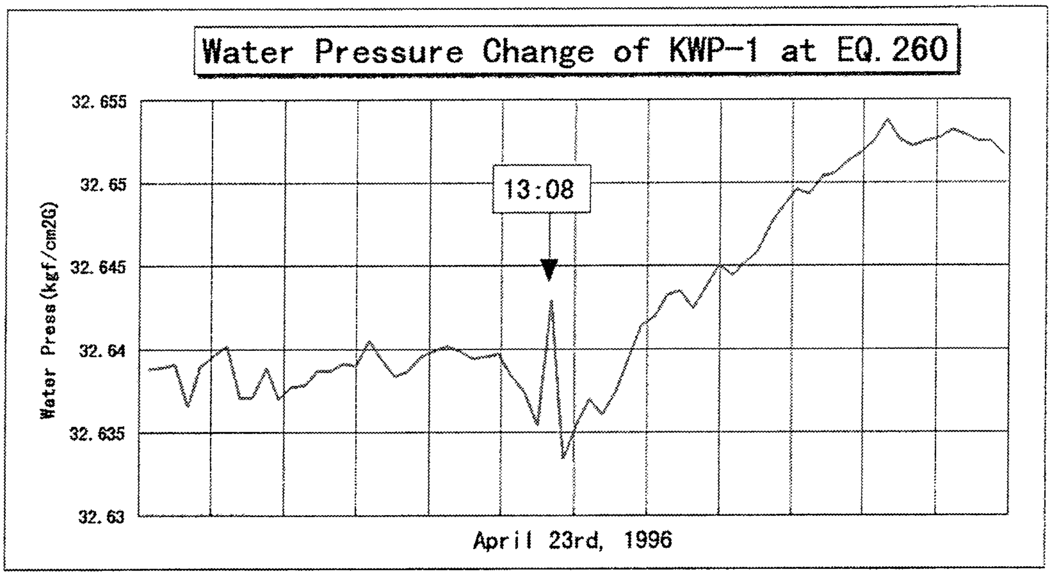
Two earthquakes gave water pressure changes. One occurred on April 23 gave a water pressure rise of about 0.008 kgf/cbcm at the borehole KWP-1, the other occurred on August 11 gave a water pressure drop of about 0.03 kgf/cbcm at the borehole KWP-2, see Figures 7-2 and 7-3.

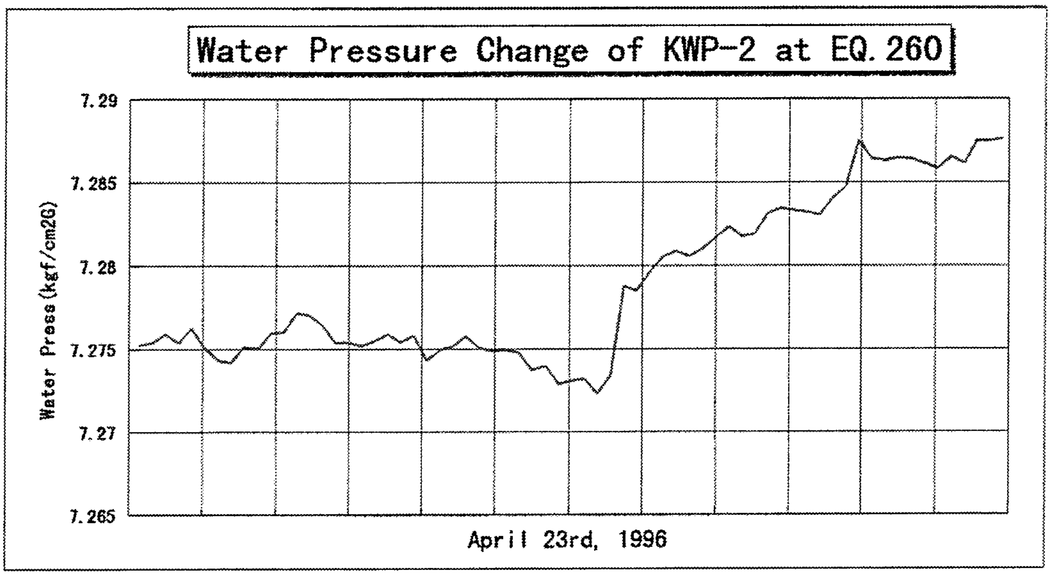
No co-seismic hydrochemical changes were recorded during the period.



Ratio of accelaration of earthquakes between
the K-1 seismograph and other seismographs.

Figure 7-1. *Ratio of accelaration of earthquakes between the K-1 seismograph and other seismographs.*





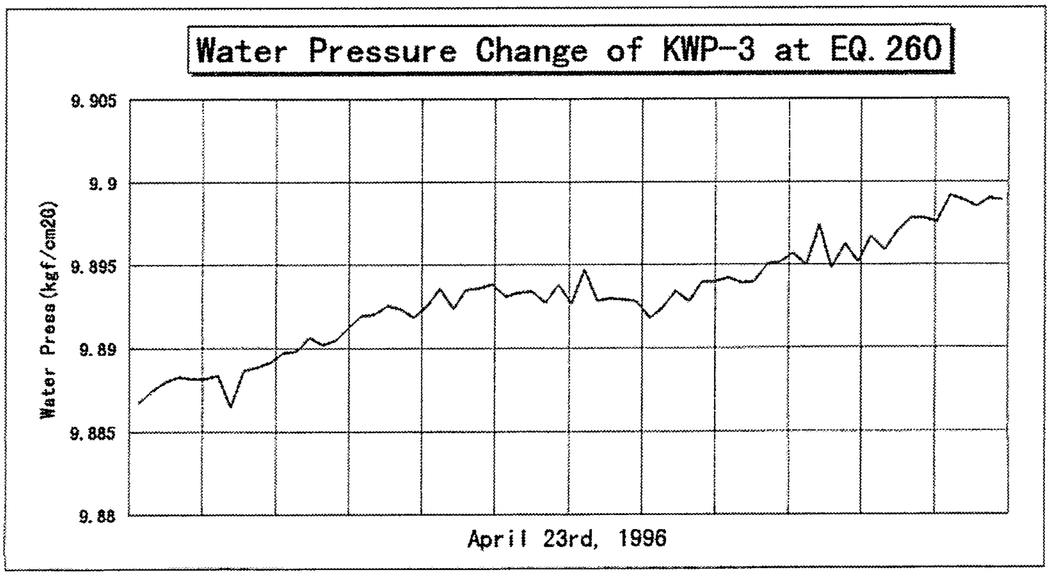


Figure 7-2. *Water pressure change of KWP-1, KWP-2, KWP-3 at EQ. 260.*

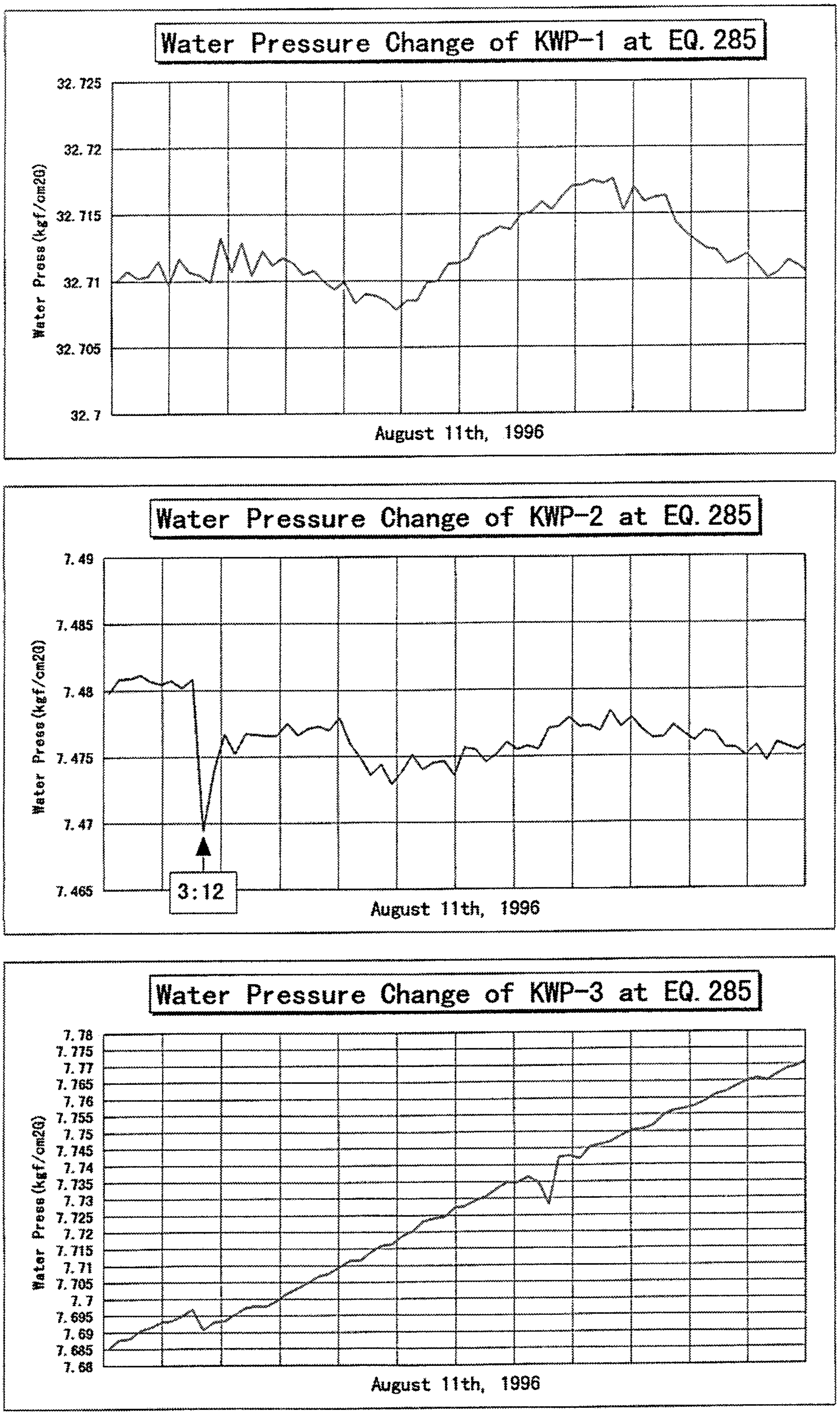


Figure 7-3. *Water pressure change och KWP-1, KWP-2, KWP-3 at EQ. 285.*

Planned work

Observations will be continued to confirm the existence of the effects on the geological environments and to understand its nature (such as the restorative nature of the changes) together with analysis of the data accumulated since 1990.

The ground motion's diminishing nature towards deep underground and the topographical effects on ground motion are also an important issue to be assessed.

7.2.3 CRIEPI

Background

CRIEPI has joined with the Äspö Hard Rock Laboratory Project from 1991. CRIEPI's activity in 1996 was focused on the modelling efforts for groundwater flow and radionuclide migration, the data analysis for the dating of fault activity and the sampling and data analysis for the dating of groundwater at the Äspö site.

Results

1. Modelling efforts

The evaluated results for the groundwater flow applying the simulation code FEGM, developed by CRIEPI was presented in the ICR-report 96-07. From these results, the effective applicability of this code was verified for predicting the groundwater flow in fractured rock with the updated geological structure model of Äspö.

Furthermore, we have conducted a prediction analysis for Task-4c and Task-4-d. In this analyses, we applied the stochastic approach based on the Monte Carlo method combined with the deterministic approaches, FEGM and FERM (Solute transport model) developed by CRIEPI. From these results, the standard derivation of drawdown on every borehole, break through time and mass recovery rate etc., were estimated, so that the predicted values were not good agreement with measured one. Considering that the tracer transport is fairly affected by the natural flow, so the second step of prediction approach was performed to take into account of the natural flow. Consequently, a good agreement between the predicted and measured values for Task-4c. As for Task-4d, the hydraulic impact is less than Task-4c (ex. for the pumping rate), so the prediction is more difficult than the case of Task-4c, see Figures 7-4 and 7-5. To evaluate in detail the tracer transport it is necessary to perform more sensitive analyses.

2. Dating of fault activity

Dating of fault movements by ESR method is originally based on the assumption that the radiation defects accumulated in fractured quartz grains are annealed by high temperature and high stress at the time of faulting. However, perfect annealing of radiation defects at the time of faulting have not been verified experimentally and it seems to be difficult to expect the perfect annealing of defects due to faulting near the groundsurface. The new method developed by CRIEPI does not depend on the assumption of the perfect annealing at faulting but the process of filling up the precursor generated at faulting by unpaired electron. Simple representation of the basis of dating fault by ESR method is shown in Figure 7-6.

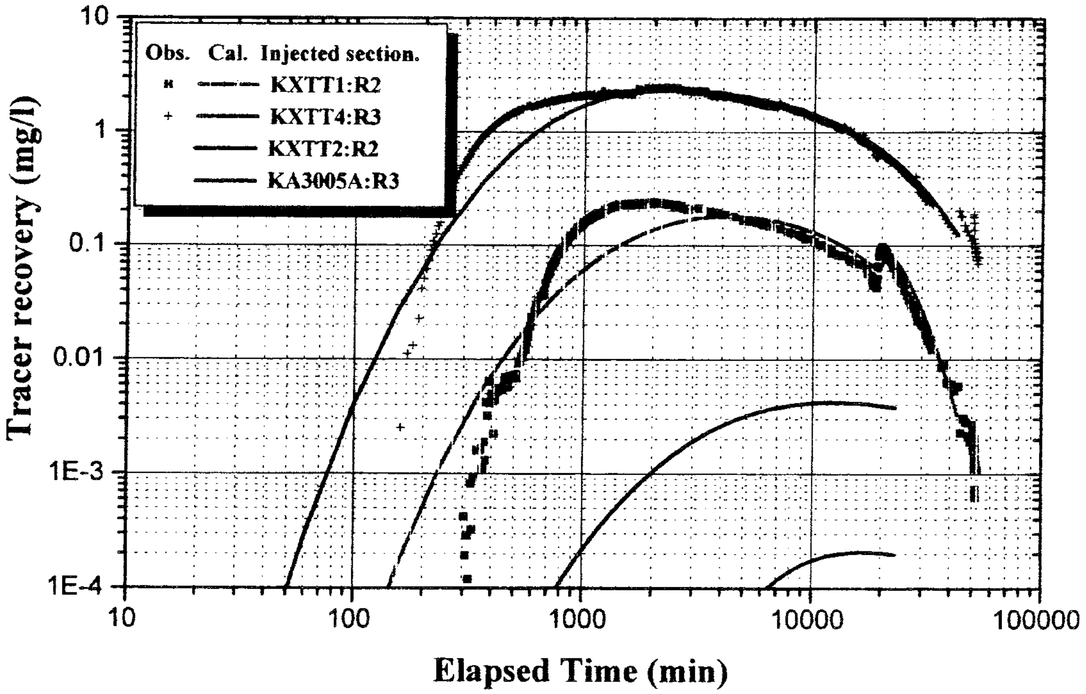


Figure 7-4. Relationship between calculated results by CRIEPI and observed data for TASK-4C. (Taking account of natural flow)

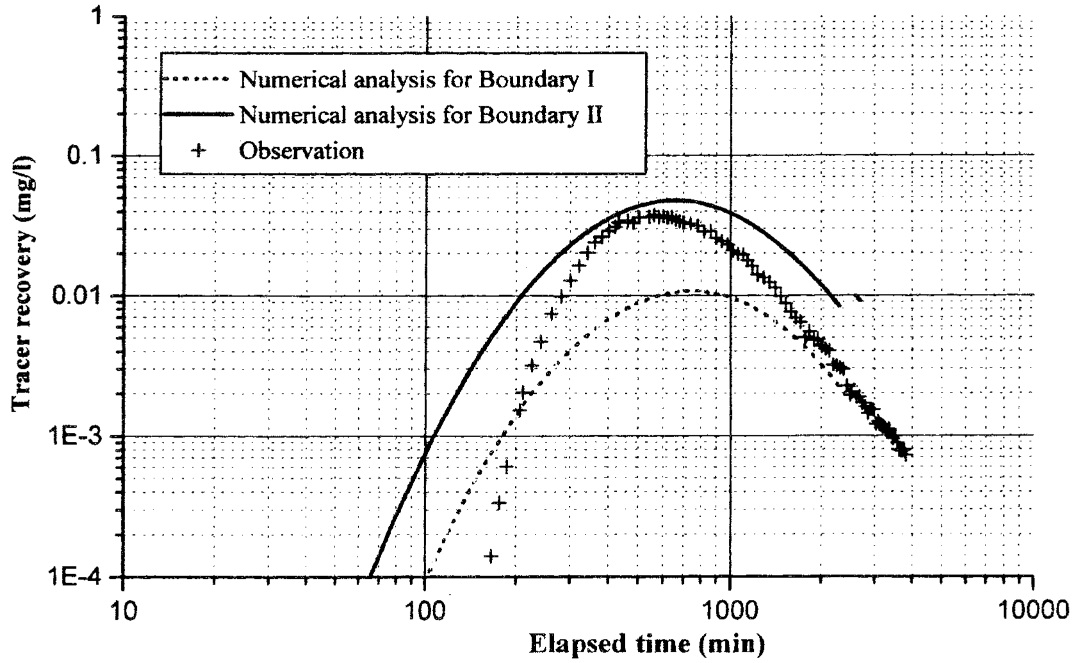


Figure 7-5. Relationship between calculated results by CRIEPI and observed data for TASK-4D#2. (Taking account of natural flow and boundary condition)

$$\text{Age of faulting} = \frac{\text{Equivalent Dose (ED)}}{\text{Dose Rate (D)}}$$

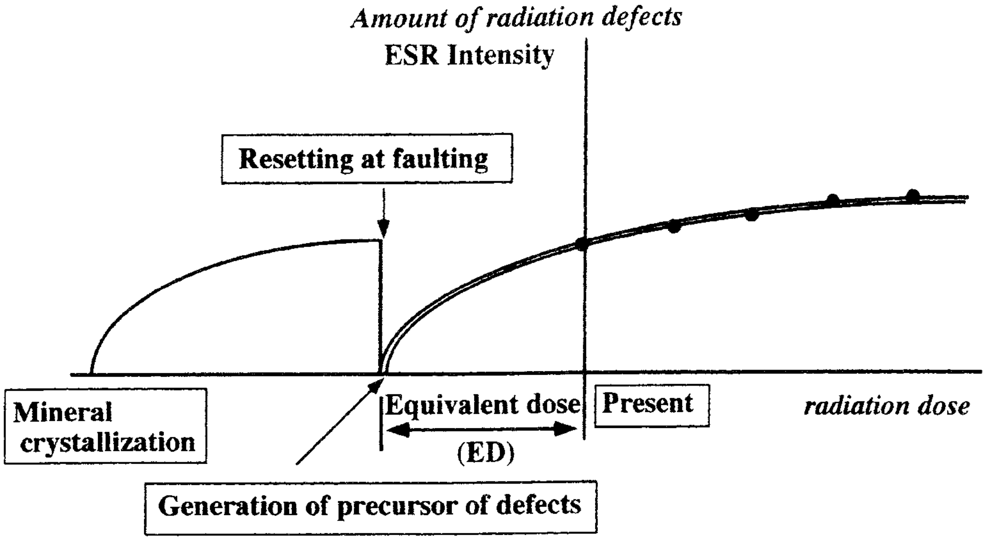


Figure 7-6. *Schematic view of process for fault dating by ESR method.*

NE-2 was selected for fault dating in this work because it is thought to cut the underground tunnel at different levels (Figure 7-7; TD 1600 m, 1860 m, 2460 m). In 1995, to identify the multiple activities of NE-2 and to determine the critical point for sampling, the internal structure of NE-2 at TD 1860 m was investigated and the undisturbed faulted materials composed of fault gouge and fault breccia at the tunnel wall were sampled by CRIEPI.

Under microscope, the detailed structure of faulted rock was investigated. Also, fractured quartz grains 75-250 μm in diameter were separated from it and observed by SEM to estimate their relative age of faulting based on the assumption that the surface texture of fractured quartz grains changes from the simple and fresh feature to the irregular and complicated texture due to the chemical erosion by ground water.

NE-2 consist of fracture zones having several m width that are composed of several fault gouge zones. Fault breccia is composed of mylonite and cataclasite that are thought to be generated in different depth and ages. Main fault plane along which unconsolidated fault gouge was distributed cuts all the previous structures and it was concluded that the latest movement has happened along this plane near ground surface, see Figure 7-8.

We recognized two types of surface texture on fractured quartz grains separated from fault gouge, i.e., sharp edge and subconcoidal surface, eroded and irregular plane (Figure 7-9), estimating that NE-2 had moved several times and some of them seem to be geologically short time before.

Quartz grains separated from fault gouge at TD 1860 m in 1995 is too small to measure the ESR signals for dating. Therefore in 1996, we collected fault gouge

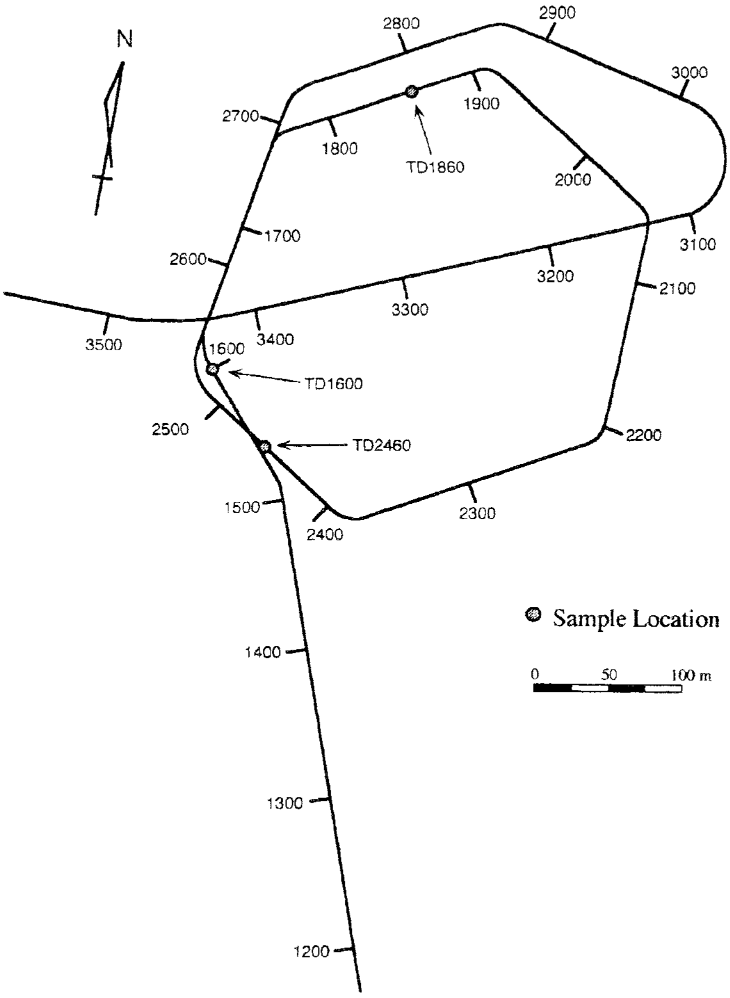


Figure 7-7. Sampling locations in Äspö HRL tunnel for fault dating on NE-2 zone.

samples again not only at TD 1860 but also at TD 1600 m, TD 2460 m. Figure 7-10 shows the sketch of NE-2 at TD 1600 m. Width of fractured zone is up to 50 cm that is composed of fault breccia and fault gouge. Fault gouge 20 cm wide cut the previous structures and it is expected that the latest activity has happened along this plane as at TD 1860 m.

Sampling were completed and ESR measuring is undergoing.

3. Dating of groundwater

CRIEPI has been investigating on the dating and the origin of groundwater to estimate the groundwater evolution at the Äspö HRL since 1995. The measured data on the dissolved noble gases and the environmental isotopes of groundwater collected at the Äspö site in June of 1995 are described as follows. CRIEPI collected 16 groundwater samples to measure contents of the dissolved noble gases and the environmental stable isotopes in the tunnel of the Äspö HRL, see Table 7-1. The sample No KA2858A analyzed only for the environmental stable isotopes, because groundwater sample was not collected without avoiding contamination with an atmospheric air. The noble gases was measured by a mass-spectrometry

Table 7-1. Sampling points for groundwater dating at Äspö HRL.

No	Name of borehole	Number of section	Diameter of borehole (mm)	Section length (m)	Section volume (l)	Assumed flow rate (l/min)	Flushing time (min)	sampling fittings	Remarks
1	KR0012B	1	38	5.57	6.3	0.3	21.1	Φ8mm tube	REDOX
2	KR0013B	1	38	9.89	11.2	8	1.4	Φ8mm tube	REDOX
3	KR0015B	1	38	10.49	11.9	1.5	7.9	Φ8mm tube	REDOX
4	SA0813B	1	56	19	46.8	1	46.8	Φ6mm tube	Sulfide rich
5	HA1327B	1	56	26	64.0	1.5	42.7	Φ6mm tube	Sulfide rich
6	SA2718A	1	56	20.6	50.7	0.3	169.1	manometer	Percussion
7	SA2783A	1	56	19.9	49.0	5	9.8	1.5 in.fittings	Percussion
8	KA2858A(g)	3 (green sec)	56	1	2.5	0.2	12.3	Φ6mm tube	Select
9	KA2862A(y)	2 (yellow sec)	56	0.96	2.4	1.2	2.0	Φ6mm tube	Select
10	KA3010A(g)	2 (green sec)	56	6.5	16.0	40	0.4	Φ6mm tube	Select
11	KA3067A(g)	4 (green sec)	56	3	7.4	0.6	12.3	Φ6mm tube	Select
12	KA3067A(b)	4 (blue sec)	56	1.5	3.7	7.5	0.5	Φ6mm tube	Select
13	KA3105A(b)	6 (blue sec)	56	2	4.9	4	1.2	Φ6mm tube	Select
14	KA3105A(r)	6 (red sec)	56	2.5	6.2	12	0.5	Φ6mm tube	Select
15	KA3110A(y)	2 (yellow sec)	56	8.58	21.1	105	0.2	Φ6mm tube	Select
16	KA3358A(y)	2 (yellow sec)	56	2.13	5.2	0.9	5.8	Φ6mm tube	Select

after extraction and separation of dissolved gases using a conventional technique for the noble gas treatments. The environmental stable isotopes were measured by a mass-spectrometry after decomposing water to hydrogen and oxygen and reaching a isotopic equilibrium.

The analysis data on environmental stable isotopes and tritium concentration were plotted in Figure 7-11 combining together with other data on the environmental stable isotopes measured at the Äspö site published in elsewhere. Figure 7-12 and Table 7-2 show the relation between the dissolved ^{4}He content and a distance from the entrance of tunnel to a sampling point. Figure 7-11 shows that data on the environmental stable isotopes are on the linear line described by the equation (1).

(1) $\delta D = 6.52\ \delta^{18}O - 8.9$

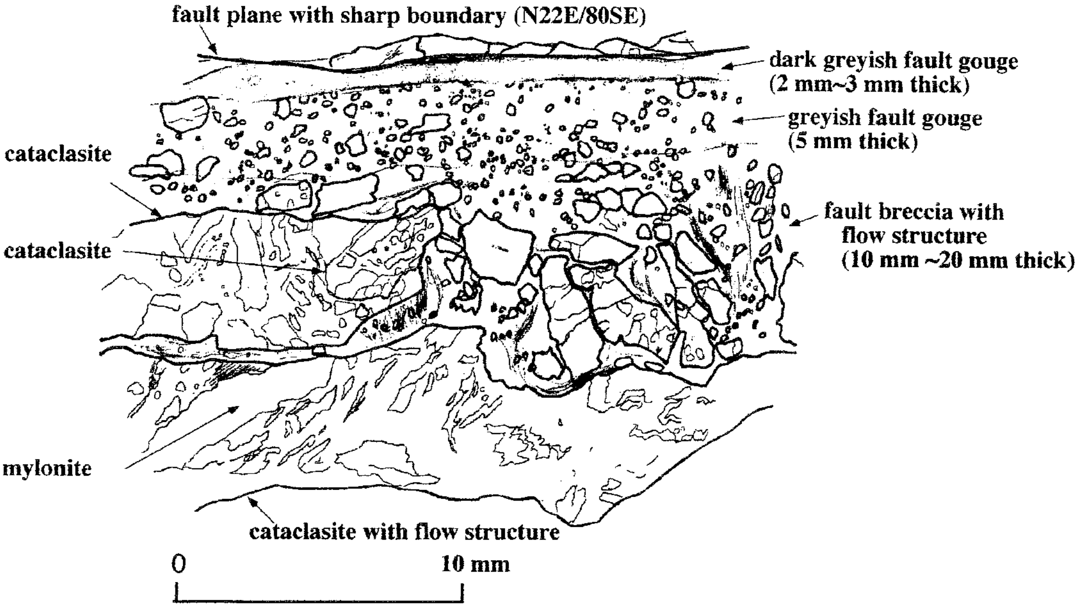


Figure 7-8. Detailed sketch of fractured zone composed of fault gouge and fault breccia (NE-2 zone).

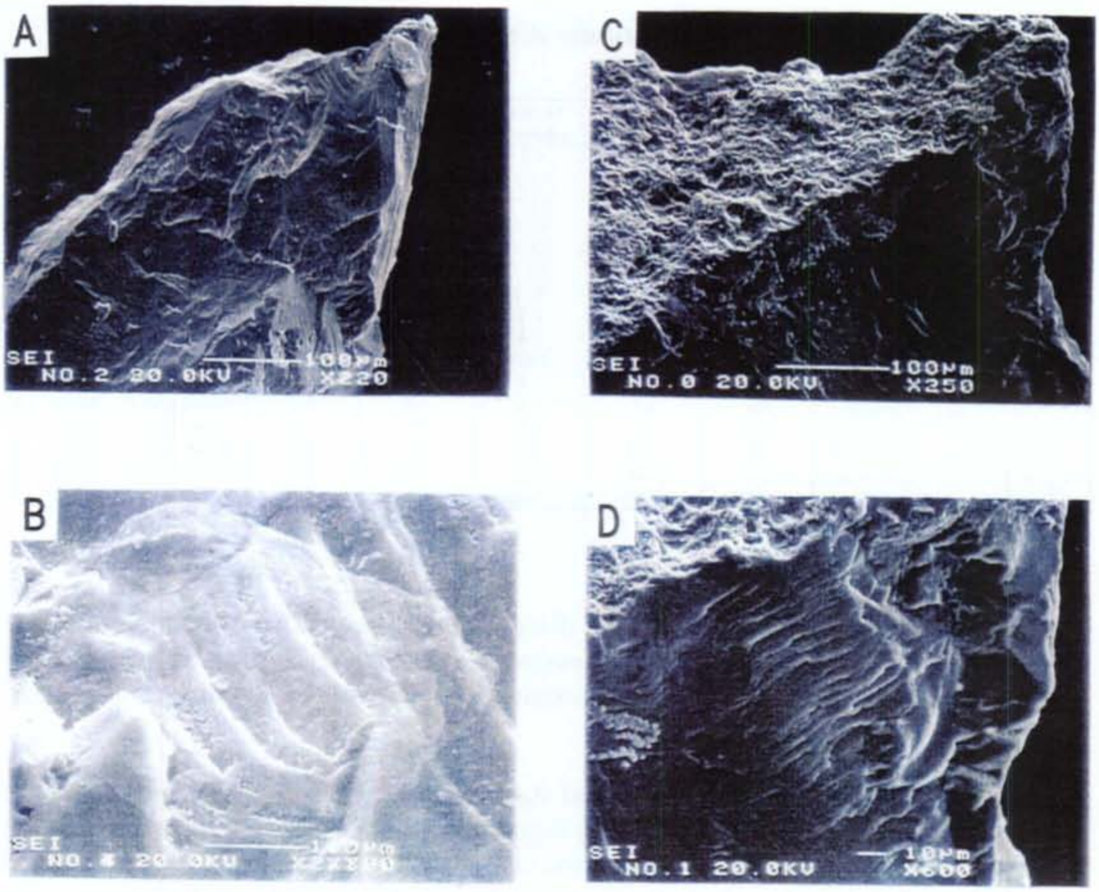


Figure 7-9. *Observed results by SEM for fractured quartz grains to estimate their relative age of faulting.*

Table 7-2. Contents of ^{4}He, ^{20}Ne and ratio of (^{3}He / ^{4}He) in groundwater samples collected at Äspö HRL.

Sample name	**^{4}He (ccSTP/g)**	**^{20}Ne (ccSTP/g)**	**^{3}He / ^{4}He**
KR0015B	1.19×10^{-4}	4.3×10^{-8}	1.64618E-08
KR0013B	3.00×10^{-4}	3.6×10^{-7}	1.14772E-08
KR0012B	9.77×10^{-4}	3.3×10^{-7}	3.03640E-08
HA1327B	4.06×10^{-4}	1.2×10^{-7}	3.03640E-08
KA2783B	7.95×10^{-3}	1.1×10^{-4}	4.56676E-08
KA3010A	2.66×10^{-2}	5.8×10^{-7}	1.09328E-08
KA3067A (green)	8.23×10^{-2}	2.7×10^{-6}	1.20084E-08
KA3105A (B)	1.35×10^{-3}	7.5×10^{-8}	1.56672E-08
KA3110A	1.32×10^{-3}	1.8×10^{-7}	1.64601E-08
KA3358A	1.54×10^{-2}	2.2×10^{-7}	1.90038E-08
KA3105A (γ)	1.15×10^{-3}	3.5×10^{-7}	1.58093E-08
SA0813B	1.94×10^{-4}	9.2×10^{-8}	1.68235E-08
SA2718A	4.39×10^{-2}	1.31×10^{-7}	1.979E-08
KA2862A	8.64×10^{-2}	2.35×10^{-7}	2.465E-08

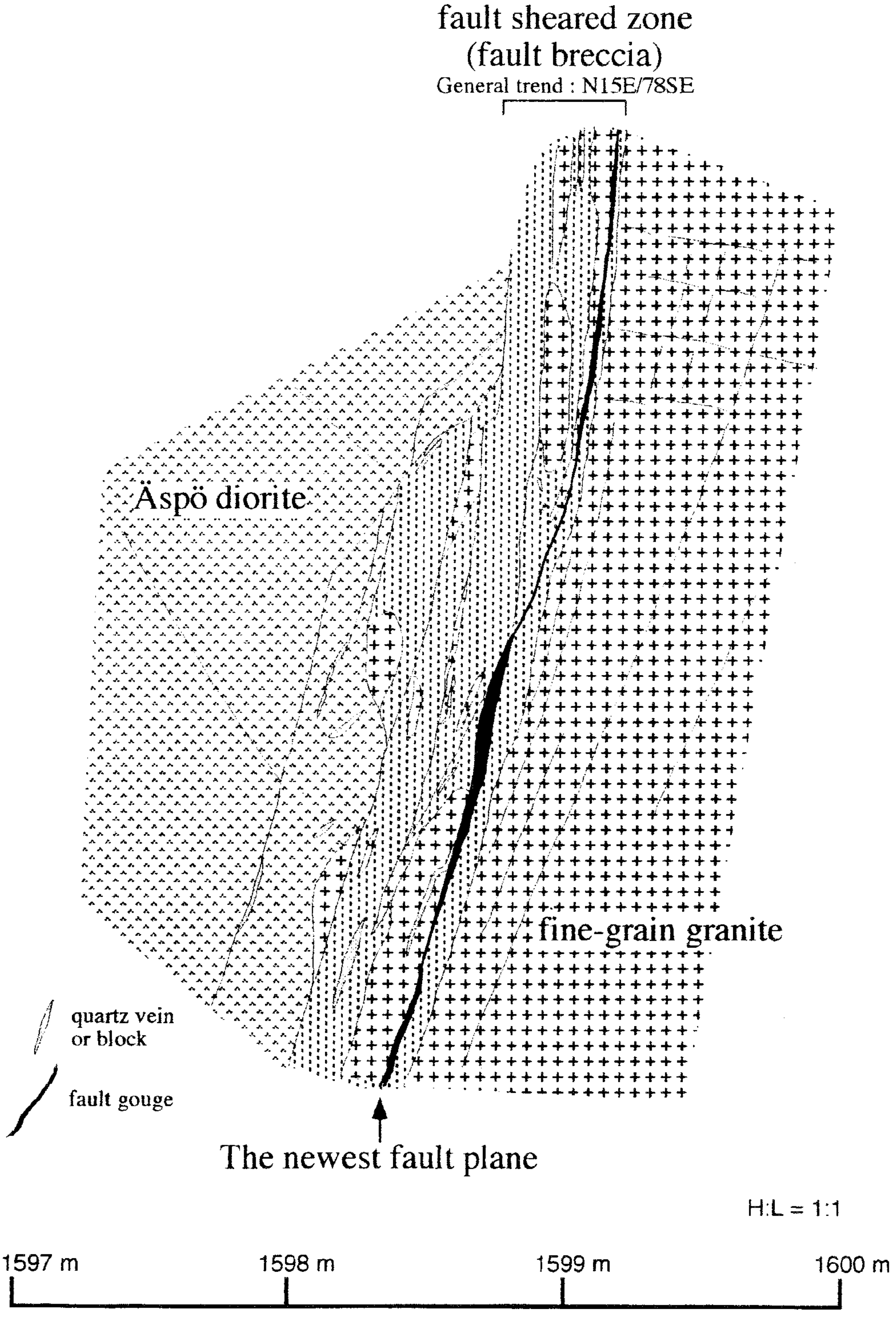


Figure 7-10. Geological sketch at TD 1600 m area of NE-2 zone in Äspö HRL tunnel.

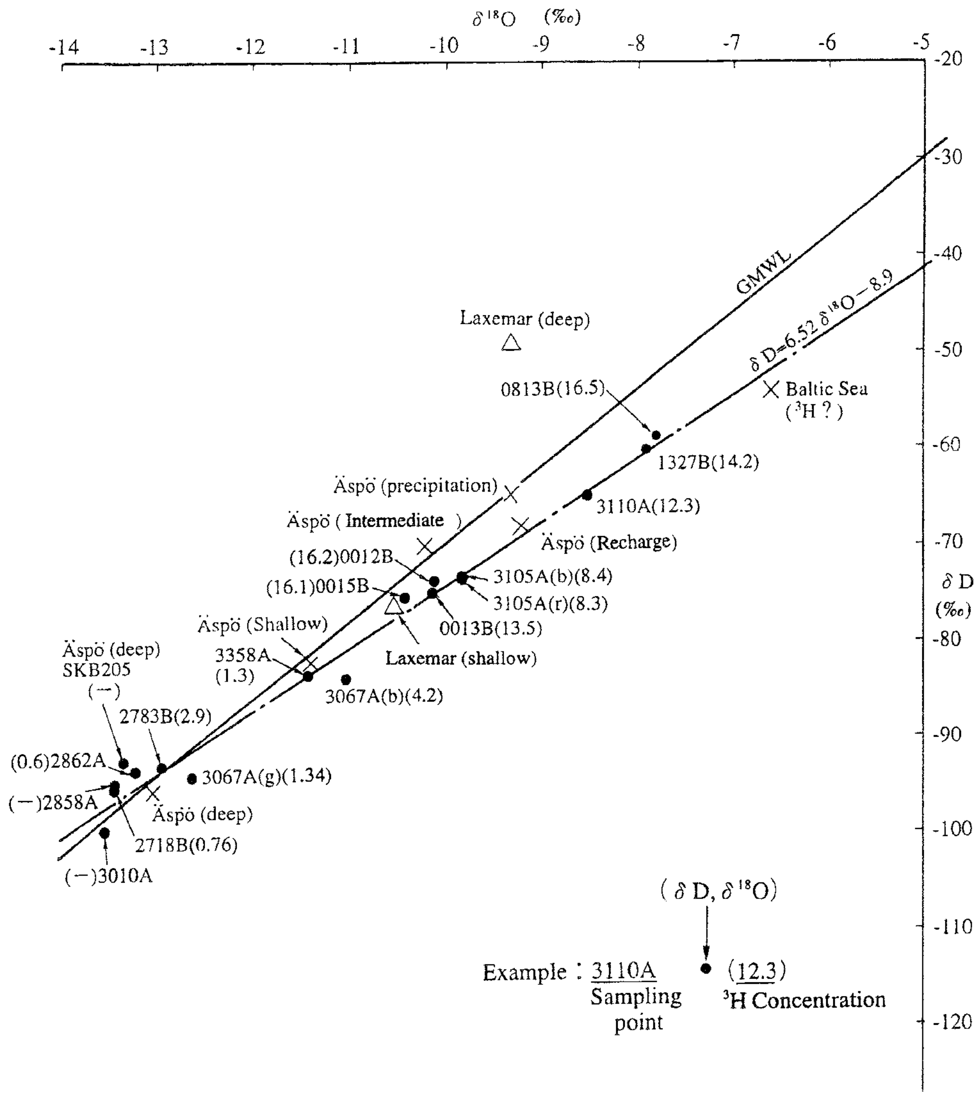


Figure 7-11. *Correlation between ^3H concentration and distribution of δ D and $\delta^{18}O$ of the environmental stable isotopes measured in groundwater collected at the tunnel of Äspö HRL with other data on environmental stable isotopes published in SKB's report.*

Furthermore, data on the environmental stable isotopes of the Baltic seawater and of the deep groundwater collected at KA2718, KA2858, KA2862, KA3010 and KA3067 were nearly plotted on the straight line of eq. (1). The correlation between δ D and $\delta^{18}O$ suggests that deep groundwater collected at KA2718, KA2858, KA2862, KA3010 and KA3067, which is characterized by a high salinity, much content of dissolved helium and low tritium concentration, is one of the origin of groundwater at Äspö Island. Moreover, the relation between δD and $\delta^{18}O$ of groundwater indicates that groundwater, collected in the tunnel of Äspö HRL, is consisted of a mixture of two endmembers which one is the aforementioned original deep groundwater and another is shallow groundwater originated from modern Baltic sea. Furthermore, a mixing ratio of the deep groundwater and the shallow groundwater is not homogeneous in the entire of tunnel. The samples of

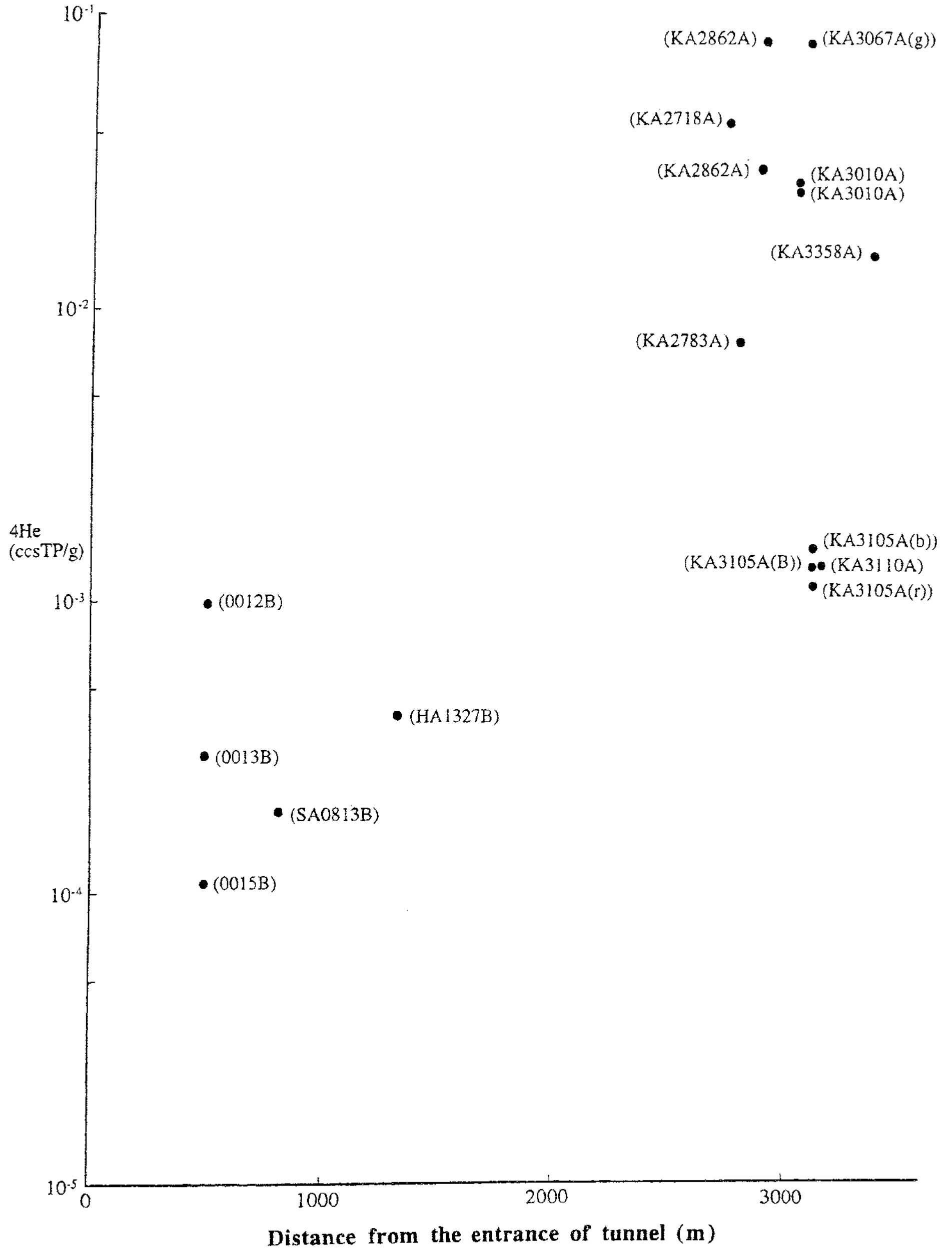


Figure 7-12. *Relation between dissolved ^4H content in groundwater and distance from entrance of tunnel to sampling point of groundwater at Äspö HRL.*

KA3105 and KA3110 have much mixture of shallow groundwater even though the altitude of positions sampling groundwater is deeper than that of KA2718, KA2858, KA2862, KA3010 and KA3067. This suggests that KA3105 and KA3110 are connected with short paths to permit the intrusion of shallow groundwater. The ratio of the mixture of shallow groundwater at KA2783 and KA3358 is less than KA3105 and KA3110. It indicates that KA2783 and KA3358 have less short paths to shallow groundwater than KA3105 and KA3110. Groundwater collected at KA2718, KA2858, KA2862, KA3010 and KA3067 are rich in lighter isotopes of water and have less than the detection limit of tritium (0.5 TU.) or a trace amount of tritium, and have a extremely high content of dissolved helium, which are close to ~ 10^{-1} ccSTP/g for ^{4}He and are three orders more than that measured in groundwater collected at the Great Artesian Basin in Australia where very old groundwater dated to be a few million years has been found. Consequently, groundwater collected at KA2718, KA2858, KA2862, KA3010 and KA3067 are isolated from shallow groundwater and other origins of groundwater and considered to be just like a stagnant water. The groundwater age of the stagnant water has been considering a helium transport analysis with a combination of the ^{36}Cl concentration.

Planned work

The modeling effort for groundwater flow and solute migration relating TRUE and REX experiments will continue.

Analysis and reporting on fault activity and groundwater dating at Äspö will continue.

The groundwater flow meter detecting velocity and direction of groundwater flow with single well will be performed in the block scale experiment area at Äspö. Furthermore, the work to transfer, compile the data base developed by SICADA at Äspö into CRIEPI's Advanced Visualization System (AVS) and develop the interface to visualize 3-D output including lithology, fracture zones, geological/geohydrological parameters etc. will be performed.

7.2.4 BMBF

Background

As a precaution and in addition to the research carried out in Germany for final disposal in a salt formation, the purpose of the cooperation in the Äspö HRL Programme is to complete the knowledge on other potential host rock formations. The work is concentrated on investigations related to groundwater flow, radionuclide transport and geochemistry, on two-phase flow investigations, and on development and testing of instrumentation and methods for detailed underground rock characterization.

Activities performed in 1996

Degassing and two-phase flow

Two-phase flow investigations to be carried out in the Äspö tunnel were prepared by GRS and BGR. For performance of in-situ experiments in collaboration with SKB the niche at 2715 m was selected as experimental location. According to a preliminary geological mapping carried out in the niche, structures with satisfying properties for performing the investigations exist. Methods for rock characterisation were evaluated. A data base for planning the experiments was elaborated.

Underground measurement methods and instruments

Methods and instruments developed in recent years for investigations at the Grimsel Test Site were tested and adapted to the conditions in the Äspö tunnel. A gas sampling campaign was performed in order to determine the tunnel air composition. Geoelectrical and thermographical measurements were performed for investigating the rock porosity and transmissivity. These methods will be used for the two-phase flow investigations mentioned above.

Task Force on modelling of groundwater flow and transport of solutes

BGR joined the Task Force in late 1995 and participated in the modelling activities of Task No 4C (Predictive modelling of the radially converging tracer tests and the dipole tests of TRUE-1). The predictive calculations of the radially converging tracer test showed a good agreement of the calculational results to the measurements. Results of the predictive modelling of the dipole test will be presented in the next Task Force meeting.

ZEDEX

In the ZEDEX Project Extension BGR measured seismic velocities in the D&B drift and in the TBM drift. The work included downhole and interval measurements of seismic velocities in boreholes and seismic refraction measurements along the drift wall. The measuring results were correlated to transmissivity measurements. The final report is being prepared.

Geochemistry

TUC started an investigation of mobilization and immobilization of chemical elements in differently altered rock types and fluids. A sampling campaign of rock and groundwater was performed in the Äspö tunnel. Analyses were performed using microprobe and x-ray fluorescence techniques. First analytical data will be available early next year.

Investigations for in-situ quantification and transport of small colloidal particles are being prepared by FZK/INE. For in-situ measurements the Laser Induced Breakdown Detection (LIBD)-method was developed further and calibrated with monodisperse colloids. A mobile equipment to be used in field experiments in the HRL was constructed. Planning was started for actinide retention investigations.

Planning for 1997

Activities intended for 1997:

- Preparation of the test field for two-phase flow experiments and detailed test field characterization, elaboration of the conceptual flow model for the fractured rock.
- Continuation of model calculations on groundwater flow and transport of solutes in the Task Force.
- Preparation and performance of in-situ experiments on migration of artificial colloids and on quantification of colloids in granitic groundwater. Planning for actinide retention investigations.

- Completion of geochemical analyses of rock and water samples aiming at modelling input and output of trace elements relevant to nuclear waste disposal.

REFERENCES

Andersson P, 1996. TRUE 1st stage tracer test program. Experimental data and preliminary evaluation of the TRUE-1 radially converging tracer test (RC-1). SKB HRL Progress Report, HRL-96-24.

Andersson P et al., 1997. Experimental plan for tests with sorbing tracers at the TRUE-1 site. Swedish Nuclear Fuel and Waste Management Company. Äspö Hard Rock Laboratory Progress Report HRL-97-07.

Andersson P et al., (in prep). Experimental data and preliminary evaluation of the TRUE-1 dipole tracer tests (DP1-DP4). Swedish Nuclear Fuel and Waste Management Company. Äspö Hard Rock Laboratory Progress Report HRL-97-XX.

Andersson P et al., (in prep). Experimental data and preliminary evaluation of the TRUE-1 complementary tracer tests (RC-2, DP5-DP6). Swedish Nuclear Fuel and Waste Management Company. Äspö Hard Rock Laboratory Progress Report HRL-97-XX.

Bäckblom G, Olsson O, 1994. Program for tracer retention understanding experiments. SKB HRL Progress Report, PR 25-94-24.

Geller J, Jarsjö J, 1995. Groundwater degassing and two-phase flow: Pilot hole test report. SKB International Cooperation Report 95-03.

Gustafson G, Liedholm M, Rhén I, Stanfors R, Wikberg P, 1991. Äspö Hard Rock Laboratory. Predictions prior to excavation and the process of their validation. SKB Technical Report, TR 91-23.

Hallbjörn L, Ingeval K, Martna J, Strindell L, 1990. New automatic probe for measuring triaxial stress in deep boreholes. Tunneling and underground space technology, Vol 5, pp. 141-145.

Jarsjö J, Destouni G, 1997a. Groundwater degassing: Pilot injection – withdrawal field tests with saturated water. SKB Äspö HRL Progress Report HRL-97-02.

Jarsjö J, Destouni G, 1997b. Conditions for fracture transmissivity reduction due to degassing of groundwater: analytical expressions, numerical simulations and analysis of laboratory and field data. SKB Äspö HRL Progress Report HRL-97-03.

Jarsjö J, Geller J, 1996. Groundwater degassing: Laboratory experiments in rock fracture replicas with radial flow. SKB Äspö HRL Progress Report HRL-96-12.

Johansson H, Byegård J, Skarnemark G, Skålberg M (in press). Matrix diffusion of some alkali- and alkaline earth-metals in granitic rock. In Proc. of Materials Research Society MRS fall meeting 1996, Boston, U.S.A.

Laaksoharju M, Skårman K, 1995. Groundwater sampling and chemical characterization of the Äspö HRL tunnel in Sweden. Swedish Nuclear Fuel and Waste Management Company. Äspö hard Rock Laboratory Progress Report PR 25-95-29.

Laaksoharju M, Wallin B (eds.), 1997. Integration of hydrogeochemical and hydrogeological models of Äspö. Proceedings of the second Äspö international geochemistry workshop, June 6-7 1995, Äspö, (in press).

Martel S J, Pollard D D, 1989. Mechanics of slip and fracturing along small faults and simple strike-slip fault zones in granitic rock. J. Geoph. Res., Vol 94, No. B7, pp. 9417-9428.

Meszaros F, 1996. Simulation of transient hydraulic effect of access tunnel at Äspö. International Cooperation Report 96-06. Svensk Kärnbränslehantering AB, Stockholm, Sweden.

Olsson O, 1992. Site characterization and validation – final report, SKB Stripa Project Technical Report 92-22. Andersson, P. 1996: Experimental data and preliminary evaluation of the TRUE-1 radially converging tracer test (RC-1). Swedish Nuclear Fuel and Waste Management Company. Äspö Hard Rock Laboratory Progress Report HRL-96-24.

Olsson O, Emsley S, Bauer C, Falls S, Stenberg L, 1996. ZEDEX – A study of the zone of excavation disturbance for blasted and bored tunnels – Volume 1 -3, SKB ICR 96-03, SKB, Stockholm, Sweden.

Olsson O, Winberg A, 1996. Current understanding of extent and properties of the excavation disturbed zone and its dependence on excavation method. In Proceedings of the Excavation Disturbed Zone Workshop, September 20, 1996 in Winnipeg, Canada (ISSN 0-919784-44-5).

Pitkänen P, Snellman M, 1996. On the origin of groundwater from Olkiluoto Island on the coast of the Gulf of Bothnia. In L. King-Clayton & N. Chapman: Proceedings of the Workshop on Glaciation and Hydrogeology, 17. – 19.4.1996, Stockholm, (to be published).

Selroos J-O, Cvetkovic V (in prep). Predictions and evaluation of radially and dipole tracer tests at the TRUE-1 site. Swedish Nuclear Fuel and Waste Management Company. Äspö hard Rock Laboratory International Cooperation Report ICR 97-XX.

Stanfors R, Gustafson G, Munier R, Olsson P, Stille H, Wikberg P, 1992. Evaluation of geological predictions in the access ramp 0–700 m. SKB Progress Report, PR 25-92-02.

Tanaka Y et al., 1996. Application of three-dimensional smeared fracture model to the hydraulic impact of the Äspö tunnel. International Cooperation Report 96-07. Svensk Kärnbränslehantering AB, Stockholm, Sweden.

Winberg A, 1994. Tracer Retention Understanding Experiments (TRUE). Test plan for the First TRUE Stage. SKB HRL Progress Report, PR 25-94-35.

Winberg A (ed) et al., 1996. Descriptive structural-hydraulic models on block and detailed scales of the TRUE-1 site. Swedish Nuclear Fuel and Waste Management Company. Äspö hard Rock Laboratory International Cooperation Report ICR 96-04.

Winberg A, 1997. Test plan for the TRUE Block Scale Experiment. Swedish Nuclear Fuel and Waste Management Company. Äspö Hard Rock Laboratory International Cooperation Report ICR 97-02.

APPENDICES

A LIST OF PAPERS AND ARTICLES PUBLISHED 1996

Bauer C, Homand-Etienne F, Slimane K B, Hinzen K G, Reamer S K
Damage zone characterization in the near field in the Swedish ZEDEX tunnel using in situ and laboratory measurements.
Eurock '96, ISRM International Symposium, Torino, Italy, September 2-5, 1996

Davies N, Mellor D
Review of excavation disturbance measurements undertaken within the ZEDEX project: Implications for the Nirex Rock Characterisation Facility Eurock '96, ISRM. International Symposium, Torino, Italy, September 2-5, 1996

Falls S D, Young R P
Examination of the excavation-disturbed zone in the Swedish ZEDEX tunnel using acoustic emission and ultrasonic velocity measurements .
Eurock '96, ISRM International Symposium, Torino, Italy, September 2-5, 1996

Gustafson G, Stille H
Prediction of groutability from grout properties and hydrogeological data.
Tunnelling and Underground Space Vol. 11, No 3, 325-332

Laaksoharju M, Skårman C
Multivariate mixing calculations used to trace modern Baltic Sea water intrusion at Äspö, Sweden.
Salt Water Intrusion Meeting, SWIM, Malmö, Sweden, June 16-21, 1996

Olsson O
Jämförande studie av den störda zonen för sprängd respektive borrad tunnel ZEDEX-försöket i Äspö.
Bergmekanikdagen, 20 Mars, 1996

Olsson O, Bäckblom G
Äspö Hard Rock Laboratory – From site characterization to demonstration of technology to be used in deep repositories.
Topseal '96, Stockholm, Sweden, June 9-12, 1996

Olsson O, Bäckblom G, Slimane K B, Cournut A, Davies N, Mellor D
Planning, organization, and execution of an EDZ experiment while excavating two test drifts by TBM boring and blasting, respectively.
Eurock '96, ISRM International Symposium, Torino, Italy, September 2-5, 1996

Olsson O, Emsley S J, Cosma C, Tunbridge L, Stanfors R, Stenberg L
Integrated characterisation of a rock volume at the Äspö HRL utilised for an EDZ experiment.
Eurock '96, ISRM International Symposium, Torino, Italy, September 2-5, 1996

Olsson O, Winberg A
Current understanding of extent and properties of the excavation disturbed zone and its dependence on excavation method. Proceedings of the Excavation Disturbed Zone. Workshop, September 20, 1996 in Winnipeg, Canada (ISSN 0-919784-44-5)

Pedersen K, Arlinger J, Ekendahl S, Hallbeck L
16S rRNA gene diversity of attached and unattached bacteria in boreholes along the access tunnel to the Äspö Hard Rock Laboratory, Sweden.
FEMS Microbiology Ecology 19 (1996), 249-262

Rosén R, Gustafson G
A Bayesian Markov Geostatistical Model for Estimation of Hydrogeological Model for Estimation of Hydrogeological Properties.
Ground Water Vol 34, No 5, 865-875

Tan X C, Lindqvist, P A and Kou S Q
Application of a splitting fracture model to the simulation of rock indentation subsurface fractures.
International Journal for Numerical and Analytical Methods in Geomechanics, Vol. 21, 1-13 (1997)

Wikberg P, Rhén I
Indirect evidences for quantification of groundwater flow: Assessment of the consistency of geohydrological groundwater flow models and hydrochemical mixing/reaction models of the Äspö Hard Rock Laboratory.
1996 International High Level Radioactive Waste Management Conference, Las Vegas, USA, April 29 – May 3, 1996

Äspö Hard Rock Laboratory. 10 years of research. 1996.
SKB, Stockholm

Post-graduate theses supported by SKB

Kou S Q; Some basic problems in rock breakage by blasting and indentation.
Luleå University of Technology, 1995:180 D

Selroos J-O; Contaminant transport by groundwater; Stochastic travel time analysis and probabilistic safety assessments.
Water Resources Engineering, Royal Institute of Technology, Stockholm, Sweden, 1996

Ekendahl S; Deep subsurface ecosystems – Numbers, activity and diversity of groundwater bacteria in Swedish granitic rock.
Dept. of general and marine microbiology, Göteborg University, Göteborg, Sweden

B DOCUMENTS PUBLISHED 1996

During 1996 the following reports and documents have been published.

International Cooperation Reports

Poteri A, 1995. Analysis of bedrock fracturing at Äspö.
SKB HRL International Cooperation Report, ICR 96-01

Korkealaakso J, Kontio K, 1996. Characterization of fracture zones by inverse analysis of interference tests – Application to NE-1-03 and NE-1-04.
Äspö experiments
SKB HRL International Cooperation Report, ICR 96-02

Olsson O, Emsley S, Bauer C, Falls S, Stenberg L, 1996. ZEDEX – A study of the zone of excavation disturbance for blasted and bored tunnels – Volume 1 -3.
SKB HRL International Cooperation Report, ICR 96-03

Winberg A (ed.), 1996. First TRUE Stage – Tracer Retention Understanding Experiments. Descriptive structural-hydraulic models on block and detailed scales of the TRUE-1 site.
SKB HRL International Cooperation Report, ICR 96-04

Dershowitz W, Thomas A, Busse R, 1996. Discrete fracture analysis in support of the Äspö Tracer Retention Understanding Experiment (TRUE-1).
SKB HRL International Cooperation Report, ICR 96-05

Mészáros F, 1996. Simulation of the transient hydraulic effect of the access tunnel at Äspö.
SKB HRL International Cooperation Report, ICR 96-06

Tanaka Y, Miyakawa K, Igarashi T, Shigeno Y, 1996. Application of three-dimensional smeared fracture model to the hydraulic impact of the Äspö tunnel.
SKB HRL International Cooperation Report, ICR 96-07

Technical Reports

SKB. 1996. Äspö Hard Rock Laboratory. Annual Report 1995.
SKB Technical Report, TR 96-06

Progress Reports

Winberg A, Andersson P, Hermanson J, Stenberg L, 1996. Result of the Select SKB HRL Project. Investigation SKB HRL. Programme for selection of experimental sites for the operational phase.
SKB HRL Progress Report, HRL-96-01

Birgersson L, Gale J, Winberg A, 1995. TRUE – Resin injection programme – Test plan for the pilot experiment.
SKB HRL Progress Report, HRL-96-02

Ittner T, Gustafsson E, 1995. Groundwater chemical composition and transport of solutes. Evaluation of the fracture zones NE-1, NE-2 and NNW-4 during preinvestigation and tunnel construction.
SKB HRL Progress Report, HRL-96-03

Olsson O m fl, 1995. Äspö Hard Rock Laboratory. Status Report October – December 1995
SKB HRL Progress Report, HRL-96-04

Olsson O, 1995. Planning report for 1996.
SKB HRL Progress Report, HRL-96-05

Stenberg L, Forslund O, 1996. Results of GPR Radar Measurements at ZEDEX site, Äspö, Sweden.
SKB HRL Progress Report, HRL-96-06

Stille H, Olsson P, 1996. Summary of rock mechanical results from the construction of Äspö Hard Rock Laboratory.
SKB HRL Progress Report, HRL-96-07

Hermanson J, 1996. Visualization of the fracture network in rock blocks along the Äspö HRL tunnel using a DFN model approach.
SKB HRL Progress Report, HRL-96-08

Puigdomenech I, Banwart S, Wikberg P, 1996. Test plan for Redox experiment in detailed scale (REX).
SKB HRL Progress Report, HRL-96-09

Sturk R, Olsson L, Tengborg P, Stille H, 1996. Construction feasibility analysis, TBM-tunnel Äspö Hard Rock Laboratory, Phase II – updated prognoses and outcome.
SKB HRL Progress Report, HRL-96-10

Gascoyne M, Frost L H, Stroes-Gascoyne S, Vilks P, Griffault L Y, 1996. Results of a geochemical tracer test, TT13, performed at the underground research laboratory, southeastern Manitoba, Canada.
SKB HRL Progress Report, HRL-96-11

Jarsjö J, Geller J, 1996. Groundwater degassing: Laboratory experiments in rock fracture replicas with radial flow.
SKB HRL Progress Report, HRL-96-12

Olsson O m fl, 1996. Äspö Hard Rock Laboratory. Status Report January – March 1996.
SKB HRL Progress Report, HRL-96-13

Enachescu C, Follin S, Wozniewicz J, 1996. Evaluation of two types of hydraulic tests performed in boreholes A4, A5 and C5 at the ZEDEX site, Äspö Hard Rock Laboratory.
SKB HRL Progress Report, HRL-96-14

Börgesson L, Johannesson L-E, Sandén T, 1996. Backfill materials based on crushed rock. Geotechnical properties determined in laboratory.
SKB HRL Progress Report, HRL-96-15

Olsson O m fl, 1996. Äspö Hard Rock Laboratory. Status Report April – June 1996.
SKB HRL Progress Report, HRL-96-16

Nyberg G, Jönsson S, Ekman L, 1996. Äspö Hard Rock Laboratory. Hydro monitoring program. Report for 1995.
SKB HRL Progress Report, HRL-96-17

Bäckblom G, 1989. Guide-lines for use of nomenclature on fractures, fracture zones and other topics.
SKB HRL Progress Report, HRL-96-18

Markström I, Erlström M, 1996. Overview of documentation of tunnel, niches and core boreholes.
SKB HRL Progress Report, HRL-96-19

Kou Shaoquan, Lindqvist P-A, Tan Xiangchun, 1996. Formulation of models for indentation depth and crack length in mechanical excavation of rock.
SKB HRL Progress Report, HRL-96-20

Olsson O m fl, 1996. Äspö Hard Rock Laboratory. Status Report July – September 1996.
SKB HRL Progress Report, HRL-96-21

Karnland O, 1996. Test Plan for Long Term Tests of Buffer Material.
SKB HRL Progress Report, HRL-96-22

Ström A (ed.), 1996. Äspö Task force on modelling of groundwater flow and transport of solutes. Summary of the predictive modelling for the RC-1 tracer experiments, Task No 4C.
SKB HRL Progress Report, HRL-96-23

Andersson P, 1996. TRUE 1st stage tracer test program. Experimental data and preliminary evaluation of the TRUE-1 radially converging tracer test (RC-1).
SKB HRL Progress Report, HRL-96-24

Olsson O, 1996. Planning report for 1997.
SKB HRL Progress Report, HRL-96-25

Rouhiainen P, 1996. Complementary evaluation of two types of hydraulic test performed in boreholes A4, A5 & C5 at the ZEDEX site, Äspö Hard Rock Laboratory.
SKB HRL Progress Report, HRL-96-26

Olsson O, Winberg A, 1996. The Äspö TRUE experiments.
SKB HRL Progress Report, HRL-96-27

Gunnarsson D, Johannesson L-E, Sandén T, Börgesson L, 1996. Field test of tunnel backfilling.
SKB HRL Progress Report, HRL-96-28

Technical Documents

11 Technical Documents were produced during 1996.

Technical Notes

21 Technical Notes were produced during 1996.

List of SKB reports

Annual Reports

1977-78
TR 121
KBS Technical Reports 1 – 120
Summaries
Stockholm, May 1979

1979
TR 79-28
The KBS Annual Report 1979
KBS Technical Reports 79-01 – 79-27
Summaries
Stockholm, March 1980

1980
TR 80-26
The KBS Annual Report 1980
KBS Technical Reports 80-01 – 80-25
Summaries
Stockholm, March 1981

1981
TR 81-17
The KBS Annual Report 1981
KBS Technical Reports 81-01 – 81-16
Summaries
Stockholm, April 1982

1982
TR 82-28
The KBS Annual Report 1982
KBS Technical Reports 82-01 – 82-27
Summaries
Stockholm, July 1983

1983
TR 83-77
The KBS Annual Report 1983
KBS Technical Reports 83-01 – 83-76
Summaries
Stockholm, June 1984

1984
TR 85-01
Annual Research and Development Report 1984
Including Summaries of Technical Reports Issued during 1984. (Technical Reports 84-01 – 84-19)
Stockholm, June 1985

1985
TR 85-20
Annual Research and Development Report 1985
Including Summaries of Technical Reports Issued during 1985. (Technical Reports 85-01 – 85-19)
Stockholm, May 1986

1986
TR 86-31
SKB Annual Report 1986
Including Summaries of Technical Reports Issued during 1986
Stockholm, May 1987

1987
TR 87-33
SKB Annual Report 1987
Including Summaries of Technical Reports Issued during 1987
Stockholm, May 1988

1988
TR 88-32
SKB Annual Report 1988
Including Summaries of Technical Reports Issued during 1988
Stockholm, May 1989

1989
TR 89-40
SKB Annual Report 1989
Including Summaries of Technical Reports Issued during 1989
Stockholm, May 1990

1990
TR 90-46
SKB Annual Report 1990
Including Summaries of Technical Reports Issued during 1990
Stockholm, May 1991

1991
TR 91-64
SKB Annual Report 1991
Including Summaries of Technical Reports Issued during 1991
Stockholm, April 1992

1992
TR 92-46
SKB Annual Report 1992
Including Summaries of Technical Reports Issued during 1992
Stockholm, May 1993

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Stockholm, May 1994

1994

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Stockholm, May 1996

1996

TR 96-25

SKB Annual Report 1996

Including Summaries of Technical Reports Issued during 1996

Stockholm, May 1997

List of SKB Technical Reports 1997

TR 97-01

Retention mechanisms and the flow wetted surface – implications for safety analysis

Mark Elert
Kemakta Konsult AB
February 1997

TR 97-02

Äspö HRL – Geoscientific evaluation 1997/1. Overview of site characterization 1986–1995

Roy Stanfors[1], Mikael Erlström[2],
Ingemar Markström[3]
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[2] SGU, Lund
[3] Sydkraft Konsult, Malmö
March 1997

TR 97-03

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

Ingvar Rhén (ed.)[1], Göran Bäckblom (ed.)[2],
Gunnar Gustafson[3], Roy Stanfors[4], Peter Wikberg[2]
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April 1997

TR 97-04

Äspö HRL – Geoscientific evaluation 1997/3. Results from pre-investigations and detailed site characterization. Comparison of predictions and observations. Geology and mechanical stability

Roy Stanfors[1], Pär Olsson[2], Håkan Stille[3]
[1] RS Consulting, Lund
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[3] KTH, Stockholm
May 1997

TR 97-05

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

Ingvar Rhén[1], Gunnar Gustafson[2], Peter Wikberg[3]
[1] VBB Viak, Göteborg
[2] VBB Viak/CTH, Göteborg
[3] SKB, Stockholm
April 1997

TR 97-06

Äspö HRL – Geoscientific evaluation 1997/5. Models based on site characterization 1986–1995

Ingvar Rhén (ed.)[1], Gunnar Gustafson[2],
Roy Stanfors[4], Peter Wikberg[4]
[1] VBB Viak, Göteborg
[2] VBB Viak/CTH, Göteborg
[3] RS Consulting, Lund
[4] SKB, Stockholm
May 1997

TR 97-07

A methodology to estimate earthquake effects on fractures intersecting canister holes

Paul La Pointe, Peter Wallmann, Andrew Thomas,
Sven Follin
Golder Associates Inc.
March 1997