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TECHNICAL REPORT 87-25

Final Report of the Borehole, Shaft, and Tunnel Sealing Test – Volume I: Borehole plugging

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Der vorliegende Bericht betrifft eine Studie, die für das Stripa-Projekt ausgeführt wurde. Die Autoren haben ihre eigenen Ansichten und Schlussfolgerungen dargestellt.Diese müssen nicht unbedingt mit denjenigen des Auftraggebers übereinstimmen.

Le présent rapport a été préparé pour le projet de Stripa. Les opinions et conclusions présentées sont celles des auteurs et ne correspondent pas nécessairement à ceux du client.

This report concerns a study which was conducted for the Stripa Project. The conclusions and viewpoints presented in the report are those of the authors and do not necessarily coincide with those of the client.

Das Stripa-Projekt ist ein Projekt der Nuklearagentur der OECD. Unter internationaler Beteiligung werden von 1980-86 Forschungsarbeiten in einem unterirdischen Felslabor in Schweden durchgeführt. Diese sollen die Kenntnisse auf folgenden Gebieten erweitern:

- hydrogeologische und geochemische Messungen in Bohrlöchern
- Ausbreitung des Grundwassers und Transport von Radionukliden durch Klüfte im Gestein
- Verhalten von Materialien, welche zur Verfüllung und Versiegelung von Endlagern eingesetzt werden sollen
- Methoden zur zerstörungsfreien Ortung von Störzonen im Fels

Seitens der Schweiz beteiligt sich die Nagra an diesen Untersuchungen. Die technischen Berichte aus dem Stripa-Projekt erscheinen gleichzeitig in der NTB-Serie der Nagra.

The Stripa Project is organised as an autonomous project of the Nuclear Energy Agency of the OECD. In the period from 1980-86, an international cooperative programme of investigations is being carried out in an underground rock laboratory in Sweden. The aim of the work is to improve our knowledge in the following areas:

- hydrogeological and geochemical measurement methods in boreholes
- flow of groundwater and transport of radionuclides in fissured rock
- behaviour of backfilling and sealing materials in a real geological environment
- non-destructive methods for location of disturbed zones in the rock

Switzerland is represented in the Stripa Project by Nagra and the Stripa Project technical reports appear in the Nagra NTB series.

Le projet Stripa est un projet autonome de l'Agence de l'OCDE pour l'Energie Nucléaire. Il s'agit d'un programme de recherche avec participation internationale, qui sera réalisé entre 1980 et 1986 dans un laboratoire souterrain, en Suède. Le but de ces travaux est d'améliorer et d'étendre les connaissances dans les domaines suivants:

- mesures hydrogéologiques et géochimiques dans les puits de forage
- chimie des eaux souterraines à grande profondeur
- écoulement des eaux souterraines et transport des radionucléides dans les roches fracturées
- comportement des matériaux de colmatage et de scellement des dépôt finals
- méthodes de localisation non destructive des zones de perturbation de la roche

La Suisse est représentée dans le projet Stripa par la Cédra. Les rapports techniques du projet Stripa sont publiés dans la série des rapports techniques de la Cédra (NTB).

ABSTRACT

The Borehole Plugging Experiment comprised field tests of the sealing function and the practicality in handling and application of plugs consisting of segments of perforated metal casings filled with cylindrical blocks of highly compacted sodium bentonite. Preparative tests had shown that the clay swells out through the perforation and embeds the casings. The field tests demonstrated that even very long holes can be effectively sealed by such plugs and that the clay becomes very homogeneous and forms a tight contact with the rock in a relatively short time. By that the plugs become practically impervious and the flow along the clay/rock contact will be insignificant. The longevity of such plugs extends over several thousand years under the conditions that usually prevail in crystalline rock.

RESUME

Le projet d'obturation de trous de forage a consisté en des essais in situ des qualités d'étanchement ainsi que l'étude des aspects pratiques de manutention et mise en place de bouchons constitués de segments de tubes en métal perforé remplis de blocs cylindriques de bentonite au sodium fortement compactée. Des essais préparatoires avaient montré que l'argile en se gonflant traversait les perforations et ancrait de la sorte les tubes. Les essais in situ ont démontré que même de très longs forages pouvaient être effectivement obturés par de tels bouchons et que l'argile crée en un temps relativement court un contact très homogène et étanche avec la roche. Le bouchon devient ainsi pratiquement impermeable et les infiltrations par le contact argile/roche seront négligeables. La longévité de tels bouchons s'étend sur plusieurs millénaires dans les conditions prévalant ordinairement dans les roches cristallines.

ZUSAMMENFASSUNG

Das Bohrloch-Versiegelungs-Experiment umfasste Feldversuche bezüglich der Abdichtungs-Eigenschaften und der Handhabbarkeit bei der Anwendung von Bentonit-Zapfen; diese Zapfen bestehen aus perforierten Metallverrohrungen, welche mit hochverdichtetem Na-Bentonit gefüllt sind. Vorversuche hatten gezeigt, dass der Ton durch die Perforation herausquillt und die Verrohrungen umhüllt. Die Feldversuche zeigten, dass auch lange Bohrlöcher mit solchen Bentonit-Zapfen wirkungsvoll abgedichtet werden können. Dabei wird der Ton sehr homogen und bildet beim Uebergang zum Gestein schon nach relativ kurzer Zeit einen dichten Kontakt. Dadurch werden die Zapfen praktisch undurchlässig und der Fluss entlang der Bentonit/Gesteins-Kontaktfläche ist vernachlässigbar. Unter Bedingungen, wie sie normalerweise in kristallinen Gesteinen herrschen, wird eine Lebensdauer solcher Bentonit-Zapfen von mehr als einigen tausend Jahren erwartet.

CONTENTS

SUMMARY

The Borehole Plugging Experiment comprised three field tests of plugs with highly compacted sodium bentonite as sealing component. The function and practicality in handling and application of such plugs were tested under real conditions, the design principle being that cylindrical blocks of compacted clay powder were contained in perforated casings of copper. After insertion in the boreholes, which were water-filled from the start, the clay was expected to absorb water and swell out through the perforation. Laboratory tests and pilot field tests had indicated that the expansion of the clay leads to complete embedding of the casing if the access to water is sufficient. The main purpose of the field tests was to investigate the rate and uniformity of the water uptake.

The plugging of a 100 m long, 56 mm diameter, almost horizontal borehole demonstrated the practicality of this plugging technique also for very long holes and this test also showed that the maturation of the plugs was sufficiently fast to resist piping or distortion by high hydraulic gradients already after about one week. The uniformity of the water content of a recovered section was determined after about 2.5 years and it was found to be very high. The clay was completely water saturated despite the large variation in fracture frequency of the rock, which indicates that water had passed through frequent fine fissures in the adjacent rock, leading to uniform uptake over the entire clay/rock interface.

The same observation was made in the testing of two 14 m long 76 mm diameter holes with plugs that were equipped with soil pressure and pore pressure cells for recording the successive build-up of internal pressures. The latter two plugs, which had different porosities of their casings, were extruded from their holes at the end of the tests for determination of the bond strength. The required force to extrude each of the 4 m long plugs was 8-10 tons, corresponding to a bond strength of about 100 kPa. Expressing this shear resistance as the product of the swelling pressure and the angle of wall friction, the latter turns out to be about 10°. The last-mentioned plugs had matured for slightly less than one year.

1 SCOPE AND PLANNING OF TESTS

1.1 INTRODUCTION

Although considerable information on rock structure and composition can be gained through ground surface geophysical investigations in the search for suitable sites for nuclear waste repositories on land, boreholes for core examination and in situ logging have to be made as well. Some of the tunnels or excavations intended for the waste storage in such an area are likely to truncate an unknown number of the holes, which thereby form short circuits between the waste packages and the biosphere. It is therefore required to seal off all boreholes drilled as part of such site investigations.

Effective sealing of boreholes and shafts below the ground water level requires a tight contact between the plug and the rock, so that no passages are created along this boundary. An additional criterion is that the plug must not be more permeable than the rock core which it replaces. These requirements imply that high density, ductile consistency, and swelling ability must be preserved for very long periods of time, which suggests the use of dense smectite-rich clays for plugging purposes. They seem to be chemically stable for geological ages in the pH range and ground water environment which are characteristic of granite and gneiss bedrock, provided that the temperature is lower than 100°C - 150°C.

The sealing properties of sodiumsaturated dense bentonites, i.e. smectite-rich natural clays, are excellent in the sense that their permeability and diffusivity are very low. The permeability coefficient is approximately 10^{-14} m/s when the bulk density is 2.0 t/m^3, while the corresponding values are about 5×10^{-13} m/s for 1.8 t/m^3, and 10^{-12} m/s for 1.7 t/m^3. The diffusion coefficient for the most important ion species is only a small fraction of that for diffusion in free water.

Bentonite in the form of Na Wyoming "Volclay MX-80" was used for the Stripa sealing tests. The mineral composition and basic properties of this commercial bentonite is fully described in earlier Stripa Project reports (1) to which the reader is referred.

1.2 THE PLUGGING OPERATION AND FUNCTION OF THE APPLIED PLUG

The main principle of the technique that was investigated in Stripa is to insert the compacted bentonite while contained in a casing (2). It consists of segments which are connected at the rock surface and successively lowered or pushed into the hole until the tip of the plug reaches the end of the hole. The segments are filled with closely fitting, cylindrical blocks of highly compacted bentonite before insertion and they are richly perforated to let the clay expand through the perforation of the casing, which is left in the hole. Preliminary considerations suggest that the perforation should cover about 50% of the surface of the casing, the ends of which must be closed.

The clay blocks must occupy a large part of the hole, i.e. the slot between the rock and the casing and between the casing and the clay, must be narrow in order to yield a sufficiently high final density. This is required in order to reach a low permeability and to obtain a sufficient bearing capacity so that the clay column does not consolidate under its own weight. This can happen if the swelling pressure is lower than the effective vertical pressure and a rough estimation suggests that water saturated, homogeneous bentonite with an average bulk density of 1.7-1.8 t/m^3 or more will form a mechanically stable clay column in boreholes with a length of several hundred meters. Initial inhomogeneities or density variations, which may appear in the course of the swelling, tend to be evened out by the strong self-healing ability of the bentonite. No centering of the pipe in the hole is required since the clay will expand and fill up any slot, practically regardless of its width.

The major components of the technical system are shown schematically in Fig 1-1. All metal components are preferably copper, which is chemically very stable in this environment, but the use of other metals should be possible as well provided that chemical reactions (ion exchange, etc) will not cause clay mineral transformations or brittleness. Fig 1-2 serves as an illustration of how the swelling potential of the clay is utilized.

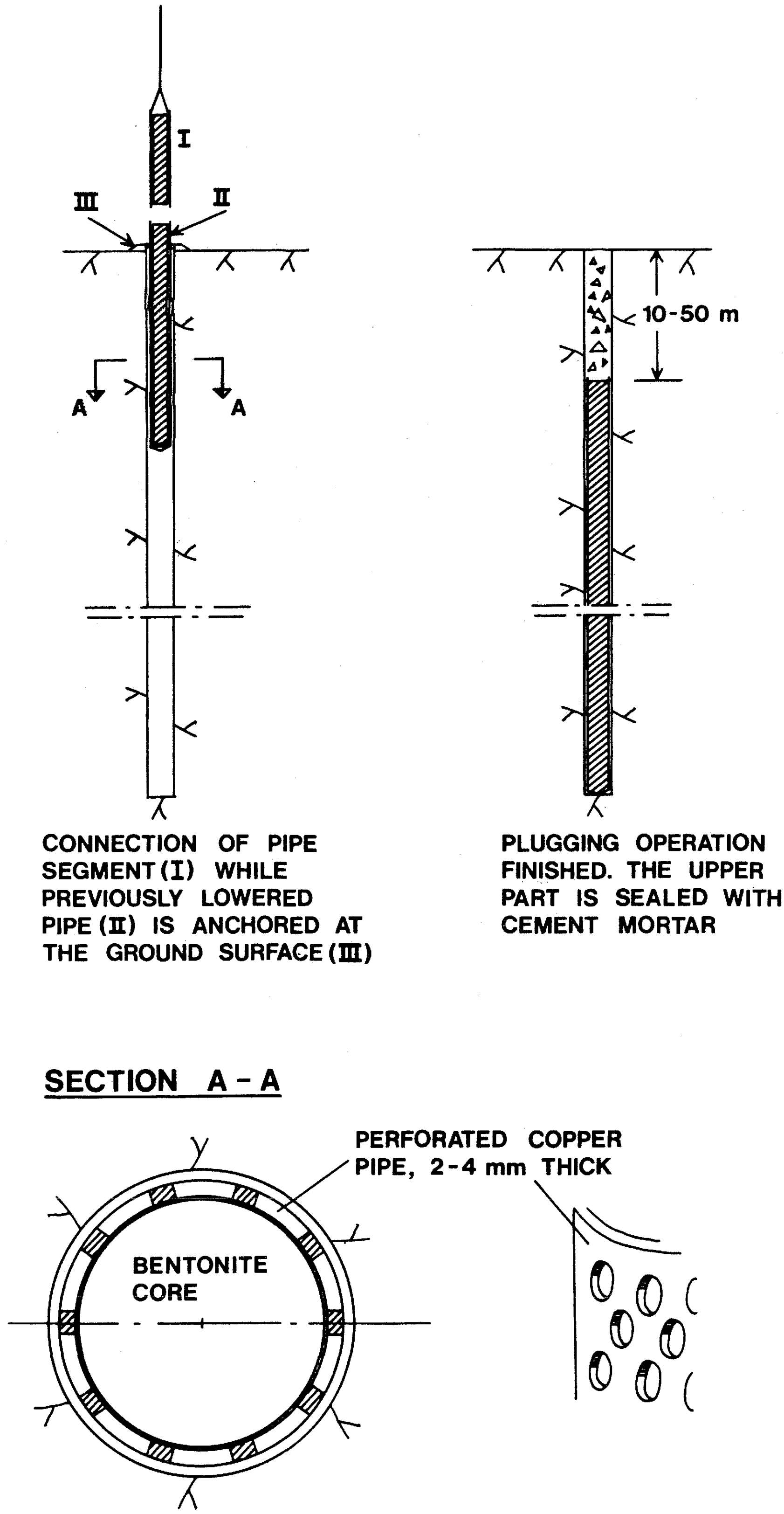


Figure 1-1. Schematic picture of components and technique of the investigated sealing method

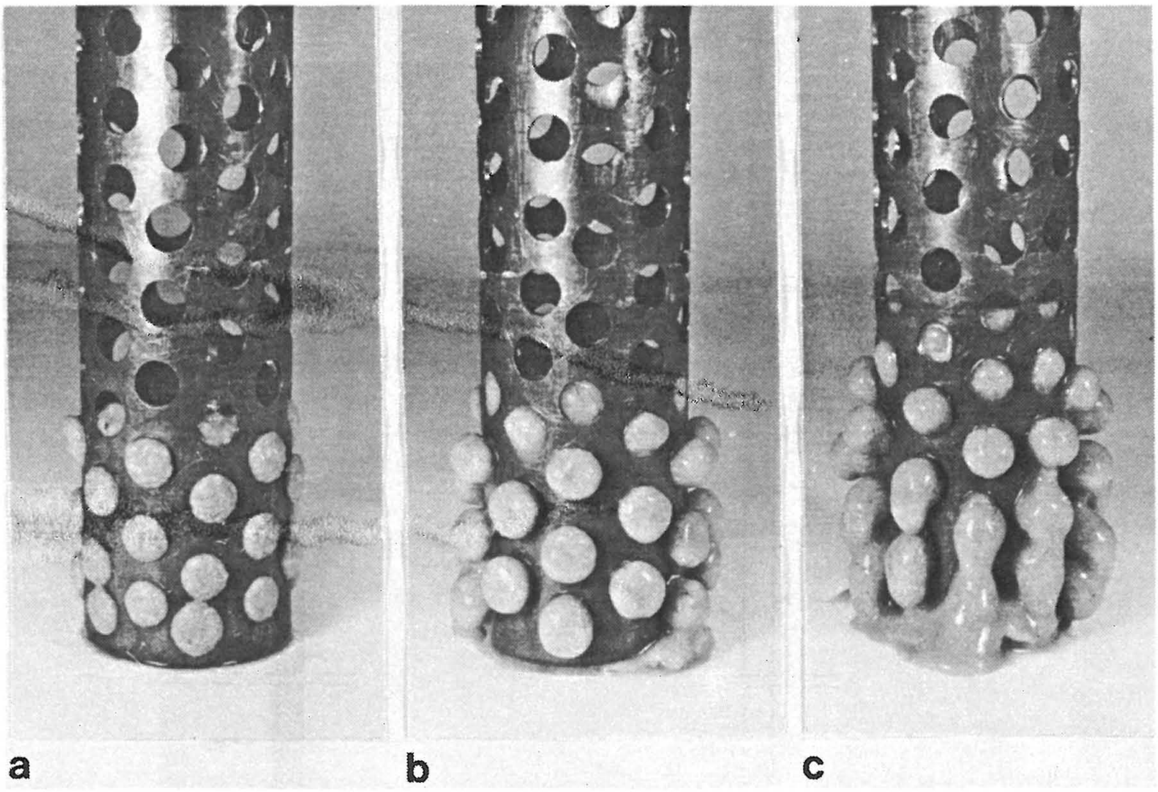


Figure 1-2. Swelling of highly compacted Na bentonite through the holes of the perforated casing. a) appearance after submerging the plug in water for 1 hour, b) 8 hours, c) 24 hours

The dense blocks can be produced by compacting granulated Na bentonite powder under high pressure. The bulk density of such blocks has been found to be in the interval 2.00-2.15 t/m^3 if the compaction pressure is 50-120 MPa. The water content of the powder and therefore of the manufactured blocks depends on the humidity of the atmosphere. It is usually on the order of 10 % which corresponds to about 50-60% degree of water saturation of the dense blocks. The high affinity of the bentonite to water means that the blocks take up additional water from the rock by which they swell to fill up the boreholes and finally become saturated. The casing is left in the hole and will be embedded in the clay, which ultimately becomes homogeneous.

1.3 SCOPE OF TESTING

Although various laboratory tests and some field experiments (3) have verified that Na bentonite should be very suitable for borehole plugging except, possibly, for use in heavily fractured rock and very saline groundwater, a number of questions remained to be answered and called for full scale field testing. The major questions were:

- Is it possible to seal long horizontal boreholes or boreholes extending upwards by use of the intended technique?
- Is the rate of maturation of the plugs sufficient to resist high hydraulic gradients in the axial direction of the borehole soon after the plugging operation without producing piping or displacement of the plug?
- What is the general relationship between the rate of maturation and the structure and distribution of water-bearing fractures in the rock?
- Are there advantages in using casings with a high perforation ratio?

These questions made it suitable to separate the borehole sealing test into three different experiments with the following main features:

I The DbH2 plugging test

The main purpose was to test if a clay plug could be inserted in a 100 m long almost horizontal, Ø56 mm diameter borehole and to determine the rate of maturation by measuring the required hydraulic gradient to produce piping at various periods of time after the application of the plug.

IIa Test of the standard plugging technique in Ø76 mm borehole

This test involved insertion of a 4 m long clay plug in a 14 m long Ø76 mm diameter borehole. The plug was equipped with pressure transducers to measure the total and effective pressures in the course of the maturation process. Water overpressure was initially applied at the upper, and later at the lower end, to determine the critical pressure at which piping occurred. At a late stage the bond strength was determined by applying an axial force that extruded the plug.

IIb Test of plug with highly porous casing in Ø76 mm borehole

The perforated casing of the standard plug was replaced by a highly porous metal net in a test which was otherwise identical to the IIa test. The aim was to investigate whether the higher porosity of the casing would yield a significant increase in maturation rate.

2 THE DbH2 PLUGGING TEST

2.1 PURPOSE

The DbH2 test was planned to comprise plugging of an almost 100 m long slightly inclined borehole with a diameter of 56 mm, and to determine the maturation rate of the bentonite by exposing different parts of the plug to high hydraulic gradients at different periods of time after the application of the plug. Also, excavation of the rock was planned so that part of the plug could be recovered at a late stage of the test for inspection and investigation of the clay.

2.2 LOCATION

The DbH2 borehole was drilled in conjunction with the "Macropermeability" test that was conducted by the Lawrence Berkeley Laboratory (LBL). It was initially about 100 m long but had been shortened to 96.6 m by blasting of the rock prior to the present experiment. The hole runs close to and almost parallel to the Buffer Mass Test drift, the location and orientation of the hole being shown in Fig 2-1. This figure demonstrates that the distance from the drift is only about 1-1.5 m and that the hole is slightly curved. The exit of the hole is close to the computer center on the 337 m level, the coordinates being x=340.29, y=980.17, and z=335.80.

2.3 ROCK CONDITIONS

2.3.1 General

The core from the drilling operation was carefully mapped by the Swedish Geological Survey with special respect to the location of fractures and mineralogy of the rock. The interval 25-35 m from the outer end of the hole, which corresponds to the part of the plugged hole where measurements of the maturation rate were made, was found to contain zones of richly fractured rock of natural origin (Fig 2-2).

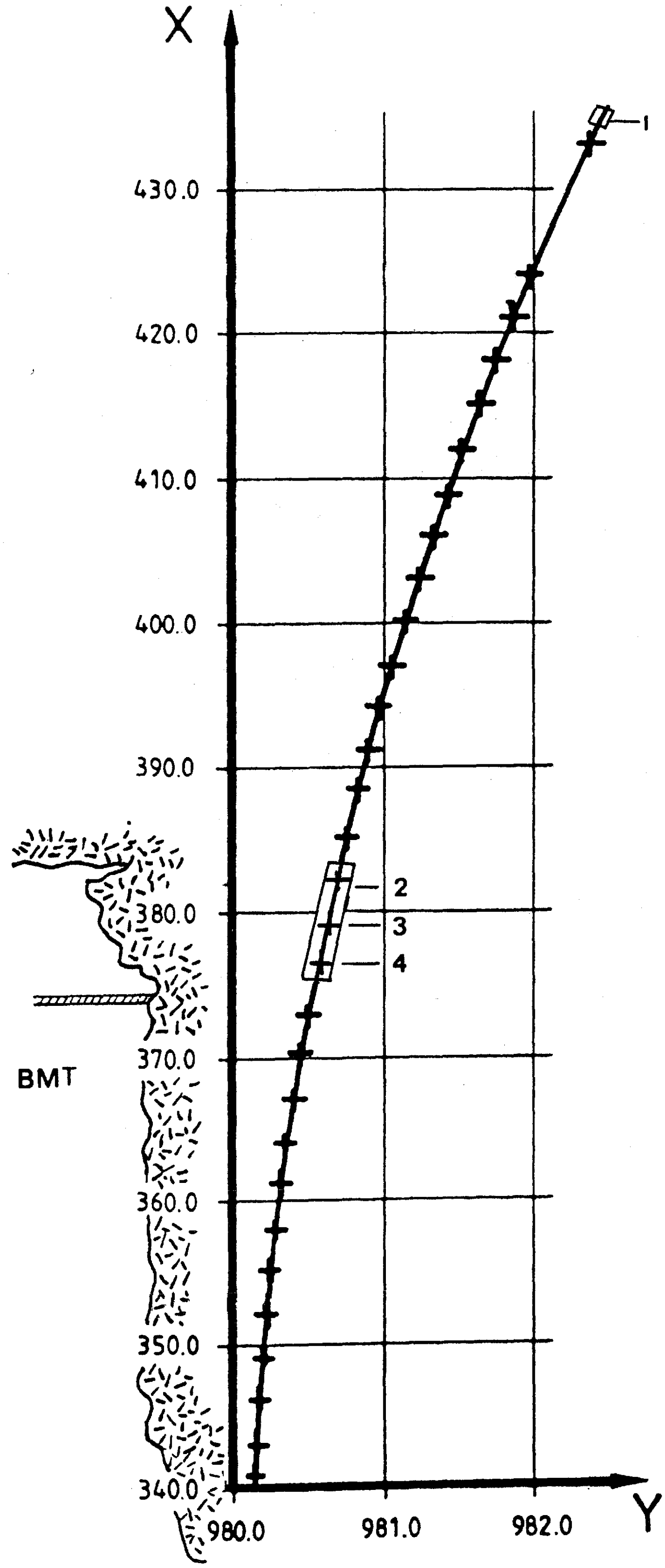


Figure 2-1. Shape and location of the Ø 56 mm borehole DbH2

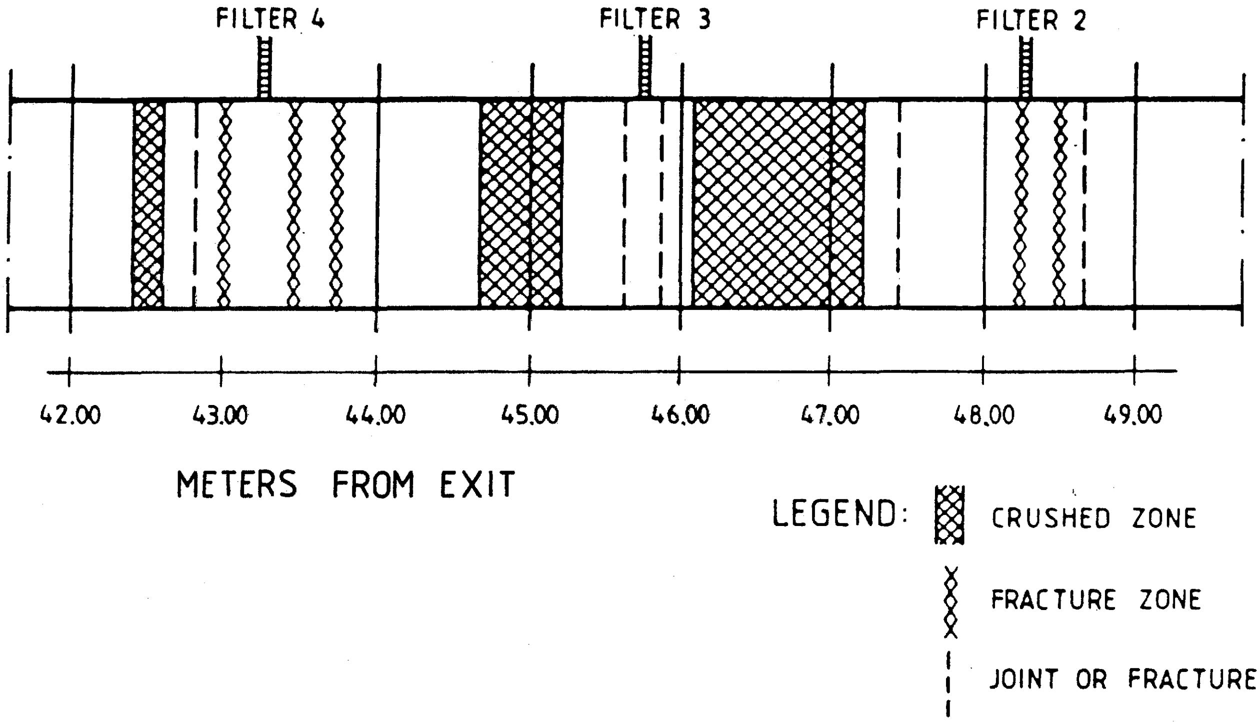


Figure 2-2. Generalized picture of joints and fractures in the 5 m test section of DbH2

The rock matrix is of the same type as that of the BMT area, i.e. a medium-grained, massive grey/reddish granite with a grain size typically varying between 1 and 5 mm. Chemical analyses of reddish and grey granite in the DbH2 area made by LBL have shown the main minerals to be quartz (35-44 %), partly sericitized plagioclase (35-39 %), microcline (12-24 %), subordinate components being chlorite, muscovite, biotite and epidote. SiO_2 typically varies between 74.0 and 75.3 %, while Al_2O_3 and K_2O represent 12.1-13.5 % and 4.5-4.8 %, respectively. Fe_2O_3 and CaO are in the range of 1.0-1.8 % and 0.4-0.7 %, while MgO represents 0.18-0.22 %.

2.3.2 Rock stresses

The rock stress conditions as concluded from nearby stress measurements (1) are characterized by a major principal stress of about 20 MPa oriented horizontally and almost perpendicularly to the BMT drift and a minor, almost vertically oriented principal stress of about 4 MPa. This is expected to yield very low tangential stresses in the walls of the drift, which in turn suggests that the DbH2 hole is located in a relatively stress-free environment.

2.3.3 Hydraulic conditions

As to the gross hydraulic conductivity of the rock mass, the LBL study had shown that it ranged between 10^{-12} to about 10^{-10} m/s, while laboratory tests of apparently fracture-free rock material have yielded values on the order of $5x10^{-13}$ m/s. The conductivity of the rock that is traversed by the borehole is of course determined by the water-bearing capacity of individual fractures and by the local hydraulic gradients. It is concluded from the LBL test and from the BMT study that the piezometric head drops rapidly from about 1-1.5 MPa at a distance of 3-5 m from the drift periphery to about 100-300 kPa at 1 meter distance from the periphery. This suggests that the water pressure in fractures intersecting DbH2 should be about 100-500 kPa close to the inserted clay plug.

2.3.4 Groundwater chemistry

The composition of the non-saline groundwater in Stripa is summarized in Table 2-1. The data are based on various tests by LBL and by the Geological Survey of Sweden. It should be noticed that pH is in a range which does not affect the chemical stability of phyllosilicate minerals of the smectite type. Also, we see that Na and Cl are the major cation and anion, respectively, in the test area.

Table 2-1. Chemical analyses of Stripa groundwater. Sample no 6 represents water from the DbH2 hole

Analysis ppm	Water sample 1	2	3	4	5	6	7
pH (field)	6.7	6.5	7.3	7.0	8.7	9.1	8.9
Ca			21	24	14	19	17
Mg			5.7	4.7	0.3	0.5	0.3
Na			4.0	4.5	51	37	61
K			2.0	1.0	0.2	0.4	0.2
Cl			1.5	4.0	49	44	85
SO_4			2.0	10.0	1.4	2.4	2.4
HCO_3	1	5	93	82	73	79	52
SiO_2			13.6	9.9	12.0	12.0	12.1
Fe					0.06		
NO_2					0.01		
No_3					0.12		
PO_4					0.01		
NH_4					0.14		

2.4 TEST ARRANGEMENT AND PROGRAM

The general idea was to apply the plug in one sequence to fill the inner 87 m length of the borehole and immediately seal the outer 10 meters by injecting cement mortar so that the rate of maturation could be tested not more than a few days hereafter. This testing was planned to be made by use of 3 filters embedded in the clay and located as shown in Fig 2-3. A fourth filter, termed number 1, was located at the inner tip of the plug.

The test program comprised injection of water at an early stage in Filter 2 while measuring pressure reactions in Filter 3, and to repeat this procedure by injecting water in Filter 4 at a later stage to get information of the maturation rate. Repeated tests after various periods of time were planned in order to determine how effectively the clay self-healed.

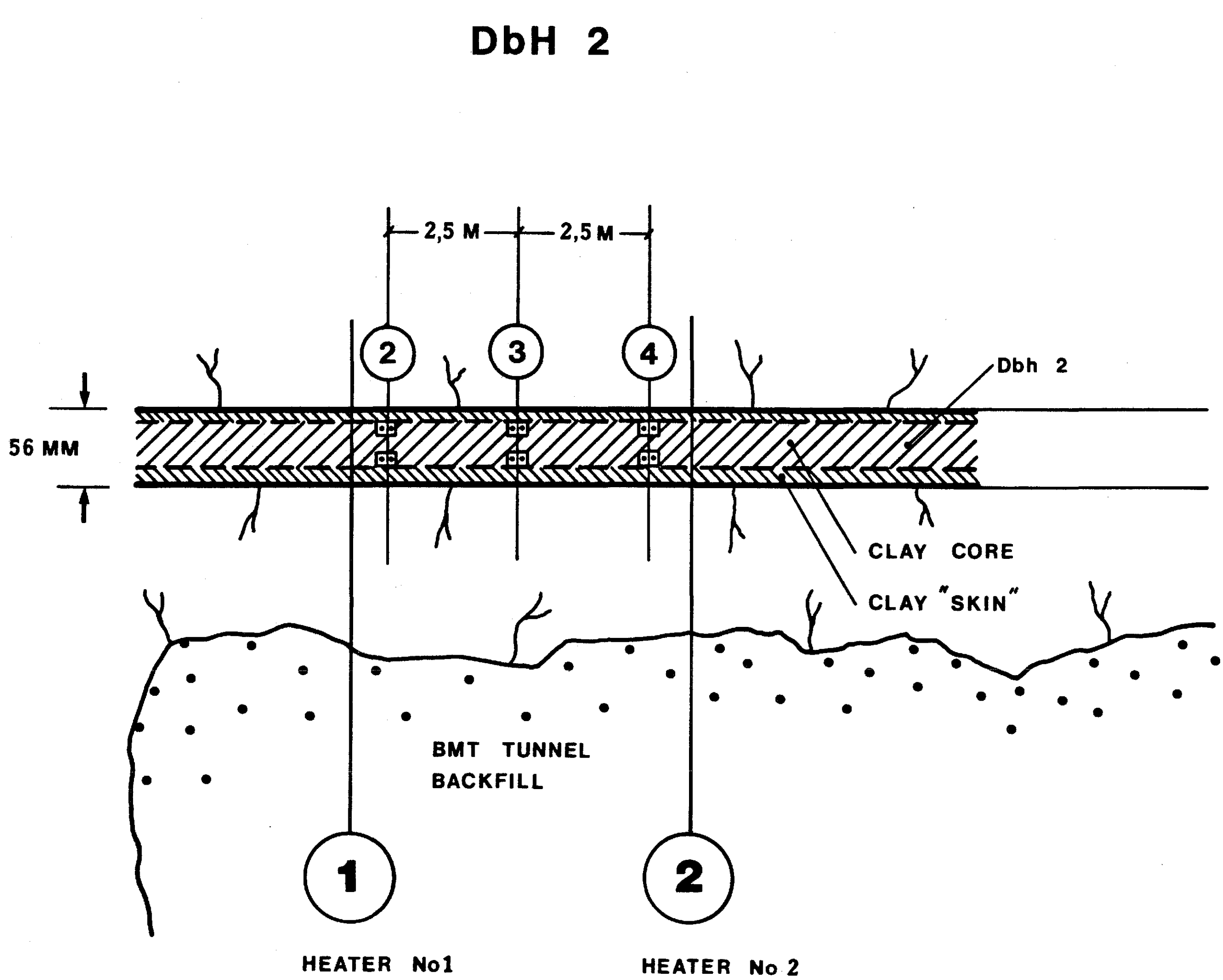


Figure 2-3. Filter arrangement in the DbH2 test. Filter no 1 is located at the inner end of the hole, i.e. about 52 m from Filter no 2 (cf. Fig 2-1)

2.5 PLUG DESIGN

2.5.1 General

While a clay plug for practical use simply consists of a series of interconnected perforated casings filled with cylindrical blocks of highly compacted bentonite, the design of the DbH2 plug had to be made so that filters and tubings could be installed in the clay. This called for rather short segments and a central pipe for the tubings, which made the application of the plug rather complicated and time-consuming.

2.5.2 Dimensions

The small diameter of the borehole and the significant space occupied by the central pipe hosting tubings for applying and measuring water pressures in the filters required a rather thin and large diameter casing in order to obtain a reasonably high density of the clay after expansion. Still, the diameter of the casing had to be selected so that it could be inserted without difficulties.

The perforated casing consisted of 39 2.5 m long copper segments with 54 mm outer diameter and 50 mm inner diameter. The perforation, covering about 50 % of the surface, was made by drilling Ø 11 mm holes. The segments were connected at their ends as shown in Fig 2-4, the jointing operation being made in the course of the application of the plug.

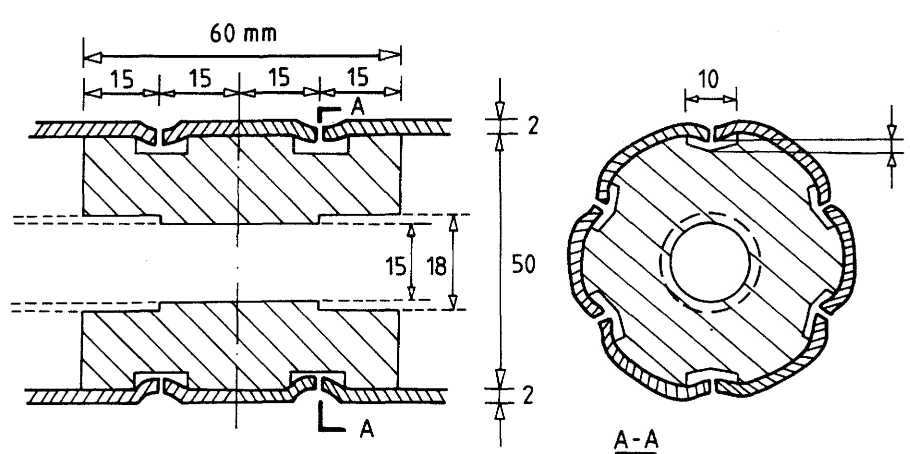
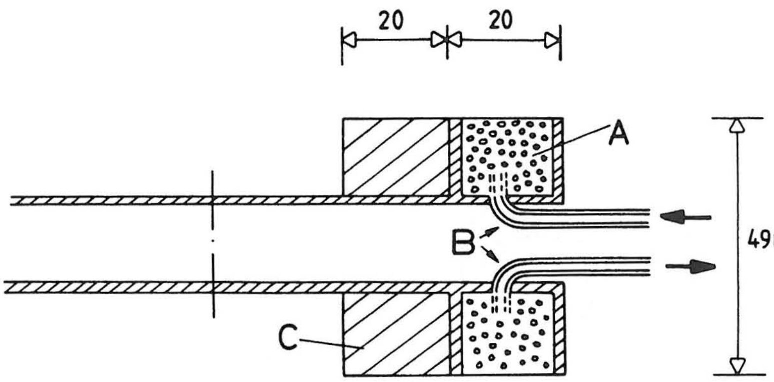


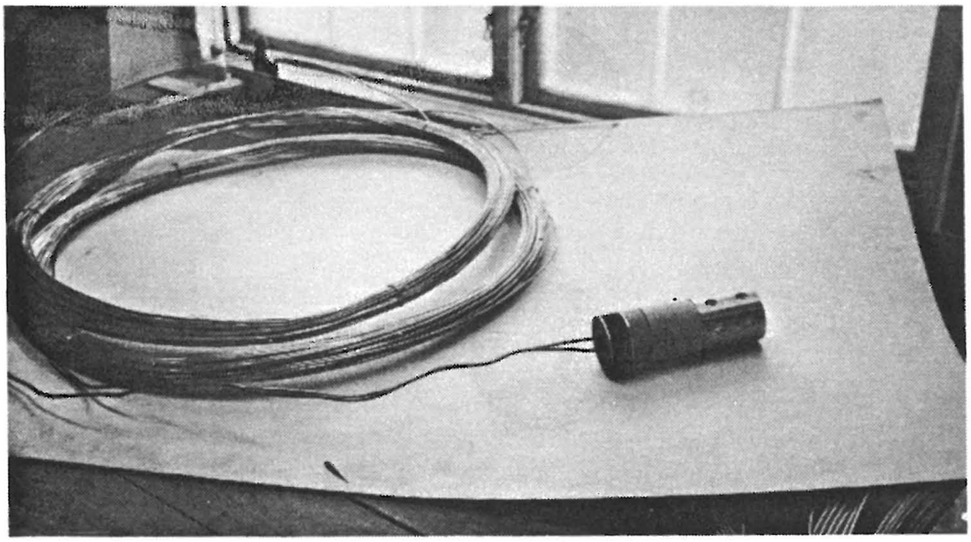
Figure 2-4. Connection of casing segments to inner jointing sleeve of copper

The clay blocks, which were produced by compacting Volclay MX-80 bentonite powder with an initial water content of 11 % to a bulk density of 2.11 t/m^3, had an outer diameter of 48.7 mm. They were given annular shape, the inner diameter being 18.3 mm, to host a central pipe through which tubings from the filters passed to the outer end of the hole where they were connected to a system for injecting water and measuring water pressures. The compaction pressure to obtain the required density of the blocks was 120 MPa. The theoretical net density after complete homogenization was estimated at 1.9 t/m^3, corresponding to a water content of about 32%.

The filters, which also had an annular form (Fig 2-5), were prefabricated by use of epoxy-stabilized sand. Two copper tubings per filter with Ø 3.2 mm outer diameter were cast in the filters to permit saturation, drainage and pressurizing of the filters in the respective testing phase.

Typical sections through the clay plug are shown in Fig 2-6, while Fig 2-7 illustrates the general arrangement of filters and tubings. The arrangement for injection, de-airing (saturation) and pressure recording was designed by Jeff Irvine, former LBL Staff member. It is shown schematically in Fig 2-8.





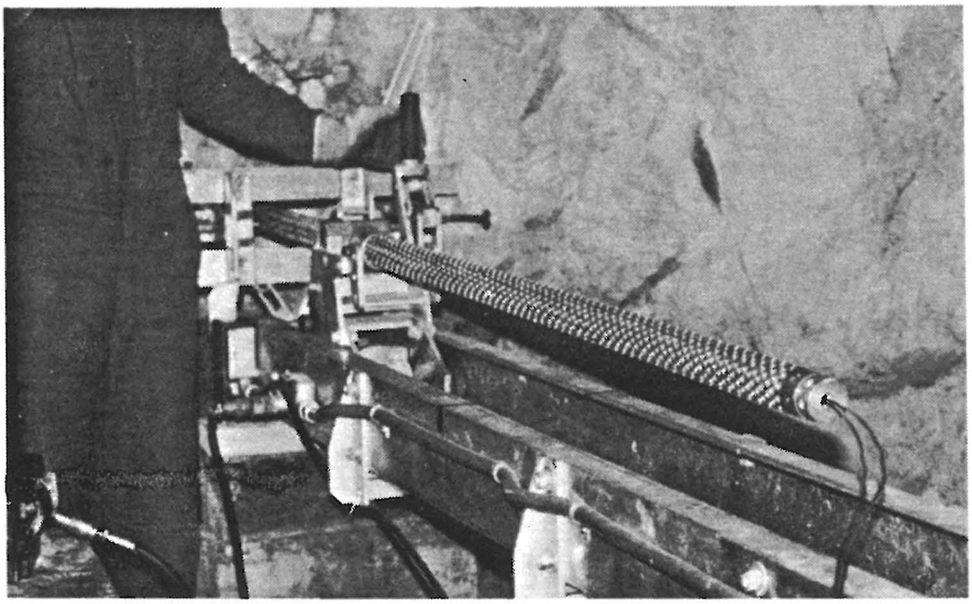


Figure 2-5. Upper picture: Longitudinal section through filter. Central picture: Assembly of filter with tubings (left), plastic ring, bentonite block and jointing sleeve. Lower picture: First segment being jacked into the borehole. Notice the copper tubings extending through the outer end

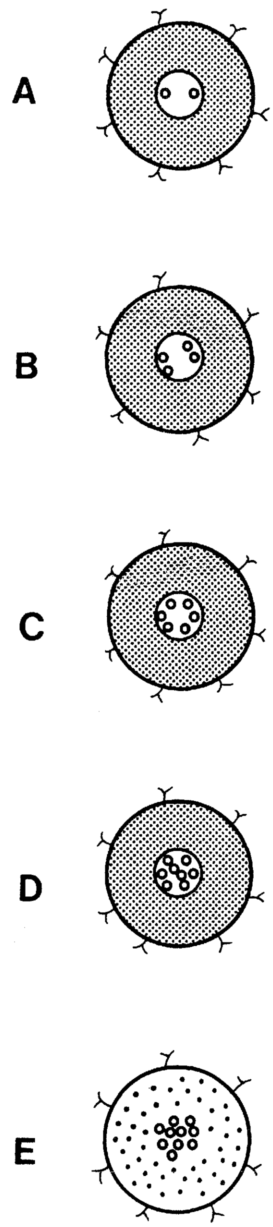


Figure 2-6. Cross section through the clay plug. A between Filters 1 and 2, B between Filters 2 and 3, C between Filters 3 and 4, D outside Filter 4, E cement-grouted part with two extra tubings to make drainage of the central pipe possible

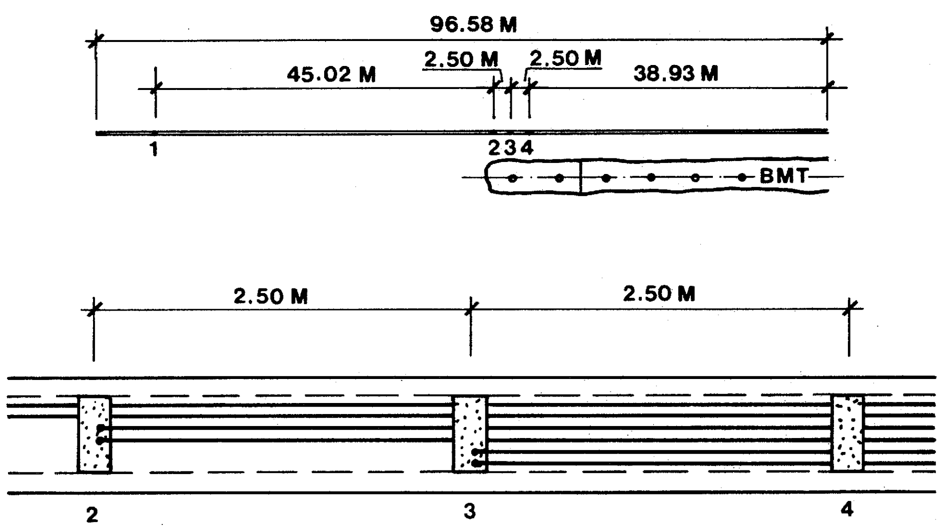
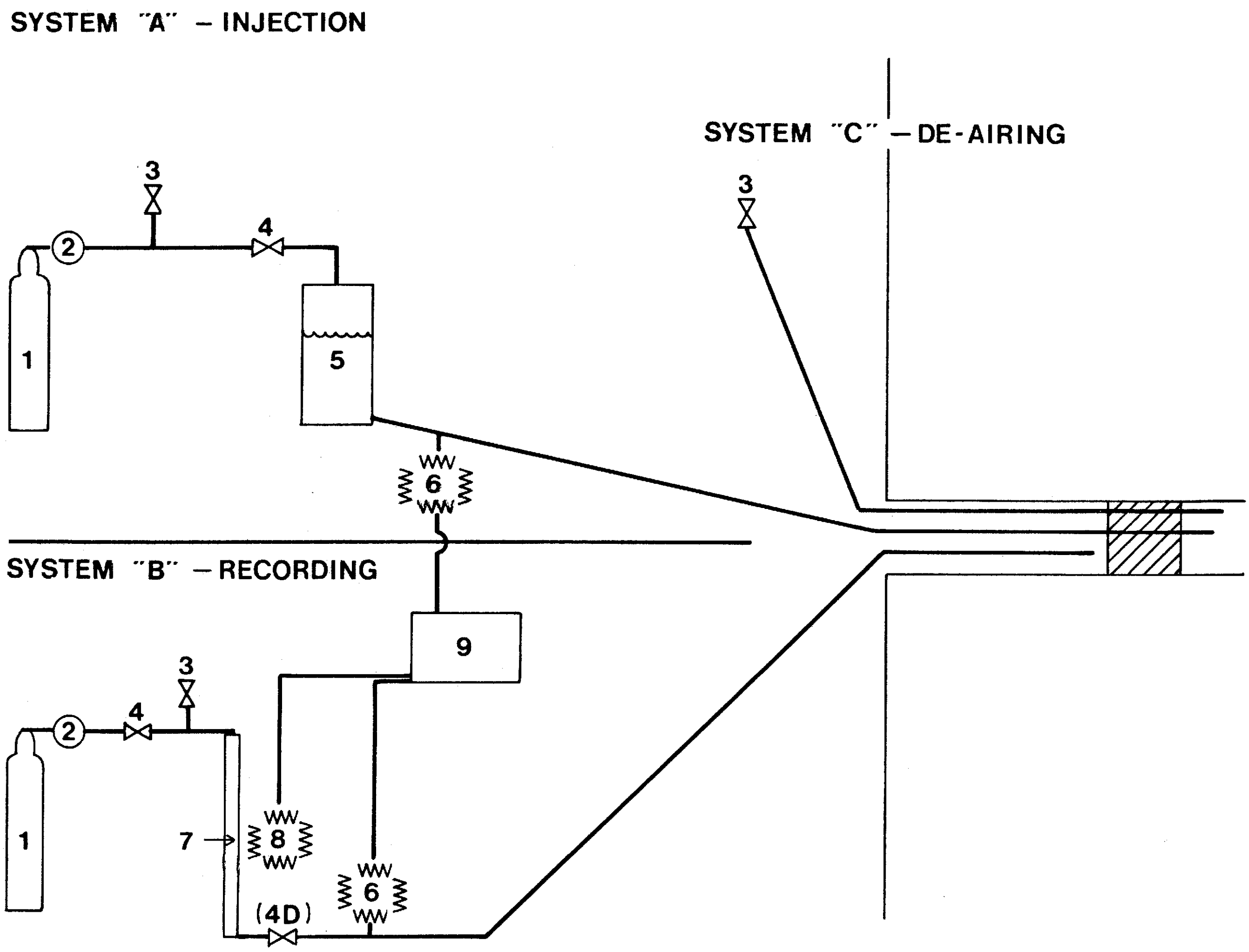


Figure 2-7. Schematic picture of the arrangement of filters and tubings



1 Nitrogen gas
2 Regulation device
3 "Bleed" valve
4 Stopcock
5 Pressure vessel (infiltration tube)
6 Transducer
7 Water head
8 Differential transducer
9 Plotter

Figure 2-8. Arrangement for injection and flow measurement, de-airing, and pressure recording

2.6 RESULTS

2.6.1 Installation

The casings and the clay blocks had been prepared in advance at the University of Luleå, while filling the segments with blocks and application of filters in them were made in Stripa (Fig 2-9). The successively lengthened series of interconnected plug segments was pushed into the hole by use of a 10 kN hydraulic jack, the total time required to bring in the entire plug being about 2.5 hours. This relatively slow procedure was mainly due to the difficulties that arose at late stages when the friction between the bunch of copper tubings and the inner pipe became significant. The corresponding time if no instrumentation had been contained in the plug was estimated at less than one hour.

The outer 4 segments were dummies that were not connected to the rest of the plug, and they were removed so that only the tubings from the filters extended from the hole. The outer 10 m length of the hole was then cement-grouted by Stabilator AB (cf. Fig 2-6). All the tubings were left open to let air out and allow for saturation of the filters. The application and grouting operations were finished on June 7, 1983.

It is concluded from the installation that a few hundred meter long, horizontal or slightly inclined boreholes can be plugged by the technique applied in the Stripa test. Vertical holes that can be plugged from above may be as long as 1 kilometer or more before practical problems arise. Vertical or steeply inclined holes extending upwards from tunnels may offer difficulties at considerably shorter lengths than that.

2.6.2 Determination of the maturation rate

Two days after the grouting water appeared in all the tubings and they were then connected to the injection/recording system for reading the natural water pressures that were expected to be built up in the filters. The pressure quickly rose to 1200 kPa in Filter 1 at the inner end of the plug and to 200 kPa in Filter 4, while no pressure was recorded in Filters 2 and 3. These were still the conditions on June 15 when the first injection test took place. The fact that the natural high water pressures could be resisted by the clay plug so soon after the closure of the drainage, shows that considerable maturation had taken place very rapidly, in certain zones at least. The absence of water pressures in the centrally located filters showed, however, that they were still not saturated.

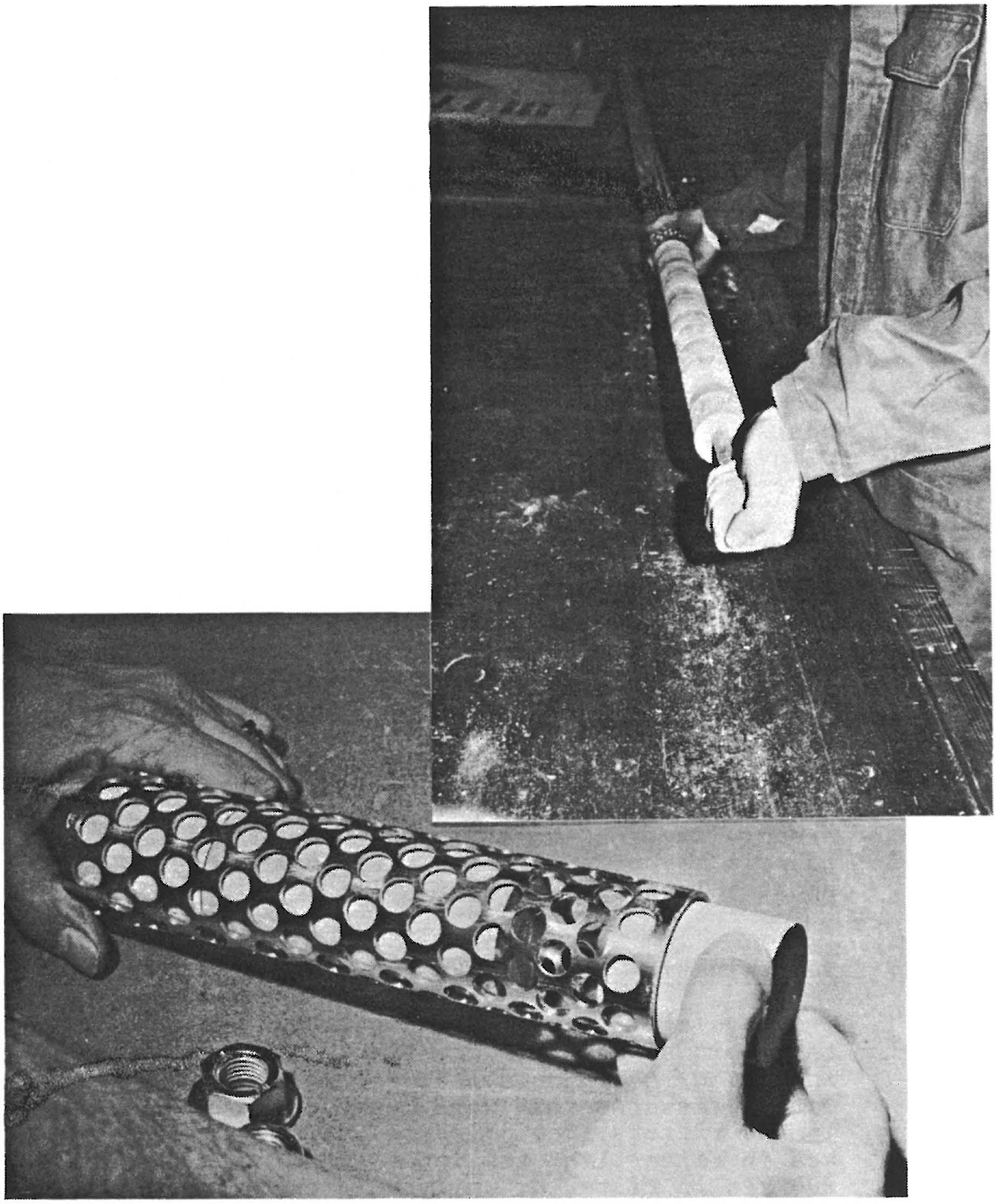


Figure 2-9. Mounting of clay blocks in casing with central pipe for the filter tubings

First injection

Filter 2 was pressurized in 30 kPa steps up to 800 kPa, each lasting for one minute. The pressure steps were then increased to 100 kPa, each with a duration of 2 minutes. When the pressure was raised to 1400 kPa, critical conditions appeared and a sudden inflow of a few milliliters took place with a simultaneous pressure drop to about 800 kPa. The operator then immediately released the pressure by shutting the valve of the injection tube.

The inflow was not associated with any pressure increase in or outflow through Filter 3 thus showing that piping or clay displacement had obviously only been local. It was suspected that the observed pressure drop could have been caused by "hydraulic fracturing" of the rock, and to find out what really caused it, the pressure was raised again in 100 kPa steps. The idea was that if a fracture had been opened in the rock by the 1400 kPa pressure, then a reopening would require approximately the same pressure. The repeated injection actually gave a renewed inflow at a pressure which was slightly lower than 800 kPa with a subsequent drop to about 600 kPa, but the pressure quickly rose again and could be increased to 2000 kPa without further inflow. About 30 minutes after applying this pressure, which was the maximum recording capacity, the pressure began to rise in the outflow filter. It reached a value of about 100 kPa and then tended to drop somewhat during the 3 hour long injection period. These observations gave the conclusion that piping or clay displacement had occurred while hydraulic fracturing of the rock had not taken place.

The following scenario at the first injection is most probable:

Immediately after the insertion of the plug, clay material began to expand through the perforation of the casing and formed stiff "columns" with a rather irregular soft and initially non-saturated clay gel in between. This process, which is familiar from pilot tests, is illustrated in Fig 2-10. The heterogeneous and non-saturated clay mass could resist a water pressure up to about 1400 kPa when the injection started, but at higher pressures the clay was instantaneously compressed close to the inflow filter by which air pockets were closed. The renewed pressure increase extended the compression over a larger part of the 2.5 m distance between the filters, and a continuous water passage was ultimately formed that transferred water to Filter 3 (Fig 2-11). The injected water was absorbed by the confining, non-saturated clay which sucked up water, self-sealed, and stopped further penetration of water. The pressure recorded in Filter 3 did therefore not continue to rise but stayed constant for a few hours and then tended to drop.

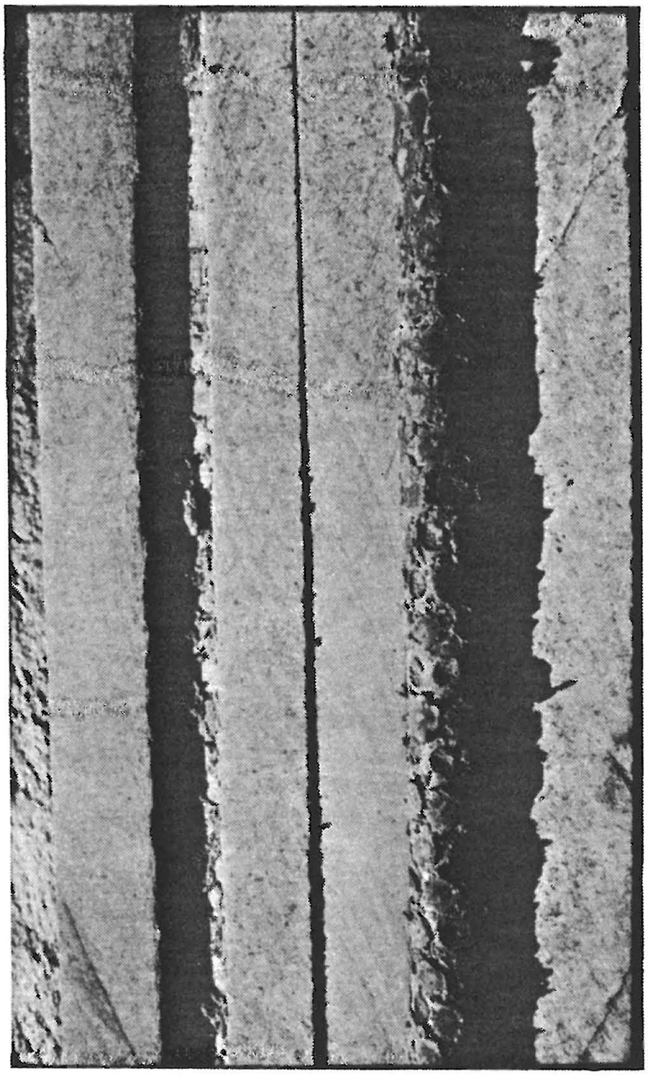


Figure 2-10. Example of a 6 months old overcored clay plug. Notice the stiff clay "columns" extending from the central core in the lower part of the plug. Some of the clay was stuck at the left rock half. Together with the clay on the other half a complete clay skin between the rock and the casing is formed

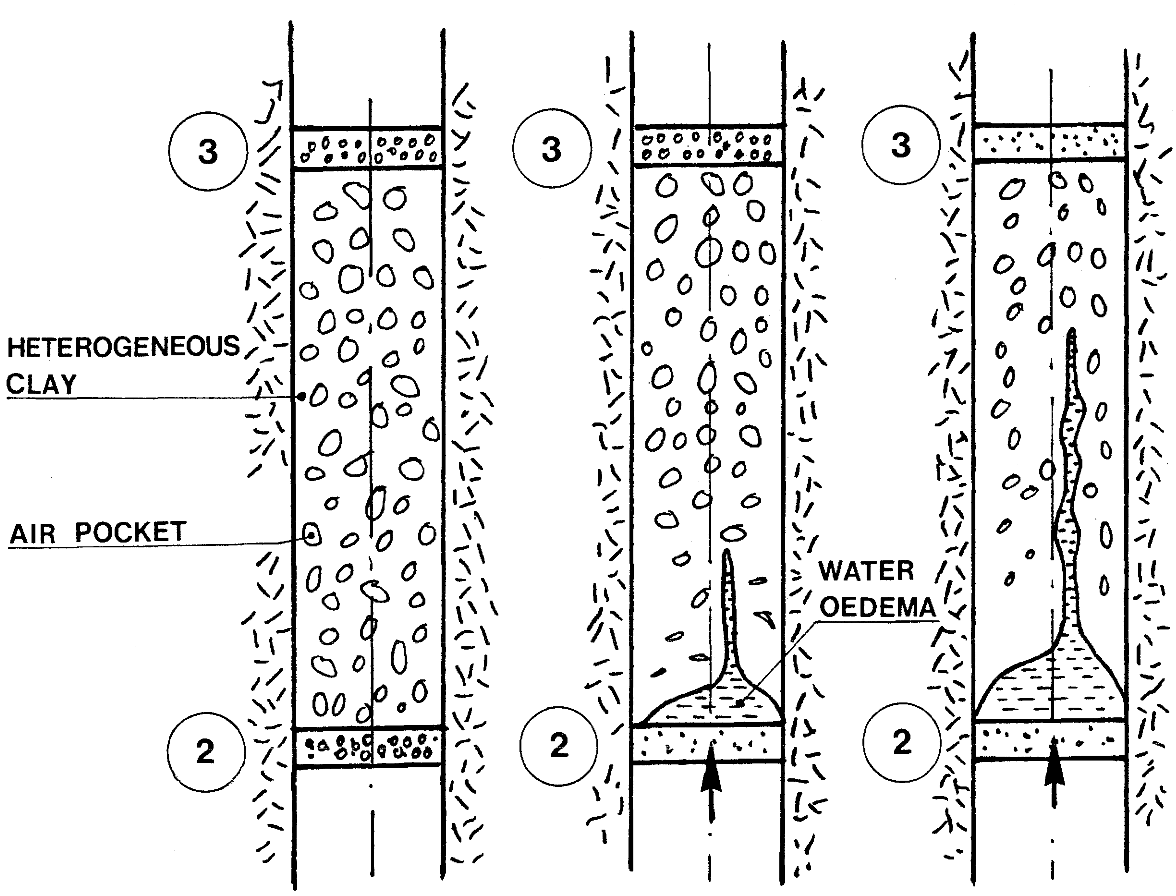


Figure 2-11. Schematic picture of the piping or displacement process in the gel formed around the casing. a) original structure, b) critical pressure applied, c) repeated pressure application

Second injection

According to the original plan, Filter 4 was not going to be injected until early July. However, the fast maturation of the clay, as indicated by the first injection test and by the considerable pressures that were built up in two of the filters before this injection, suggested an earlier testing of the clay plug between Filters 3 and 4. Filter 4 was therefore pressurized already on June 15, i.e. on the same day as the first injection test took place. The pressure steps were 100 kPa with a duration of 5 minutes. No reaction in Filter 3 was observed even at the maximum pressure 2000 kPa, which suggests that the clay gel was stronger between Filters 3 and 4 than between Filters 2 and 3. This is explained by more water being available in the first-mentioned section at least close to Filter 4, which was water saturated and under pressure before the injection took place.

Third injection

A third injection test was conducted on July 6, i.e. about 4 weeks after the plug installation. This time Filter 3 was pressurized with 50 kPa steps, while Filter 2 was drained. At 1 MPa pressure slight leaching from the filter appeared at an approximately constant rate and it increased almost linearly with the applied pressure. At 4.5 MPa pressure the total water loss had become about 10 liters and water had started leaching through the cement plug bringing with it some bentonite. The probable explanation of the water loss is that the injection forced water into the central open pipe through a joint close to Filter 3, filled the pipe and finally caused a breakthrough of the largely heterogeneous cement plug along the tubings.

Fourth injection

A fourth test was made a few hours after the third injection test by pressurizing Filter 4, while keeping Filter 3 drained. The pressure steps were 100 kPa with a duration of 2 minutes and this lead to a pressure of 4.5 MPa without any flow or leakage. When the pressure was finally raised to 5.0 MPa, leakage took place indicating piping or displacement of the clay.

The injection tests showed that the maturation of the clay was unexpectedly fast and no further testing of this sort was considered to be meaningful. The tubings were therefore connected to manometers and the water pressures recorded. The initial build-up of natural water pressures, which is illustrated in Table 2-2, led to high hydraulic gradients. The fact that they actually increased over the first months verifies that the clay plug soon became strong and erosion-resistant and also largely impervious.

Table 2-2. Water pressures in DbH2 filters, kPa

Time after last injection test	Filter no 1	Filter no 2	Filter no 3	Filter no 4
1 week	1640	28	0	98
2 weeks	1650	32	0	197
3 "	1650	35	14	369
4 "	1650	49	28	626
5 "	1650	56	28	742
8 "	1650	63	32	770
12 "	1630	105	43	730
16 "	1630	147	53	760

The development of the pressures and gradients that were operative in the clay plug segments between Filters 2 and 3, and 3 and 4, respectively, later changed their character. Thus, as demonstrated by Fig 2-12, we see that the pressure in Filter 4 soon reached a maximum value and then fluctuated because of various activities in other parts of the mine - which indeed verifies the interconnectivity of major water-bearing structures - finally tending to stabilize at about 600 kPa. Contrary to the rapid initial increase of the pressure in Filter 4, Filters 2 and 3 were only slowly pressurized. Almost the same piezometric heads were reached in Filters 2 and 4 about 16 months after test start, while the pressure in Filter 3 never exceeded 250 kPa. A logical explanation of the different behavior is that Filter 4 was located in water-bearing rock with fractures that were not effectively drained to the BMT drift, while such drainage probably took place at Filter 3. Filter 2 appears to have been intermediate in this respect. This view is supported by the core mapping, which shows that all the filters were located in or close to fracture-rich water-bearing rock, the most permeable part being the wide, richly fractured zone close to Filter 3 (cf. Fig 2-13). It must be added here that the pressure rise in the filters must have been somewhat affected by the successive saturation of the backfill in the BMT drift, by which the water pressure at the interface between the backfill and the rock rose to a maximum pressure of 50 kPa. However, the influence of this pressure rise was obviously not significant as concluded also from the fact that the pressures in the DbH2 filters remained almost constant many weeks after the excavation of the backfill.

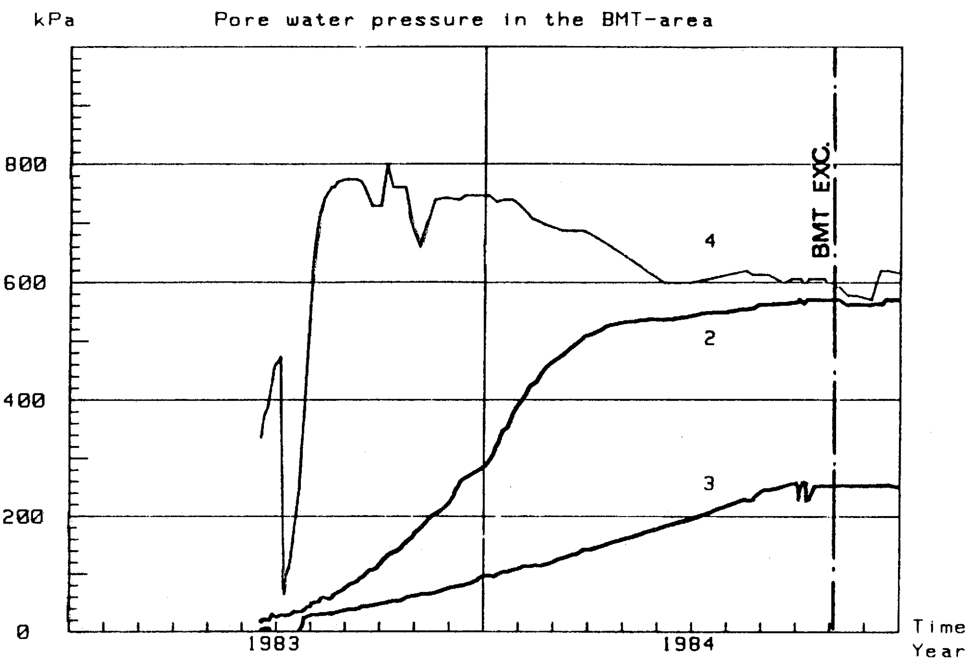


Figure 2-12. Build-up of water pressures in Filters 2, 3 and 4

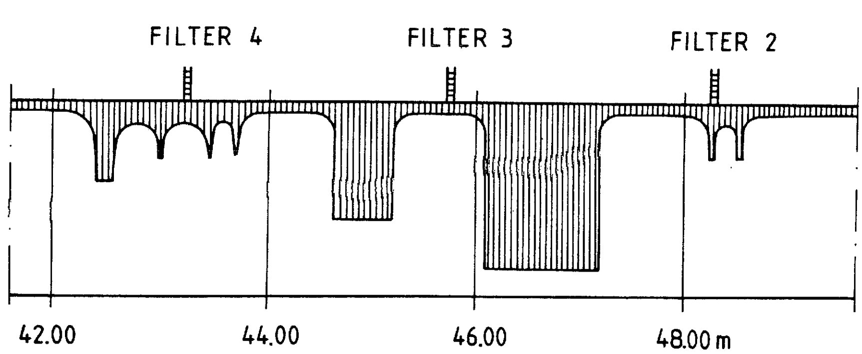


Figure 2-13. Estimated, qualitative distribution of inflow of groundwater into the DbH2 hole over the filter-equipped part

2.6.3 The clay state at excavation

In early February 1986, i.e. slightly more than 2.5 years after the application of the clay plug, a 0.6 m long part of the plugged hole was extracted by slot-drilling technique. The wedge-shaped rock block containing the plug appeared to be monolitic before the drilling started but it fell in several pieces at the extraction, which is assumed to be the result of fissures induced by the blasting of the drift.

The plug, which gave the impression of being very homogeneous, was cut into two halves and 10 samples of the intact clay core were taken for determination of the water content and bulk density. All the values except one were in the interval 32-34 %, which thus demonstrates that the investigated part of the plug was completely water saturated and fully matured. The exception was a sample that had a water content of 39 %. The bulk density of almost all the samples was in the range of 1.8-1.9 t/m^3.

2.7 MODEL FOR WATER UPTAKE AND MATURATION

2.7.1 Basic theory

The basic model for water uptake in highly compacted bentonite that was derived from the Buffer Mass Test predicts that water first enters the clay from water-bearing fractures, which tend to be blocked rather soon by penetrating clay. Water under pressure in the surrounding rock then follows "second order" passages, i.e. fine fissures, which in turn become blocked by expanding clay. Then, the narrow joints of the crystal matrix lead water to the hole which yields a rather uniform wetting over the clay/rock interface. Where the rock is relatively fractured and water available all around the hole as in the present case, the rate of water uptake is expected to follow the diffusion-type migration specified by Eq. (1):

$$\frac{\delta w}{\delta t} = D\nabla^2 w \qquad (1)$$

where w = water content
t = time
D = "diffusion coefficient"

Laboratory investigations as well as the conclusions from the BMT study suggest an average D-value of 4×10^{-10} m^2/s (4, 5).

2.7.2 Application of the diffusion model

In the initial planning of the DbH2 test an earlier model of how water is taken up by highly compacted bentonite in boreholes was in use. It was based on the assumption that only clearly visible water-bearing fractures in the rock serve as water sources from which water diffuses into the clay, and this model was actually supported by earlier field experiments in a 6 m long plugged hole (3). This hole, which had a diameter of only 38 mm and was located in a rock mass with low piezometric heads, was overcored 6 months after the plugging and complete saturation of the clay was only found where the rock was richly fractured. It was later concluded that the limiting factor for the uptake was the capacity of the rock to furnish the hole with water and this is largely a matter of the the hydraulic pressure. Since the piezometric pressures were low in the rock, its wetting capacity was concluded to be insufficient to yield full saturation of certain parts of this clay plug.

Several cases with various fracture constellations in DbH2 were investigated by use of FEM technique to estimate the wetting rate using the early fracture-source model. The calculations, which were simplified in the sense that the perforated casing and central pipe were omitted, were based on the FEMTEMP II computer program (Chalmers Technical University, Gothenburg). The computer work was made by Bengt Kallenberg and Peter Gjörup as part of their MSC degrees, Royal Technical Institute, Stockholm. A typical example of the distribution of water in the clay for the relevant case of two fractures, 5 cm apart, is illustrated in Fig 2-14. It shows that the degree of saturation is expected to be very heterogeneous and far from complete after half a year. The situation after about 2 years implies improved wetting but only a small fraction of the clay will still be saturated. Considering also the process of expansion of clay through the perforation and the fact that diffusion was hindered by the solid part of the casing, the actual degree of homogeneity of the clay is expected to be even lower.

The experience gained from various field tests later led to quite another water migration model namely one which presupposes access to water over the entire periphery of the hole. As mentioned in Chapter 2.7.1, it is valid only if the capacity of the rock to supply the hole with water is not a limiting factor. Whether this condition was really valid can be checked by applying the same model as used for the heater holes in the Buffer Mass Test (5), i.e. in the following way.

The mathematical analogy of the physical model corresponds to the late phase when water migrates through the crystal matrix with the aforementioned hydraulic conductivity of $5x10^{-13}$ m/s. Approximating the matrix as a homogeneous porous medium we obtain the radial inflow into the DbH2 hole by applying simple potential theory (cf. Fig 2-15):

$$q = \frac{k \cdot 2\Pi b \ (h_2 - h_1)}{\ln \ (r_2/r_1)} \qquad (2)$$

where

q = volumetric water flow rate into the infinitely long opening
k = coefficient of hydraulic conductivity
r_1 and r_2 = radial distances from the hole axis to the first and second water head measuring points
h_1 and h_2 = pressures at distances r_1 and r_2, respectively
b = length in axial direction of inflow

This flow equation is valid for steady flow conditions, which puts certain restrictions to its use. As to the pressure heads, the LBL gauges in the BMT area constantly yielded a h_2-value of 80-130 m water head at r_2 = 10 m, while h_1 was considerably lower and slowly increasing. A reasonable and conservative assumption is that h_1 was 10 m at r_1 = 0.5 m during the first year of operation. If the respective values are introduced in Eq. (2) we arrive at a radial, uniformly distributed inflow of about 8 ml/day per meter length of the borehole. This yields a total inflow of about 1.5 l in 6 months which is approximately twice the required quantity to saturate the clay plug. It means that the rock was capable of supplying the clay with water at a rate which did not restrict the diffusion-type uptake over the entire rock/clay interface.

Using Eq. (1) and assuming that water was available without limitations along the entire periphery of the clay plug, the time to reach complete saturation is found to be less than 0.5 years if the influence of the casing is omitted. Assuming this influence to cause a delay in the wetting process by 100 %, full saturation would still be expected after about 2 years, which was actually the case.

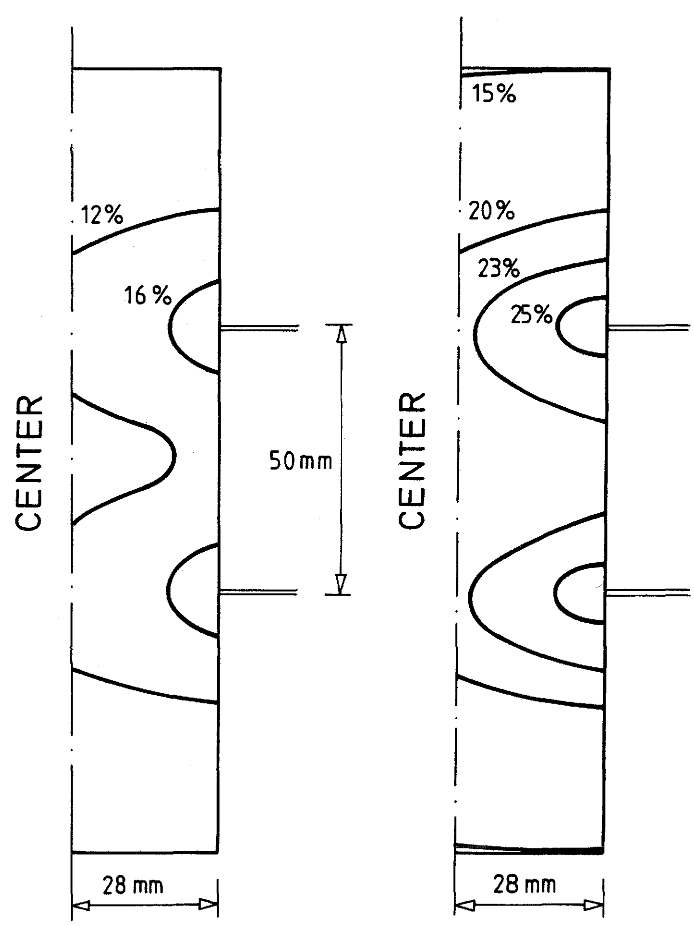


Figure 2-14. FEM-calculated distribution of the water content in the clay close to two 1 mm wide fractures that are 5 cm apart. Left figure corresponds to 1 month after onset of diffusion, right figure shows the situation after 0.5 years. Initial water content 11 %

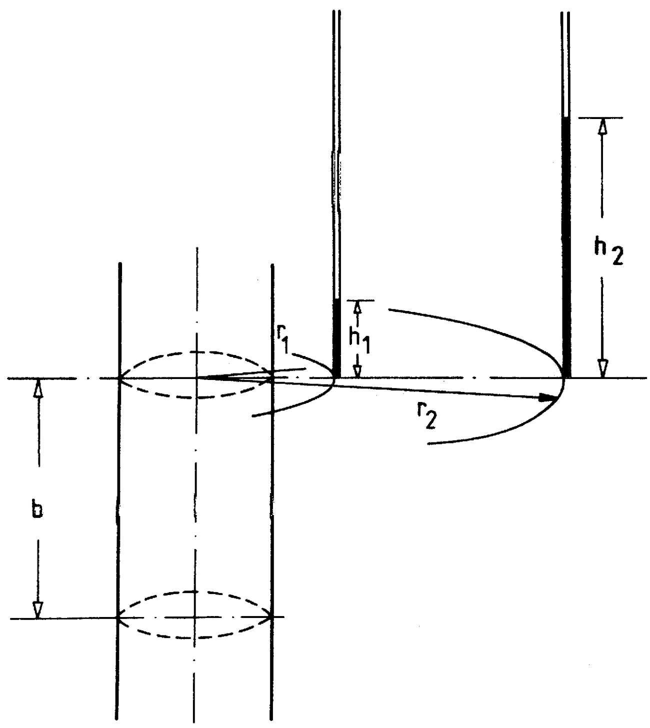


Figure 2-15. Flow conditions in porous medium with long cylindrical hole

3 PLUGGING TESTS IN Ø76 mm BOREHOLES

3.1 PURPOSE

The main object of the Ø76 mm borehole tests was to investigate the entire maturation process in greater detail and to determine the bond strength at the end of the experiments by measuring the force required to extrude the plugs from the holes. At an early stage of the planning it was suggested by the Swiss representatives of the technical subgroup that a casing with a very high perforation ratio would yield faster maturation than the "standard" version with perforated casing and one of the plugs was therefore equipped with a casing that consisted of a rather coarse net of stainless steel.

3.2 LOCATION

The two 14 m long Ø76 mm boreholes, which are parallel and 0.5 m apart, connect an existing N/S-oriented drift on the 341 m level with the almost parallel SGU drift located on the 360 m level. The exact positions of the two holes are given by the following coordinates:

	II a	II b
Upper end	x = 274.05 y = 1018.61 z = 340.31	x = 274.66 y = 1018.65 z = 340.32
Lower end	x = 272.73 y = 1019.84 z = 354.66	x = 273.42 y = 1019.91 z = 354.81

IIa was the hole in which the "standard"-type casing with perforation was used, while IIb was plugged with the net-type casing.

3.3 ROCK CONDITIONS

3.3.1 General

The criterion that extrusion of the plugs should be possible for determination of the bond strength before the termination of the field tests, required access to both ends of the holes and they were therefore drilled from the floor of the upper drift down to the crown of the underlying SGU drift (Fig 3-1). The length of the two holes, which were parallel and only about 0.5 m apart, was approximately 14 m.

The test site was located in a rock mass which contained several larger caverns and drifts and this had considerable influence on the rock stress state and hydrological conditions of the rock mass in which the present tests were conducted.

3.3.2 Fracture characteristics

Meaningful comparison of the maturation rates of bentonite plugs with differently perforated confinements requires that the holes are carefully characterized with respect to the fracture patterns. This was made by applying TV logging and core examination (cf. Figs 3-2 and 3-3), which yielded the generalized structural patterns shown in Fig 3-4. We see from the selection of core photographs in Figs 3-2 and 3-3 that the major water-bearing fractures are steeply inclined, which is in agreement with the general macroscopic fracture pattern of this part of the Stripa granite massive.

The major features in the two holes can be correlated but it is clear that although they are only 0.5 m apart, the fracture patterns are not identical, which was also demonstrated by the injection tests that were made to characterize the rock hydrologically.

3.3.3 Rock stresses

The two Ø76 mm boreholes and the vertical shaft are located in a rock slab in which the vertical rock stresses are insignificant but the horizontal stresses rather high, particularly in the W/E-direction. The latter stresses are estimated to be on the same order of magnitude or even higher than the major principal stress in the area, which has been estimated at about 20 MPa. Thus, recent stress measurements using overcoring techniques as well as hydro-fracturing indicate that the maximum horizontal stress, oriented W/E to NW/SE, ranges between 16 and 25 MPa (6). In the central part of the rock slab steep joints striking N/S are therefore expected to be well closed, while those striking W/E would instead tend to be widened. Since the major water-bearing structures have in fact a WNW/ESE to W/E strike they were expected to serve as effective inflow and outflow passages to the holes.

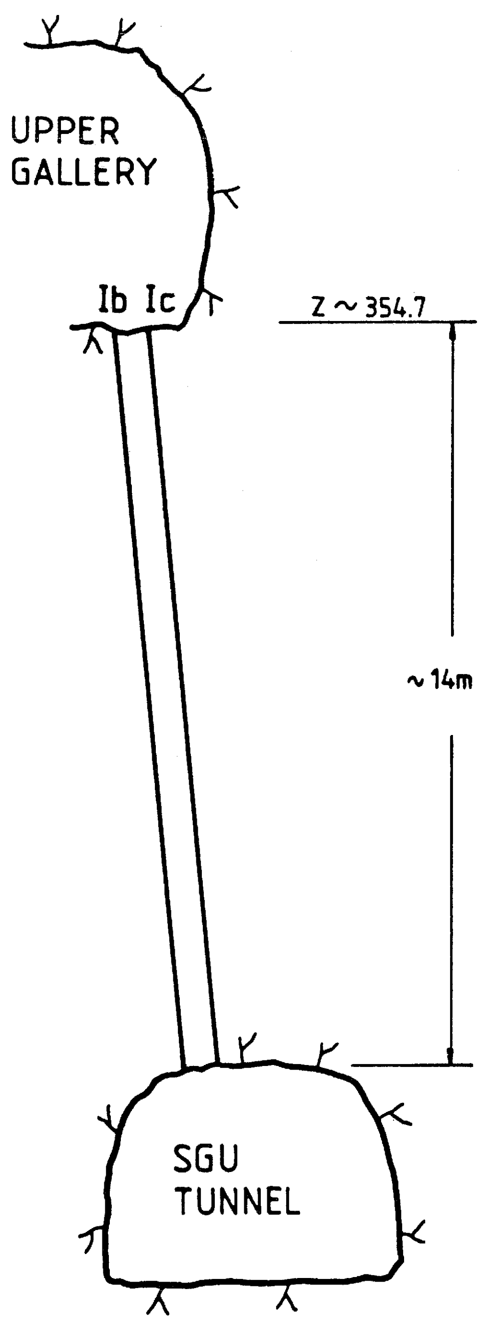


Figure 3-1. Location and orientation of the Ø 76 mm boreholes IIa and IIb

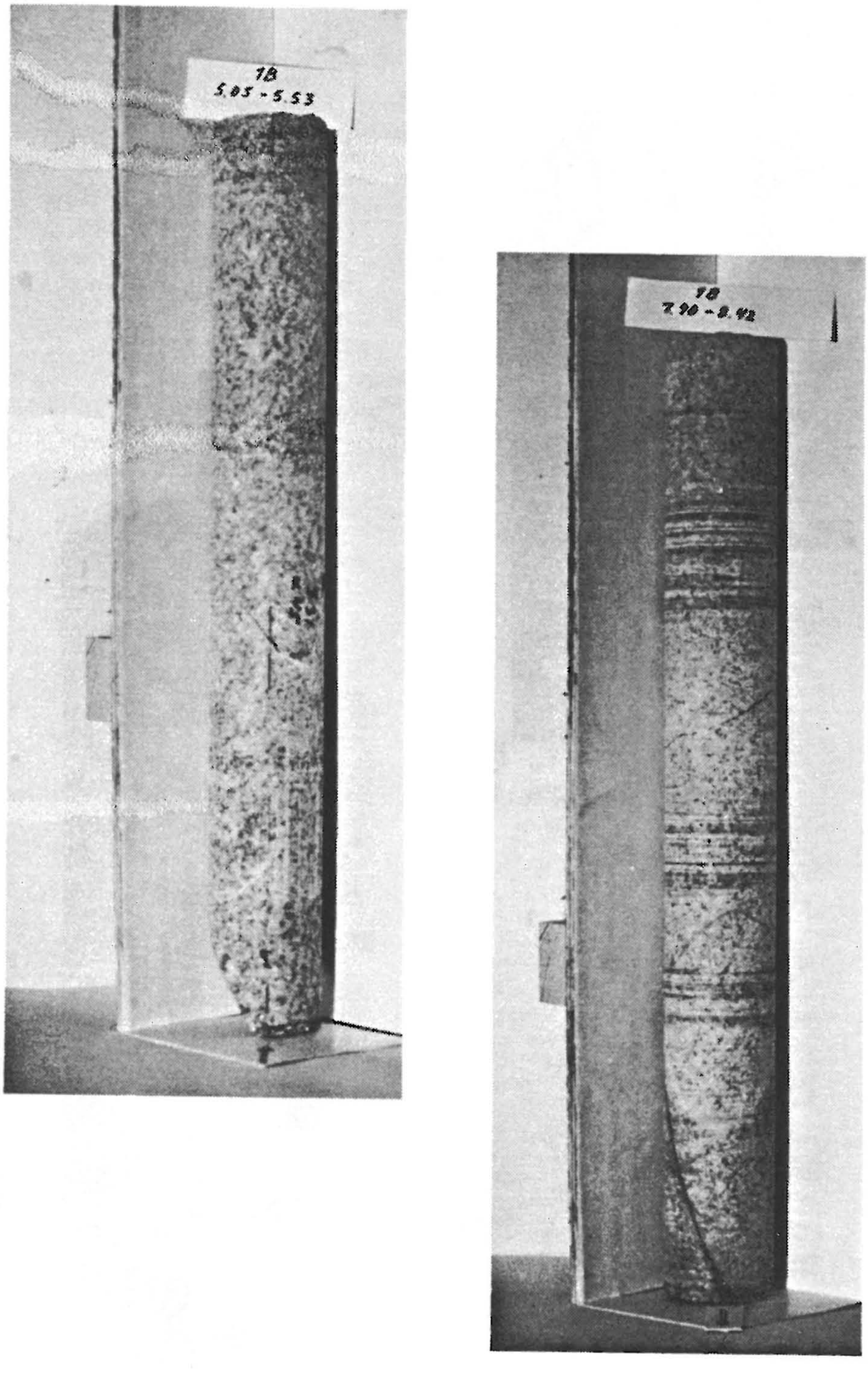


Figure 3-2. Photographs of core elements from central parts of hole IIa

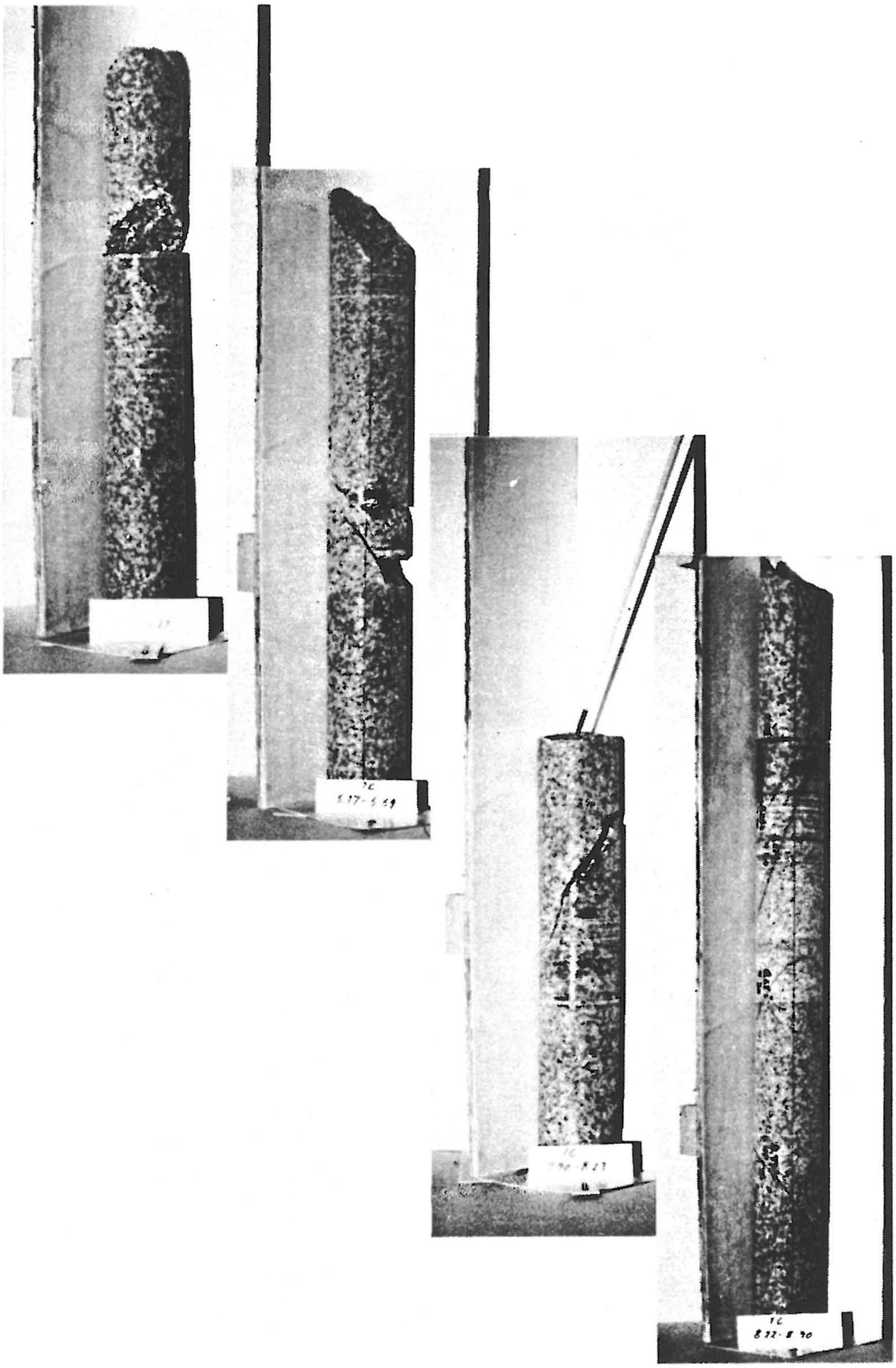


Figure 3-3. Photographs of core elements from the central two thirds of hole IIb

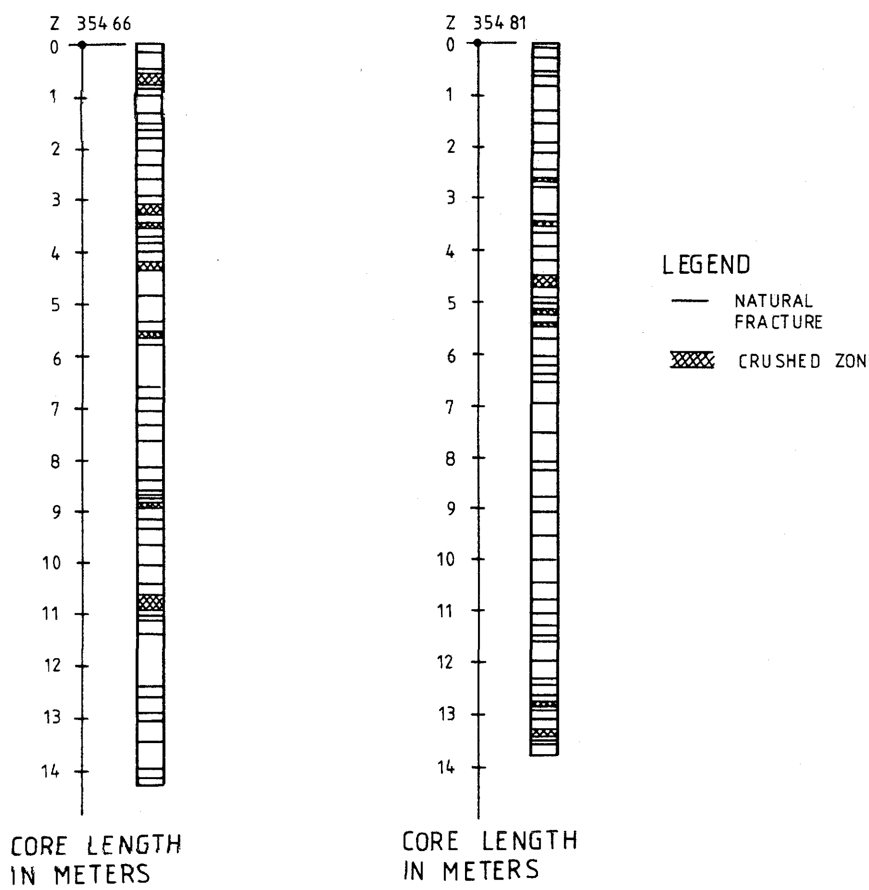


Figure 3-4. Generalized fracture mapping of the two Ø 76 mm holes

3.3.4 Hydrological conditions

The construction of the lower drift some 25 years before the plugging tests must have led to very low piezometric heads at the test site. However, it was clear already by ocular inspection that the fractures were water saturated before as well as during the tests and that the clay plugs had access to water over their entire length although it was under low pressure.

Core examination and TV logging as well as injection tests using a twin packer (1.2 m packer distance), yielded the major hydrological properties of the two holes. The injection pressure 200 kPa, which was held constant for a few hours in each packer position, was produced by applying nitrogen gas as a driving force. The flow was recorded by use of a calibrated fine-diameter nylon tubing in which the displacement of the meniscus could be determined with great accuracy. The pressure was measured by use of a precision manometer.

The flow per minute, five minutes after the onset of each injection, is given in Table 3-1. At the measurement in the respective hole, the other "twin" hole was sealed over its entire length by a gas-operated rubber packer.

Table 3-1 Total flow in milliliters per minute, 5 minutes after application of 200 kPa injection pressure

Section	IIa	IIb
z = 340.9 - 342.1	2.6	5.1
341.9 - 343.1	1.4	3.4
342.9 - 344.1	0.7	6.3
343.9 - 345.1	0.2	45.4
344.9 - 346.1	19.5	46.9
345.9 - 347.1	3.0	0.0
346.9 - 348.1	2.1	110.3
347.9 - 349.1	228.8	312.0
348.9 - 350.1	160.2	0.0
349.9 - 351.1	0.3	0.1
350.9 - 352.1	0.3	0.0
351.9 - 353.1	0.0	0.1
352.9 - 353.7	0.0	0.1

We see that although the holes are very closely located they are not identical from a hydrological point of view. The same major water-bearing rock structures are crossed in both holes, however, their rather steep inclination being obvious. Thus, the upper boundary of the main structure is z=347.9 in hole IIa and z=346.9 in hole IIb, this 1 m difference corresponding to a lateral distance between the holes of 0.5 m. It should be noticed that the rock mass has a surprisingly low hydraulic conductivity in the upper and lower 3 m long end sections.

The test of the maturation rate of the clay plugs required a moderately permeable rock at the points of injection in order to keep up the pressure and direct most of the water towards the plugs. Also, the central parts of the two plugs should be located so that their hydration should not be too slow. These criteria suggested that the most suitable positions of clay plugs and injection "chambers" were those shown in Fig 3-5. The latter were formed by placing long inflatable rubber plugs above the clay columns so that a 1.9 m free space was left for water injection. These parts of the boreholes were both known to be connected to the upper one of the major water-bearing zones.

3.4 TEST ARRANGEMENT AND PROGRAM

The main arrangement is illustrated in Fig 3-6. The lower mechanical packer P_2 had been in position since the drilling of the holes in order to preserve the piezometric conditions and to support the plugs at the installation. The upper ends of the plugs were connected to flexible filters which pressed against the rock and prevented clay from migrating into the injection chambers.

At the installation, which took place in late August 1984, the plugs were submerged in the water-filled holes and the upper packers were then immediately inflated. The recording units had been connected to the data logging system before the insertion and gave pressure reactions from the start of the injection phase. The associated inflow was measured by using the same technique as the one which was applied in the initial part of the DbH2 test.

The test program comprised water injection in the upper chamber shortly after the application of the plugs to test the rate of maturation, and to yield a largely matured clay plug at the end of the test. The first pressure step was taken as 50 kPa and it was intended then to increase the pressure in 50 kPa steps until piping or clay displacement took place. It was planned to maintain the injection pressure at 100 to 200 kPa after a short recovery so that a high degree of saturation would ultimately be produced. Finally, the bond strength, i.e. the shear strength at the interface between clay and rock, was going to be determined by measuring the axial force required to push out the largely matured plugs.

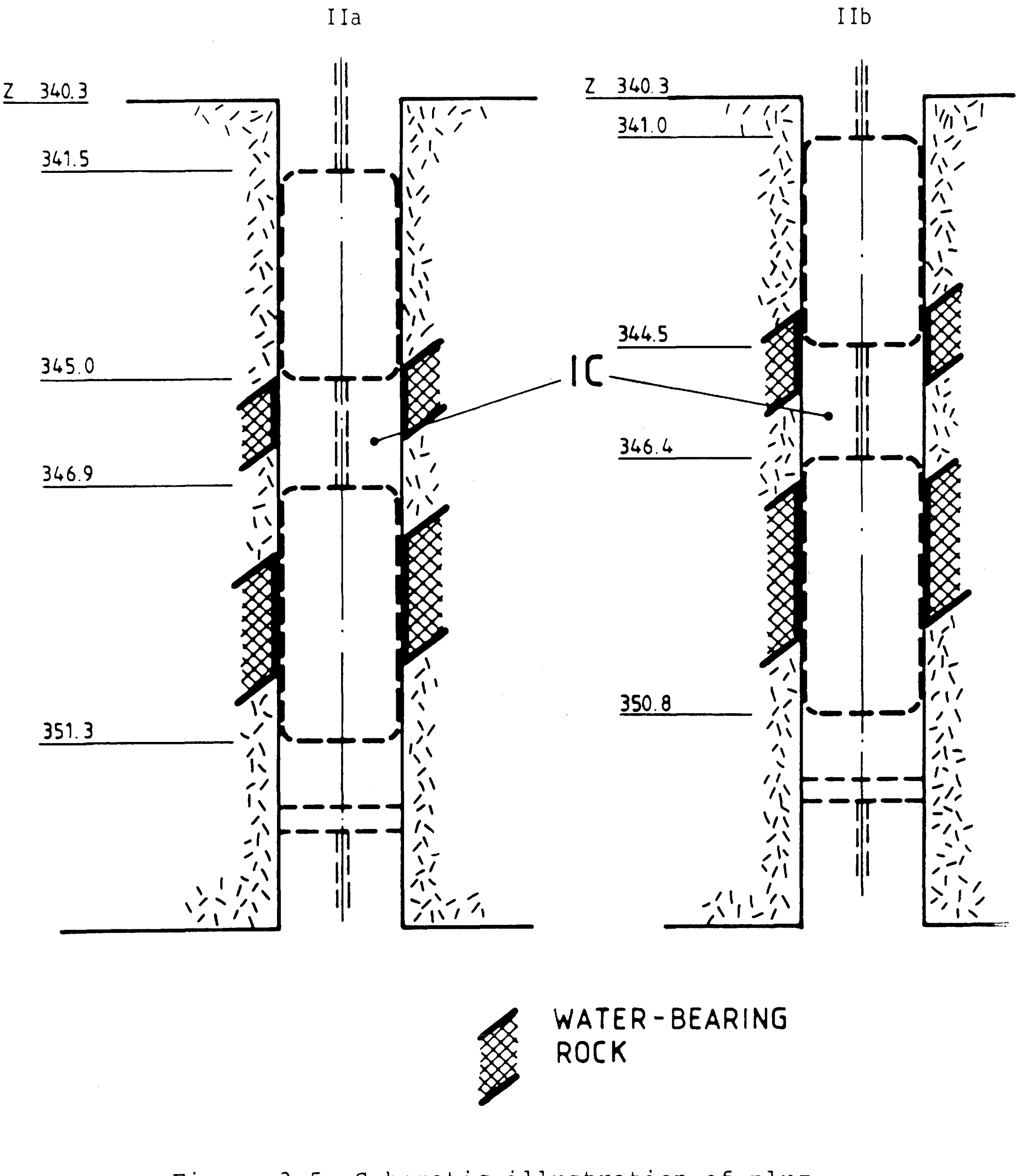


Figure 3-5. Schematic illustration of plug locations and injection chambers (IC) in the Ø 76 mm boreholes. The upper plugs in the holes are long inflated rubber tubes, while the lower are 4 m long clay plugs. The lowest unit in the holes is a mechanical packer

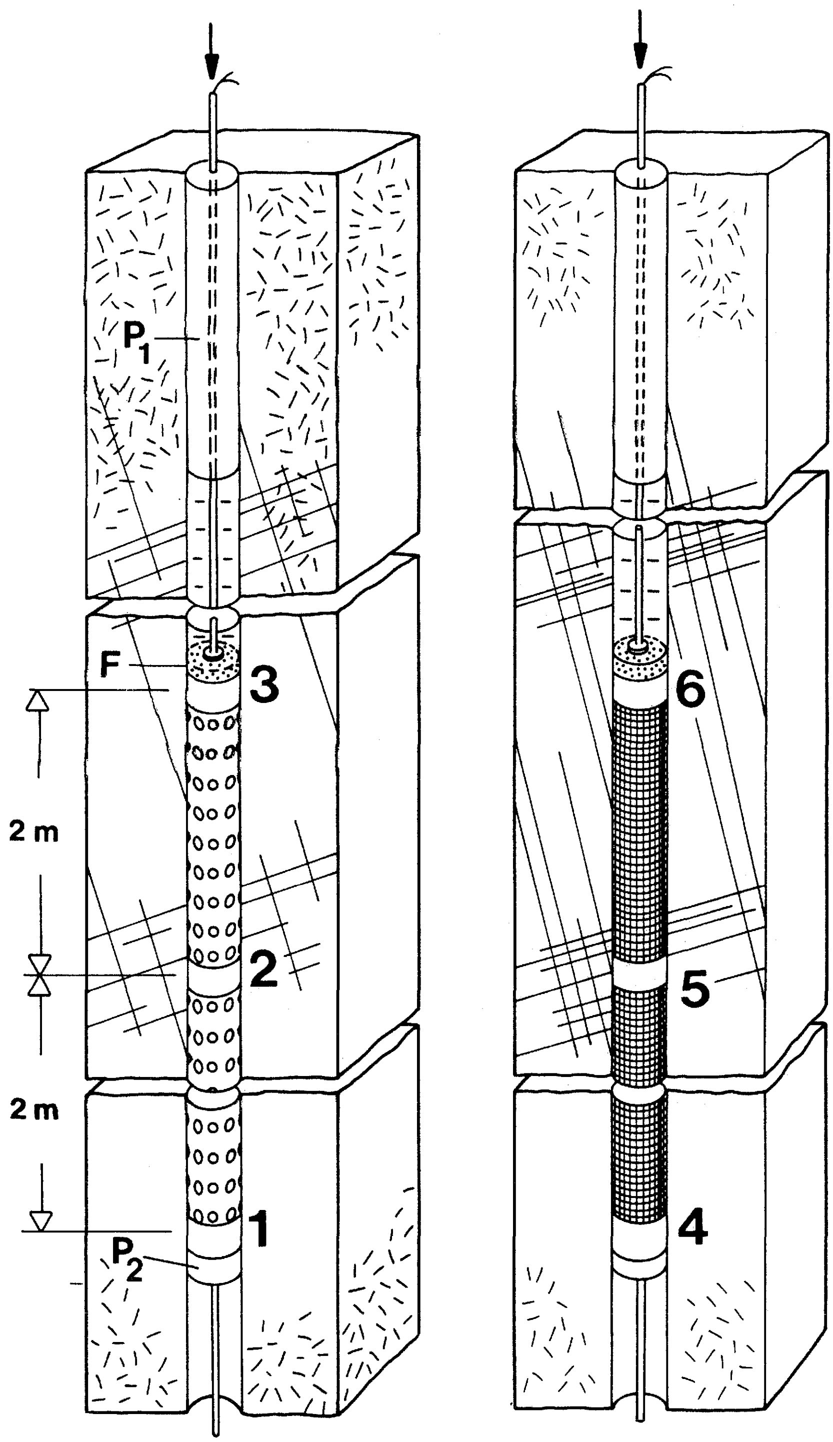


Figure 3-6. Schematic picture of the plug arrangement in holes IIa (left) and IIb (right). P_1, inflatable rubber packer. P_2, mechanical packer, 1-6 measuring units for recording total pressures and pore pressures. F is upper filter separating the plug from the injection chamber

3.5 PLUG DESIGN

3.5.1 General

Like the DbH2 plug, the Ø 76 mm plugs required great care in the preparation because of the complicated geometry with a central pipe, hosting the cables, and a fairly large size of the gauges that had to be emplaced in the plugs. Despite careful fitting of the individual units, by which larger differences in density of the expanded clay could be avoided, the design was known to yield certain variations in homogeneity that could not be evened out in the course of the testing time.

3.5.2 Pressure gauges, logging system

The pressure gauges were mounted in conical copper housings, which were connected by a central pipe with the cables, and which served to joint the two 2 m long plug segments in the respective hole as well as to form the outer ends of the plugs. The gauges had the form of a few milliliter large cells equipped with dual pressure transducers. The pore pressure cells had filters (u in Fig 3-7) which were kept water saturated at the application of the plugs in the water-filled holes. The adjacent cells for measuring the total pressure were filled with silicon oil for transmitting the external pressure to the transducers and they were isolated from the surroundings by rubber membranes (p in Fig 3-7). The units appeared as shown in Fig 3-8 before mounting in the plugs.

The signals from the 12 transducers were amplified and recorded by use of a simple logging system consisting of an ABC 80 Luxor computer and a Micorl 82 A, type 5233 printer. Readings were taken once a day after the first few days when the time intervals were much shorter. The entire system of gauges and their mounting as well the logging facilities were manufactured and made operational by Electromed Systems, Solna, Sweden.

3.5.3 Dimensions

The perforated copper casing of hole II a had an outer diameter of 68.6 mm and an inner diameter of 65 mm. The perforation, covering about 50 % of the surface, was made by drilling Ø 11 mm holes.

The ring-shaped clay blocks were produced by compacting Volclay MX-80 bentonite powder with an initial content of 10 % to a bulk density of 2.1 t/m^3. They were given an outer diameter of 63 mm while the inner diameter was 20 mm, which yields a theoretical net bulk density of 1.82 t/m^3 after complete expansion and homogenization in those parts which were located between the pressure gauges. The corresponding, theoretical water content is slightly less than 40 %.

3.6 RESULTS

3.6.1 Experience from handling and application of the plugs

While the plug with the perforated copper casing (IIa) formed a mechanically strong and stiff unit which was easily handled and could be inserted in the water-filled borehole with great ease, the plug equipped with the net casing was very flexible despite the central pipe serving as "backbone" (Figs 3-9 and 3-10). It had to be effectively supported and carefully handled to avoid such plastic deformation of the net that would have made the insertion very difficult or even impossible. Since practicality is one of the major criteria for selecting useful borehole sealing techniques it is clear that plugs with net-type casings of the type tested in hole II b should only be used for vertical or steeply inclined holes with a maximum length of a few meters. It is required also that such plugs have to be lowered into the holes from above since pushing from below would be difficult, at least without the use of an outer supporting casing.

3.6.2 Determination of the initial maturation rate

According to the test program the first injection experiment with a water pressure of 50 kPa was planned to start the day after the plugs had been applied. By accident the injection pressure became 250 kPa which caused rapid outflow from the 1.9 m long injection chamber, most of the flow probably taking place through the pervious zone in the rock that traversed the chamber. This was concluded from the preceding hydrological tests and later tests which all showed greatly increased outflow through the rock at injection pressures exceeding 100 kPa. It is not excluded, however, that some of the flow was related to slight piping or displacement of the one day old, soft and very heterogeneous clay gel that had been formed between the casing and the rock in the boreholes. In order to allow for some self-healing of the gels the injection was stopped and started again on the third day after the application at 50 kPa pressure. This pressure was maintained for 1 week with insignificant outflow from the injection chamber and, thus, without any sign of piping or clay displacement. The pressure was then increased to 100 kPa still without causing the clay to yield, but producing an almost steady outflow through the rock of 3-3.5 liters per day. After about 9 months the injection pressure was increased to 200 kPa for about 1 months and then to 300 kPa for slightly more than 3 months without causing piping or displacement of the clay but producing a flow into the pervious rock zone that exceeded 16 liters per day for the highest pressure. This clearly demonstrates the influence of injection pressures on the evaluated hydraulic conductivity in standard packer tests.

3.6.3 Later stages of the maturation, physical processes

The idea of keeping the injection chamber pressurized was also to feed the fractures in the rock close to the boreholes with water so that they remained saturated throughout the tests. This was assumed to be necessary since water uptake and expansion of the clay plugs would otherwise be retarded or stopped by lack of water. The predicted behavior of the system was a slow and steady build-up of water and total pressures, starting at the upper end of the plugs and being almost completely developed within about 1 year after the installation of the plugs. As demonstrated by the diagram in Fig 3-11 the actual behavior was different.

A few weeks after the test start all piezometer gauges signalled negative pressures which was thought to be due to the suction power of the non-saturated, expanding bentonite clay. It was evidenced by a simple test by Electromed in which a spare gauge with clay surrounding the piezometer filter was submerged in water, the test actually showing that part of the porewater initially contained in the filter was sucked up by the expanding clay. The fact that porewater tension was recorded in the field tests indicates that the uptake of water by the clay was faster than the inflow of water into the parts of the holes where the pressure gauges were located or, alternatively, that non-saturated clay expanded rapidly in an axial direction from the clay-rich parts of the plugs to cover the filters and prevent pressurized water to reach the filters. The second explanation appears to be most probable for the upper part of the plugs and for the larger part of the plug that had a net casing since the total pressures increased here, which implies that clay had surrounded the membranes of the pressure gauges. The first explanation may be valid for the lower parts of the plugs since they were at larger distance from the injection chamber and were probably not effectively fed with water.

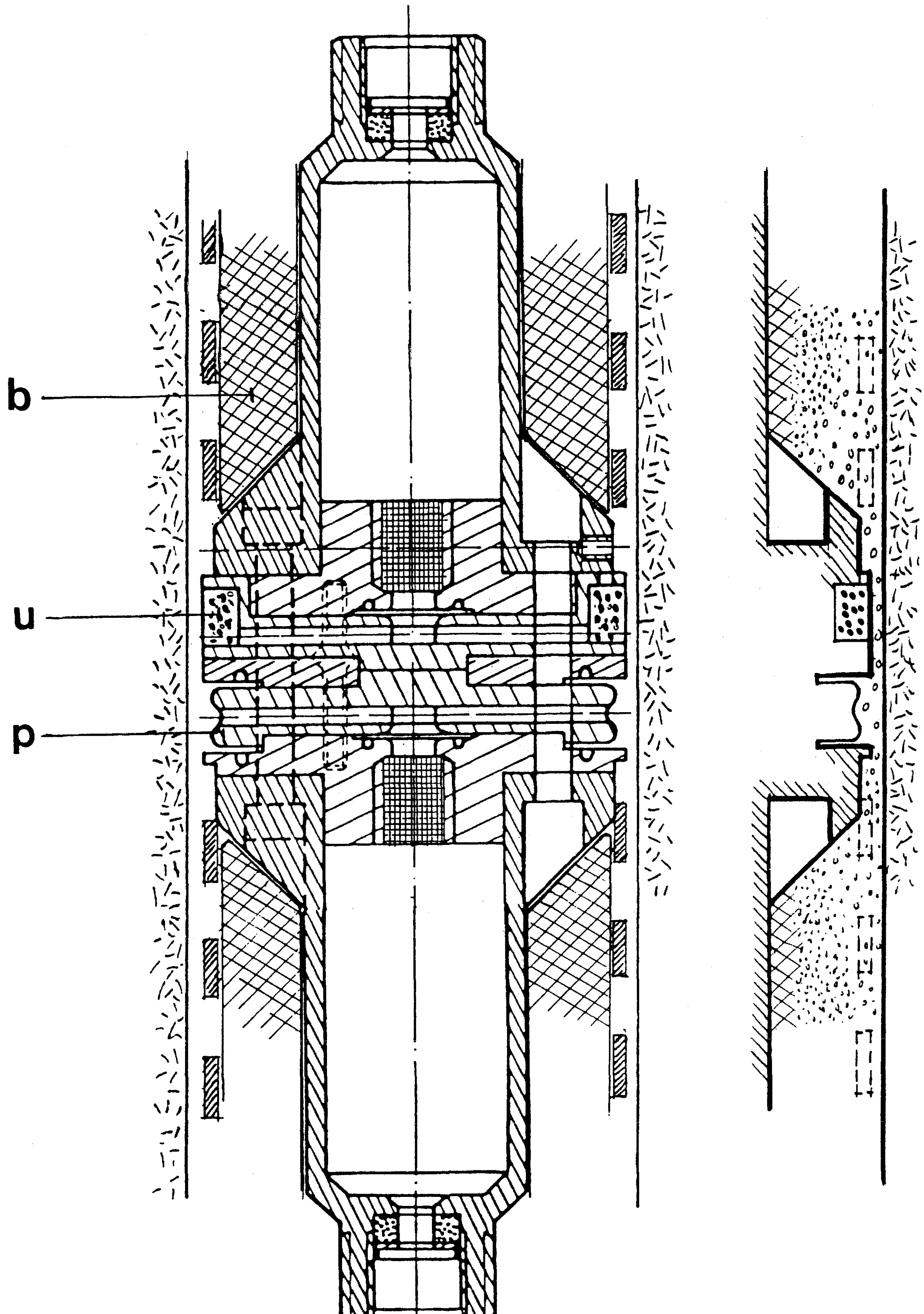


Figure 3-7. Design of gauge for pressure pressurements

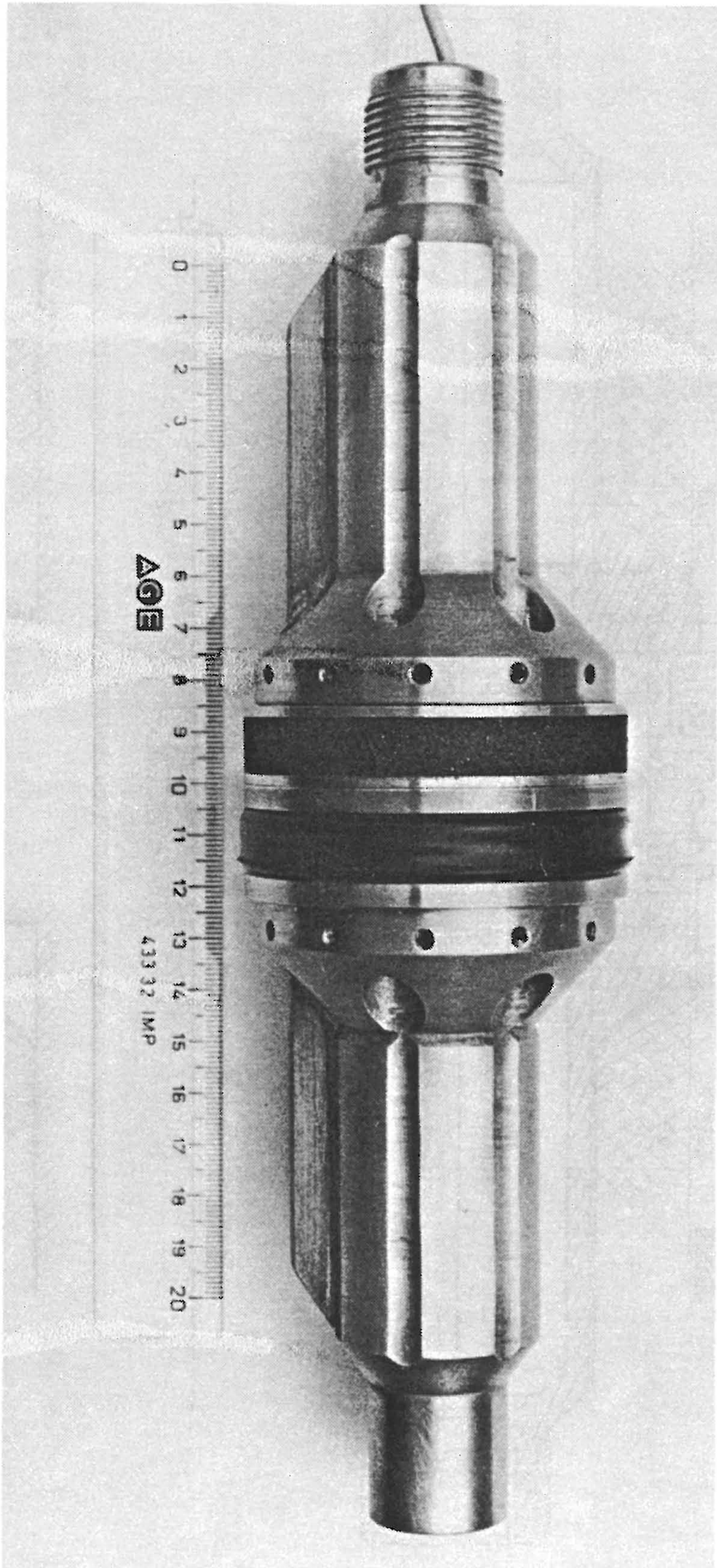


Figure 3-8. Copper housing with pressure cells
prepared for installation in the casings

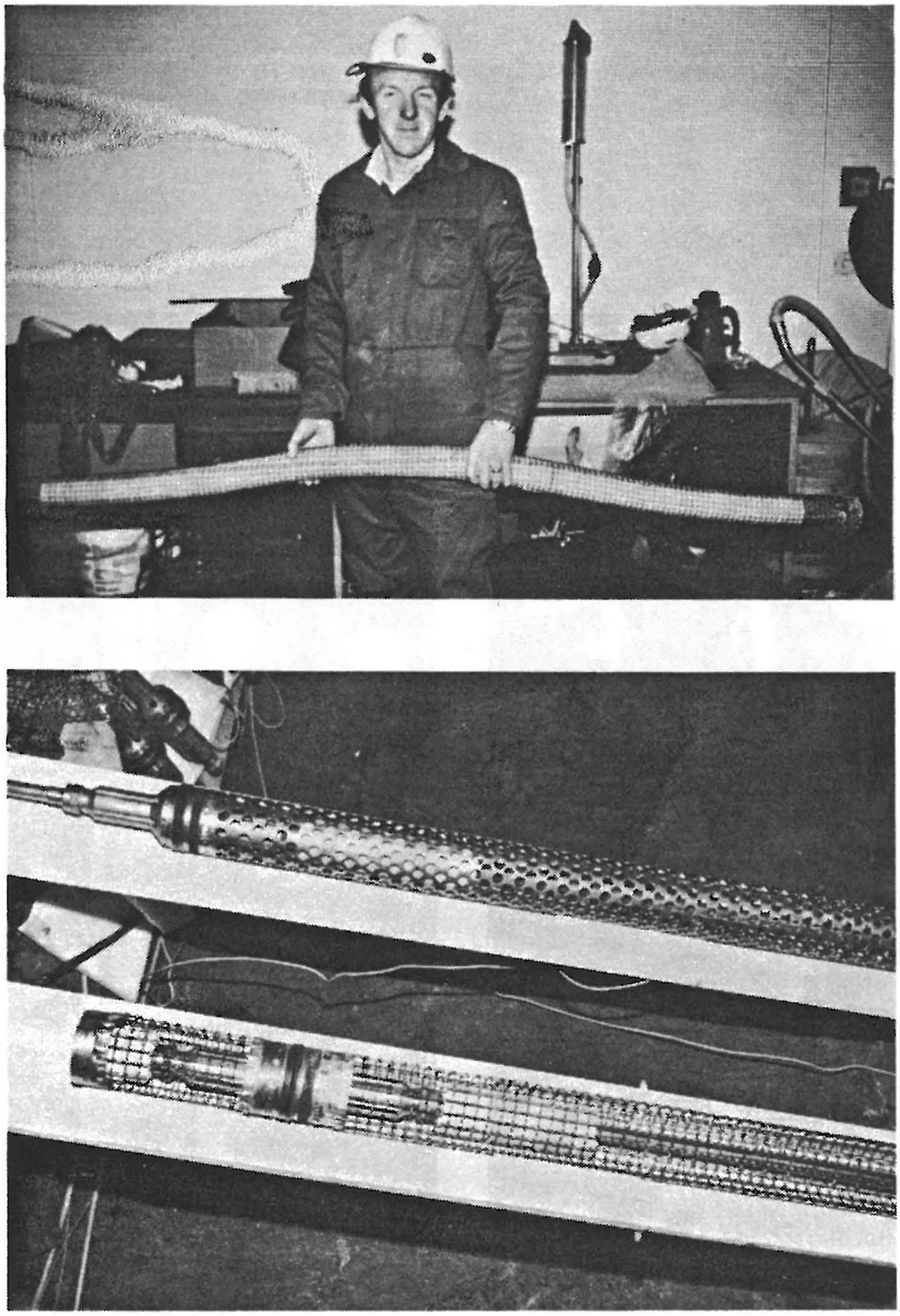


Figure 3-9. The flexibility of the plug with a net casing was very obvious and called for very careful handling

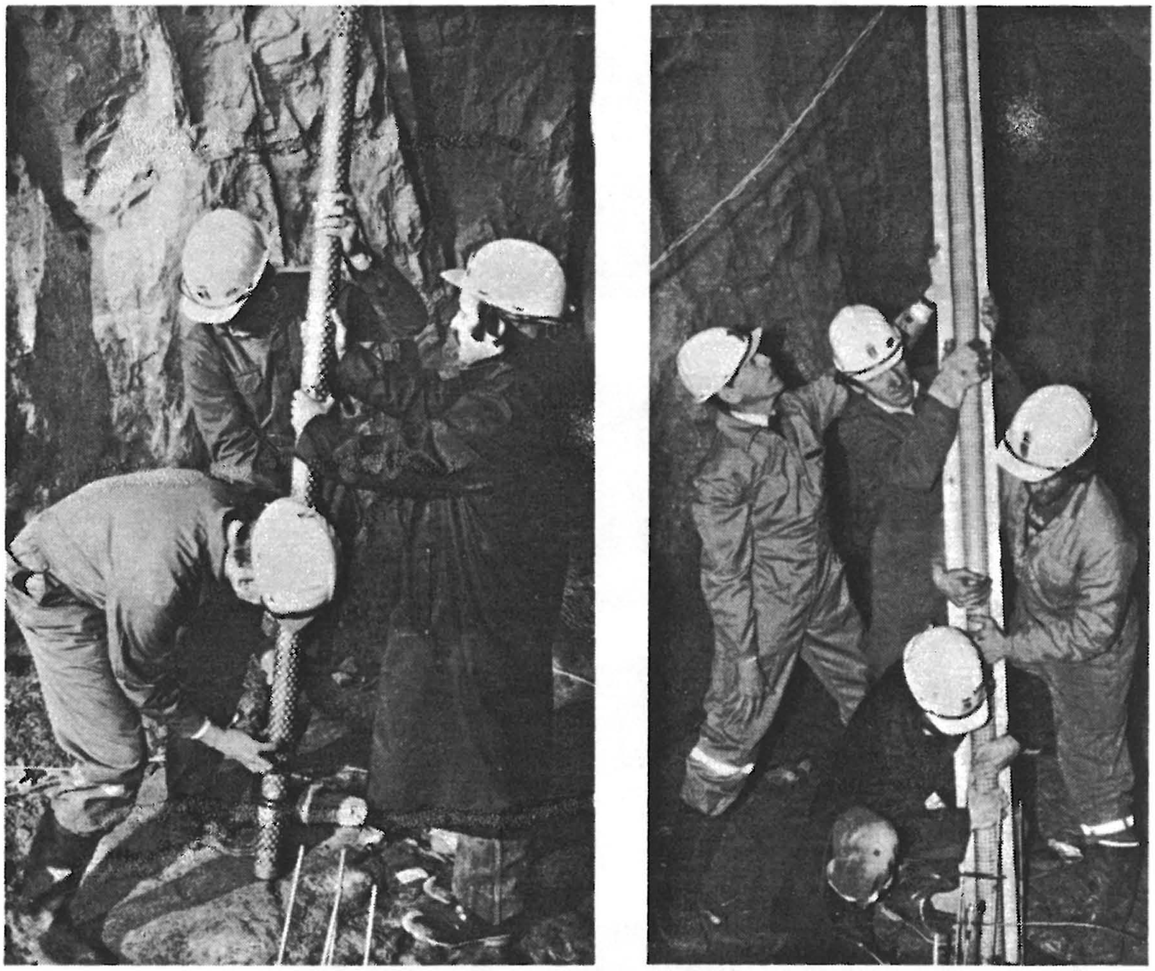


Figure 3-10. Application of Ø 76 mm borehole plugs

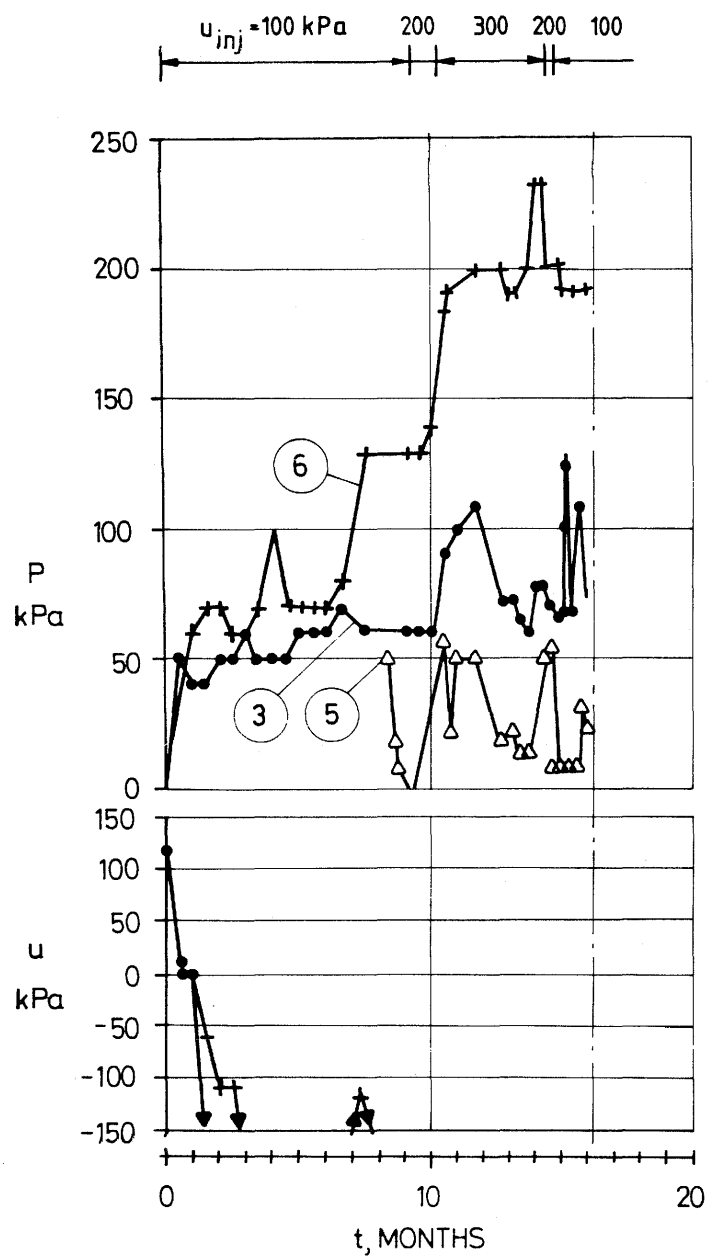


Figure 3-11. Development of water (u) and total pressures (p) in the clay plugs in the Ø 76 mm holes. The encircled figures refer to the gauge numbers in Fig 3-6

The observation that the gauges in the lower parts of the plugs did not give any sign of maturation at a rate that was comparable to that of the upper parts is a very good illustration of the general behavior of dense bentonite borehole plugs: they quickly absorb water from the rock where they pass through richly water-bearing rock, which is actually where fast sealing is required, while they remain largely unactivated in dry parts of the holes until water enters these parts in sufficient quantities. This property was rather unwanted in the presently described field tests, however, since relevant bond strength determinations required largely homogeneous clay plugs. In August 1984, i.e. about 9 months after test start, the bottom part of the plugs was therefore rearranged so that filters for water injection, like the ones at the upper end of the plugs, could be mounted. Water injection was thereafter made at the same pressure as in the top chambers. No response to this additional pressurizing was recorded, however, which may be explained by a rather high degree of maturation of the lower ends of the clay plugs despite the lack of pressure reactions. Thus, the clay-rich parts of the plugs may have expanded rather far and prevented injected water to reach the gauges. Most of the water injected from below may therefore have been directed from the holes towards the potential sink represented by the underlying drift.

3.6.4 Theoretical aspects of the maturation rate

Disregarding from the possibility that the non-reacting gauges were out of order it was concluded that the lack of reaction must have been that water had not been effectively driven to the lower parts of the plugs. Still, the degree of maturation should have become rather high as demonstrated by the following reasoning. Considering that the holes were initially filled with water, radial redistribution of this quantity and of outwards expanding clay was sufficient to produce rather homogeneous clay plugs with a bulk density of about 1.6-1.8 t/m^3 with approximately 75 % degree of saturation. Actually, only about 5 liters of water would be required to yield complete saturation of each plug. Assuming the porosity of the rock to be 0.5 % as an average, this quantity of water is usually contained in as little as 1 m^3 of rock, and it was concluded that the hydraulic gradients set up by the suction power of the clay - they can be estimated at something between 1 and 100 - would be sufficient to bring at least part of the required 5 liters into the respective plug in the course of the field test. This led to the decision to extrude the plugs in June 1985 for determination of the bond strength.

Prediction of the degree of homogenization of those parts of the plugs where the highest total pressures were recorded was made by considering how fast clay had expanded to cover the pressure gauges and reach a density that corresponded to the measured pressures. This was made by use of simplified models of the penetration of clay into slots, since the clay had to move through narrow passages to reach the membrane and filter of the respective pressure gauges (cf. Fig 3-7).

Considering first the simple case of swelling regarded as inverse consolidation, Fig 3-12 applies. The model is based on the assumption that a negative pore pressure is established with a magnitude equal to the swelling pressure - with opposite sign - and that water is sucked up with a simultaneous advance of the soft gel front. Since the distance of backward water migration increases steadily, the penetration rate is strongly retarded as demonstrated by Fig 3-13, which is the theoretical penetration depth versus time of expanding MX-80 clay with an initial density of about 2.1 t/m^3 in a fully saturated state. If this diagram is applied we find that the penetration should be 5 cm in 1 month and about 20 cm in 1 year, which would have filled the space between the gauges and the rock in a few months with a soft gel. This gel should then have become largely homogenized in about 1 year.

Experience shows that clay penetration into slots of the present shape, i.e. with a width of only about 2 mm, is significantly delayed by wall friction. Available data (7) suggest that the front of an expanding MX-80 gel would only be about 0.7 cm in a 0.5 mm slot in 2 months under fresh-water conditions, which suggests a penetration depth in the borehole plug slots of 1-5 cm after 1-2 months. This would be in fairly good agreement with the observed rate of pressure build-up.

A second model, derived by Börgesson for the displacement of the interface between the highly compacted bentonite and the overlying backfill in the heater holes of the Buffer Mass Test, offers an alternative approach. It concerns the possible state of force equilibrium between expansion and wall friction while it disregards creep effects. The wall friction component is expressed in terms of a friction angle, which can be estimated to be in the interval 5-10° for low densities. Fig 3-14 demonstrates the resulting approximate gel densities and swelling pressures at equilibrium, and from this diagram we can see that the model applies reasonable well when Ø is in the range of 5-10°. As will be shown later in the report, the angle of wall frictiion is about 10° as evaluated from bond strength determinations for clay with a density of about 1.9 t/m^3, and the low density 1.62 t/m^3 may well correspond to 5°. The pressure distribution curve for this density thus appears to be representative, in principle, for the situation at the upper end of the plugs.

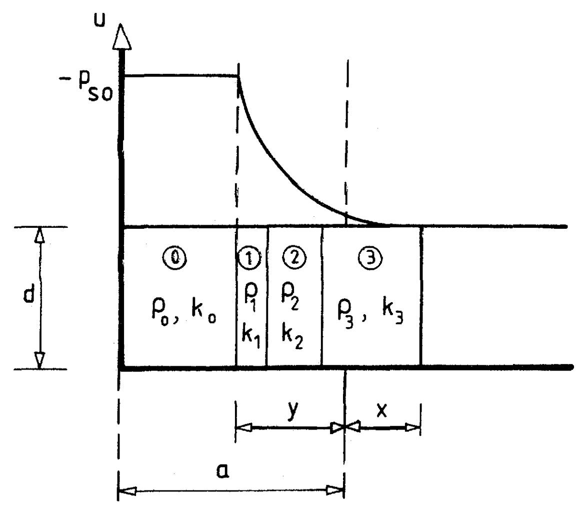


Figure 3-12. Model for stepwise calculation of the swelling process in a clay zone with the original density ρ_o, negative pore pressure u_o and hydraulic conductivity k_o. x is the front of the expanding clay

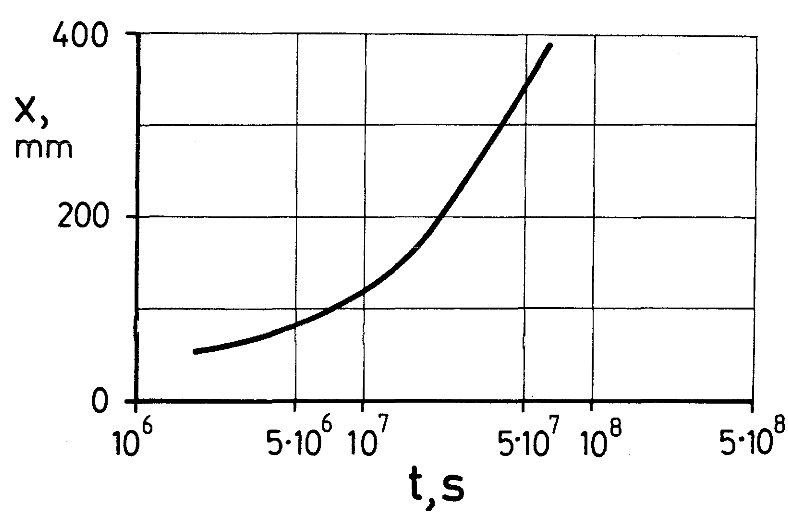


Figure 3-13. Calculated penetration (x) of the front of swelling MX-80 bentonite as a function of time (t)

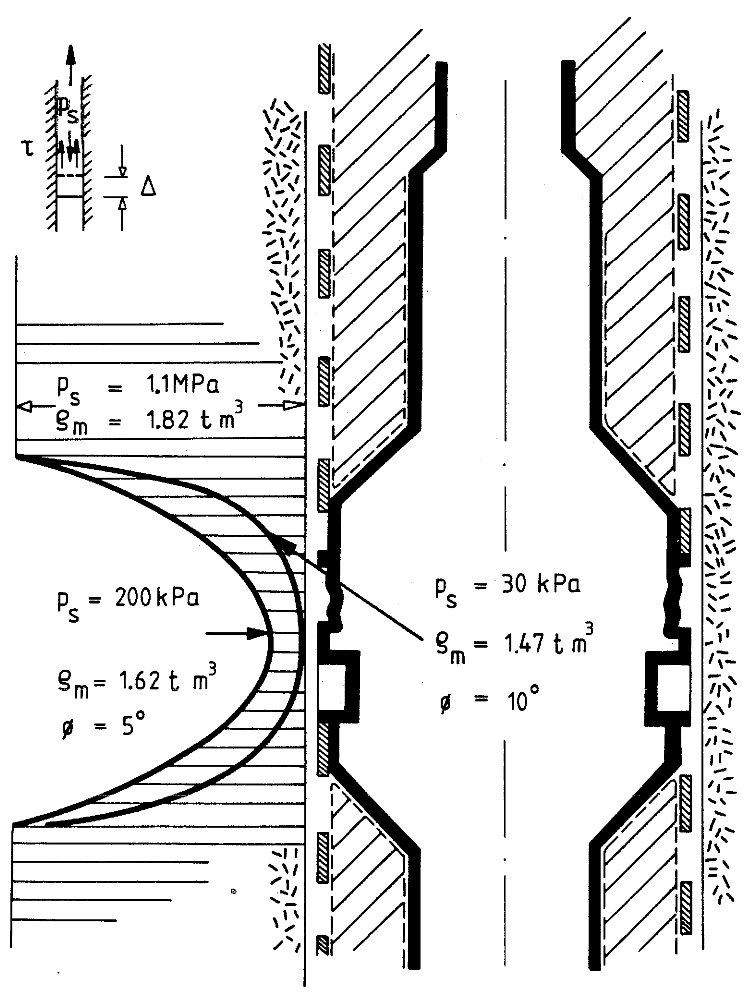
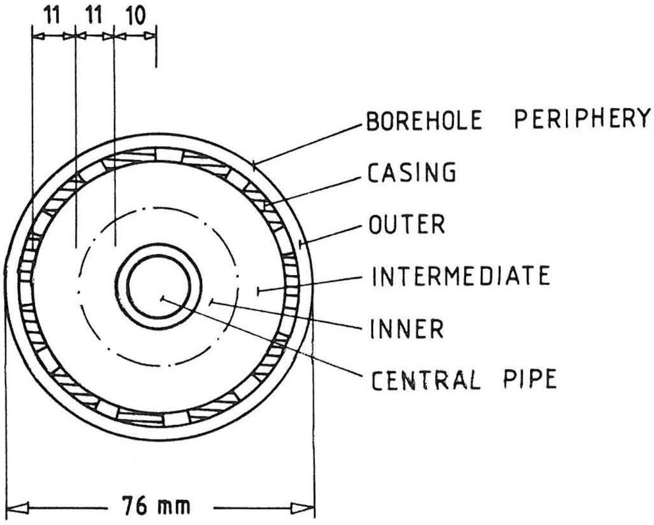


Figure 3-14. Theoretical bulk densities and swelling pressure distribution in the pressure gauges areas of the Ø 76 mm holes using Börgesson's model



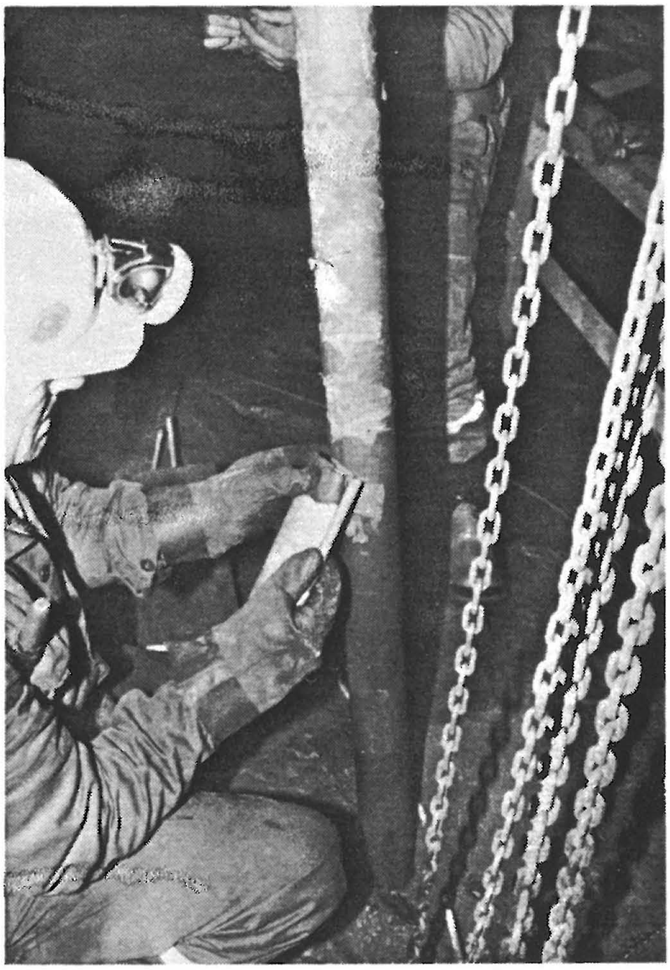


Figure 3-15. Definition of sample units at the determination of water contents and densities after the extrusion. The photographs shows the sampling of clay from the "outer" part. Notice the homogeneous appearance of the lower part which has not yet been sampled

3.6.5 Actual distribution of water and degree of homogeneity at the end of the test

After the extrusion of the plugs in early July 1985, which gave an average value of the bond strength and which will be described in the subsequent chapter, samples were taken systematically of the extruded plugs to illustrate the distribution of the water content. The samples were divided into three parts (Fig 3-15), the outer part ("outer") consisting of the material between the casing and the rock, the second ("intermediate") and third ("inner") parts representing the inner halves of the clay core. The data are given in Tables 3-2 and 3-3.

Table 3-2. Water contents in percent of samples from the clay plug in hole IIa (perforated casing)

Interval from upper end, cm	Outer part	Intermediate part	Inner part	Remark
<10	-	43-51	44-53	
10- 20	158-252	51-81	53-78	Gauge
20- 30	195-252	-	-	"
30- 40	67-120	38-53	38-53	"
40- 50	60- 63	37-38	36-38	
50- 60	58- 59	36-37	36	
60- 70	58	35-36	35-36	
70- 80	56- 58	35	35	
80- 90	56	35	35	
90-100	54- 56	35	35	Dens. 1.9 t/m^3
100-110	49- 54	35	35	
110-120	49- 50	35	35	
120-130	50	35	35	
130-140	49- 50	35	35	
140-150	49- 50	35-36	36	
150-160	50- 51	35-36	35-36	
160-170	51	35	35	
170-180	50- 51	35-37	35-36	
180-190	50- 53	37-39	36-39	
190-200	53- 61	39-47	39-52	
200-210	61-108	47-56	52	Gauge
210-220	108	-	-	"
220-230	69-108	39-54	39-66	"
230-240	58- 69	37-39	36-39	
240-250	55- 58	36-37	36	
250-260	54- 55	36	35-36	
260-270	52- 54	35-36	35	
270-280	50- 52	35	35	
280-290	50- 51	35	35	
290-300	49- 51	35	35	
300-310	48- 49	34-35	34	Dens. 1.9 t/m^3
310-320	46- 48	34	33-34	
320-330	46	34	33-34	

Cont Table 3-2

Interval from upper end, cm	Outer part	Intermediate part	Inner part	Remark
330-340	46	34	34	
340-350	46- 47	34-35	34	
350-360	47	35	34-35	
360-370	47	35-36	35	
370-380	49	36	35-36	
380-390	49- 56	36-38	36-38	
390-400	56-104	38-49	38-50	Gauge
400-410	82-106	-	-	"
410-420	65- 82	43-52	43-52	"

The bulk density values refer to the clay inside the casing

Table 3-3. Water contents of samples from the clay plug in hole IIb (net casing)

Interval from upper end, cm	Outer part	Intermediate part	Inner part	Remark
<10	-	49-61	50-69	
10- 20	96- 97	61-63	68-69	Gauge
20- 30	95-102	-	-	"
30- 40	64- 95	49-72	49-82	"
40- 50	52- 64	41-49	41-49	
50- 60	49- 52	40-41	39-41	
60- 70	48	39-40	39	
70- 80	48	39	38-39	
80- 90	48- 50	39	38	
90-100	47- 50	38-39	38	
100-110	48	38	38	
110-120	48	38	37	
120-130	47	38	38	Dens.=1.87 t/m^3
130-140	47	38	38	
140-150	48	38	38	
150-160	48	38-39	38	
160-170	46- 48	38-39	38	Dens.=1.89 t/m^3
170-180	46- 47	38	38	
180-190	46- 47	38-39	38-39	
190-200	46	39-40	39-40	
200-210	46- 47	40-45	39-48	
210-220	47- 58	45-54	47-56	Gauge
220-230	59-130	-	-	"
230-240	67- 87	43-70	43-89	"
240-250	52- 65	39-44	39-43	
250-260	46- 53	37-39	37-39	
260-270	46	36-37	36-37	
270-280	46	36	35-36	
280-290	42- 46	36	35-36	

Cont Table 3-3

Interval from upper end, cm	Outer part	Intermediate part	Inner part	Remark
290-300	42- 43	36	36	
300-310	43	36	36	
310-320	40- 43	36	36	
320-330	40- 41	35-36	35	Dens.=1.89 t/m^3
330-340	39- 41	35	35	
340-350	39	34-35	34-35	
350-360	38- 39	34	34	
360-370	37- 38	34-35	34-35	
370-380	37- 38	35-36	35-37	Gauge
380-390	38- 39	-	-	"
390-400	37- 38	41-47	41-48	"

The bulk density values refer to the clay inside the casing

While ocular inspection of the extruded plugs gave the impression that the clay plugs were totally homogeneous, we see from Tables 3-2 and 3-3 that there are variations in water content as was also expected because of the slow expansion of the clay to fill the space between the gauges and the rock.

The following main conclusions have been drawn:

- The inner and intermediate zones showed practically the same water content values meaning that the entire clay core inside the casing had become largely homogeneous.

- The outer zone was significantly wetter than the inner part indicating that the clay plug was not wholly homogeneous. However, at least part of the difference in water content between the outer zone and the inner ones was concluded to be caused by wetting at the extrusion by which temporary contact between the clay and water could not be avoided.

- The water content varied only insignificantly along the entire plug length in the respective hole except for the gauge zones, which were rather wet because of the much softer consistency of the gel that had emerged from the adjacent clay-rich parts of the plugs. This shows that variations in rock properties, i.e. fracture frequency and geometrical distribution of water-bearing features did not have any significant effect on the maturation.

- There is only a small difference between the water contents of the two plugs, meaning that their maturation rates were approximately the same despite the obvious difference in porosity of the casings. Part of the difference in water contents is explained by the smaller volume of the net casing, which yielded a larger clay volume and therefore a slightly lower density and somewhat higher water content than for the solid, perforated casing.

- The average water content of the "intermediate" and "inner" zones in the non-instrumented parts was 35 % in hole IIa and 37 % in hole IIb. We find this to be in good agreement with the predicted values at complete homogenization, which would suggest a bulk density at saturation of 1.85 t/m^3.

3.6.6 Bond strength

The planning of the bond strength tests, which were made by extruding the plugs from their holes, was preceded by simple laboratory tests in which the process was simulated. For this purpose the LuH swelling pressure oedometer was used (Fig 3-16). Three samples of MX-80 bentonite were saturated with distilled water in the oedometer to a density of about 1.9 t/m^3 and the oedometer was then dismantled so that the clay plug could be extruded at a constant rate of strain. This rate was varied but as demonstrated by Table 3-4, the evaluated shear strength, expressed in terms of the angle of wall friction and as maximum shear stress, remained almost constant.

Table 3-4. Bond strength (clay/steel) of MX-80 bentonite at laboratory extrusion tests. Bulk density about 1.9 t/m^3

Swelling pressure p_s MPa	Strain rate mm/min	Max shear stres MPa	Angle of wall friction $\emptyset$
1.0	1.0	0.18	10.1
1.0	0.1	0.17	9.4
0.85	0.001	0.15	10.2

Assuming the bulk density of the clay in the boreholes to be 1.85 t/m^3 at the extrusion stage and taking the swelling pressure and angle of wall friction to be 0.85 MPa and 10°, respectively, and assuming furthermore the effective plug length to be 3 m, the theoretical force to extrude the plugs would be 10.8 t (108 kN). As demonstrated by the diagram in Fig 3-17 the mobilized shear stress was only slightly reduced at large strain, the reduction being about 80 % of the maximum strength value. This would yield a theoretical extrusion force of about 8.5 t.

The extrusion of the plugs from the boreholes was made by use of mechanical jacks applied to the lower ends of the plugs via a number of rigid steel tube sections (Fig 3-18). The strain rate was about 0.1 mm/s.

A maximum force of 8.7 t was reached after about 36 mm displacement of the lower end of the plug in hole IIa with the perforated casing (Swedish plug), while the corresponding force was 8.7 t at about 70 mm displacement of the lower end of the plug with the net casing (Swiss plug) (Fig 3-19). This verifies the conclusion from the analysis of the water contents that the two plugs had maturated to approximately the same state and it is also in good agreement with the predicted value of the extrusion force. We see from the diagram that the plug in IIa was compressed by about 3 cm in the course of the extrusion. This strain was found to be developed in the form of buckling of the casing over the lower 50 cm part of the perforated casing. Consequently, the plug was not moving as one unit until the force had risen to about 8 t and it was then sheared off over its entire perimeter. As suggested by the laboratory experiment the force required to push it further along in the hole dropped to about 80 % of the maximum value.

The large displacement of the plug with the net casing (IIb) that was developed before it was sheared off from the rock was due to internal plug deformations, mainly through buckling of the central pipe. The net turned out to be deformed by buckling rather uniformly over its entire length and this must have caused the additional force that was required to extrude the plug after shearing it off from the rock.

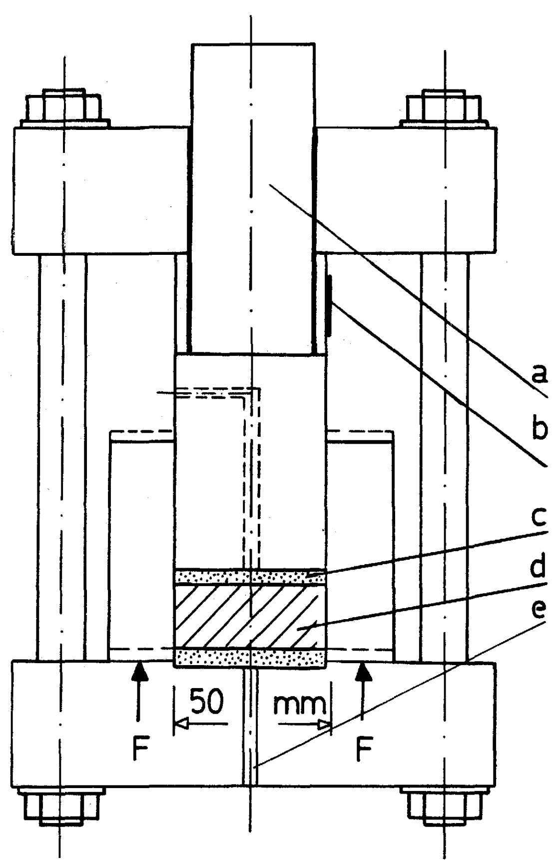


Figure 3-16. The swelling pressure oedometer used for the extrusion tests. At the extrusion the bottom plate was removed and forces F applied to push out the sample. a) piston used for loading the sample in the determination of the swelling pressure. b) ring with strain gauge that signals when the force on the piston balances the swelling force. c) filter of stainless steel. d) clay sample. e) water inlet in the saturation phase

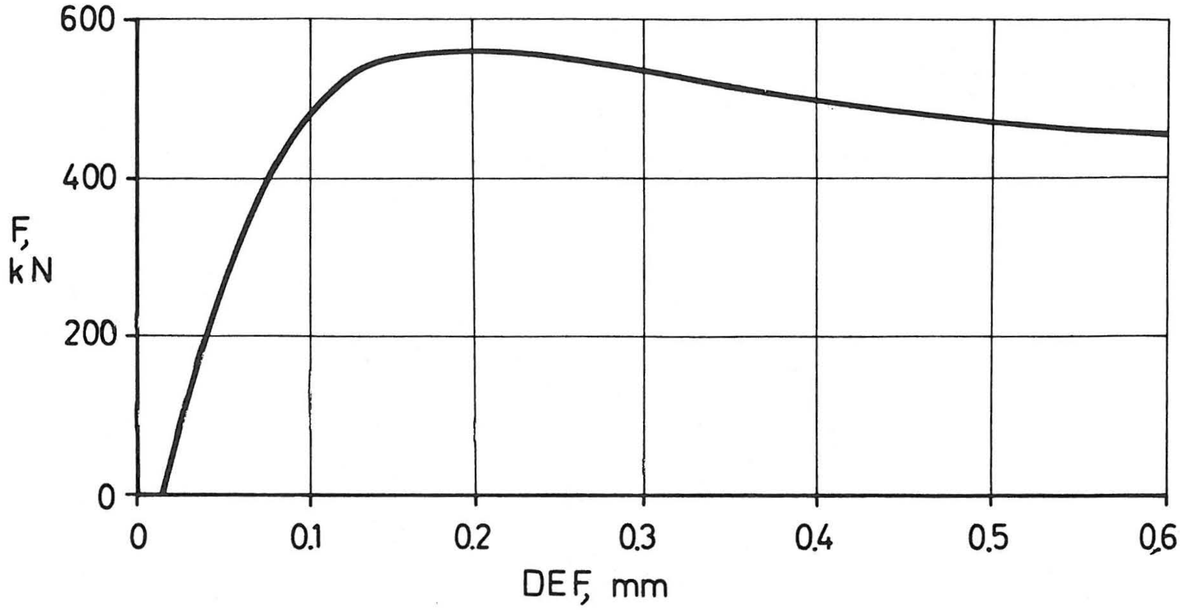


Figure 3-17. Example of the recorded extrusion force versus displacement in the laboratory tests

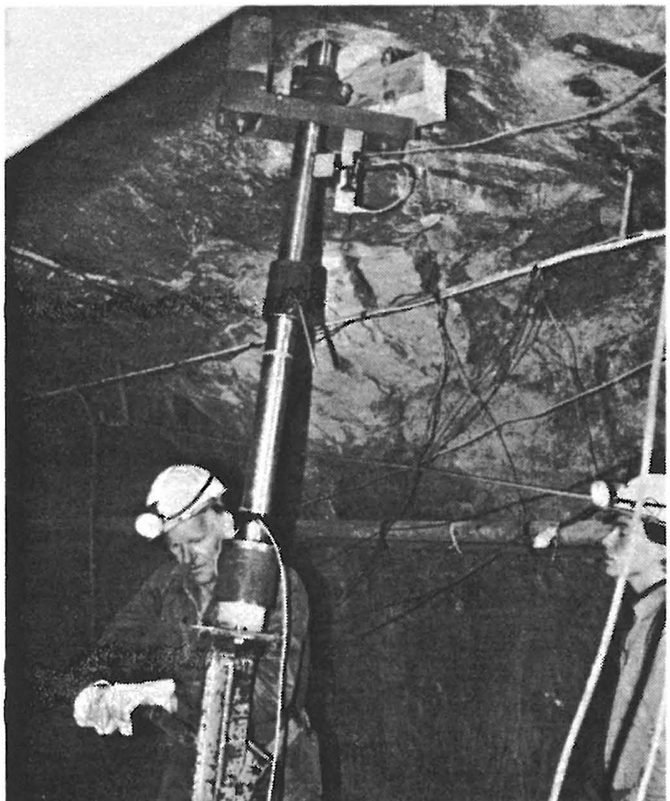
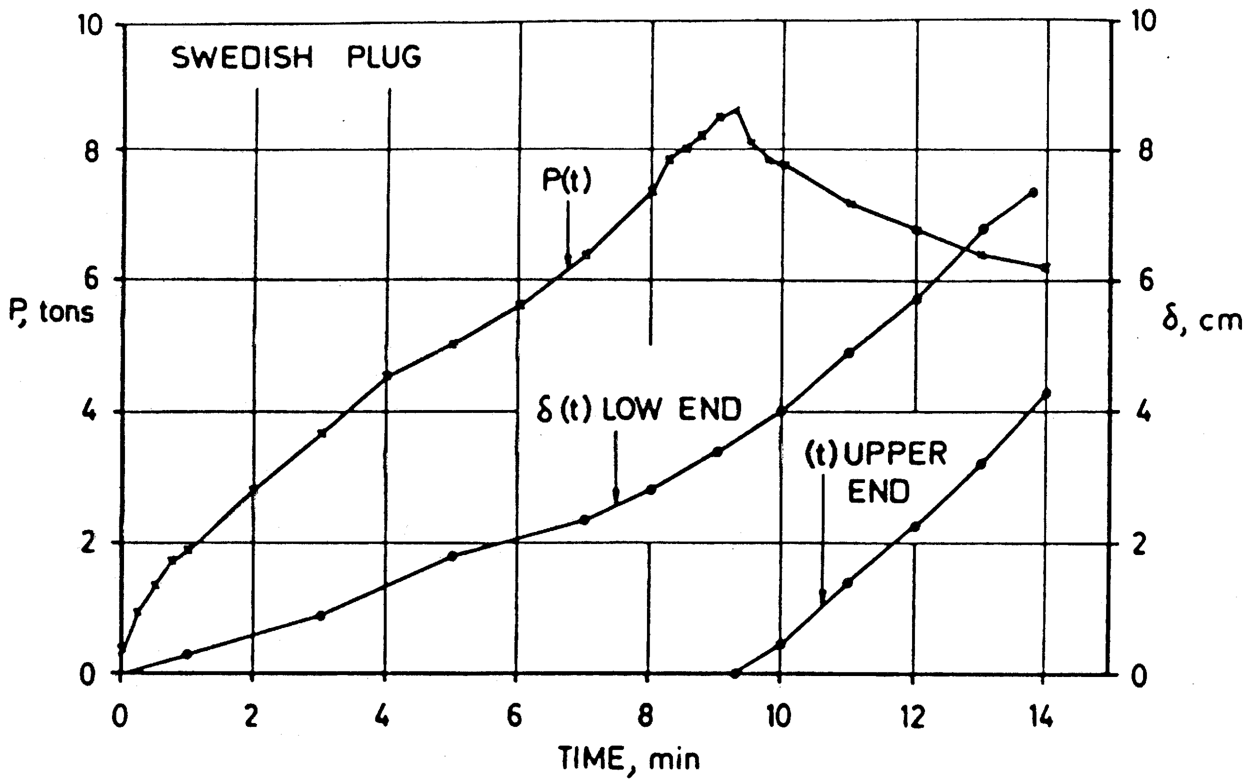


Figure 3-18. Extrusion of the Ø 76 mm borehole plugs by jacking



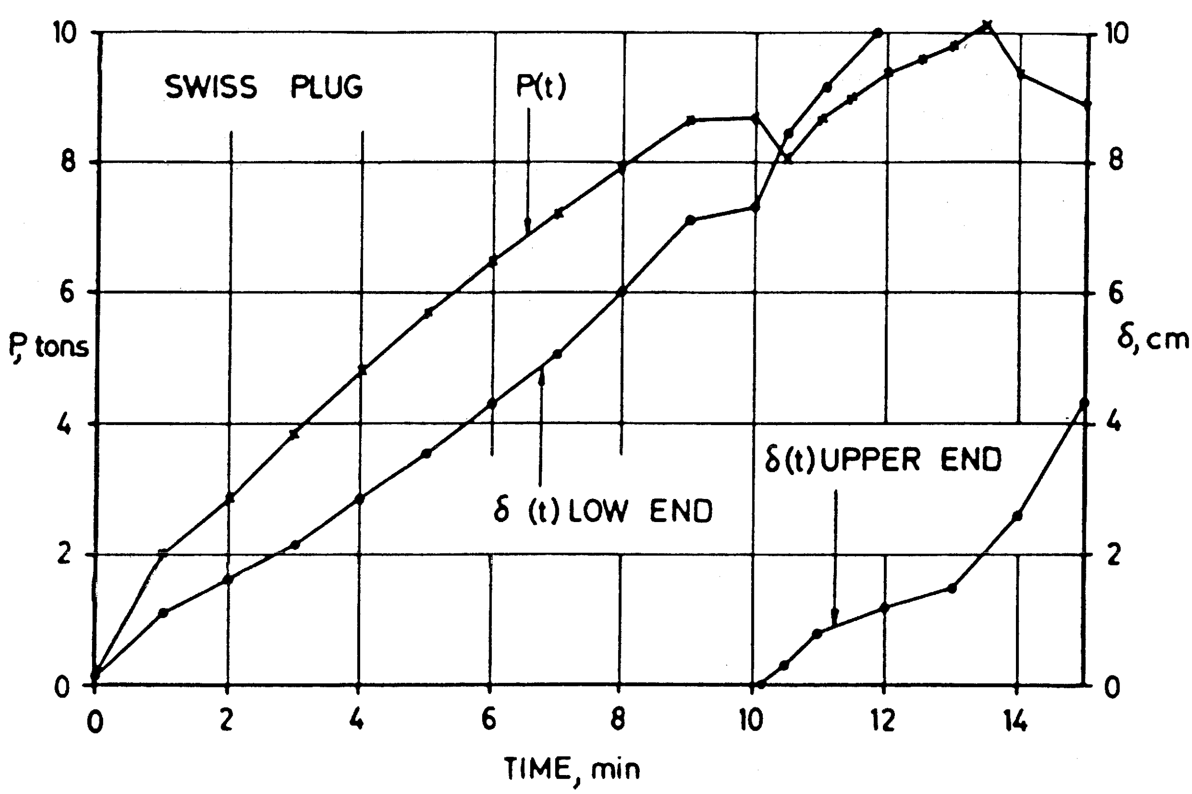


Figure 3-19. Axial force versus displacement at the extrusion of the plugs. Upper diagram refers to the plug with perforated casing in hole IIa

4 CONCLUSIONS

4.1 GENERAL

The usefulness of the investigated borehole sealing technique has been fully confirmed by the field tests. Thus, the process of rapid expansion of blocks of highly compacted smectite-rich clay through porous casings and the embedding of the casings in this clay as predicted by early laboratory tests (Fig 4-1), were found to take place also under real conditions in the rock.

The tests indicate that the technique of using rather stiff metal casings makes it possible to plug boreholes that are more than one kilometer long from above, and that horizontal and slightly inclined boreholes of a few hundred meter length can also be safely sealed. Even boreholes extending upwards from drifts or caverns can be plugged to a considerable depth. Weak, highly porous casings may cause problems at the application but they tend to yield a somewhat faster maturation. It is important, of course, to keep in mind that the boreholes must be stable and that strongly fractured zones should be mechanically stabilized before the plugging starts. This can be made by grouting the zone and then repeating the drilling. Also, it is required that the outer end of the boreholes be sealed with cement or some other suitable substance to prevent the clay from expanding axially.

If the boreholes are water-filled at the insertion of clay plugs, the initially present water is sufficient to make the clay expand and establish firm contact with the rock. From these "columns" (cf. Fig 4-1) a clay gel grows that successively invades the voids and ultimately forms a largely homogeneous clay of the same density as the central clay core. Although the homogeneity of the clay is initially low, it appears to be very resistant to water pressures and hydraulic gradients of considerable magnitude. Thus, an instantly applied water pressure corresponding to a piezometric head of several hundred meters can be carried by an axially confined clay plug of the presently investigated type about one week after its application, provided that it has had access to enough water to become matured. Higher water pressures may produce piping or internal displacements of non-matured plugs. The entire plug may be displaced as one unit in a hole that is open at both ends if the maximum adhesion is exceeded.

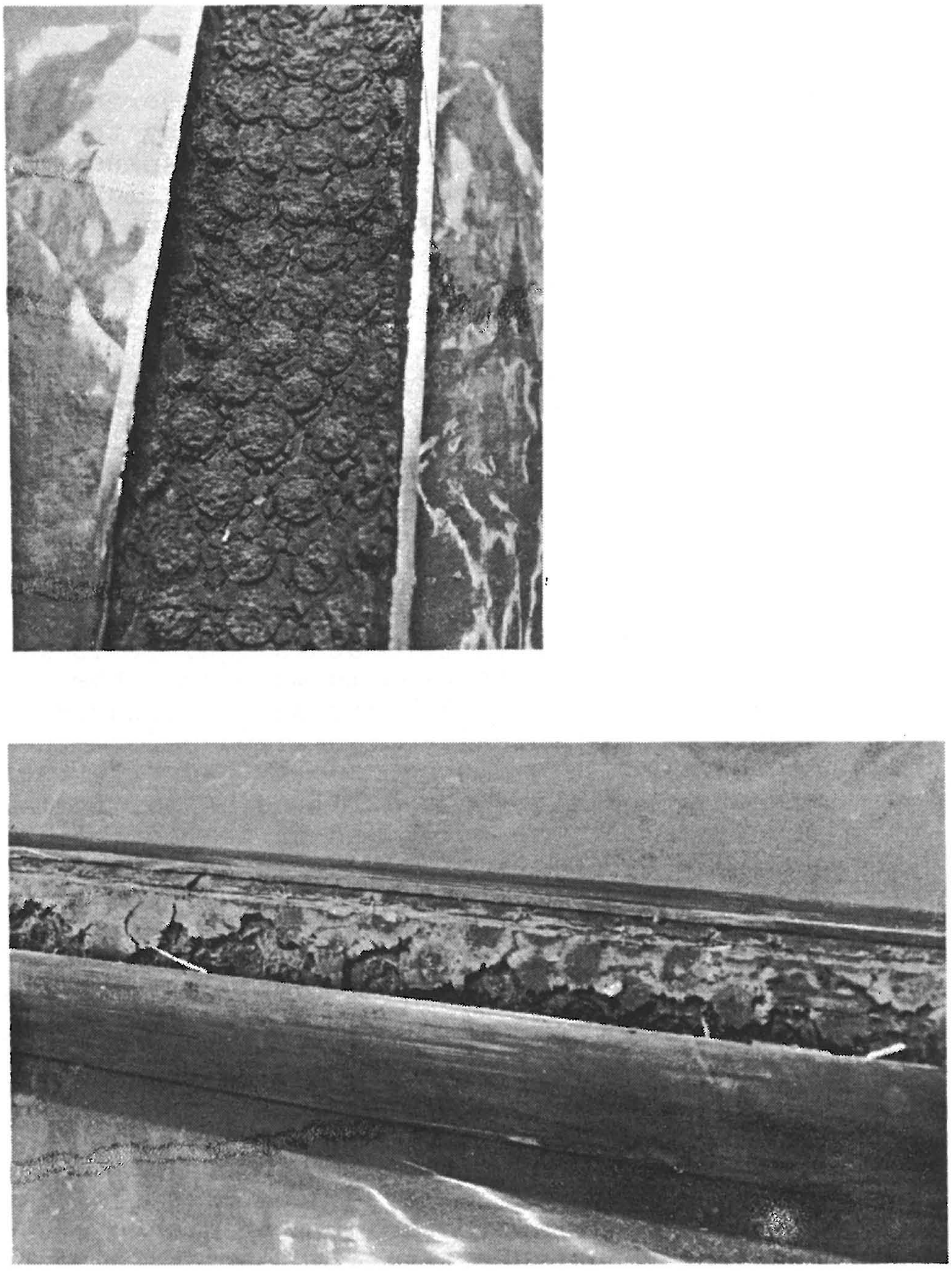


Figure 4-1. Laboratory pilot test in 1980 showing the major features of the sealing process. The upper picture shows the expansion of solid columns of clay through the perforation of the casing. Below is seen the formation of a continuous clay "skin" filling the space between the rock, simulated by a brass-pipe, and the perforated casing

This case may appear if a plugged hole that is pressurized at one end becomes truncated by excavating a drift at large depth. The bond strength, which is easily estimated if the relationship between bulk density and swelling is known for the particular clay, is a function of the degree of maturation. Since there are no practical difficulties in reaching a bulk density of 1.8 t/m^3, which yields a bond strength of at least 0.1 MPa, we see that such a plug in a Ø 56 mm hole is able to carry an axial load of about 2 t per meter length without yielding. This means that for an axial pressure of 8 MPa the plug only needs to be 1 m long. Considering also that the hydraulic conductivity of such a plug does not exceed 10^{-12} m/s it is concluded that matured clay plugs consisting of smectite-rich clay serve as very effective sealings.

The rate of maturation depends on the access to water at the clay/rock interface. It is concluded from the tests that as long as the water pressure in the close vicinity of the plugged hole is on the order of a few hundred kPa, water will be driven through the rock matrix sufficiently fast not to be a limiting factor of the plug maturation. Where the water pressure is low and the rock essentially dry, maturation beyond the initial stage will be very slow and may even stagnate. This is, however, not a disadvantage from a practical point of view since no sealing is actually required under such circumstances. The essential point is that expansion and sealing is produced by the clay when water sooner or later reaches the plugged hole. It may well be accepted that large parts of plugged holes contain "dormant" clay segments as long as its potential to swell is preserved if water appears in the boreholes.

4.2 LONG TERM FUNCTION

4.2.1 General

Although the long term function of clay plugs in rock could not be tested in Stripa, possible threats to safe long term function of the clay needs to be mentioned. They are briefly discussed in the subsequent text.

4.2.2 Major factors

Rapidly flowing groundwater in porous rock zones containing smectitic clay plugs may produce erosion and removal of clay that expands into fractures. This risk is eliminated for a considerable period by grouting and renewed drilling before introducing clay plugs, but chemical deterioration of the grout and thermally or tectonically induced displacements in the rock may lead to reopening of major fractures. Proper composition of the grout, implying a high content of resistant components like quartz powder, will minimize the risk of chemical degradation and erosion but some loss of clay is probably unavoidable. The problem may be solved by applying the principle of clay-sealing only to those parts of the rock that are free from major fracture zones, and filling the parts of the holes that pass through such zones by a suitably graded, slightly cement-stabilized quartz particle mass.

A second, important factor is the chemical composition of the groundwater. The rather high swelling pressure and very low hydraulic conductivity that are characteristic of the clay used in the borehole sealing tests in Stripa is due to the fact that the clay is rich in montmorillonite and that the major adsorbed cation is sodium. Experience shows that also large changes in the porewater electrolyte composition do not significantly affect the swelling pressure at higher densities than about 2 t/m^3, but since it is hardly possible to reach higher densities than about 1.9 t/m^3 in boreholes such changes need to be considered. What can happen is that bi- or polyvalent cations that originate from the casings or from the groundwater of the surrounding rock diffuse into the clay plug and replace the initially adsorbed sodium. A second possibility is that salter water, still with sodium as dominant cation, yields a higher salinity of the clay porewater. Both processes lead to a drop in swelling pressure and to an increased hydraulic conductivity. Considering for example the bulk density range 1.8-1.9 t/m^3 the swelling pressure when passing from the sodium state to calcium or copper states is expected to drop by 20-50 %, while the hydraulic conductivity may increase by 2 to 5 times. An increase in porewater salinity of the clay to that of the oceans is expected to reduce the swelling pressure to about 50 % of the original value, while the hydraulic conductivity may well increase by as much as 5 times. These effects are even stronger at lower bulk densities, but it is concluded that they have a moderate influence on the physical properties and sealing efficiency at those bulk densities which should be aimed at.

Another chemical process that may induce a considerable change in the properties of the clay is the possible transformation of montmorillonite to hydrous mica (illite) or, depending on the pH conditions, to some other collapsed phase such as kaolinite. The matter is dealt with in the reports from the Buffer Mass Test (8) and is currently being investigated in several countries. Our present opinion is that alteration to the smectite family member beidellite is the primary risk because transformation to hydrous mica will then only be a matter of availability of potassium in the porewater. There are theoretical reasons to assume that beidellitization, which has the form of replacement of silica in the SiO_4 tetrahedrons by aluminum, takes place at a temperature of about 100°C. In addition to the charge change, which is produced by this process and which is the reason for the fixation of potassium, there is actually also a risk of cementation by precipitation of silica. It should be added here that higher temperatures than 100°C may not yield complete transformation of montmorillonite to hydrous mica. It may only be partial and very slow and may therefore be accepted.

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FIGURE TEXTS (Final report of the borehole, shaft and tunnel sealing test, Volume I: Borehole plugging)

Figure 1-1	Schematic picture of components and technique of the investigated sealing method
Figure 1-2	Swelling of highly compacted Na bentonite through the holes of the perforated casing. a) appearance after submerging the plug in water for 1 hour, b) 8 hours, c) 24 hours
Figure 2-1	Shape and location of the Ø56 mm borehole DbH2
Figure 2-2	Generalized picture of joints and fractures in the 5 m test section of DbH2
Figure 2-3	Filter arrangement in the DbH2 test. Filter no 1 is located at the inner end of the hole, i.e. about 52 m from Filter no 2 (cf. Fig 2-1)
Figure 2-4	Connection of casing segments to inner jointing sleeve of copper
Figure 2-5	Upper picture: Longitudinal section through filter. Central picture: Assembly of filter with tubings (left), plastic ring, bentonite block and jointing sleeve. Lower picture: First segment being jacked into the borehole. Notice the copper tubings extending through the outer end
Figure 2-6	Cross section through the clay plug. A between Filters 1 and 2, B between Filters 2 and 3, C between Filters 3 and 4, D outside Filter 4, E cement-grouted part with two extra tubings to make drainage of the central pipe possible
Figure 2-7	Schematic picture of the arrangement of filters and tubings
Figure 2-8	Arrangement for injection and flow measurement, de-airing, and pressure recording
Figure 2-9	Mounting of clay blocks in casing with central pipe for the filter tubings