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Rock Sealing – Large Scale Field Test and Accessory Investigations

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TECHNICAL REPORT

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ROCK SEALING

LARGE SCALE FIELD TEST
and
ACCESSORY INVESTIGATIONS

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A list of other reports published in this series is attached at the end of the report. Information on previous reports is available through SKB.

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THE ROCK SEALING PROJECT - LARGE SCALE FIELD TEST AND ACCESSORY INVESTIGATIONS

SUMMARY

The experience from the pilot field test and the basic knowledge extracted from the lab experiments have formed the basis of the planning of a Large Scale Field Test. The intention is to find out how the "instrument of rock sealing" can be applied to a number of practical cases, where cutting-off and redirection of groundwater flow in repositories are called for. Five field subtests, which are integrated mutually or with other Stripa projects (3D), are proposed. One of them concerns "near-field" sealing, i.e. sealing of tunnel floors hosting deposition holes, while two involve sealing of "disturbed" rock around tunnels. The fourth concerns sealing of a natural fracture zone in the 3D area, and this latter test has the expected spin-off effect of obtaining additional information on the general flow pattern around the northeastern wing of the 3 D cross. The fifth test is an option of sealing structures in the Validation Drift. The longevity of major grout types is focussed on as the most important part of the "Accessory Investigations", and detailed plans have been worked out for that purpose.

It is foreseen that the continuation of the project, as outlined in this report, will yield suitable methods and grouts for effective and long-lasting sealing of rock for use at strategic points in repositories.

1 INTRODUCTION

The outcome of the laboratory experiments on reference grouts as well as the experience from a rather comprehensive pilot field test at Stripa in January 1988 have formed the basis of the planning of a Large Scale Field Test and accessory lab investigations. Various forms of conducting these tests have been considered by the Task Force, which finally decided to recommend to the TSG the test program that is specified in this document. This decision was taken at the Task Force meeting at Watford, England, on March 18, 1988.

2 PURPOSE OF SEALING

2.1 GENERAL

If fractures intersecting deposition holes (KBS 3) or tunnels (NAGRA) can be sealed so that groundwater flow becomes virtually none within a distance of 1-2 meters from the periphery, the chemical stability of smectitic canister envelopes can be largely preserved over the operative lifetime of the repository. Furthermore, the resistance to diffusive migration of dissolved agents that affect the integrity of the metal canisters and the time of transfer of radionuclides to the biosphere are increased by orders of magnitude (KBS 3). While such sealing improves the tightness only of the "nearfield", it is very advantageous if sealing can be made also of disturbed zones serving as "superconductors" and highly permeable intersecting zones, which may act as short-circuits as illustrated in Fig 1. Naturally, this would extend the volume of rock containing stagnant water to many meters from the canisters resulting in a very significant increase in isolation power.

The manifold application of rock sealing suggests that the large-scale field test should be concerned with the following three, major types of water-bearing structures:

- Discrete fractures (D in Fig 1) intersecting deposition holes (relevant also for tunnels)
- Disturbed zones, i.e. "damaged rock" (B in Fig 1)
- Natural fracture zones (A in Fig 1)

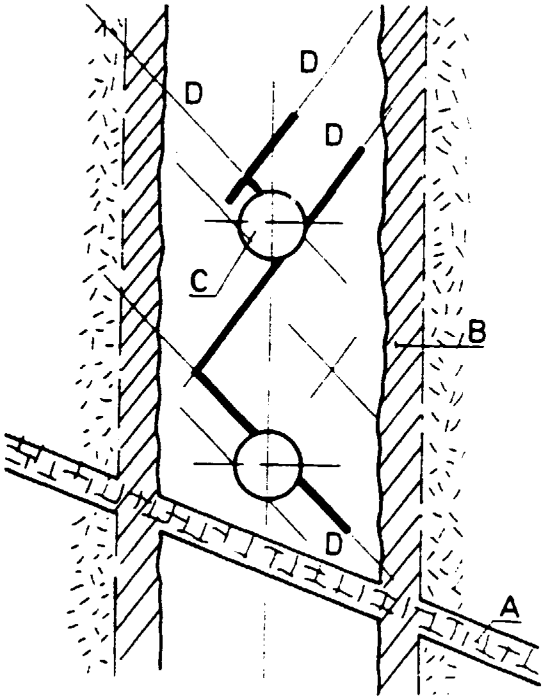

Fig 1. Principle of shunting off fractures (D) serving as short circuits; thick lines indicating sealed parts. A is major hydraulically active rock zone, B disturbed zone of increased permeability ("superconductor"), C is canister hole

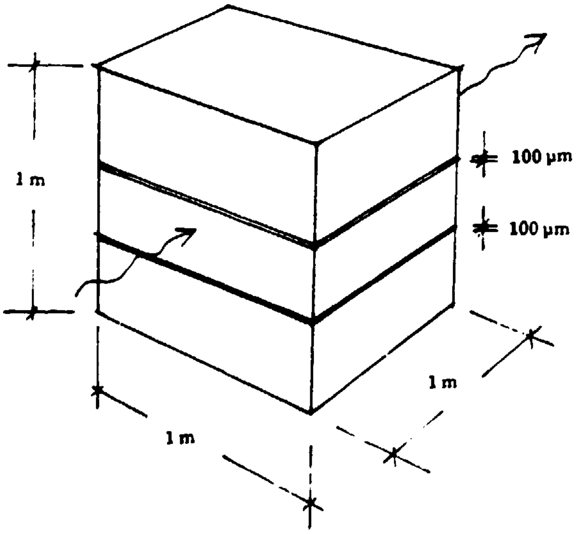

Fig 2. Rock block with set of 100 μm slots, percolated as indicated by the arrows

1.2 EXPECTATIONS

An illustration of the effect of sealing is offered by considering the simple case of regularly fractured rock characterized by two plane, parallel slot-shaped fractures per m^2 cross section (Fig 2). For an actual aperture of 100 µm, the average hydraulic conductivity at flow across a 1 m^3 block of this type is about $2 \cdot 10^{-6}$ m/s, which is representative of a disturbed zone close to a shaft or tunnel. Complete filling of the fractures by grouting yields a net average hydraulic conductivity of the rock as given in Table I, from which we conclude that a hydraulic conductivity of about 10^{-6} m/s of the grout reduces the permeability by four orders of magnitude. If the k-value of the grout can be reduced to 10^{-8} m/s, the rock will be characterized by a very low permeability value ($k \sim 2 \cdot 10^{-12}$ m/s).

Table I. Net, average hydraulic conductivity k m/s of the rock block in Fig 2. k_g is the conductivity of the grout

Fractures	Fracture breadth, cm	Non-grouted	Grouted		
			$k_g = 10^{-4}$	$k_g = 10^{-6}$	$k_g = 10^{-8}$
Two 100 cm broad and 100 µm wide fractures	2x100	$2 \cdot 10^{-6}$	$2 \cdot 10^{-8}$	$2 \cdot 10^{-10}$	$2 \cdot 10^{-12}$
Two fractures, each with ten 1 cm broad and 100 µm wide "channels"	2x(10x1)	$2 \cdot 10^{-7}$	$2 \cdot 10^{-9}$	$2 \cdot 10^{-11}$	$2 \cdot 10^{-13}$

For the more realistic case of "channeling", and assuming that the fracture holds ten slots with an aperture of 100 µm and a breadth of 1 cm per meter, across the flow direction, we find that the initial hydraulic conductivity is $2 \cdot 10^{-7}$ m/s, while the net average hydraulic conductivity after grouting with a material that has a k-value of 10^{-8} m/s is on the same order of magnitude as the crystal matrix, i.e. about $2 \cdot 10^{-13}$ m/s (cf. Table I, lower part). It should be noted that the post-grouting conductivity will not exceed about 10^{-10} m/s even if the hydraulic conductivity of the grout is as high as 10^{-5} m/s.

These very simplified examples serve to illustrate that water flow through a fractured zone that intersects a repository tunnel, or axial flow through the disturbed zone of a tunnel or shaft, can virtually be stopped whereby the flow is redirected, leaving practically stagnant water in the vicinity of such excavations. An equally effective isolation of the near-field may be obtained by sealing the few major fractures that are expected to intersect deposition holes of the KBS 3-type. The essence is, of course, that grouting should not be applied to make a repository water-tight, but to retard or block water flow at strategically selected points, of which the ones mentioned are examples.

3 OUTLINE OF FIELD TEST

3.1 OPTIONS

In principle, five field activities are planned and they are directed to the sealing of different types of hydraulically active structures in a repository. Agreements has been reached on a largely integrated study that comprises the following activities:

Test 1	Sealing of discrete natural fractures intersecting deposition holes
Test 2	Sealing of damaged zone resulting mainly from blasting
Test 3	Sealing of disturbed zone resulting mainly from stress relief
Test 4	Sealing of large, natural fractured zone
Test 5	Quick sealing activity ("May-day") in the Validation drift

Tests 2 and 3, which both concern the zone of disturbance, and which are intimately coupled, are presented as different subtests in order to emphasize the purpose of distinguishing between two major disturbing effects.

3.2 MAIN FEATURES OF PROPOSED SET OF IN SITU TESTS

3.2.1 Field conditions

Very precise, quantitative documentation of the sealing effect of grouting implies that the hydraulic conductivity of the rock zone in question is determined before and after the sealing operation. A virgin test site is not very suitable for systematic sealing tests since determination of the initial water pressure state and flow properties would use up too much time and the site may still turn out to be unsuitable for a sealing project. Three of the proposed activities that are of basic type (i.e. Tests 1, 2 and 3), are therefore planned to take place in the BMT drift, which is very well characterized with respect to the rock structure and to the water pressure conditions in the floor with already existing deposition (heater) holes, as well as in the rather richly instrumented rock surrounding the drift. The BMT test gave qualitative indications of a high axial conductivity of the disturbed zone and systematic flow tests before and after grouting of the inner part of the drift are expected to give a quantitative measure of this conductivity and of how effectively the disturbed zone can be sealed by grouting. In particular, the considerable number of installed piezometers both close to the drift (BMT piezometers) and at larger distance (R- and HG-holes instrumented by LBL), offer good opportunities of demonstrating, in a quantitative way, how local stagnant water conditions can be created, and how groundwater can be redirected at larger distances from a repository tunnel.

Test 4, which is planned to be a practical application of how effectively groundwater flow can be shunted off from a repository tunnel by grouting a large, natural fractured zone, may also give new information of the water flow around the 3D test drift.

Test 5, finally, simulates the situation in an actual repository when a quick sealing effort is required in the course of the excavation of a repository tunnel.

3.2.2 Grouts

As to the choice of grout materials two "standard" materials, i.e. 50% Na bentonite/50% quartz filler and CSF/SP (w/c = 0.42), are presently being considered as major candidates although this may be changed in the course of the current research. In principle, any grout can be used provided that the fluidity is expressed in terms of standard flow parameters (viscosity, shear resistance) and that the parameter values, which are determined by use of viscometer tests, suggest that a sufficient penetration power will be obtained. The presently applied philosophy is that the near-field rock should be grouted with smectite-based materials, while the disturbed zone and natural fracture zones are suitably grouted with cement. The reasons for this is firstly that the latter zone is exposed to higher gradients for a fairly long time. Also, the flexibility of smectite clay is considered to be a most valuable property for near-field isolation where thermomechanical effects may be strong and where a long-lasting seal is particularly valuable.

3.3 SEALING OF DEPOSITION HOLES (TEST 1)

The general purpose of the experiment is to test what the size of a sealed "near-field" rock volume may be like, i.e. how far from a deposition hole or tunnel that water flow can be stopped

3.3.1 Test site, characterization

The two ϕ 76.5 cm diameter heater holes in the inner part of the BMT drift are selected for testing. The typical fracture features of granite are exhibited also by this rock in the sense that only very few water-bearing fractures intersect these holes (Fig 3).They have similar inflow data, i.e. 24 l/day and 12 l/day, respectively, as recorded after the BMT. The inflow from the lower half of each hole is estimated to be 10/20 % of the total inflow as concluded from early tests, meaning that the large majority of the inflow originates from the fractured tunnel floor.

3.3.2 Test arrangement

A reasonable criterion is that the grout should fill the major parts of all fractures with an actual geometrical aperture ≧ 100 μm that intersect deposition holes to within a distance of 1-2 m from the holes. The goal is to find out how effectively, and to what distance from the heater holes that major intersecting fractures can actually be grouted. The idea is to grout the fractures from the holes by using "megapackers" (cf. Fig 4). After initial Lugeon testing, such packers are first placed at the upper end of the holes for cement injection, the purpose being to fill major shallow fractures in order to block vertical flow up to the floor of bentonite grout that will be injected at the subsequent sealing of fractures deeper down in the holes. After the sealing, Lugeon testing is made whereafter the temperature is increased for 0.5 years by inserting heaters. After cooling to approximately the initial temperature, the Lugeon testing is repeated. Thereby, the influence of heating and compression expansion on the sealing effect on fracture-fillings will be examplified.

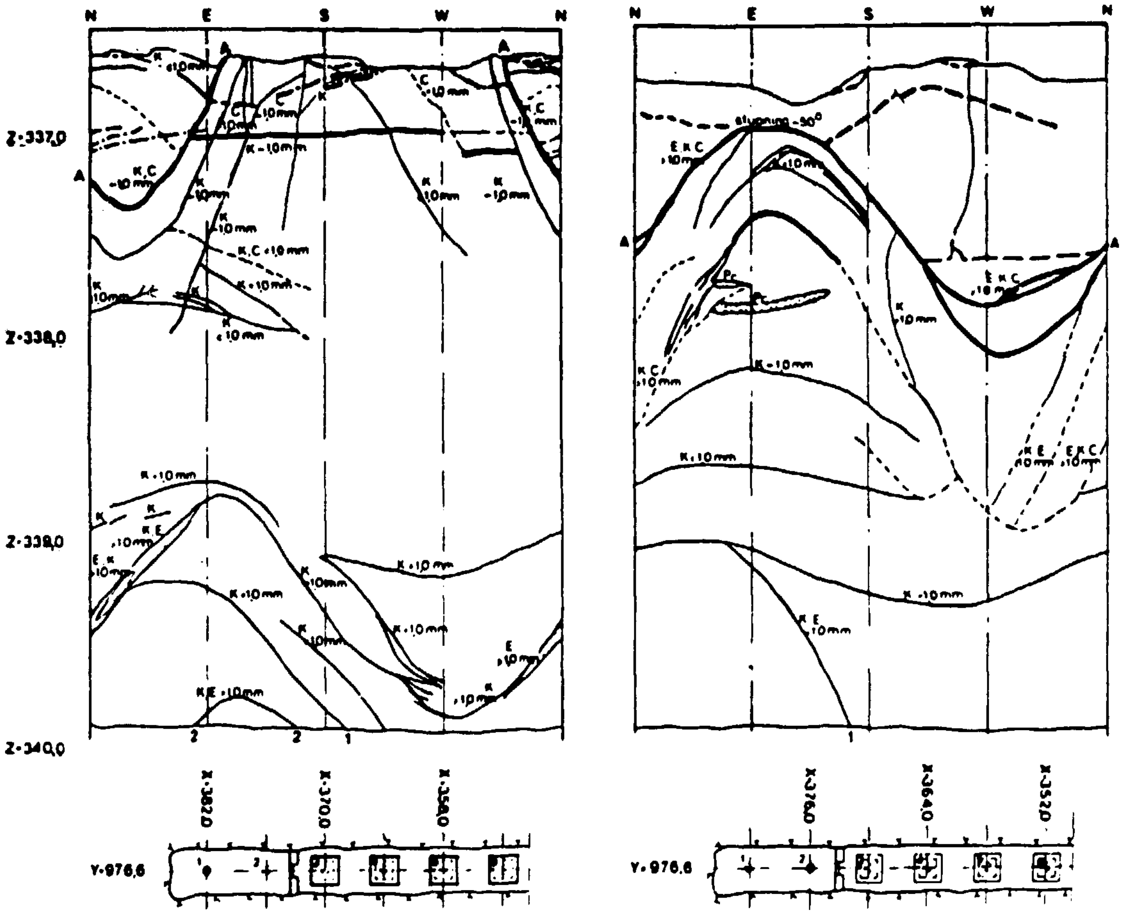

Fig 3. Location and appearance of water-bearing fractures in heater holes no 1 and 2

The field tests are preceded by systematic investigations in a simulated heater hole with a 100 µm slot to find the most suitable form of megapacker and injection dynamics. If this study would indicate that such sealing is less efficient than grouting from a number of "external" slim holes, the latter technique is still an option.

Much effort will be put in checking and - if necessary - developing the grout flow model so that the grout penetration can be predicted on the basis of megapacker Lugeon tests.

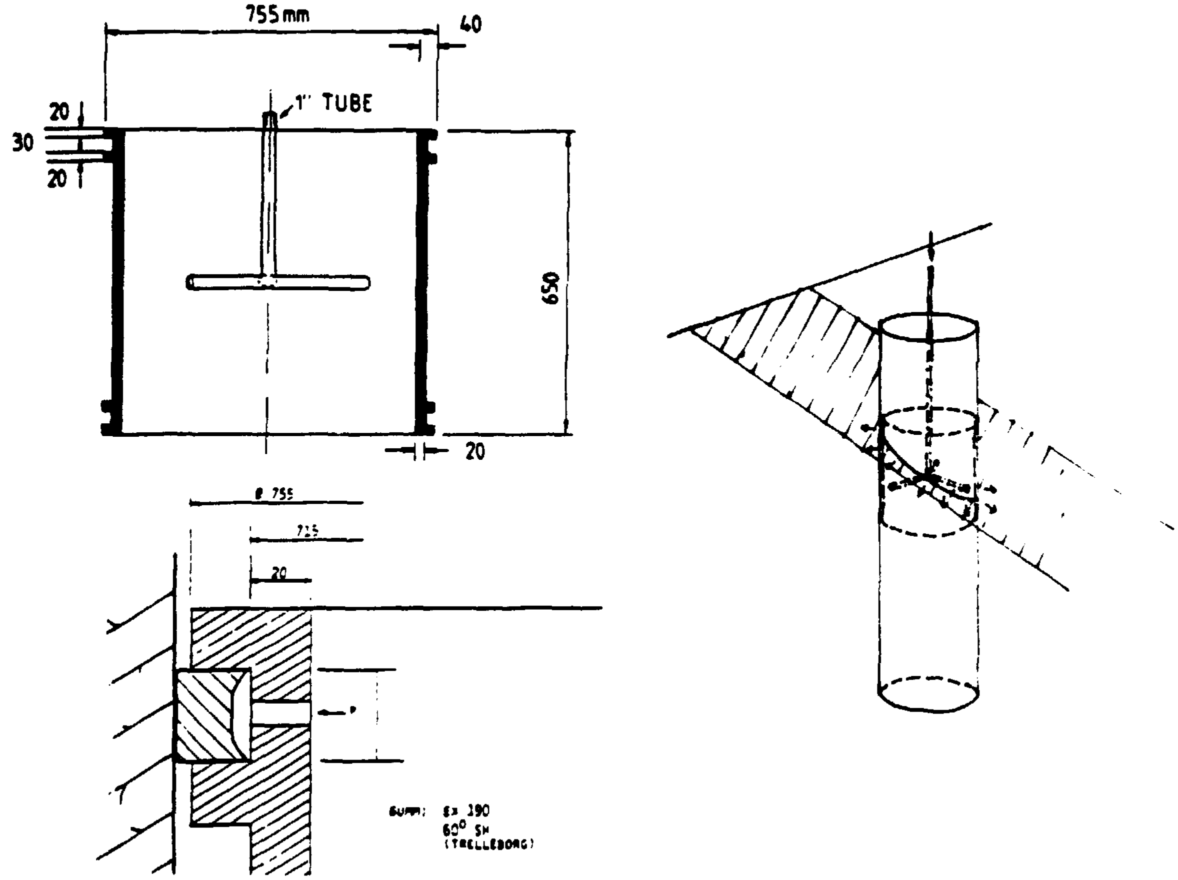

Fig 4 Equipment for pilot injection test in simulated deposition hole. Upper picture shows the packer while the lower illustrates the appearance of the rubber sealing. The right figure indicates the field arrangement

3.3.3 Measurements

The present test comprises the following steps:

1 Lugeon testing by use of megapackers in the holes before and after grouting at ambient rock temperature, as well as after heating the grouted rock to 90°C at the hole perimeter and about 40°C at a distance of 1 m

2 Evaluation of the fracture apertures and prediction of the amount of grout by using the Lugeon values and the evaluated frequency and character of the fractures, and by applying the grout flow model

3 Measurement of the amount of injected grout

4 Attempt to locate the grout by applying Cosma's remote sensing "sonar" technique in boreholes drilled close to the major fractures. Preliminary tests have indicated that open (unfilled) fractures with an aperture of about 50 µm can be distinguished from filled ones. This technique is expected to be of great value also for detecting aperture changes in the heating period

5 Identification of the location of the grout by excavating the rock

The heater-hole sealing test is the first experiment in the series and it leaves the major part of the rock in the BMT area unaffected, except for the floor. Thus, very little influence on the general groundwater flow and water pressure regimes is expected in this test, while the subsequent sealing of the disturbed zone will have such effects. Since the proposed test is integrated in the subsequently described tests, which last for about 2 years, the rock excavation will not be made until about 2 years after test start.

The effect on the rock of injection pressures, as well as the thermo-mechanical behavior will be predicted by using suitable codes, such as MUDEC. An experimental laboratory study on the influence of normal stress on the hydraulic conductivity and the groutability will be performed by NGI (Barton).

3.3.4 Expectations

A rough estimation of the average aperture of the major intersecting fractures yields values ranging between 20 and 200 µm. Applying the flow model it is foreseen that low-viscous grouts will fill the "channels" to within a distance of 1-3 m from the holes. This will effectively block groundwater percolation through the holes and within 1-3 m from their peripheries. Since the two holes are less than 6 m apart, the larger part of the rock mass below the tunnel floor will be sealed and a generalized picture of the expected effect is thus the one indicated in Fig 1.

The heat pulse is assumed to compress the major, steep fractures by which clay grout in such fractures becomes consolidated, while the subsequent cooling phase will yield opening of certain fractures by which the bentonite clay network is expanded. The heat-induced compression, which is expected to squeeze the grout into very fine parts of the fractures, may not only increase the bulk density of the clay but also its homogeneity, which should result in a high erosion resistance of the material in the subsequent "cold", expanded state.

3.3.5 Time schedule, costs

The major parts of the test and the necessary time and funding are as follows:

Activity	Time months	Cost MSEK
Detailed planning	1	0.1
Lugeon testing Field work Evaluation	3	0.3
Heating Preparation Heaters Recording	8	0.8
Grouting Pilot test series Megapackers Modelling	8	1.6
Thermo-mechanical modelling Physical model Rock mechanics	5	1.0
Geophysics Boreholes Measurement	2	0.5
Excavation of rock Field work Lab analyses	6	0.5
Time frame July 1 1988 -Dec 31, 1989 and Oct 1990 - Oct 1991	Total	4.8

3.4 SEALING OF DAMAGED ZONE (TEST 2)

The general purpose of the experiment is to find out whether there is a disturbed zone around blasted tunnels and if it can be effectively sealed by short-hole injection

3.4.1 Test site, characterization

The inflow tests that preceded backfilling of the BMT indicated that the inflow of water from the surrounding rock into the inner 12 m part of the unfilled drift is about 35-40 l/day. At a late stage of the BMT, i.e. when the backfilled drift was largely water saturated, a theoretical estimate gave a figure of the absorption of the backfill of about 20 l/day meaning that about 15-20 l/day were discharged axially along the drift. Actually, this was the recorded outflow as concluded from the measurement of water that was collected in Heater hole no 3, which is located immediately outside the bulkhead and which was left open in this part of the test. The average hydraulic gradient in the axial direction of the drift was concluded to be approximately 0.2, and assuming that the disturbed zone can be represented by a porous, circumferential zone extending 0.5-1 m from the periphery its average hydraulic conductivity was concluded to be about 10^{-7} to 10^{-6} m/s. This indicates that there is actually a zone of disturbance around the blasted drift although it is not known whether it has the character of a strongly fissured shallow zone adjacent to the drift, or if it is due to a significantly increased aperture of a few interconnected fractures oriented more or less parallel to the axis of the drift, the widening being due mainly to stress relief. The presently suggested test comprises an accurate determination of the axial hydraulic conductivity of the shallow disturbed zone as a function of the normal pressure, which can be controlled in a real repository by selecting a suitable density and smectite content of the backfill. Subsequently, the zone is sealed by systematic short-hole grouting, by which the possibility of sealing shorter or longer sections of "disturbed" rock around repository tunnels and shafts will be investigated. To a certain extent this test is relevant also to the case of natural fractured zones that intersect tunnels and shafts.

3.4.2 Test arrangement

3.4.2.1 General

The purpose of the test is twofold, i.e. 1) to determine the average axial hydraulic conductivity of the disturbed zone around a "typical" repository tunnel and 2) to seal it. The BMT test site is very suitable because:

1 It would fit excellently with the heater hole sealing project and give an opportunity to test how effectively one can minimize water flow through a unit section of a repository tunnel including the associated "disturbed" zone and all major internal "short circuit" fractures that intersect the deposition holes. Actually, combination of the heater hole sealing experiment and the presently discussed one would yield an example of a section of a completely sealed, non-pervious "model repository".

2 The existing bulkhead serves as a rigid outer boundary of the test area, which allows for pressurizing the inner part of the drift, i.e. the chamber. Some reconstruction of the bulkhead is required, however. Pressurizing is made 1) to guarantee that the lining will be tightly pressed against the rock, and 2) to find out whether a variation in effective pressure on the disturbed zone affects its permeability

3 The drift is already equipped with piezometers installed at different depths from the rock surface. By this, the distribution of the water pressure and, particularly, the pressure drop in the axial direction of the drift can be recorded in the flow tests. Of special importance is that the increase in piezometric head in the surrounding rock that will be generated by the strongly reduced hydraulic conductivity after sealing can be directly measured.

3.4.2.2 Detailed outline of the test

The test, which is initiated directly after the heater hole sealing, i.e. about 0.5 year after the start of the heater hole tests, comprises the activities listed below. The field test will be preceded by a study of the efficiency of a new generation of grouting equipment, developed so as to give low amplitudes at the dynamic injection.

1 Reconstruction of the BMT site comprising removal of about 4 m of the concrete foundation and repair of the bulkhead. These activities take place prior to the heater hole tests

2 Lining of the inner part of the drift to form a "pressure chamber" and cutting of slots for permeation of the "disturbed zone" (Figs 5 and 6). Closely spaced, radially oriented holes are drilled to about 6 m depth from the inner end of the slots so that the rock can be pressurized to about 7 m from the lined rock surface. The lining consists of 3 layers of epoxy primer and 3 layers of polyurethane which makes it completely watertight for pressures up to 20 MPa. The epoxy primer makes the liner stick very effectively to the rock surface so that no leakage will take place along the rock/lining interface.

3 Flow test for determination of the axial hydraulic conductivity of the disturbed zone. The chamber is water-filled and stepwise pressurized to 0.5, 1.0, 1.5 and 2.0 MPa the pressures corresponding to those generated by backfills with different densities and smectite contents. The water pressure applied in the inner slot for the percolation of the disturbed zone will range between 0.3 and 1.5 MPa, i.e. somewhat lower than the water pressure in the chamber.

4 Grouting with cement in regularly spaced (1 m), short boreholes (1.5 m) that are drilled through the lining (Fig 7). Two packer positions in each hole, one at 0.5 m distance from the rock surface and the other at the rock surface in each hole may be required to yield complete fracture-filling. Prestressed "expander" bolts equipped with load cells and strain gauges will be applied in the open holes surrounding the hole that is being grouted. By this the rock is stabilized and good information is expected on the penetration and distribution of pressurized grout

5 Flow tests for determination of the hydraulic conductivity of the disturbed zone after grouting, using the same technique as described in paragraph 3.

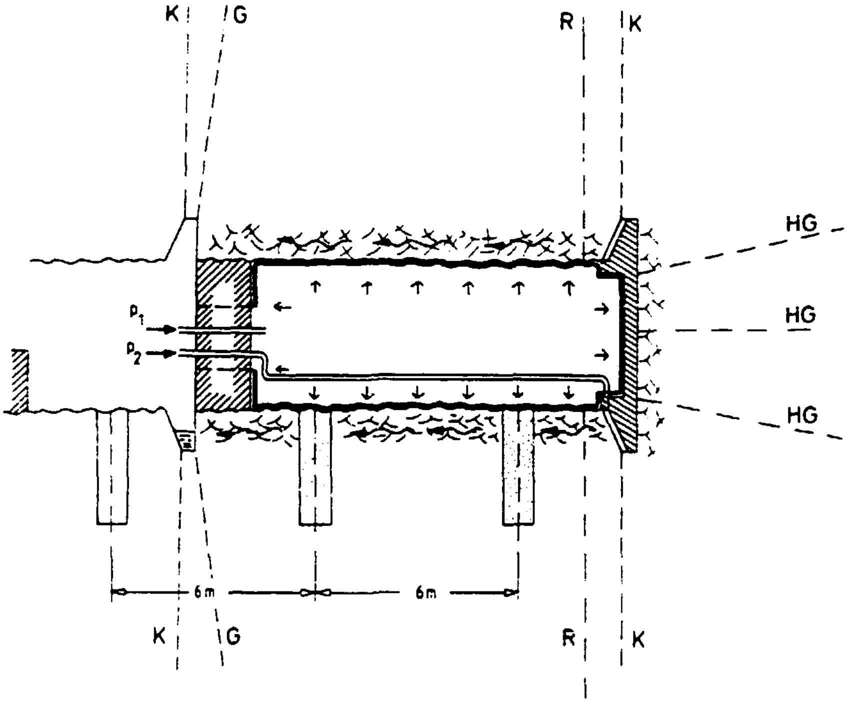

Fig 5. Schematic section of the inner part of the BMT drift at the flow tests. The large, closed space is water-filled and pressurized (p_1), while percolating the "disturbed" zone under a separate, variable pressure (p_2). K holes are closely spaced and drilled radially to 6 m depth for pressurizing the inner end of the zone and for collecting of percolate at its outer end. G holes are used for grouting in Test 3

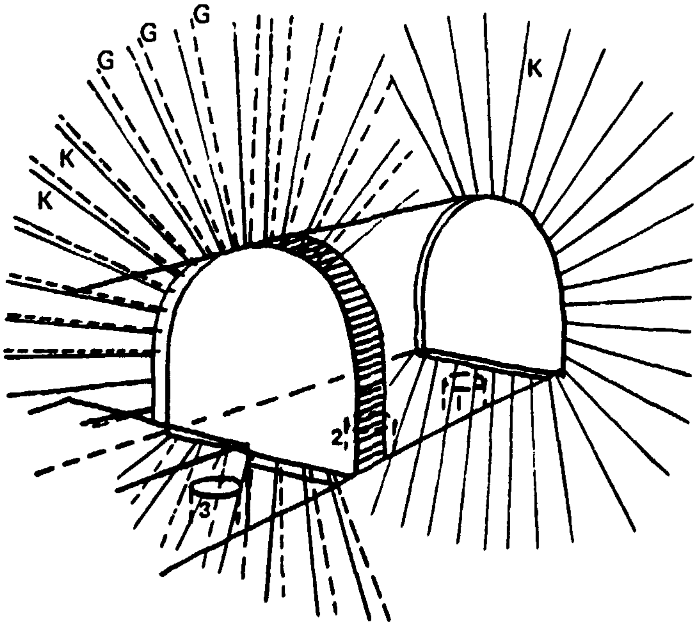

Fig 6. View of the drift with boreholes for pressurizing (K) and water collection (K), and grouting (G)

6 Cosma's "sonar" technique is tried in a few of the short boreholes before the grouting and after removal of the grout by drilling. Comparison between the results before and after grouting of the zone is expected to yield a significant change that may offer a simple technique for quality checking of the applied type of sealing.

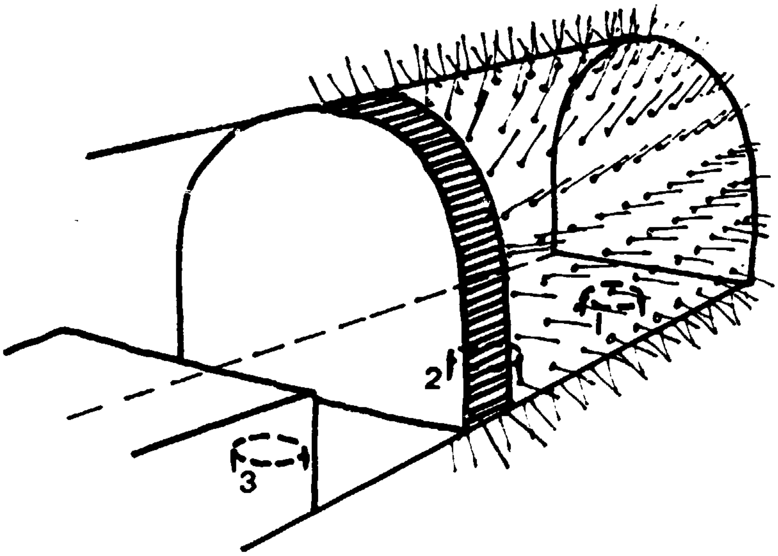

Fig 7. View of the BMT drift with short holes for systematic grouting all around the periphery

3.4.3 Measurements

The major recording activities are:

1 Measurement of the axial water flow through the disturbed zone before and after grouting by collecting water in the outer slot

2 Core mapping of short injection holes

3 Lugeon testing in short injection holes for evaluation of the aperture and extension of fractures. Prediction of the penetration of grout.

4 Measurement of the amount of injected grout

5 Identification of grout paths by measurement of forces in anchor bolts

6 Recording of water heads along the rock/lining interface by use of existing piezometers for evaluation of the axial hydraulic gradient and conductivity at the water flow tests

7 Recording of time-dependent water pressure changes after the grouting by use of piezometers also at larger distances, i.e. LBL gauges around BMT (Figs 8 and 9) and piezometers in the Time Scale drift (French holes), which is known to be hydraulically connected to the BMT

8 "Sonar" testing before and after grouting

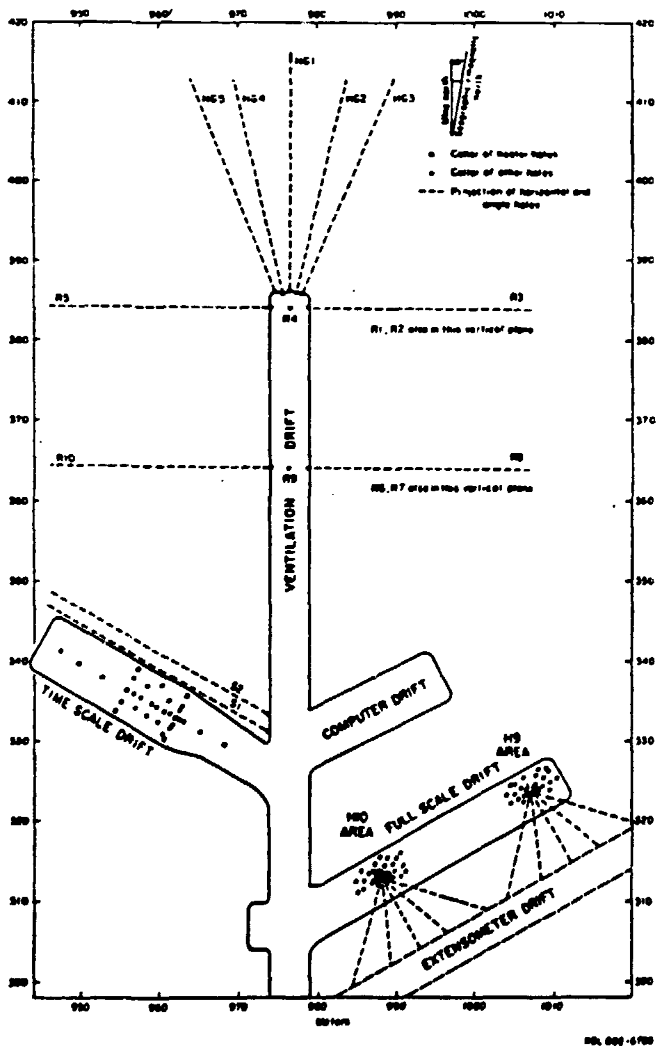

Fig 8. Plan view of the BMT area (Ventilation drift) at Stripa with operative LBL holes

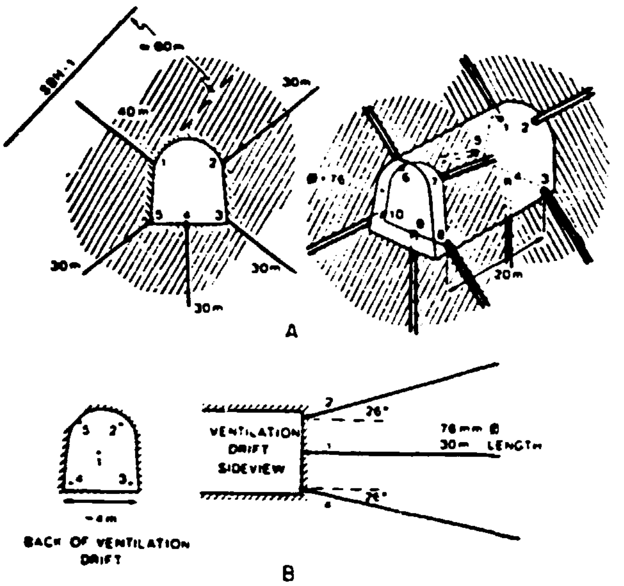

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Fig 9. Perspective image of LBL holes

3.4.4 Expectations

The pilot field test in Stripa demonstrated that grouting with cement mixed with superplasticizer yields a very high degree of fracture-filling. Thus, in the present experiment it is expected that all fractures with apertures down to 10-20 μm in the shallow rock will be effectively sealed and that the axial conductivity of the disturbed zone will drop from an assumed initial value of 10^{-7} m/s (ungrouted rock) to 10^{-10} m/s provided that the radial extension of the damaged zone is 1 m at maximum.

The change in piezometric heads at larger distance from the test drift can hardly be predicted with any accuracy. However, it is felt that once the sealing has been made, the pressure close to the drift may be raised to 0.5-1.5 MPa. Also in the R-holes (Figs 8 and 9) and in the Time Scale drift the pressure is expected to increase, indicating that the present drainage from the rock surrounding the BMT drift has been halted. In turn, this would be an example of how effectively stagnant water regions can be created by grouting.

3.4.5 Time schedule, costs

The major parts of the test and the necessary time and funding are as follows:

Activity	Time months	Cost MScr
Detailed planning	1	0.1
Reconstruction of BMT	5	1.8
Removal of concrete		
Repair of bulkhead		
Rearrangement of gauges		
Preparation of chamber, etc	5	1.3
Lining		
Slots, injection device		
Boreholes		
Grouting	8	1.9
Boreholes		
Lugeon tests		
Injection		
Predictions		
Improvement of grout technique		
Flow tests	10	1.3
Pressure system		
Water injection		
Evaluation		
Flow modelling		
Geophysics	1	0.5
Time frame	Total	6.9
July 1 1988 -June 1, 1991		

3.5 SEALING OF STRESS-INDUCED, DISTURBED ZONE (TEST 3)

The purpose of this test, which is intimately connected to Test 2, is 1) to verify the basis of that test, i.e. to check whether the average conductivity of the rock at larger distance than 1.5 m from the periphery of the drift is at all lower than that of the ungrouted shallow zone, and 2) to find out whether the disturbed zone has a radial extension of more than about 1.5 m.

3.5.1 Test site, characterization

While the preceding text described sealing of the shallow 0.5-1.0 m wide zone that is characteristic of blasted tunnels, the present test concerns sealing of rock at larger distance from the tunnel periphery, i.e. the outer part of the disturbed zone where stress relief may have caused an increase in axial hydraulic conductivity. The hydrological importance of such stress-induced alteration of the axial conductivity is illustrated in Fig 10 for the simple case of initially isotropic stress conditions, elastic behavior and cubic law-type flow dependence on stress changes. One finds that the axial (longitudinal) conductivity is theoretically increased by about 3 times to within r = 1.5 a, which corresponds to about 3 m distance from the periphery of the BMT drift. The actual increase is probably much more obvious in strongly anisotropic stress fields, such as that in the BMT area. It is therefore expected that although the shallow sealing made in Test 2 will strongly reduce the axial conductivity, the surrounding stress-generated disturbed zone will still yield a higher conductivity in axial direction than that of the virgin rock. Test 3 is planned to investigate how effectively this outer zone can be sealed off. The study comprises a rock mechanical study using the MUDEC code to predict the flow distribution around the BMT drift.

3.5.2 Test arrangement

The presently described test, which can be understood as a complement to the preceding one, comprises sealing of the rock at the outer end of the bulkhead in the BMT drift by cement grouting of closely spaced holes drilled radially at the outer edge of the bulkhead to a depth of 7 m (G-holes in Figs 5 and 6).

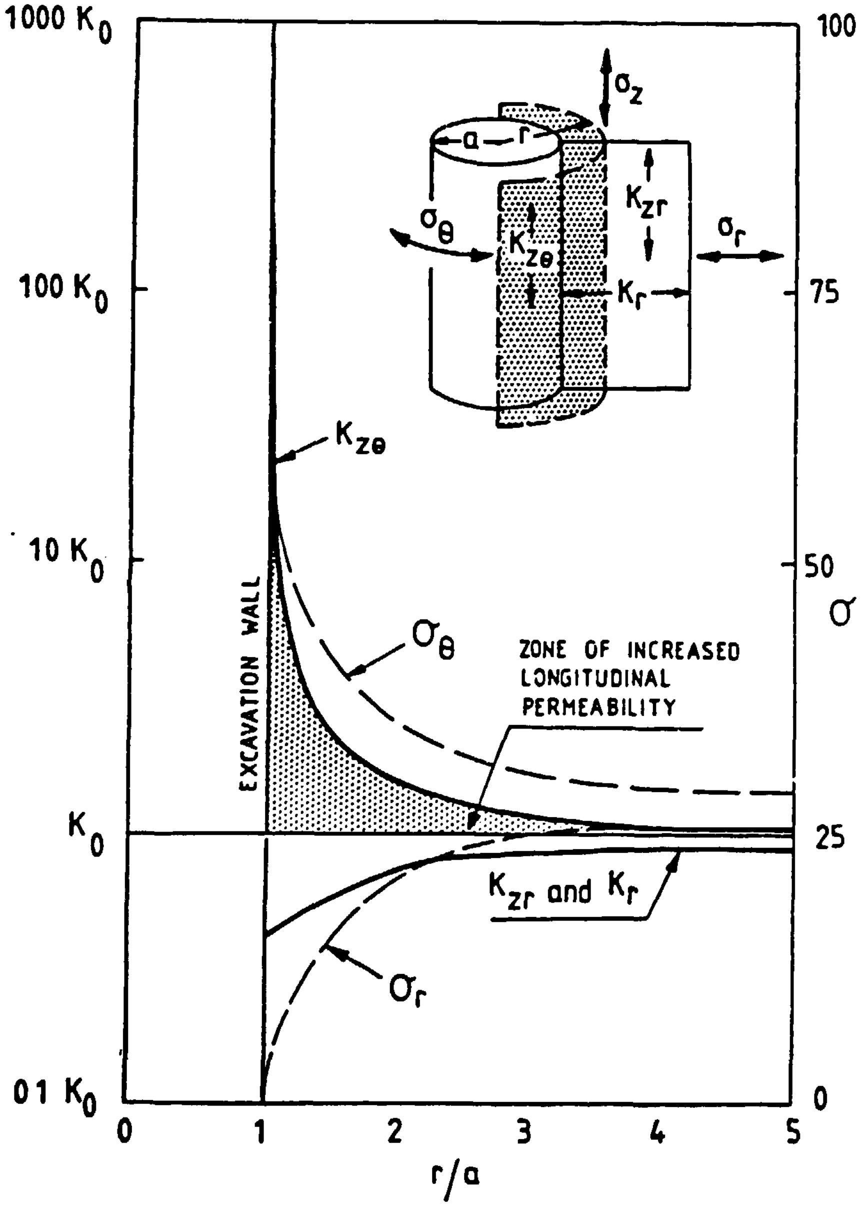

Fig 10. Predicted permeability alteration of the disturbed zone around a circular excavation at isotropical initial stress condition

K_{zr} = Permeability of radial fractures in the axial direction
$K_{z\theta}$ = Permeability of oinionskin fracture in the axial direction
K_r = Permeability in the radial direction
K_θ = Permeability of the undisturbed rock (isotropic)

The grouting is made at released pressure in the confined chamber behind the bulkhead and with no water overpressure in the injection slot at the inner end of the drift, thus simulating the conditions at grouting in a repository that has not yet been backfilled. The K-holes are kept pressurized or packed off while grouting the G-holes.

3.5.3 Measurements

The major recordings are the following:

1. Lugeon testing of grouting holes for evaluation of fracture apertures, using the core mapping as a basis for defining the probable number of active fractures. The data are used for predicting the grout penetration.
2. Measurement, before and after grouting, of the axial flow by collection of water in the outer slot. The chamber and the disturbed zone are pressurized to the maximum level that was applied in Test 2.
3. Measurement of the amount of injected grout.
4. Evaluation of the axial hydraulic conductivity of the disturbed zone.

3.5.4 Expectations

The difference in average hydraulic conductivity before and after grouting of the short holes (Test 2), and after grouting of the long G holes (Test 3) should give a good measure of the respective contribution of the two disturbed zones to the net axial conductivity, and of how effectively they can be sealed. It is expected that the sealing of the short holes yields the most obvious drop in axial hydraulic conductivity. However, the rock mechanical analysis that precedes Tests 2 and 3 may modify these expectations.

3.5.5 Time schedule, costs

The major parts of the test and the necessary time and funding are as follows:

Activity	Time months	Cost MSEK
Detailed planning	1	0.2
Grouting	2	0.5
Lugeon tests		
Predictions		
Flow tests	4	0.8
Water injection		
Evaluation		
Flow modelling		
Total time frame	Total	1.5
June 1990-Dec 1991		

3.6 SEALING OF NATURAL FRACTURED ZONE (TEST 4)

The purpose of this test is 1) to check whether a richly water-bearing natural fracture zone can be effectively sealed, 2) to demonstrate that such sealing has a shunting and redirecting effect on the groundwater flow in repositories, and 3) to give new information on the water source that supplies the 3D drift with water

3.6.1 General

While Test 2 concerns sealing of shallow rock with fractures oriented and located so that the sealing must be made with considerable care in order not to break up the rock, natural fractured and strongly water-bearing rock zones that intersect tunnels or shafts and have a large extension are preferably grouted by applying high injection pressures in rather deep holes that are packed off in stages. Test 4 comprises grouting of such a zone, the wet eastern part of the 3D cross being considered as a suitable test site.

3.6.2 Test site, characterization

The only part of the 3D drift where there is significant inflow of water is at the eastern end of the 3D cross. The source is not known at present. The structure is a steeply oriented 3-5 dm wide zone of aligned long-extending fractures, which can be seen both in the eastern arm of the cross and in the northern part of the main arm (Fig 11).

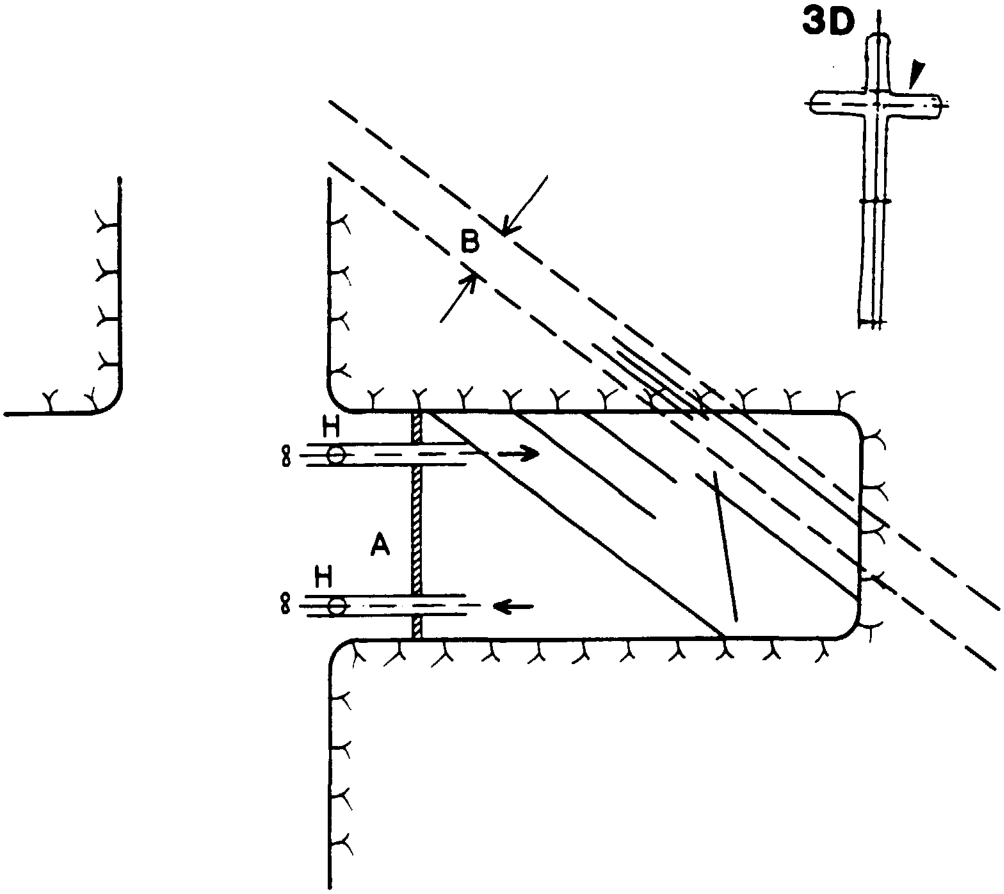

Fig 11. Location of major water-bearing fracture zone (B) in the 3D drift. Test arrangement: A is light wall, H is ventilation with accurate measurement of flow capacity and humidity

3.6.3 <u>Test arrangement</u>

3.6.3.1. Scope of test

Assuming the eastern arm of the cross to represent a repository tunnel that is intersected by a pervious zone, strategic planning of how to isolate such a conductor suggests sealing of the zone all around the tunnel. It is assumed here that it is required to reshape the zone to be low-pervious to within 5 meters distance from the periphery. The purpose of the test is to investigate if the zone can be sealed off so effectively that the inflow through it to the drift is reduced to be the same per unit area exposed in the tunnel as for the rest of the drift. This would make the entire eastern arm virtually dry.

3.6.3.2 Detailed outline of the test

The evaluation of the sealing effect is suggested to be made by applying a simple version of the Macropermeability test. Thus, a light wall is built at the western end of the drift and curtain grouting to 5 m depth is made around it. The water inflow into the drift is evaluated from blowing ventilation air with a known capacity and humidity into the drift and measuring the humidity also in the exit tube. Six sets of ϕ 56 mm boreholes extending to 2, 5 and 10 m depth are drilled in two sections and equipped with piezometers for measuring the piezometric heads. After the hydrological characterization, a large number of radially oriented, 5-7 m long boreholes are drilled for grouting so that the zone is hit at an angle of about 20-30° (Fig 12). The borehole spacing will be in the interval of 0.5-1 m. Grouting is made by use of cement with three packer positions, i.e. at 4, 2 and 0.5 m distance from the rock surface, in each hole.

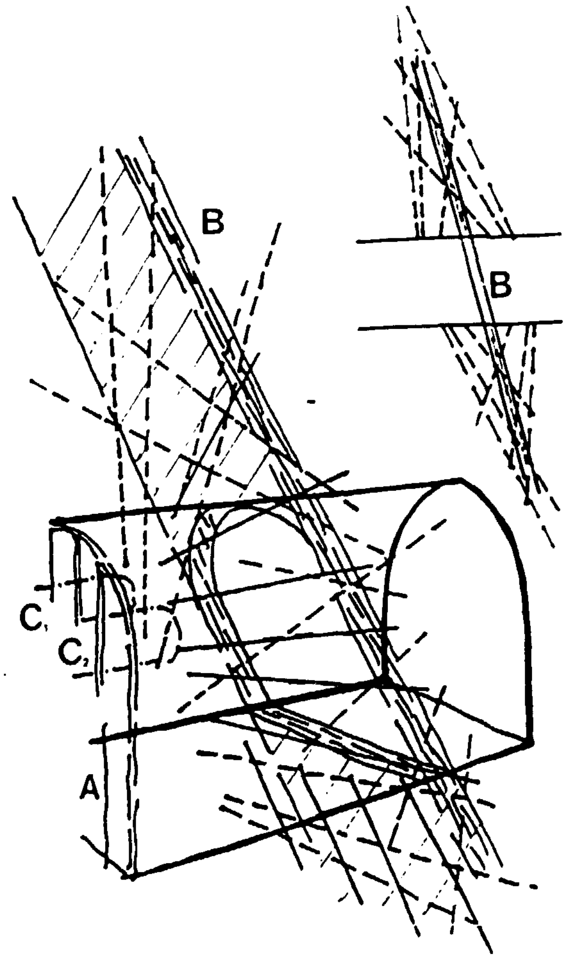

Fig 12 Schematic picture of the arrangement for grouting of the natural fracture zone in 3D

3.6.4 Measurements

The major recordings are the following:

1 Measurement of the inflow of water into the drift before and after grouting

2 Measurement of piezometric heads before and after grouting

3 Injection of tracer-doped water in the zone at different distances from the drift periphery, before and after grouting to identify possible changes in flow directions and to check the tightness of the zone

4 Lugeon testing in the grouting holes for evaluation of fracture apertures and for predicting the grout penetration depth. This work is based also on careful core mapping

5 Measurement of the amount of injected grout

3.6.5 Expectations

The test is expected to illustrate how effectively a natural long-extending, fracture-rich and strongly water-bearing rock zone can be isolated from a repository tunnel. Most probably, the water that flows in today will be redirected to and discharged in the northern part of the 3D cross. Also, it should be possible to demonstrate that systematic grouting with successively displaced packer positions in each hole results in a homogeneously sealed zone of any desired extension.

Finally, it is expected that the test will give indication on the art and location of the water source, which would be beneficial for the current 3D test.

3.6.6 Time schedule, costs

The major parts of the test and the necessary time and funding are as follows:

Activity	Time months	Cost MSEK
Detailed planning	2	0.2
Construction etc	3	0.4
Light wall		
Grouting		
Piezometric meas	5	0.5
Boreholes		
Packers, piezometers		
Recording syst		
Tracer tests	5	0.3
Boreholes		
Packers		
Injection equipment		
Sampling, analysis		
Grouting	5	0.8
Boreholes		
Lugeon tests		
Injection		
Modelling		
Flow tests	12	1.2
Meas of water inflow		
Evaluation		
Modelling		
Total time frame July 1988-July 1990	Total	3.4

3.7 QUICK SEALING ACTIVITY ("MAY-DAY") IN THE VALIDATION DRIFT

Tests 1, 2, 3 and to a certain extent also Test 4, represent defined sealing projects with a very good chance of evaluating the sealing effect and of understanding its physical background. The experience gained in the course of the tests, both with respect to the injection pump equipments and the behavior of various grouts, will make it possible to conduct sealing of rock structures without much preparation if required. This may appear to be the case when the Validation Drift has been excavated. Thus, fast and unexpected inflow of water in intersected structures may call for quick sealing. Also, sealing of one or several structures in the Validation Drift may help to identify interconnections between various hydraulically active fracture zones at the end of the Stripa Phase 3.

Although it will most certainly be possible to offer help with such quick sealing, extra funding would be required. In our mind more comprehensive sealing activities at a very late stage of the Validation Drift experiment would not offer a possibility of scientific documentation.

4 ACCESSORY INVESTIGATIONS

4.1 GENERAL

While a considerably deepened insight in the longevity of cement and smectite has been gained in the current work, a number of questions remain to be answered concerning the chemical longevity but also respecting the physical stability, i.e. piping resistance, erodability, bond strength and expandability. Naturally, the matter of physical and chemical stability is very essential for the final selection of candidate grouts, and further systematic work, which will be specified in this chapter, needs to be made.

4.2 CHOICE OF CANDIDATE MATERIALS

At the preparation of cement grouts for the field tests, the grain size of the cement as well of the silica fume was checked and it was then observed that a fairly large part of these constituents were bigger than 50 µm and that some grains were as big as 300 µm. They could not be easily disintegrated and would have caused problems at the grouting, and the materials were therefore replaced by other blends. One would assume that the Japanese Alofix cement is more fine-grained since the grain size curve (max d = 17 µm) is explicitely given in the manufacturers brochures. However, as indicated by NGI experience there is a similar deviation from the specification also of this cement. Probably it is a common phenomenon that is due to hydration during storage and shipping of the cement, for which more strict rules should be developed. As to the silica fume it appears to be difficult to get hold of a material with a guarenteed maximum grain size of 1 µm.

Still, the composition of cement grouts for further study in the project and future practical use, should be approximately the one intended for the Pilot Field Test, i.e. cement + 10 % silica fume + 1 % (dry weight) superplasticizer. Thus, it is preliminarily recommended that this type of grout is nominated as one of the two grouts for use in the Large Scale Field Test.

As to clay grouts, further lab tests, particularly with Ca bentonite, must be made before a definite choise is made. 50/50 Na bentonite and quartz filler is presently the strongest candidate but there are a few options that need to be considered. One of them is based on the fact that the liquid limit of Na montmorillonite drops considerably on mixing with salt water. Thus, Tixoton mixed with 2 and 10 % NaCl solution has a liquid limit of about 120 and 95 %, respectively. Adding salt water to $1.5xw_L$, yields water contents of 180 and 140 % respectively, and a flow resistance that is clearly lower than that of bentonite mixed with distilled water (Fig 13). After injection into fractures in rock of lower salinity, the salt rapidly diffuses into the crystal matrix and yields a "fresh-water" clay with a density of up to 1.3 t/m^3. Such clay is expected to have a hydraulic conductivity lower than 10^{-9} m/s and a considerable piping resistance and also a certain expansion potential. Theoretically, the critical pressure to produce piping would be about 10 times higher than that of fresh-water Tixoton at $1.6xw_L$, i.e. at least 0.3-1 MPa. The fact is that the amount of salt that is introduced in the rock by using "clay/brine" is very insignificant, which means that it cannot have a noticeable effect on the corrosion of a steel canister. This option has a high priority in the research work that precedes the Large Scale Field Test.

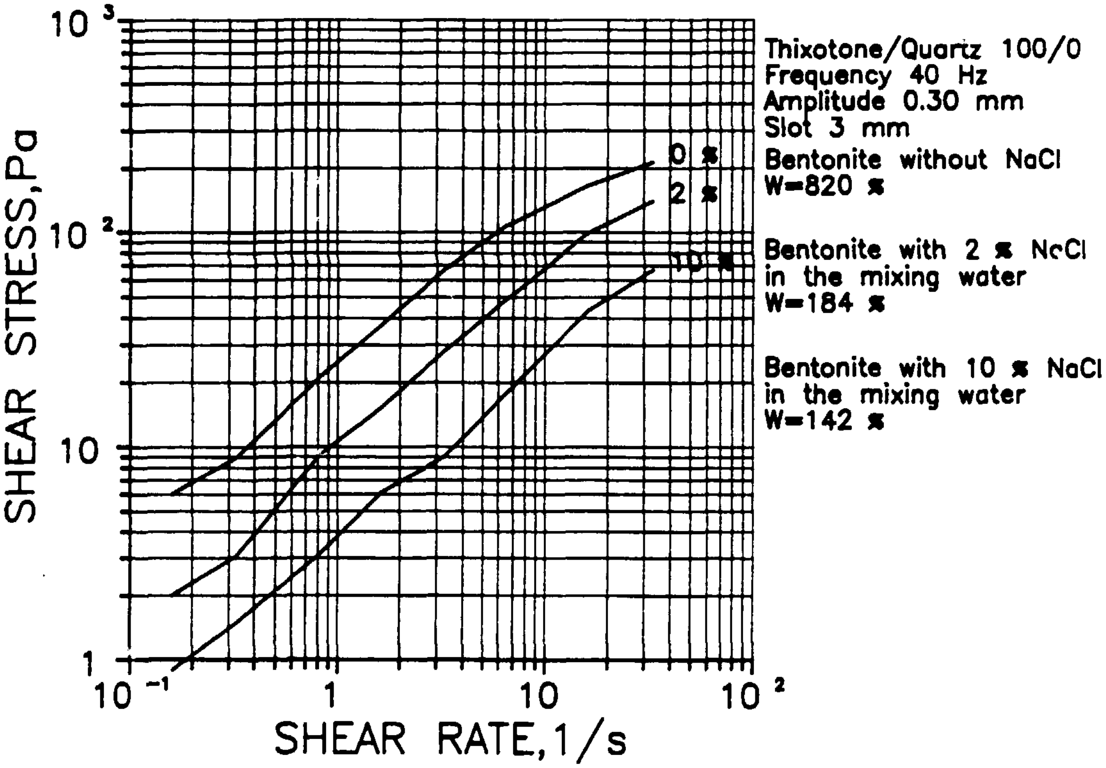

Fig 13. Flow behavior of Na bentonite mixed with water of different salinities

4.3 LONGEVITY

4.3.1 Introduction

It is beyond doubt that the major problem that remains to be solved in the sealing project is the physical and chemical stability of the grouts. There is good hope for getting a clear picture of the potential for survival of the nominated cement and of smectite clay in an extended study, as concluded from the already available results. The required investigations are outlined in the subsequent chapters.

The cone-in-cone apparatus offers excellent possibilities of conducting flow experiments in which a complete scenario of expected events in clay- and cement-grouted "near-field" rock can be simulated. In particular, piping and internal erosion can be investigated as a function of the piezometric head, temperatures up to 95°C, porewater chemistry, and imposed changes in aperture. Since the test arrangement represents an open system where the composition of the percolate can be controlled and analyzed with a very high accuracy, hydrothermal experiments at moderate water pressures can be conducted as well.

4.3.1.1 Clays

It is concluded from the current chemical longevity tests that as long as the temperature does not exceed about 90°C, at least 50 % of the montmorillonite is expected to be preserved over half a million years, the rest being converted to non-swelling hydrous mica (illite). Some cementation by precipitation of heat-induced release of silica is expected to be associated with this conversion but it is concluded to have a minor influence on the bulk physical properties.

For temperatures exceeding about 90°C the long term influence on the mineralogy is more significant as indicated by a number of rather vague geological analogies but it may still have a very moderate effect on the physical properties of clay gels. This can be investigated by conducting accelerated hydrothermal percolation tests at higher temperatures, applying rather high hydraulic gradients and varying also the porewater chemistry. If associated microstructural changes can be quantified and related to changes in hydraulic conductivity, and if the exact process of heat-induced interlamellar collapse and silica release can be identified, a complete model of hydrothermal effects on smectite grouts would be at hand. The work that is required to reach this goal is specified below in "Outline of research program" and it is expected to be very fruitful since it will also benefit from the national research programs in the various member countries. The techniques and ways of interpreting and evaluating recorded data have been described previously in detail to the Task Force. In summary, the following goal is set for the study:

- The critical pressure for piping and its relation to the gel strength, as well as the effect of erosion on the sealing power of clay-grouts in fractures will be determined for low-saline and saline solutions. This represents the physical condition in the first few years after backfilling.

- The effect on the sealing power of temperature- and shear-dependent cyclic expansion/contraction of clay-grouted fractures will be determined for various porewater compositions. This is an accelerated scenario of physical changes in the first few thousand years.

- The solution of montmorillonite and possible neoformation of silicate compounds such as hydrous mica will be studied in accelerated tests under open and closed conditions at temperatures ranging between 90 and 200°C

- The matter of whether there is a critical temperature for Si-release and beidellitization will be clarified by use of nuclear physics on hydrothermally treated samples. If a critical temperature exists, a great step forward has been taken in presetting the lifetime of montmorillonite sealings.

- The net products of a complete chemical reaction of montmorillonite in water of different composition (open system) will be determined by applying thermodynamics. "Worst-case scenario".

Outline of research program (Work conducted by R. Pusch, Sweden)

Problem area	Grout type	Subject	Technique, variables	Analysis	Time period	Cost MSEK
Physical stability	Clay	Hydr cond	Cone-in-cone * Density * Slot apert * Temp * Porewater chem	● Flow meas ● Microstruct analysis TEM SEM OM	Jul 88- Dec 90	0.5
		Piping/ erosion	Cone-in-cone * Density * Slot apert * Temp * Porewater chem * Pres head	● Microstruct analysis TEM SEM OM ● Rheometry	Jan 89- Dec 91	0.4
Chem stability	Clay	Hydro-thermal effects (I) Experimental	Cone-in-cone * Temp * Porewater chem (K, Ca)	● Microstruct & elem analysis STEM XRD ● Percolate analysis Elem pH	Jul 88- Dec 90	0.6
		Hydro-thermal effects (II) Water/ smectite interaction	MAS/NMR (FTIR)	● Lattice struct analysis Si coord Al coord	Jul 88 Dec 91	0.5
		Hydro-thermal effects (III) Solubility	Thermo-dynamics, open systems	● React prod Preference of cation uptake	Jul 88- Dec 91	0.8
					Total	2.8

1) Optical microscopy

4.3.1.2 Cement (Authors: M. Gray, AECL, & W. Coons, IT Corp)

While the conclusions from the current research on clay longevity has been extensively described in a separate "interim report", the corresponding reporting on cement has been short. Therefore, the presentation is more comprehensive on cement in this document. The conclusions from the current longevity studies, which indicate that cement grout has a potential for long-term performance (10.000 to > >100.000 years), can be summarized as follows:

- Solid-solid phase transitions may decrease density but existence of metastable phases in ancient materials and natural analogues indicate kinetic hindrance

- Decreased performance by leachability is a strong function of initial hydraulic conductivity, K_0, and leachant. At low K_0 realistic leachants and with high hydraulic heads, models indicate potential for very long life.

- Superplasticizer content does not appear to affect longevity. It is taken up during hydration by CSH phases (ettringite) with an undetermined residual possibly in pores.

- The reference cement grout appears to have a self-healing potential that is comparable to that of clay grouts and which becomes enhanced at elevated temperatures.

However, it is essential that the following matters be investigated in great detail:

- **What evidence exists that cement grout has potential for long-term performance?**
  - What are the potential effects of solid-solid phase transitions?
  - What are the potential consequences of leaching?
- **What is the leachability of reference grout?**
  - What parameters determine leachability?
  - How does reference mix perform in comparison to grouts not specially developed for repository conditions
- **How do superplasticizers function?**
  - What phases/sites are hosts for superplasticizer?
  - How do superplasticizers affect longevity?
- **Can self-healing properties be engineered into cement grout?**

The major features of a suitable research program are the following:

- **Enhance confidence of preliminary conclusions**
  - Continue leach tests and superplasticizer studies
  - Reduce and analyze data already generated

The formulation of the respective problem and outline of the laboratory techniques can be described as follows.

Physical/mechanical stability

The leachability of Portland cement grout is strongly dependent on the volumes of water that have access to the cement phases during a given time period. At a given hydraulic gradient, this volume is a function of the initial conductivity of the grout (K_0) and its initial effective porosity. Changes in porosity that could result from solid-solid phase transition and/or dissolution and removal of cement phases can change the K_0 with time. In order to assess the change in K_0 it is therefore neccessary to establish empirically, what the relation between grout conductivity and porosity is. An empirical relation is approximated by:

$$K_i = K_o \cdot 10^{[(11.14) - \frac{\Delta_v}{v_T}]}$$

where K_i = calculated conductivity
v_T = total original volume of solids
Δv = difference between volume of solids precipitated minus volume of solids dissolved

Further studies are needed to confirm that this relation holds for the specific reference grout selected. To accomplish this, K_i as a function of porosity (i.e. different w/c ratios) will be investigated. The lab research program in condensed form is given below. The work is conducted in Sweden by R. Pusch in close cooperation with M. Gray, AECL, and W. Coons, IT Corp.

Outline of research program

Problem area	Grout type	Subject	Technique, variables	Analysis	Time period	Cost MSEK
Physical stability	Cement	K_i/n- relationship Self-healing	Cone-in-cone * Slot apert (expansion) * Temp * Porewater chem	● Flow meas ● Microstruct analysis STEM ● Percolate analysis	Jan 89-Dec 90	0.5

Longevity program for Portland cement grouts

Solid-solid phase transitions

Portland cement grout is a material comprised of multiple phases including amorphous and crystalline materials. It is commonly assumed that these phases are thermodynamically metastable and that in time, they will revert to more stable forms. These transformations have been a cause for concern because if they result in an increase in grout porosity in a time period of interest (tens of thousands of years), then permeability of the grout could increase to unacceptable levels. To investigate this phenomenon a limited kinetic investigation will be performed through thermodynamic analysis of natural analogues and ancient cements combined with observations derived from leach tests conducted on the reference grout. These data will be used to calculate porosity increases as related to increased grout permeability through empirical relationships. Additional observations related to second generation of residual cement in the reference grout (e.g. hydration due to fracture healing) be used in the derivation of the model.

Reaction/leaching studies

The interaction of flowing groundwaters and the reference grout may lead to a progressive increase in grout conductivity. This decrease would largely be due to removal (mass transport) of material from the grout. Grout components that may be of concern include (but are not limited to): superplasticizer, CSH gel, tobermorite, intermediate CSH, crystalline phases, ettringite, CAH as well as the cured multicomponent grout itself.

One objective of the work will be to further clarify the mechanisms of superplasticizer adsorption with emphasis on the influence of mixing water content on the phase of residence of the Na-SNF. Blends of pure cement compounds will be investigated and attempts will be made to clarify the form of the adsorbed superplasticizer. Superplasticizer leaching tests using ^{35}S tagged Na-SNF will continue in combination with complete leachate analysis to attempt to associate Na-SNF leaching to cement phase dissolution. Studies of blends of pure compounds and industrial grade cements will be effected.

Available data from leach tests are limited to reference grout and MC-500 at 3 w/c ratios. The ability of granite, or clay and granite in combination, to buffer cement dissolution was not investigated. Data indicate that the effects of granite could be significant. The study will be broadened to include pure cement compounds, the buffering effects of granite and the combined buffering effects of granite and clay. Studies of pure cement compounds and their blends in combination with industrial grade cements should provide some of the information required to support modelling activities.

Ettringite formation is seen by some as one of the mechanisms of grout degradation. Free surfaces of grout may swell and exfoliate: thus physical erosion of the grout may be enhanced. Ettringite formation requires the reaction of sulphate ions with the CAH product in the cement. The sulphates may be derived from the superplasticizer or arrive at reaction sites in the hardened cement by diffusion through the paste. It is well known that sulphate migration rates can be affected by the presence of chlorides, carbonates and bicarbonates in the system. Using radioactive tracers, accelerated tests will be used to determine the rates of ettringite formation and the rates of migration of harmful ions through hardened cement grouts, singly or in combination. Microscopic examination will be used to identify the rate of degradation of and phase transformation in the hardened pastes.

Where the grout it confined, ettringite formation and grout swelling may enhance the rock/grout bond. Microscopic examinations will be undertaken to evaluate these time dependent changes at the grout/rock interface.

Expectations

Performance of the reference grout for durations of tens of thousands of years cannot be derived from experiments alone. In order to assess such long-term performance, a predictive model must be developed. Preliminary development of a simplified model has given indications that long-term (i.e. >>100.000 years) performance is potentially obtained with the reference Portland cement grout. This potential obtains due to the low initial conductivity of the grout as measured in the laboratory (10^{-14} m/sec). To improve the confidence of preliminary results, an enhanced model will be developed using data obtained from the experimental program. Expectations are that the model will include the ability to:

- Assess long-term effects of solid-solid phase transitions (if necessary)
- Project the effects of long-term leaching on porosity/permeability of the grout including:

- The effects of dissolution, precipitation, reaction, leachant composition, and temperature on K_i
- Estimating changes in interconnectal porosity as a function of time

Condensed form of program (work conducted by M. Gray (AECL) and W. Coons (IT Corp)

Problem area	Grout type	Subject	Technique, variables	Analysis	Time period	Cost MSEK
Chem stability	Cement	Solid-solid phases	• Closed form solutions	T, phase composition	Sep 88 Sep 89	0.34
	Cement	Leaching studies & predictions of longevity	• EQ3NR/EQ6 Modelling leach	T, compos of groundwater, hydr grad	Jul 88 Dec 91	1.46
			• Lab tests leach	SEM, leachate anal	Jul 88 Sep 90	0.55
			• Lab tests w/superplasticizer	SEM, XRD Autoradiogr leachate anal	Jul 88 Sep 89	0.55
			• SO_4^{2-}, Cl^- and HCO_3^- Diffusion + ettringite formation	Diffusion tests coupled & uncoupled anions SEM, XRD	Sep 89 Dec 91	0.30
					Total	3.1

Note: 1.4 MSEK refers to M. Gray's work and 1.7 MSEK to W. Coons' study

5 TIME SCHEDULE AND COST ESTIMATES

5.1 GENERAL

The current research work as specified in the program of 1986 is exactly on time and is expected to be completed within the allocated budget frame, i.e. 7 MSEK (cf. Table 2). The planned work that has been specified in this report is summarized in Table 3, while the estimated costs are given in Table 4.

Table 2. Time schedule of current work

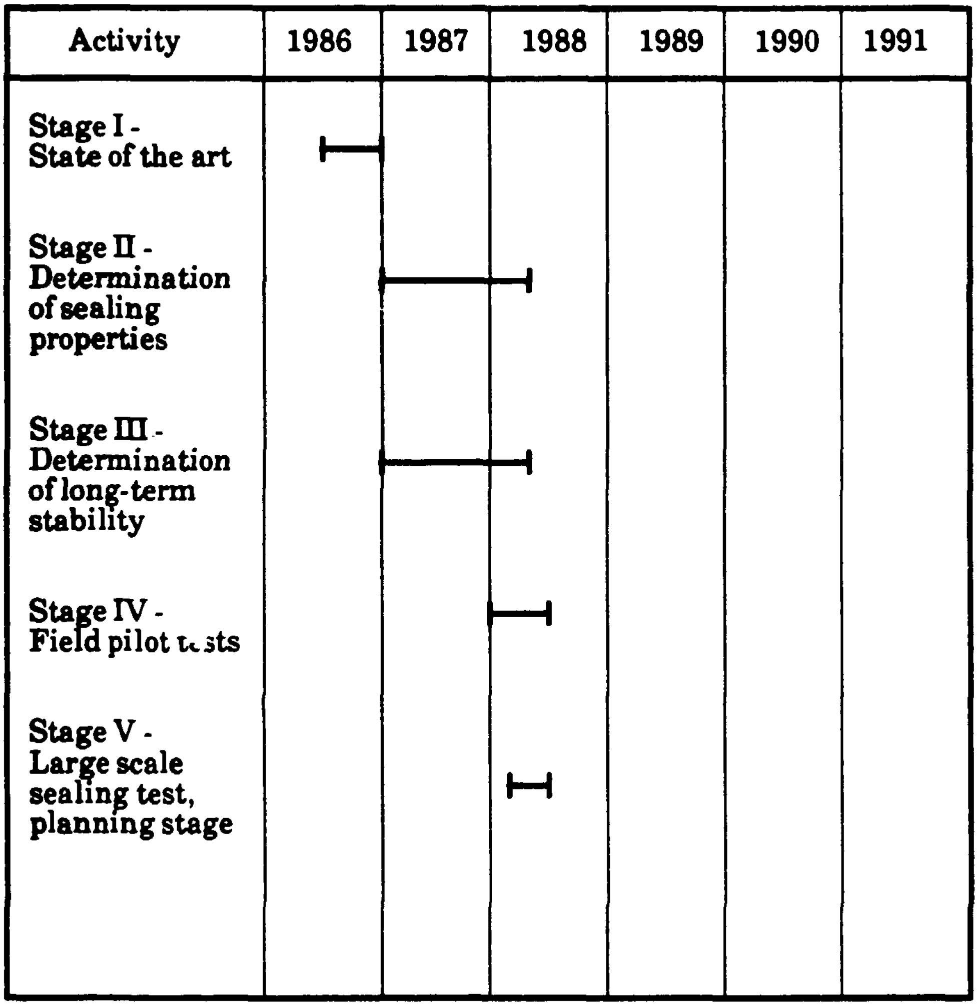

Table 3. Time schedule of proposed, continued work

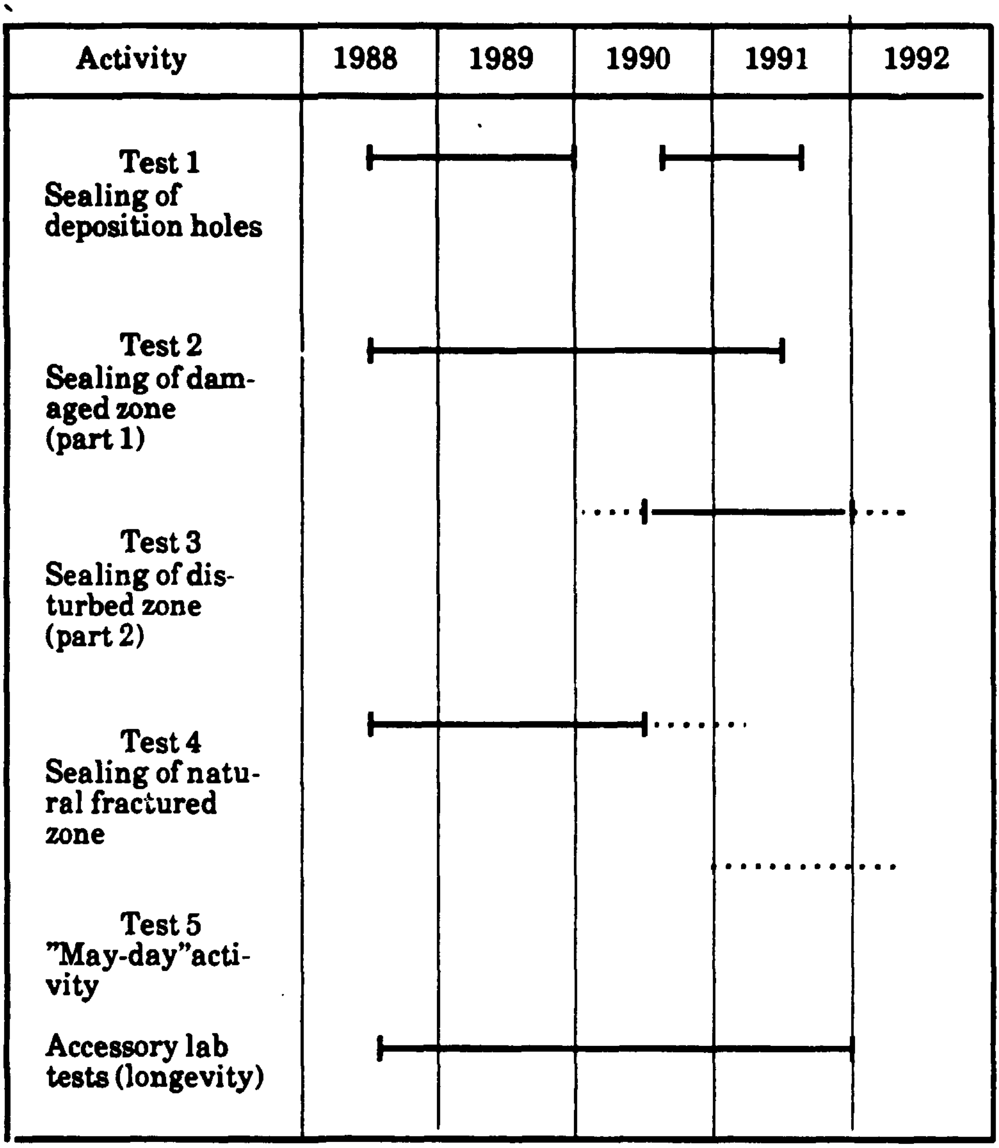

Table 4. Estimated costs of proposed, continued work in MSEK, price level 1988

Activity	1988	1989	1990	1991	Total
Test 1 Sealing of deposition holes	0.4	2.9	1.0	0.5	4.8
Test 2 Sealing of damaged zone (part 1)	0.9	3.0	2.0	1.0	6.9
Test 3 Sealing of disturbed zone (part 2)			0.7	0.8	1.5
Test 4 Sealing of natural/ fractures zone	0.6	2.0	0.8		3.4
Test 5 "May-day" activity	Not	in	budget		
Accessory lab tests, (longevity)	1.5	1.7	1.6	1.6	6.4
TOTAL	3.4	9.6	6.1	3.9	23.0

6 CONCLUSIONS AND RECOMMENDATIONS

The rather systematic work that has been made in the available 1.5 years clearly shows that grout candidates of great potential use have been identified, namely at least one smectitic compound (50 % Na Tixoton bentonite and 50 % finely ground quartz filler), and finely ground cement with silica fume and superplasticizer. Their flow properties have been found to be such that they can be driven into fractures with a hydraulic aperture of down to 10-20 µm by using recent versions of the "Dynamic Injection Device".

It is of particular value that the flow model that has been developed appears to be a useful instrument in predicting the grout distribution in the sealed rock. Thereby, it is possible to define the boundaries of rock volumes through which no percolation of ground water will take place, provided that the sealing properties of the grout are preserved. This latter point, which concerns the physical stability (piping, erodability, expandability) as well as the chemical longevity, has been considered in some detail and a preliminary estimate is that smectite clay will be largely intact, with respect to its general mineral constitution, for hundreds of thousand years at temperatures below 90-100°C ,while the microstructure and thereby certain physical properties may be somewhat changed. Further research is required to find out how and to what extent these changes occur. As to cement, the preliminary conlusions are that the chemical longevity may be largely preserved over several tens or hundreds of thousand years, depending on the percolation rate and groundwater chemistry. "Self-healing" through expansion has been identified in lab experiments, which largely increases the potential usefulness of cement, but further research is required to certify this.

The general conclusion is thus that the goal that was set at the start of the current research work has been reached, and that the basis has been laid for practical, large-scaled applications. These are proposed to have the form of tests in the BMT and 3D areas as described in the preceding text, the intention being to test how the instrument of fracture sealing can be used for cutting and redirecting ground water flow in a repository. The proposed continuation of the longevity study gives good hope of arriving at very long-lived grouts.

Stripa Project – Previously Published Reports

1980

TR 81–01

"Summary of defined programs"

L Carlsson and T Olsson
Geological Survey of Sweden, Uppsala
I Neretnieks
Royal Institute of Technology, Stockholm
R Pusch
University of Luleå
Sweden November 1980

1981

TR 81–02

"Annual Report 1980"

Swedish Nuclear Fuel Supply Co/Division KBS
Stockholm, Sweden 1981

IR 81–03

"Migration in a single fracture Preliminary experiments in Stripa"

Harald Abelin, Ivars Neretnieks
Royal Institute of Technology
Stockholm, Sweden April 1981

IR 81–04

"Equipment for hydraulic testing"

Lars Jacobsson, Henrik Norlander
Ställbergs Grufve AB
Stripa, Sweden July 1981

IR 81–05

Part I "Core-logs of borehole VI down to 505 m"

L Carlsson, V Stejskal
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T Olsson
K-Konsult, Stockholm

Part II "Measurement of Triaxial rock stresses in borehole VI"

L Strindell, M Andersson
Swedish State Power Board, Stockholm
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Swedish Nuclear Fuel Supply Co/Division KBS
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"Buffer Mass Test – Data Acquisition and Data Processing Systems"

B Hagvall
University of Luleå, Sweden August 1982

IR 82–03

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T Olsson
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"Buffer Mass Test – Predicitions of the behaviour of the bentonite-based buffer materials"
L Börgesson
University of Luleå
Sweden August 1982

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"Geochemical and isotope characterization of the Stripa groundwaters – Progress report"
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Tommy Olsson,
Geological Survey of Sweden, Uppsala
John Andrews,
University of Bath, UK
Jean-Charles Fontes,
Université, Paris-Sud, Paris, France
Jean L Michelot,
Université, Paris-Sud, Paris, France
Kirk Nordstrom,
United states Geological Survey, Menlo Park
California, USA
February 1983

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Stockholm, Sweden April 1983

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Sven Knutsson
University of Luleå
Sweden May 1983

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"Buffer Mass Test – Site Documentation"
Roland Pusch
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Jan Nilsson
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Gunnar Ramqvist
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