R-08-42

KBS-3H post-grouting

Mega-Packer test at –220 m level at Äspö HRL

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December 2008

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Keywords: KBS-3H, Post excavation grouting, Mega-Packer, Silica sol, Repository, Ground water leakage, Äspö.

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

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Contents

1 Introduction

1.1 Objective

This study concerns grouting of horizontal deposition drifts to be used as storage of spent nuclear fuel. The study is made on behalf of the Swedish Nuclear Fuel and Waste Management Co (SKB) and Posiva, Finland, as a part of the ongoing KBS-3H project. The objective is to present results and experiences from practical test on post-grouting horizontal drifts at Äspö with the overall purpose of validate Mega-Packer as potential grouting method.

1.2 Background

Techniques for storage of spent nuclear fuel are currently evaluated in Sweden and Finland. In Sweden the Laxemar area in Oskarshamn and Forsmark area in Östhammar are concidered sites for a nuclear waste repository. In Finland a repository will be built in Olkiluoto island in Eurajoki. The reference layout for a repository in Sweden and Finland is based on vertical deposition (KBS-3V). Horizontal deposition in drifts (KBS-3H) is considered as an alternative designdeveloped further parallel to the vertical deposition design. KBS-3V and KBS-3H are designs variants of multi barrier KBS-3 method.

Horizontal drifts for deposition of canisters of spent nuclear fuel have been evaluated in the Swedish and Finnish waste management program as a potential deposition design. Drifts for deposition are planned to have a diameter of 1.85 m and a maximum length of about 300 m. In the drift a number of canisters will be emplaced, separated by blocks of bentonite. The layout is visualised in Figure 1-1.

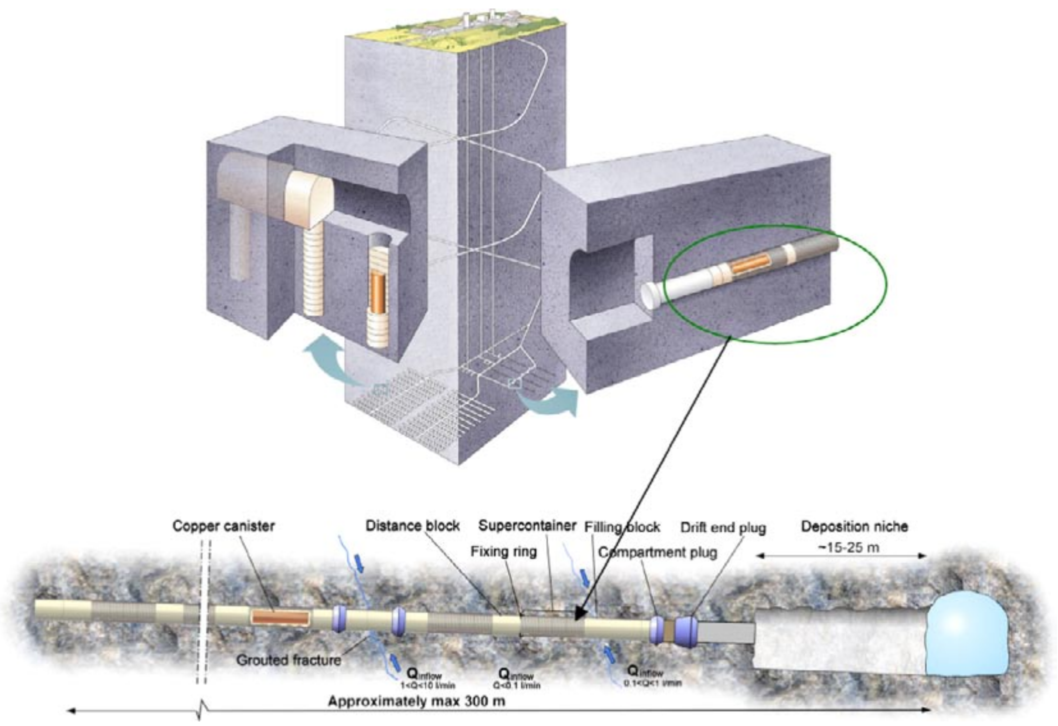

Figure 1-1. *Deposition drift /Autio et al. 2008/.*

A key issue for horizontal deposition is the groundwater control. Methods have to be developed to manage reduction of water inflow before, during and after excavation. Before excavation grouting in pilot holes or grouting holes are conceptually possible. During excavation pre-grouting similar to common tunnel grouting may be utilized if suitable equipment can be obtained or developed. However, it is likely that measures for reduction of water inflow must be applied after excavation, i.e. using post-grouting methods. Post-grouting is known to be difficult and considering both practical and theoretical issues, conventional post-grouting is not likely to be successful. Instead the concept of grouting with a Mega-Packer is evaluated as one method for sealing leaking sections.

A horizontal drift as a storage of nuclear waste has several advantages as deposition method, but the groundwater inflow in the drift may be a potential problem. Values for the inflow permitted at each position are preliminary and may be changed. As the tests with the Mega-Packer were performed, the following mentioned values were guiding principles for the inflow permitted. A value of inflow that can be accepted for deposition of canisters is 0.1 litres/minute per canister position. If the inflow exceeds this value, deposition of canister is not allowed. If the inflow exceeds 0.1 litres/minute but is less than 1 litre/minute filling blocks are placed in these positions. Sections in the drift with inflow over 1 litre/minute per 10 m long super container sections are isolated by using compartment plugs /Autio et al. 2008/.

The grouting methods in horizontal drifts to be used as storage of nuclear waste are limited by the fact that drilling grouting holes outside the tunnel contour (penetrating the nearby rock with drilling holes) is not favourable from a safety point of view. The grouting may be performed as pre-grouting using conventional grouting material or silica sol in the pilot borehole or in a grouting fan that is kept inside the tunnel contour. If the effect of the pre-grouting does not fulfil the requirements regarding water inflow other methods have to be used to seal the tunnel. Regarding the requirements not to drill a grouting fan outside the tunnel contour, conventional post-grouting cannot be performed, since this includes drilling a grouting fan outside the tunnel contour.

A theoretical evaluation of Mega-Packer was made in /Autio et al. 2008/. In this report the sealing method and its theoretical potential are presented in detail.

2 Method of approach

2.1 General

According to the theoretical studies made so far on the Mega-Packer concept it has potential to fulfil the needs to reduce the water inflow as desired. Due to the complexity of the problem, the theoretical studies have to be verified by practical tests.

The overall method of approach is to:

- Present an a-priori estimate of the method potential.
- Design and execute practical test.
- Validate the current knowledge.
- Summarize data for detailed post priori modelling.
- Present results for future calculations and tests.

In this report the design of the Mega-Packer and practical tests using silica sol are presented.

The goal with the tests was primary to verify the Mega-Packer as a grouting method, secondary to fulfil the requirements set up regarding water leakage per position grouted after the grouting had been performed.

The tests of the Mega-Packer were performed in two sets, at two occasions due to limited access time at the test location. In the first set, performed in November 2007, hydraulic characterisation was made for all of the five positions and position 1 and 3 was grouted. Position 3 was grouted two times.

The time between the two test sets was used to make improvement of the equipment and method applied in the characterisation and the grouting.

The tests continued in Mars 2008. Then position 2, 4 and 5 were hydraulic characterised and grouted. Position 5 was grouted two times.

2.2 Deposition drift

The demonstration drift is located at Äspö Hard Rock Laboratory at the –220 m level.

In 2004 and 2005 two horizontal drifts were drilled /Bäckblom and Lindgren 2005/, see Figure 2-1 and Figure 2-2. The longer of the two drifts, DA1619A02, was drilled in 2005 and is 94.45 meters long and has a diameter of 185 centimetres and is the one used for the Mega-Packer tests. The shorter drift, DA1622A01, was drilled in 2004. It is 15.85 meters long and has not been used in the tests but the ground water inflow has been measured in order to study how grouting in the main drift DA1619A02 affects the ground water inflow in the shorter drift.

The distance between the two drift varies due to the fact that they diverge with an angle of about 15 degrees. The openings are placed about 4 meters apart, and the distance between the drifts is as most about 8 meters.

In the longer drift five inflow points (positions) were relevant and represented what could be expected in a KBS-3H deposition drift, see Figure 2-3.

In June 2005 the total inflow to the drift was measured to around 12 litres/minute. According to /Bäckblom and Lindgren 2005/ the inflows was characterised by a high pressure gradient and a channelled flow, resulting in a sprinkling or dripping flow, see Figure 2-4.

The initial inflow was considerably more than prior to the experiments in October 2007 when the inflow was measured to around 4.5 litres/minute.

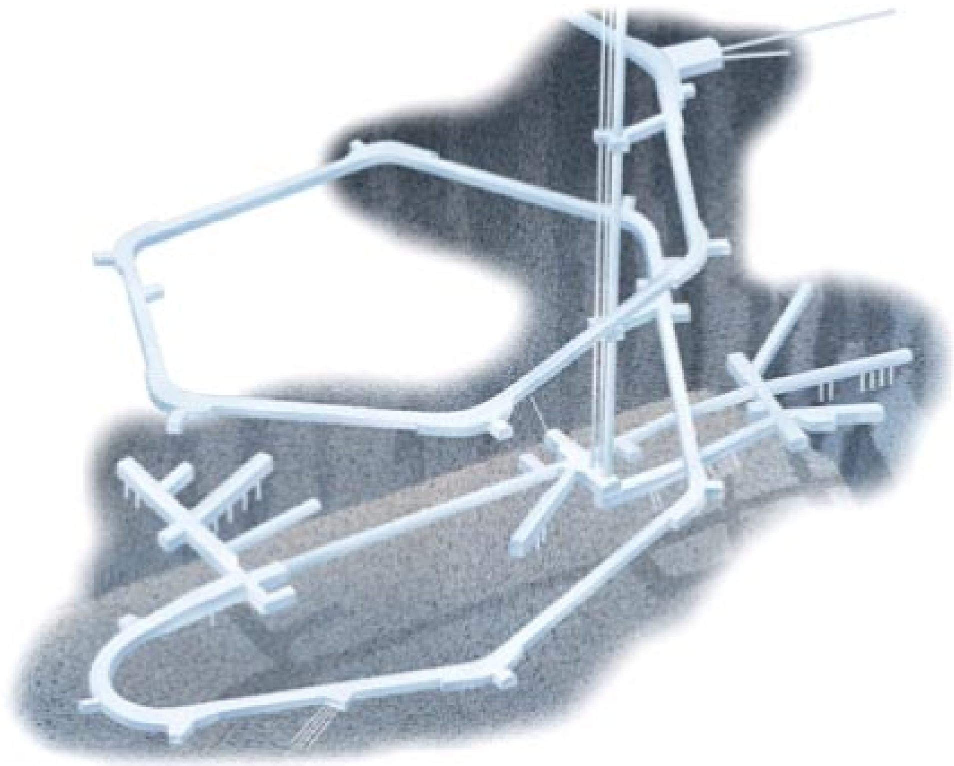

__Figure 2-1.__ Overview from Äspö Hard Rock Laboratory.

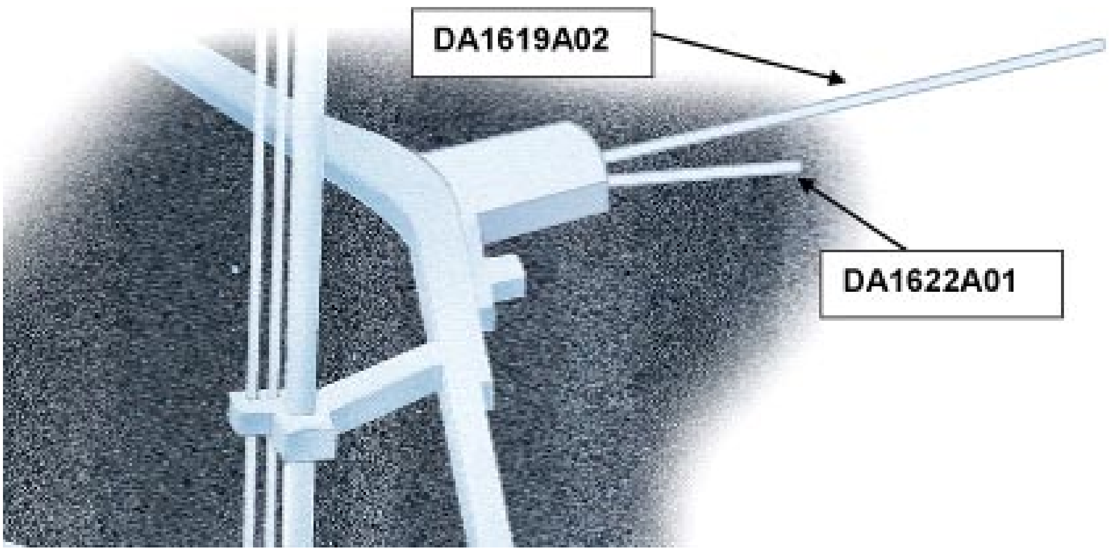

__Figure 2-2.__ Close up figure showing DA1619A02 and DA1622A01.

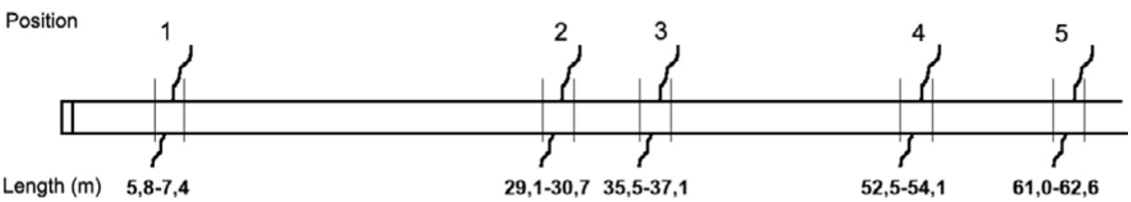

__Figure 2-3.__ Principle overview over the five selected positions to grout.

Figure 2-4. *Picture from the initial situation with a sprinkling flow due to high pressure gradient / Bäckblom and Lindgren 2005/.*

2.3 Geology

The main rock type in the drift is granodiorite (Äspö diorite). Several dykes or veins of red, fine grained granites and coarse grained pegmatites have intruded the granodiorite.

The rock also contains minor parts of so called Småland granite and several xenoliths of greenstone. The granodiorite has gone through a brittle-ductile stage of deformation after the intrusion of pegmatites and aplites. The overall fracture frequency is about 1 fracture per meter and three fracture sets have been observed. The first group traverses the drift perpendicular or in steep angels. The second group represents sub-horizontal fractures.

Fracture filling is noted as epidote and/or calcite. The leaking fractures are noted to strike the full drift.

In 2004–2005 a drill core was made in the place where DA1619A02 was going to be drilled. From that drill core the fracture frequency has been analysed. /Bäckblom 2005/

Fracture length, distance and rock type is presented in /Bäckblom 2005/.

2.4 Design of the grouting

Design of the grouting was made with the target of reaching an inflow of maximum 0.1 l/min in one grouting position. Due to the case with one fracture in each inflow position this means that the grouting is designed to reach a maximum inflow of 0.1 l/min in each fracture.

Calculation on design have been carried out in the pre-study and the equations used are presented in /Autio et al. 2008/. A detailed design for each grouting situation could be made. However, in this case it was found valuable to have the same design in all grouting situation. All grouting rounds were planned and adjusted using the grouting time to fulfil a theoretical penetration length of 5 m. A sensitivity study was also made to estimate the penetration length for cases of 20%, 50% and 80% open area in the fracture plane, i.e. under the assumption of a channelled flow.

A further presentation of the grouting design is made in Section 2.7.5.

2.5 Silica sol

2.5.1 General

To use silica sol as grouting material was a pre-requisite for the experiment. For this reason no other grouting material has been evaluated.

Silica sol consists of very small, spherical particles of amorphous silica, SiO_2, suspended in water. The pH-value is around 10 /Axelsson 2005/. Silica sol can penetrate fractures of at least an aperture of 15 µm /Funehag 2007/.

The gel time of the grout can be controlled using different amount of salt solution or different concentrations of the salt in the solution. In the experiments a salt solution of NaCl (10%) was used. The silica sol used in the grouting tests is Meyco MP 320.

2.5.2 Gel time tests on silica sol

To find out a recipe fulfilling the demands regarding gel time for grouting in the deposition drift, different proportions of accelerator and silica sol was tested. The tests were performed so that different proportions of accelerator and silica sol were mixed and the gelling time was measured. The mix proportions that reached the required gelling time were then used when mixing the silica sol prior to the grouting sessions inside the drift.

Tests were also performed using different proportions of water leaking in to the actual position in the drift, to investigate the change in gelling time when silica sol was diluted with saline ground water. See 5.2.2.

2.6 Equipment

The equipment used in the experiments consists of:

- The Mega-Packer.
- Data Taker (data logging equipment).
- Unigrout including Logac (data logging equipment).
- Water Injection Controller (WIC).
- Pressure tanks.
- Nitrogen gas tubes.
- Various kinds of hoses and tools.

2.6.1 The Mega-Packer

The Mega-Packer denotes equipment consisting of a large tube with a diameter of 182 centimetres, 1.97 meters long (grouting length 1.59 meters) of 48 mm steel, only slightly smaller (30 mm) than the drift (e.g. 15 mm gap between the Mega-Packer and the drift when centred), with packers sealing off selected positions at both ends see Figure 2-5 and Figure 2-6. The steel tube has connections for valves, so that hoses and measurement equipment can be connected.

The length of the Mega-Packer is flexible and can be adjusted to suit different lengths of fractures about to be grouted.

The packers were inflated with water at a pressure required to resist grout penetrating out between the packers and the rock wall during grouting.

The Mega-Packer has been tested in the experiment for characterisation and grouting of selected positions in the drift.

For moving the Mega-Packer in the drift, four wheels were attached. These are made of steel and can raise and lower the equipment.

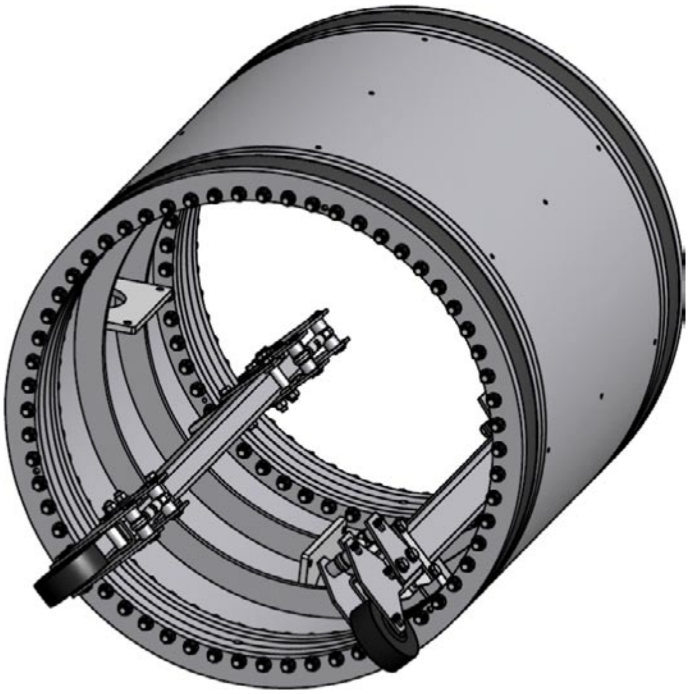

Figure 2-5. A sketch of the Mega-Packer.

Figure 2-6. The Mega-Packer.

2.6.2 The Data Taker

The Data Taker equipment is used to log the data produced during the grouting and in the pressure build up tests. After the experiments, data is extracted from the Data Taker to a PC where the data can be further analysed.

The Data Taker DT50 series 3 was connected to the gap between the Mega-Packer and the rock wall via a cable and a sensor assembled to one of the valves of the Mega-Packer body.

2.6.3 The Unigrout

The Unigrout is a platform used for grouting manufactured by Atlas Copco. It consists of a pump, a logging equipment (Logac) and an agitator to mix and store grouting material. During the experiments two different types of grouting equipment were used.

Unigrout E 22 H

The older version of Unigrout, Unigrout E 22 H was used in the grouting sessions performed in November 2007, see Figure 2-7.

The Unigrout E22H is constructed for cement grouting originally.

This equipment is quite simple in it's construction. It consists of a mixer to store and mix the grouting material, a pump to pump the grouting material in to the gap, hoses to lead the grouting material from the Unigrout equipment to the Mega-Packer, a logging equipment (Logac) to store grouting data such as pressure, time, flow and the volume pumped. There is a control panel to adjust the grouting pressure from the pump. The volume capacity of the pump is 0–120 litres per minute and the pressure capacity ranges from 2–100 bar. The amounts of accelerator and silica sol were dosed by hand by volume.

Figure 2-7. *The Unigrout equipment used in November 2007.*

Unigrout EH22 200-140 AWB-SS

The newer Unigrout EH22 200-140 AWB-SS that was used in the second stage of the experiments is especially adjusted for silica sol grouting. It consists of four different tanks; one mixer, one for the accelerator, one for water used to clean the equipment and one not being used in the experiments, see Figure 2-8.

The newer Unigrout system was equipped with a system to log the weight of the different tanks. The weight was logged for the tank in which silica sol was mixed and kept during the grouting. The weighing system was connected with a control panel and a display. With the control panel the mixing can be adjusted, the display can be shifted to show the weight of the different tanks, the water from the storage tank can be pumped in to the system for cleaning et cetera.

With help from the weighing system the amounts of silica sol and accelerator from the recipe was pumped from the containers to the tanks of the Unigrout.

The logging equipment Logac G5 registers data from the grouting process. It registers pressure, flow and time. The data can be extracted from the Logac via an USB memory stick to be further analysed.

In addition, the scale system was connected to the Data Taker equipment. The Data Taker equipment registered the total volume left in the Unigrout during the grouting. The data extracted was then being used to evaluate the volume of silica sol grouted, since the Logac equipment didn't work to log the pumped volumes with the accuracy needed.

2.6.4 The Water Injection Controller (WIC)

The water loss measurement equipment is named WIC- 20-65/20, See Figure 2-9.

The pressure is kept constant during the measurement session and is adjustable during the measurement if it's needed.

The equipment consists of a pump and a logging computer. The computer logs pressure and flow every other second. The pump is adjustable and the accuracy of the water flow is < 20 ml/minute. The logging data is stored in the equipment and can be transferred to MS Excel to be further analysed.

Figure 2-8. *The new Unigrout Equipment (EH22 200-140 AWB-SS) used in Mars 2008 /Atlas Copco 2007/.*

Figure 2-9. *The Water Injection Controller /Geosigma/.*

2.6.5 Pressure tanks

Pressure tanks were used when inflating the packers to control the pressure put on them. The actual pressure was 50 bar, and with help from the pressure tanks this could be controlled.

The pressure tanks were connected to the nitrogen tanks in the top. The nitrogen tanks put a pressure on the water in the pressure tanks. The pressure tanks were connected to the packers via a hose in the bottom. Since the water in the pressure tanks was pressurized it could be easily controlled that the pressure on the water out to the packers was right. See Figure 2-10.

2.7 Test strategy

The strategy of the testing in the drift was to hydraulically characterise each of the five selected positions in the drift before and after grouting (pre and post characterisation) and evaluate the grouting effect. The pre characterisation consists in three activities; ground water pressure build up test, measurement of the amount of water leaking in to the drift and water loss measurement. The post characterisation consists in measuring the water leaking in to the drift after grouting in all positions.

The tests program includes:

1. Performance test of the packers.
2. Hydraulic pre characterisation of the five positions (inflow measurements, pressure build up tests and water loss measurements).
3. Grouting design.
4. Grouting tests with silica sol.
5. Evaluation of performed test – post characterisation.

2.7.1 Performance test of the packers

To be able to perform any tests the sealing off effect of packers had to be tested. If the sealing off effect was not perfect, then the other tests such as the pre characterisation and the grouting tests could not be performed.

Figure 2-10. *Pressure tanks (in the front) connected to the packers.*

2.7.2 Inflow measurements

The inflow measurements shall be performed as the Mega-Packer is put in place for the actual position and the gap is filled with water. The water leaking into the gap from the fracture that is going to be characterised will over fill the gap so that it leaks out of the top valve of the Mega-Packer. The water leaking out is measured with a graduated cylinder during one minute in three sets to get as correct values of the inflow as possible.

The inflow is governed by the transmissivity (T) of the fractures and the ground water pressure (h) as expressed by Equation 2-1, where r is the radius of the opening of the drift /Eriksson and Stille 2005/.

$$Q = \frac{2\pi \cdot T \cdot h}{\ln\left(\frac{2h}{r}\right)}$$

Equation 2-1

Equation 2-1 can be used to estimate the transmissivity of the fracture based on the measured inflow.

2.7.3 Pressure build up test

The ground water pressure build up tests were performed in means that the Mega-Packer body was filled with the ground water leaking in to the actual position. When the gap was over filled, the top valve was closed and the ground water pressure in the gap was built up.

This pressure was logged with a logging equipment (Data Taker) with help from a sensor connected to one of the valves in the Mega-Packer.

The pressure build up test is used to find out the ground water pressure and the transmissivity of the actual position. The transmissivity can be calculated from a curve where the water pressure is plotted on the Y-axis and the time is plotted in log scale on the X-axis. The transmissivity is related to the hydraulic aperture and number of fractures in the surrounding rock.

The instant ground water pressure was measured, which also was that pressure that was of interest regarding getting values for the grouting design. No further ground water pressure was measured, since when the ground water pressure was developed after 15 minutes, the ground water took other ways getting out in the drift in neighbouring fractures.

The transmissivity of the section can be evaluated using Equation 2-2 and the monitored pressure built up assuming only one transmitting fracture. Q is the evaluated inflow in the section and ds" is the pressure increase over the time according to Jacob's method, see /Gustafson 2008/.

$$T = \frac{0.183 \cdot Q}{ds''}$$ Equation 2-2

Based on the evaluated value of T the hydraulic aperture can be evaluated using cubic law (Equation 2-2) in the form of Equation 2-4.

$$T = \frac{b^3 \cdot \rho \cdot g}{12 \cdot \mu_w}$$ Equation 2-3

$$b = \left(\frac{T \cdot 12 \cdot \mu_w}{\rho \cdot g} \right)^{1/3}$$ Equation 2-4

2.7.4 Water loss measurement

The water-loss measurement gives a value of the conductivity of the surrounding rock. The test is performed in the same way as grouting, but water is used instead of grout.

The goal with a water-loss measurement is to reach a stable flow of water into the surrounding rock at a certain pressure (10 bar over the ground water pressure). The water loss is measured instantly and gives a value of the water loss measured in litres per minute.

The transmissivities from the water loss measurement is evaluated using Equation 2-5 (Thiem's equation). In this the radius of influence (R_0) is needed. It may be that this radius of influence is different for the different inflow positions but is assumed to be the same and equal to 100 times the drift radii (r).

$$T = \frac{Q}{2 \cdot \pi \cdot \Delta h} \cdot \ln\left(\frac{R_0}{r} \right)$$ Equation 2-5

2.7.5 Grouting

After the hydraulic characterisation (water inflow measurement, pressure build up test and water loss measurement) was performed, the grouting design was created based on the values from the pre characterisation. Following the grouting design, the grouting was performed.

Based on the pressure build up test performed at the actual position the pumping pressure for the water loss measurement and the grouting was decided. The pressure used when performing the water loss measurement and the grouting was 10 bar over the ground water pressure, found out by the pressure build up test, e.g. the pressure at the water loss measurement and the grouting was equal.

Based on the flow measured in the water loss measurement the pumping time for silica sol was decided. It was assumed that the silica sol solution had a viscosity 10 times the one of water and that the target was to fill theoretically 5 m outside the contour. Based on the expected hydraulic aperture this gave different grouting times and the gelling time of the silica sol was adjusted to fit this pumping time.

The pumping time was longer than the grouting time, since silica sol diluted by ground water leaking in to the actual position had to be removed. About 20–30 litres were removed out of the upper valve. The time needed to fill the hoses, gap and evacuate the diluted silica sol was added to the gel time to get the pumping time.

2.7.6 Evaluation of performed tests – post characterisation

To facilitate evaluation of the performed test post characterisation at each position was made. In this the inflow after grouting was measured. Based on this value the obtained sealing effect can be evaluated.

3 Implementation and result

3.1 Preparing work

3.1.1 Moving the Mega-Packer

The moving of the Mega-Packer in to the drift, in the drift and out of the drift was performed with a wire winch.

The removal of the Mega-Packer i.e. the moving out of the drift, after the grouting was considered as a potential problem, but after the first grouting session it was showed that the Mega-Packer could be transported out of the drift with the wire winch and no other equipment for removing the Mega-Packer after grouting was required. The reason why another equipment might had been required is that the silica sol was thought to have a gluing effect between the Mega-Packer and the rock wall. The gluing effect was however so small so that the wire winch was solid enough to bridge it.

3.1.2 Performance test of the packers

The performance test of the packers was done two times, one time in November 2007 and one time in March 2008.

The test of the packers was done in a position in the drift with no visible fractures. The position was chosen due to the absence of fractures. In the absence of fractures the water pumped into the gap would have no place to escape apart from leaking out between the packers and the rock wall, if the packers would not meet the requirements in the sealing off effect.

The gas bottles with nitrogen gas, the pressure tanks, water hose and electricity was installed in the Mega-Packer body. The equipment was assembled and prepared for the functional test.

The packers were pre filled with water from the water hose. The pressure tanks were filled with water and connected to the gas tubes and the packers were pressurised with 50 bars. During the pressurising procedure the packers was de-aired, to guarantee that they only contained water.

Further the gap was filled with water, approximately 125 litres. The pressure equipment (gas bottles and the pressure tanks) was connected to the gap and pressure was put on the water in the gap. The pressure was increased stepwise and finally was 40 bars reached.

During the session where the water was pressurized in the gap, water leaking out from the gap between the packers and the rock wall was not observed. In Figure 3-1 it is seen that a complete sealing off effect was achieved.

No change of the water level in the vessel outside of the pressure tank was observed during the performance test, showing that the pressure in the packers was constant during the performance test.

3.2 Hydraulic pre-characterisation of the five points

The hydraulic pre characterisation of the five positions was performed in three steps:

1. Water inflow measurements.
2. Ground water pressure build up tests.
3. Water loss measurements.

3.2.1 Water inflow measurements

To perform the water inflow measurements, the gap was filled with water. The top valve was opened and water oozed out of the gap at the same rate as water came out of the actual fracture that was covered by the Mega-Packer. The water inflow measurements were performed with a graduated cylinder collecting the water leaking out of the top valve.

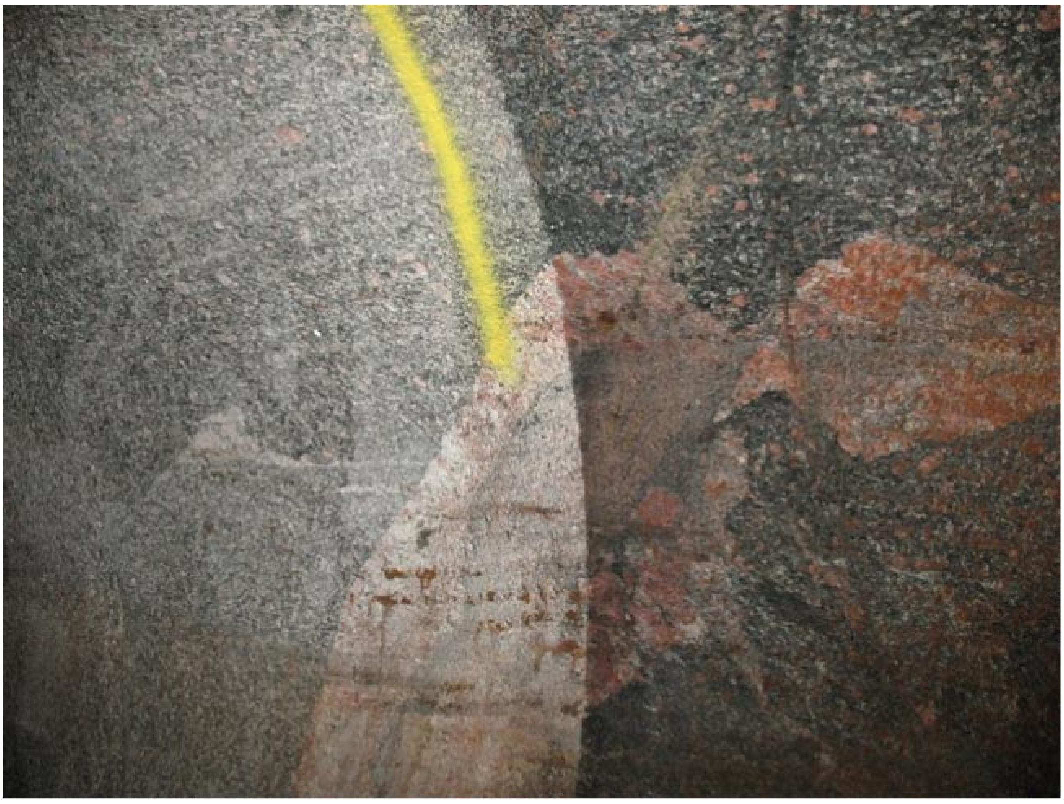

Figure 3-1. *Picture showing a wet rock wall and a dry rock wall. This photo is showing that the performance test of the packers was performed perfectly and that the packers had an excellent sealing off effect.*

The measurements were performed after about 30 minutes with open valve and flowing water, to get a stable flow. Three measurements were done, and a mean value of the inflow was calculated from these.

Before the grouting the inflow was visible in all positions as drops or as a minor streams of water down the rock wall.

3.2.2 Ground water pressure build up tests

The ground water pressure build up tests were performed as the first of three tests to hydraulically characterise the actual position. Then the Mega-Packer was placed in position and the packers were pressurised and the measurement and logging equipment was connected to the Mega-Packer via a pressure sensor, see Figure 3-2. The gap was filled with water and all of the valves were closed.

3.2.3 Water loss measurements

The water loss measurements were performed in 15 minutes long runs. A hose was connected between the WIC and the Mega-Packer and water was pumped in to the gap of the Mega-Packer at a pressure of 10 bars over the ground water pressure found measured during the ground water pressure build up tests.

The WIC-equipment logged the pressure and the instant water loss every other second.

3.2.4 Moving the Mega-Packer

Moving of the Mega-Packer was the most complicated step in the tests since the wheels were not functioning as predicted. This led to problems in moving the device as the wheels made the Mega-Packer rotating while moving it. See Figure 3-3. There was a risk of a great rotation might had caused an overturn of the Mega-Packer in the drift.

Figure 3-2. *Logging during the ground water pressure build up test.*

Figure 3-3. *The Mega-Packer in the drift. The position of the wheels tells that there has been a rotation of about 15 degrees.*

In the first set of experiments in the autumn of 2007 the problem was counteracted with lead weights, loaded at the side of the Mega-Packer moving upwards during the movement of the device. The load was about 400 kilos and was required to manage to move the Mega-Packer in the drift without overturning. However, some times the lead weights had to be moved to the other side as the Mega-Packer started to rotate in the opposite direction.

Before the second session of the tests (March 2008), the wheels were re-constructed so that they were able to adjust and in that way the Mega-Packer could be steered, and the risk of overturning was attended to.

3.2.5 Results from the pre characterisation

The pre characterisation of the five selected positions was performed in three different steps; water inflow measurements, pressure build up test and water loss measurements.

In November 2007 all five selected positions were pre characterised hydraulically, which is summarized in Table 3-1.

The ground water pressure measurements for position 1 and 2 did not give any stable values.

In Mars 2008, after grouting of position 1 and 3 in November 2007, the positions 2, 4 and 5 were pre characterised once again. The result is summarized in Table 3-2.

After grouting of position 5 the first time and grouting of position 2 and 4, a new hydraulic characterisation was done for the actual position. The result can be seen in Table 3-3.

The overall result is showed in Table 3-4 where the water inflows in to the tunnel are showed before and after grouting.

It has been noted that as the main fractures in the drift have been sealed, the ground water partly has found other ways of reaching it, using smaller fractures that before the grouting not conducted water in to the drift. Two such fractures were detected after the grouting was finished, at 11 m and 17 m. See Figure 3-4.

Hydraulic characterization of these new inflow positions has not been performed, but may be object for further work. See 7.1.

Table 3-1. The results from the pre characterisation in November 2007.

Position	Water inflow (ml/min)	Ground water pressure (bar)	Water loss (l/min)
1	2,400	> 1.4	12
2	25	> 1.45	0.18
3	490	8.3	0.86
4	1,470	7.9	2.25
5	148	3.6	0.38

Table 3-2. The results from the pre characterisation in Mars 2008.

Position	Water inflow (ml/min)	Ground water pressure (bar)	Water loss (l/min)
2	145	11.0	0.6
4	1790	10.7	2.2
5	190	7.0	0.37

Table 3-3. The hydraulic characterisation of position 5 after grouting of all other positions.

Position	Water inflow [ml/min]	Ground water pressure [bar]	Water loss [l/min]
5	190	21.1	*

* = The water loss measurement could not be performed, while the WIC only can perform water loss measurements up to 20 bars. Since the ground water pressure was 21.1 bars and a pressure of 31.1 bars was required to perform the water loss measurement, this parameter was left out.

Table 3-4. Result from the grouting. The table shows values of ground water leaking in to the drift per position before grouting and after grouting.

Position	November 2006 Before grouting of any position [ml/min] *	November 2007 Before grouting of any position [ml/min]	Mars 2008 Before grouting of position 2, 4 and 5 [ml/min]	Mars 2008 After grouting of position 5 [ml/min]	Mars 2008 After grouting of position 4 and 5 [ml/min]	Mars 2008 After grouting of all positions [ml/min]
1	2960	2400	–	–	–	4
2	90	25	–	–	145	7
3	870	490	–	–	–	15
4	2240	1470	–	1760	–	3
5	280	148	190	–	–	25

* = No information can be received from SICADA on how the measurements were performed.

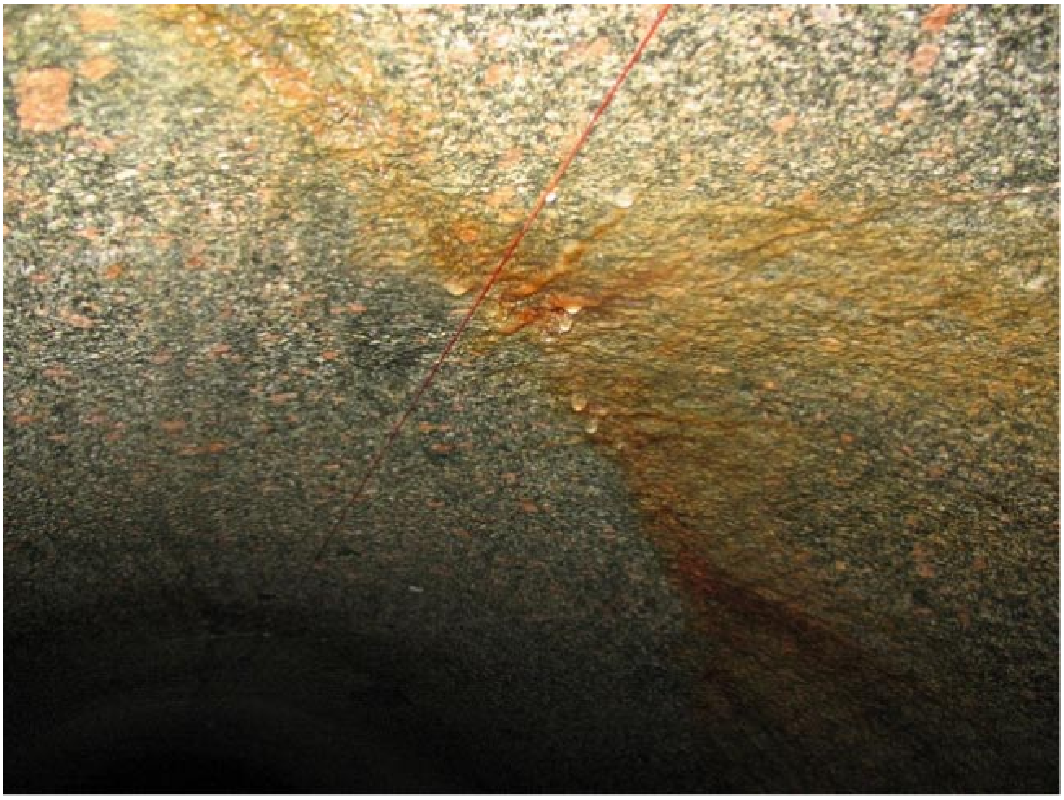

Figure 3-4. New water inflow in the roof at 17 m from the opening of the drift DA1619A02.

3.3 Grouting

The grouting was performed in two stages.

In the first stage, two positions were grouted, position 3 and then position 1. The equipment used at these two grouting positions was the older version of Unigrout from Atlas Copco, E 22 H. The grouting equipment included a flow meter, Logac, with which the instantaneous flow and the total flow was to be measured. However, the flow meter did not manage to measure the flow correctly. The intolerance of the flow meter due to the beating of the piston in the pump resulted in inexact values of the volume silica sol grouted in to the rock for position 3.

After grouting of these two positions, a break in the experiments was taken.

The flow measurement equipment was evaluated as not good enough to meet the requirements for the experiments performed and the forthcoming experiments of position 2, 4 and 5.

As the grouting of position 2, 4 and 5 started, the new Unigrout EH22 200-140 AWB-SS was used. The new Unigrout was equipped with a Logac to log the flow, but as in the previous experiments at position 3 and 1, this Logac did not measure the flow with the accuracy required. This was known before the grouting of position 2, 4 and 5 started the second time and therefore the Data Taker logged the weight of the silica sol in the container of the Unigrout. The Data Taker logged the whole grouting session and the times when the grouting started and finished could be recorded exactly. In the logging from the Data Taker, the weight of the silica sol at the beginning and at the end of the grouting could be found out with an accuracy of 0.1 kilos. Following this new concept of measuring the volumes pumped in to the rock during the grouting, positions 2, 4 and 5 were grouted.

The grouting design was followed during the grouting sessions. The grouting time in the grouting design was the starting point in which recipe to follow regarding mixing proportions between silica sol and NaCl.

When the correct proportions of accelerator and silica sol were mixed, a sample was taken in a cup to control the gel process of the silica sol. Since it is important to stop the grouting if the gelling of the silica sol proceeds too long it was necessary to stop the grouting when the silica sol in the test cup started to gel. It is important to stop the grouting and start to clean the grouting equipment before the gelling has proceeded too far, otherwise it may cause problems cleaning the grouting equipment

3.3.1 Grouting stage 1

Position 3

The grouting of position 3 was the first grouting performed. See Figure 3-5. This position was grouted two times, due to problems in the first grouting session.

The first grouting session lasted for 25 minutes and it is estimated that the amount of silica sol used was about 60 litres. Due to the inexact measurement of the Logac equipment the amount of silica used is a rough estimation.

The first grouting of position 3 did not succeed. The gap between the Mega-Packer and the rock wall was not completely filled with silica sol. A volume at the top of the gap was left unfilled with silica sol, which was discovered when the Mega-Packer was freed from the position.

Since the first grouting session was unsuccessful, another grouting session at the same position was performed. In this second grouting an improved method of filling the Mega-Packer was applied. See 5.1.

The second grouting at position 3 succeeded. The gap became completely filled, and it was hereby proved that the gap could be completely filled.

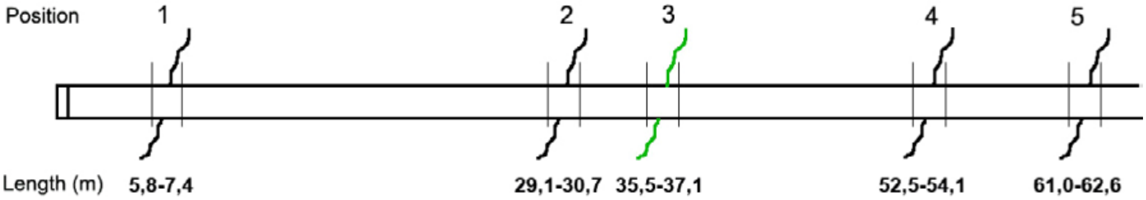

Figure 3-5. *Grouting of position 3.*

Position 1

The grouting of position 1 lasted for 18 minutes. This was the third grouting performed in the drift, and the last grouting using the old Unigrout. Since the problem with the logging was well known at this time, another way of finding out the volume of silica sol grouted was applied.

After 1 minute it could be observed in the smaller drift DA1622A01 that the silica sol had penetrated the actual fracture at position 1 and been transported in that fracture to the smaller drift, also cut by this actual fracture. In the smaller drift the silica sol first could be observed in the roof and a few minutes later it was observed in the wall directed to the main drift.

This time the level in the container containing the silica sol in the Unigrout was measured before the grouting started and after the grouting was finished. The volume grouted was estimated since the volume of the hoses could be estimated, and the volume of the gap between the Mega-Packer and the rock wall could be estimated. The volume of silica sol grouted could then be calculated. The accuracy of this calculation is low, and the amount of silica sol must be seen as a rough estimation.

The requirements of the accuracy of the measurements of the pumped volume silica sol are higher than the estimations done. The estimations give understanding on the approximate volumes of silica sol pumped in to the rock however, even though the accuracy is not god enough.

Figure 3-6 shows a principal sketch over the drift and the two grouted positions 1 and 3. The green colour indicates that the position has been grouted.

3.3.2 Grouting stage 2

Position 5

The grouting at position 5 lasted too short time due to miscalculation of the time and pressure needed to fill the hose between the Mega-Packer and the Unigrout.

The grouting lasted for 12 minutes, since it took a longer time to fill the hoses and the gap than calculated. After that time the gelling in the test cup had proceeded so far that it was decided to cancel the grouting to be able to clean the grouting equipment.

After the freeing of the Mega-Packer it was clear that the grouting not had succeeded since water dropped from the roof part of the fracture meant to seal with the grouting in the actual position.

It was decided to perform another grouting session at the same position once again, after grouting of position 2 and 4. This time the principal aim was to show that two grouting sessions may be needed and can be used to get a good result.

The actual position is showed in the sketch below (Figure 3-7).

Position 4

The grouting of position 4 lasted 15 minutes, which was the grouting time specified in the grouting model.

Figure 3-8 shows the situation of grouted positions in the drift as position 4 is being grouted.

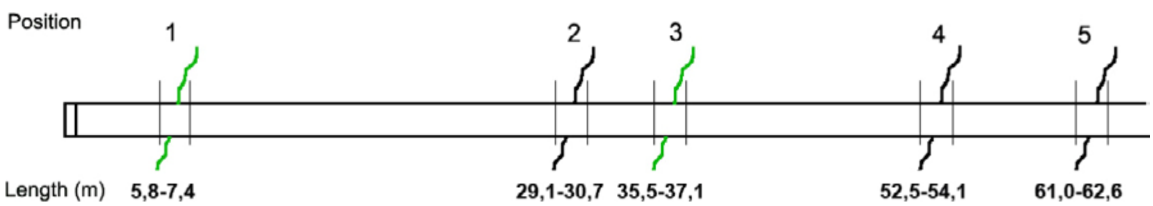

Figure 3-6. *Grouting of position 1, position 3 grouted.*

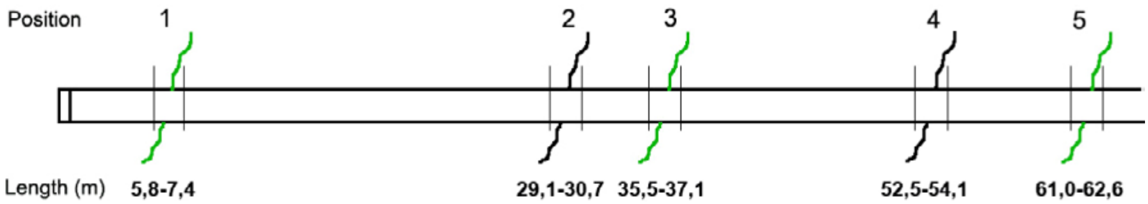

Figure 3-7. *Position 1 and 3 grouted. Position 5 is about to be grouted and the hydraulic pre characterisation is done.*

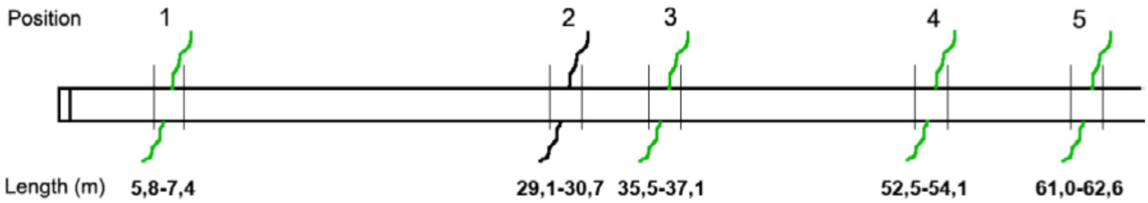

Figure 3-8. *Position 1,3 and 5 grouted. Position 4 is about to be grouted.*

Position 2

The grouting of position 2 lasted for 18 minutes and proceeded without any remarks.

Figure 3-9 shows the grouting procedure as position 2 is about to be grouted.

Position 5

The hydraulic pre-characterisation done before the grouting started showed an equal water loss as before the first grouting round, but a higher ground water pressure. The grout take in this grouting session was low. The piston of the pump did not beat one whole beat during the grouting. From the scale system on the Unigrout and the Data Taker, it was not indicated that there was a grout take at all. But from the Unigrout equipment it could be seen that the piston in the Unigrout pump had moved, but had not beaten a whole beat during the grouting session. The fact that not a single beat was performed by the piston resulted in that the scale did not register a loss of silica sol in the container on the Unigrout. Therefore, to get an approximation of the volume of silica sol grouted, the volume of the piston was calculated to 1.15 litres. Since the piston had not beaten a whole beat it was now known that the grout take was less than 1.15 litres for the actual position.

3.3.3 Results

In November 2007, positions 1 and 3 were grouted and in Mars 2008, positions 2, 4 and 5 were grouted. Position 3 and 5 were additionally grouted since the first grouting session at booth positions failed.

The grouting followed a grouting design, calculated from the values given in the pre characterisation.

The data from the grouting design (found out in the pre characterisation) and the grouting of the positions 1–5 are summarized in Table 3-5.

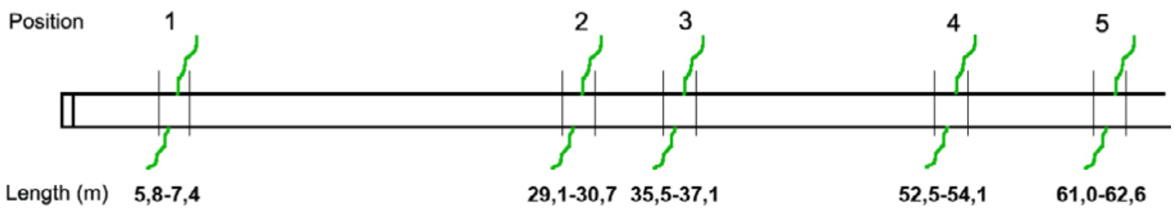

Figure 3-9. *Position 1,3,4 and 5 grouted. Position 2 is about to be grouted.*

Table 3-5. Showing the grouting data.

	Values from the pre characterisation		Values from the grouting design (theoretical)			Values from the grouting (practical tests)			
Position	**Water loss [l/min]**	**Ground water pressure [bar]**	**Grouting pressure [bar]**	**Grouting time [min]**	**Grout take [l]**	**Grouting pressure [bar]**	**Grouting time [minutes]**	**Amounts of silica sol (grout) used [litres]**	**Mixing proportions (silica sol: accelerator)**
1	12	<1.4	12	15	17	14	18	~ 60	4.7:1
2	0.18	<1.45	10	15	1.8	21	18	9.3	4.4:1
3a	0.86	8.3	18	20	2	18	25	~11	4.7:1
3b	–	–	–	–	–	18	28	~7	4.7:1
4	2.25	7.9	18	25	4	21	15	30.7	4.4:1
5a	2.2	7	10	15	33	17	12	2.8	4.4:1
5b	0.4	21.1	31	15	3	31	19	< 1.15	4.4:1

3.4 Post-characterisation and grouting effect

After grouting of all five selected positions the post characterisation was done.

After the grouting, in the post characterisation the water inflow was tiny. At some positions such as position 3 and 5 it was visible as drops forming in the roof.

At position 1, 2 and 4 no drops were visible, but very tiny channels in the coating formed by iron oxidizing bacteria could be seen, indicating a very small value of the ground water leaking in to the tunnel. See Appendix 5.

A more comprehensive presentation of data from the pre characterisation, grouting and post characterisation can be found in Appendices 1–4.

The post characterisation was performed measuring the amount of ground water leaking in to the tunnel at each specific position, which had been grouted, see Table 3-6. The post characterisation was performed after grouting of all positions in Mars 2008.

3.4.1 Grouting effect

The evaluation of the grouting effect is based on the measured inflow before and after grouting as shown in Equation 3-1.

$$Sealing\ effect = \frac{(Inflow\ before\ grouting - Inflow\ after\ grouting)}{Inflow\ before\ grouting} \times 100\ \ [\%]$$

Equation 3-1

Grouting effect denotes the decrease in inflow as a result of the grouting expressed in percent. The values before grouting were measured in November 2007 and were selected as values before grouting. See Table 3-7.

3.4.2 Total amount of ground water flowing into DA1619A02 (the main drift)

The measurements of the ground water leaking in to the drift DA1619A02 have been performed frequently since November 2004.

Variations in the flow can be seen, probably depending on activities in the drift have affected the amount of water flowing in to the drift.

Measurements on the inflowing water from September 2007 are presented i and graphically in Figure 3-10. The values from September 2007 and October 2007 have been collected from SICADA.

Table 3-6. Post characterisation of all positions.

Position	Water inflow [ml/min]
1	4
2	7
3	15
4	3
5	25

Table 3-7. Table showing the evaluated grouting effect. The measurements of inflow are performed before the grouting started (pre characterisation) and after the grouting was finished at each position (post characterisation).

Position	Inflow before grouting [ml/min]	Inflow after grouting [ml/min]	Grouting effect [%]
1	2,400	4	99.8
2	145	7	95.2
3	490	15	96.9
4	1,760	3	99.8
5	190	25	86.8

A pronounced decrease in the amount of water leaking in to the drift can be seen in Table 3-8 from November 16th to December 3rd. During this time, grouting in position 3 and 1 was performed.

As grouting of position 2, 4 and 5 was performed in Mars 2008, a remarkable decrease in the water inflow could be seen again.

The first grouting session of position 5 failed due to too short gel time and too long time needed to fill the hoses and the gap between the Mega-Packer and the rock wall, and therefore it is not valid as a grouting.

Table 3-8. The total inflow in the drift (DA1619A02) as the grouting proceeds.

Date	Inflow [ml/min]	Remark
2007-09-20	4400	
2007-10-04	4300	
2007-11-01	4150	
2007-11-16	4350	
2007-11-19	–	Grouting of position 3:1
2007-11-22	–	Grouting of position 3:2
2007-11-28	–	Grouting of position 1
2007-12-03	2800	
2007-12-20	2680	
2008-03-10	2400	
2008-03-12	–	Grouting of position 5
2007-03-14	–	Grouting of position 4
2008-03-17	690	
2008-03-18	–	Grouting of position 2
2008-03-19	580	
2008-03-25	–	Grouting of position 5
2008-03-26	420	
2008-03-27	420	
2007-03-28	420	
2008-03-30	400	
2008-03-31	400	

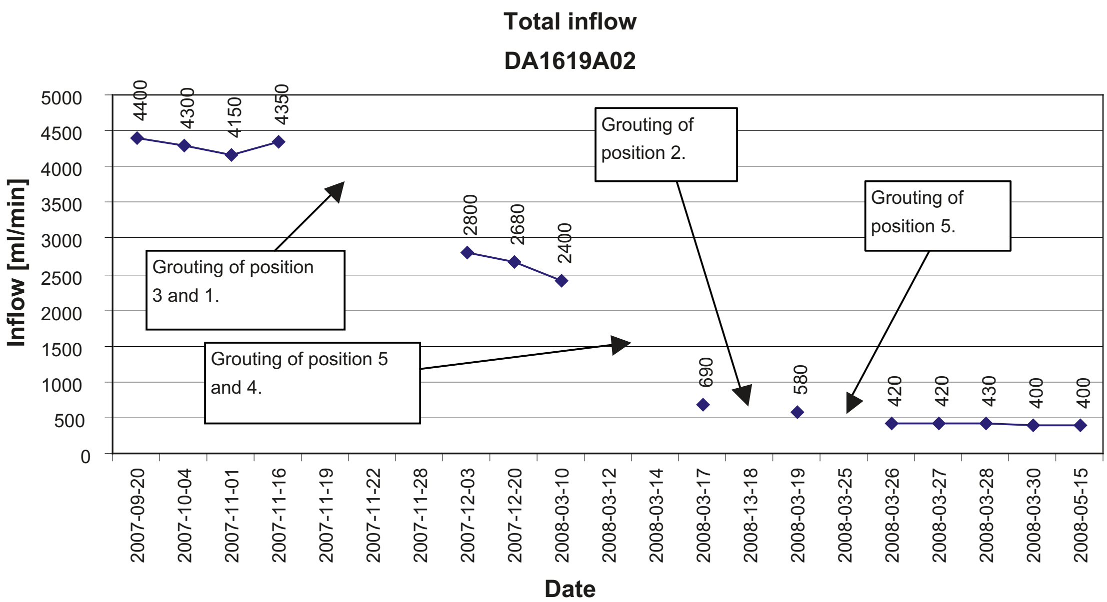

***Figure 3-10.** Diagram showing the measured total inflow in the drift DA1619A02 (the main drift).*

However, after grouting of position 4 (considering that the first grouting of position 5 was not valid) the water inflow into the drift decreased with 1,7 litres per minute.

After grouting of position 2 the ground water inflow into the drift decreased about 0,1 litres per minute.

After the grouting of position 5 the second time, the water inflow into the drift decreased about 0,15 litres per minute.

Totally the leakage from the drift decreased with 90,8%.

3.4.3 Total amount of ground water flowing into DA1622A01 (the shorter drift)

The total amount of ground water flowing in to the tunnel was measured before the grouting started and after grouting of all positions.

The results are shown in Table 3-9 and in Figure 3-11. It is seen that an increase of water inflow was noted in the tunnel during grouting in the neighbouring tunnel.

Figure 3-12 shows the amount of water flowing in to the booth drifts as grouting proceeds.

Table 3-9. Showing the total inflow in the shorter drift DA1622A01 as the grouting proceeds in the main drift DA1619A02.

	Inflow [ml/min]	Remark
November 2007	65	Before grouting
November 2007	–	Grouting of position 1 and 3
Mars 10 2008	270	
Mars 12 2008	–	Grouting position 5 (failed)
Mars 14 2008	–	Grouting position 4
Mars 17 2008	280	
Mars 18 2008	–	Grouting position 2
Mars 19 2008	280	
Mars 25 2008	–	Grouting position 5
Mars 26 2008	295	
Mars 27 2008	290	

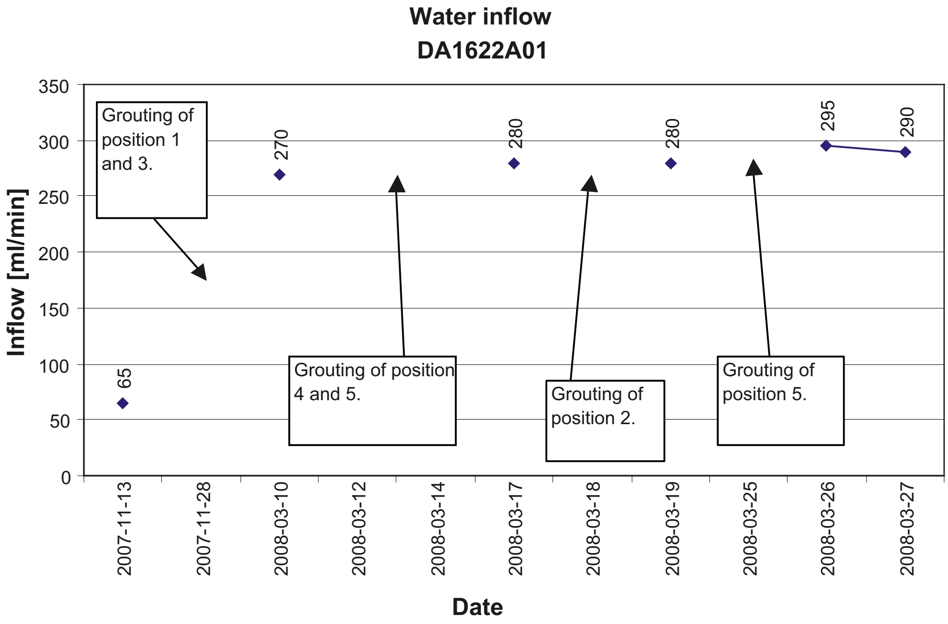

Figure 3-11. *Water inflow in the shorter drift DA1622A01 as the grouting in the main drift DA1619A02 proceeds.*

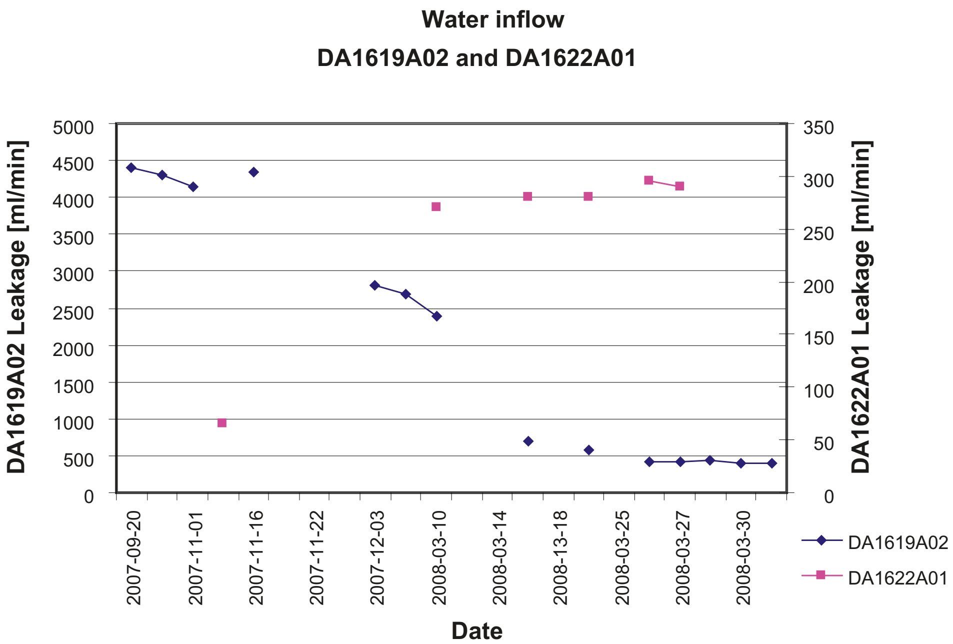

Figure 3-12. *All in all view over the amount of water leaking in to the drifts DA1619A02 (the main drift) and DA1622A01 (the shorter drift) as the grouting proceeds.*

4 Analysis

In this section a further analysis is made concerning the obtained results. The objective is to reach a more detailed understanding of

- the test result concerning what fractures that have been successfully grouted,
- the overall effect of grouting on the inflow situation in the drift and vicinity of the drift,
- the results in relation to prognosis for grouting in the repository and using KBS-3H.

4.1 Total inflow reduction

Considering inflows measured before the test started they show a continuing decrease, this is in line with observations from other tunnels. When the pre-characterisation was made the pressure build up tests showed drained conditions, or a hydraulic situation with long pressure build up periods. Stable ground water pressure could not be measured since the Mega-Packer could isolate only partial sections of the tunnel.

After grouting of different positions an increased ground water pressure was measured. This had the effect that some position experienced an increased inflow as other positions were sealed. This can be seen in Table 4-1. The clearest example is position 2 where the flow increased from around 25 ml/min to around 145 ml/min due to the grouting in positions 1 and 3.

Table 4-1. An overall presentation of measured inflow and ground water pressures in the tunnel after different grouting rounds.

Position	November 2006 *		November 2007		March 2008 Before grouting of position 2, 4 and 5		March 2008 After grouting of position 5		March 2008 After grouting of position 4 and 5		March 2008 After grouting of all positions	
	Water inflow (ml/min)	Ground water pressure (bar)	Water inflow (ml/min)	Ground water pressure (bar)	Water inflow (ml/min)	Ground water pressure (bar)	Water inflow (ml/min)	Ground water pressure (bar)	Water inflow (ml/min)	Ground water pressure (bar)	Water inflow (ml/min)	Ground water pressure (bar)
1	2,960		2,400	> 1.4	–	–	–	–	–	–	4	–
2	90		25	> 1.45	–	–	–	–	145	11.0	7	–
3	870		490	8.3	–	–	–	–	–	–	15	–
4	2,240		1,470	7.9	–	–	1760	10.7	–	–	3	–
5	280		148	3.6	190	7.0	–	–	–	–	25	–

* = No information about the measurement method has been received from SICADA.

4.2 Evaluated transmissivities and fracture apertures

Charts for the transmissivities can be found in Appendix 4.

The transmissivities are estimated based on the pressure build up tests, measured inflow, and water loss measurements, see Table 4-2. The pressure build up tests could not be evaluated in terms of transmissivities in position 1 and 2.

It is noticed that the transmissivity evaluated based on the pressure build up test differs from the values evaluated from the inflow and water loss measurement. See Table 4-3.This can be due to a larger structure in the surrounding rock or a connection to the drifts or the niche.

A good correlation is noticed between the aperture based on inflow and the aperture based on water loss measurement. In Figure 4-1 the two series of apertures are compared and the trend is that the aperture based on the water loss is around 8% larger. The same comparisons were made by /Koybayashi and Stille 2007/ with data from the Äspö tunnel. In that case the water loss aperture was around 74% larger. The result is dependent on the assumption of the radius of influence in Equation 2-5 but is still found to be a good agreement between the inflow and the outflow measurement.

The agreement between the transmissivities evaluated based on the pressure build up test versus the inflow measurement and water measurement is however weak and it is noticed that higher transmissivities are evaluated based on the pressure build up test. This is assumed to depend on connections in to the drifts or the niche, i.e not be a fracture property.

4.3 Amount of used material

The amount of silica sol used during the grouting is shown in Table 3-4.

Table 4-2. Evaluated transmissivities for each position based on different characterisation methods.

Position	Transmissivity based on pressure build up [m^2/s] Using eq. 2	Hydraulic head based on pressure build up [m]	Transmissivity based on inflow and hydraulic head [m^2/s] Using eq. 1	Transmissivity based on water loss [m^2/s] Using eq. 5
1	–	20	1.20 * 10–6	1.71 * 10–6
2	–	20	1.25 * 10–8	2.57 * 10–8
3	1.25 * 10–6	85	7.97 * 10–8	1.23 * 10–7
4	9.7 * 10–7	85	2.39 * 10–7	3.21 * 10–7
5	4.4 * 10–7	65	2.99 * 10–8	5.42 * 10–8

Table 4-3. Evaluated fracture aperture based on the pre-characterisation.

Position	Aperture based on pressure build up test (transmissivity) [µm]	Aperture based on measured inflow [µm]	Aperture based on water loss measurement [µm]
1	–	124	133
2	–	27	33
3	126	50	55
4	116	72	76
5	90	36	42

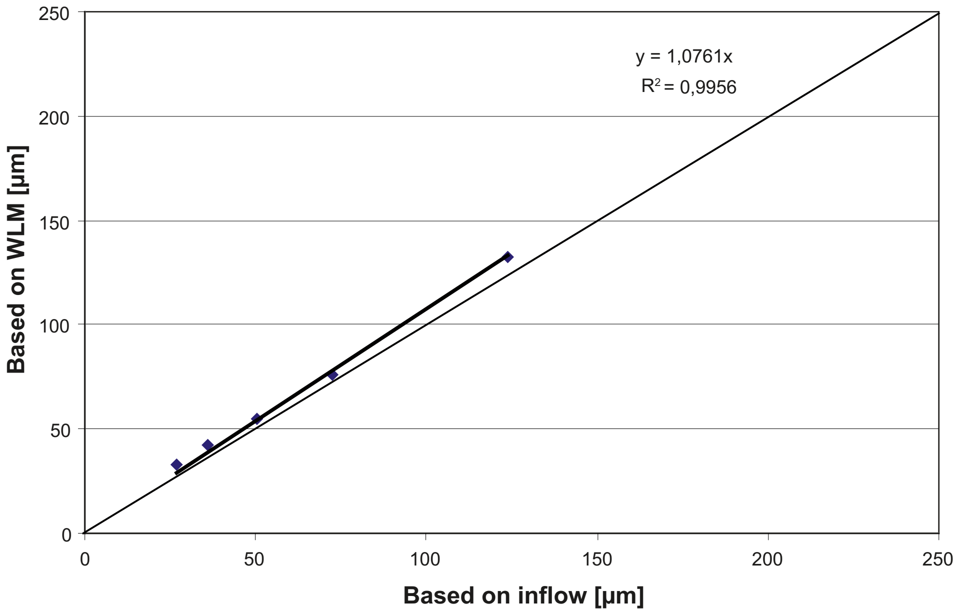

Figure 4-1. *Comparison of the hydraulic aperture evaluated from the inflow and from the water loss measurement test.*

4.4 Evaluated correlations between grout take, transmissivity and pressure build up test

A common evaluation is to study the correlation between water loss and grout take. A correlation is expected but practical issues in common grouting often makes the relation difficult to find.

In Figure 4-2 the measured water loss from the pre characterisation and the measured grout take are plotted in the same diagram. A correlation is seen and it is also seen that one value does not follow the same trend as the others. This value is the value for Position 5 where the first grouting session failed. Excluding the value for position 5 and analyse the trend for the others reveal a relation of the grout take to the water loss of $V=20x^{0.5}$, where x is the water loss.

It is natural that the water loss and the grout take are correlated since both the water loss measurement and the grouting is performed using the same technique and considering that silica sol behaves like a Newtonian fluid. The exact relation depends however on the viscosity of the fluids and the average viscosity of the silica sol is difficult to estimate due to its exponential development.

Considering the same relation for the grout take and transmissivity, this is shown in Figure 4-3 and Figure 4-4. The transmissivity from the water loss measurement and from the inflow measurement differ some and therefore two different curves are obtained.

From a design point of view, the transmissivity from the water loss measurement is interesting. From the aspect of making a prognosis of how much grout that will be used, based on an expected transmissivity distribution, the relation from the inflow transmissivity is interesting.

4.5 Sealing effect – reduction of water inflow by position

The sealing effect varies to some extent in the different positions grouted. Table 4-4 summarises water inflow, evaluated transmissivity and hydraulic aperture based on inflow, resulting inflow after grouting and obtained sealing effect. The obtained sealing effect is calculated based on the reduction of inflow in the position.

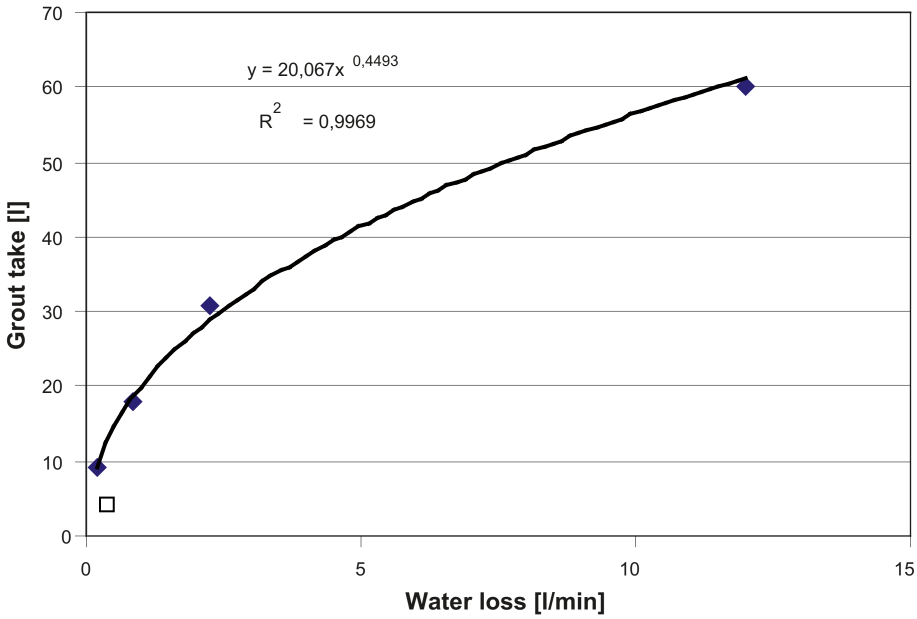

Figure 4-2. Grout take plotted versus water loss (measured in the pre-characterisation). The value for position 5 is not included in the trend line.

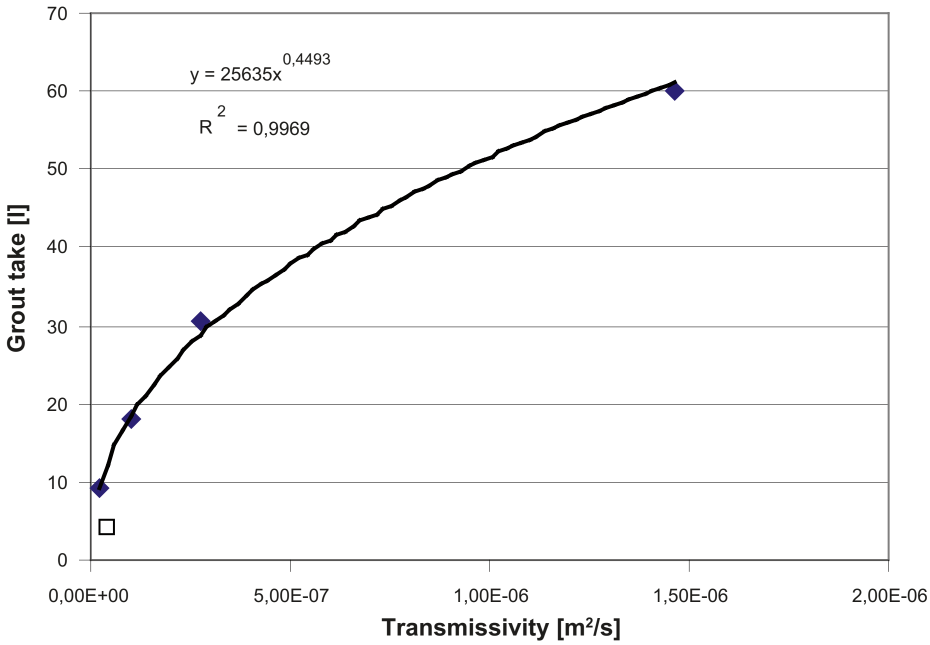

Figure 4-3. Grout take plotted versus transmissivity from the water loss measurement (measured in the pre-characterisation) The value for position 5 is not included in the trend line.

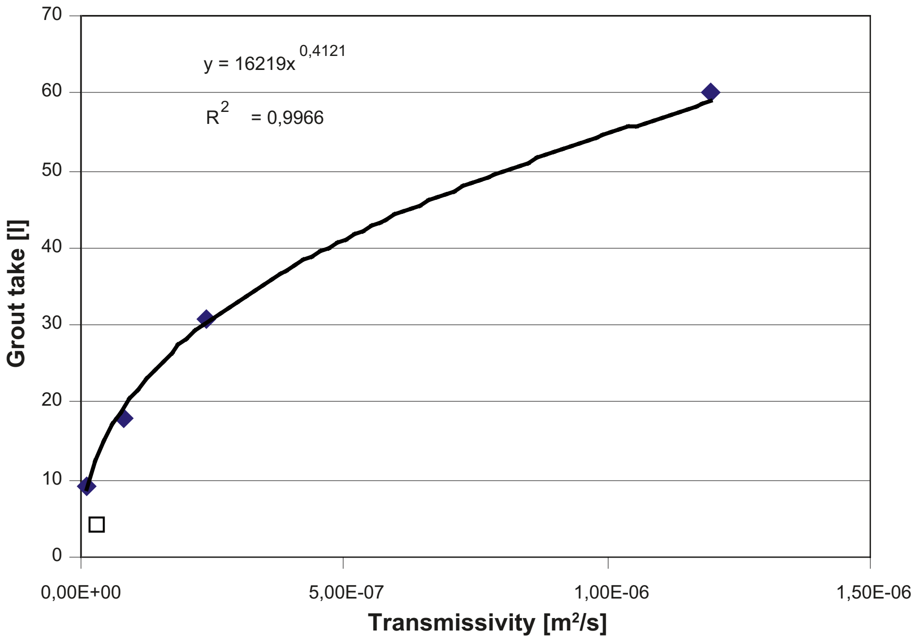

Figure 4-4. *Grout take plotted versus transmissivity from the water inflow measurement (measured in the pre-characterisation) The value for position 5 is not included in the trend line.*

Table 4-4. Summary of water inflow, evaluated transmissivity, hydraulic aperture and sealing effect.

Position	Water inflow [ml/min]	Transmissivity [m²/s]	Hydraulic aperture [µm]	Inflow after grouting [ml/min]	Obtained sealing effect [%]
1	2,400	1.20×10^{-6}	124	4	99.8
2	145	1.25×10^{-8}	27	7	95.1
3	490	7.97×10^{-8}	50	15	96.9
4	1,760	2.39×10^{-7}	72	3	99.8
5	190	2.99×10^{-8}	36	25	86.8

It is noticed that the resulting inflow after grouting at all positions are less than 0.1 l/min, which is targeted as the maximum allowed inflow in one deposition length. Considering the depth of –220 m and comparing to actual repository level –500 m it is also found that an inflow of less than half the stipulated value is obtained, i.e. < 0.05 l/min. This indicates that the targeted inflow value should be reached also on actual repository level.

It is noted that the apertures grouted are evaluated as ranging between 27 and 124 µm. It is difficult to validate what this aperture means in physical terms but based on the definition of hydraulic aperture and discussion by several authors see e.g. /Barton and Quadros 1997, Zimmermann et al. 1991, Eriksson 2002/ the evaluated value should be a minimum aperture.

In Figure 4-5 the obtained sealing effect as function of measured inflow is given. It is noticed that a smaller inflow seems to give a lower sealing effect. This is in line with the results from the simulated tests /Autio et al. 2008/.

The inflow in each position is small and the uncertainties in the measurements are difficult to estimate. If these values are in detail accurate it is found that the inflow have in percent and in absolute values been mostly reduced in the positions where the highest inflow and the largest transmissivities were found. Comparing this to theoretical results in /Eriksson 2002/, the results can be explained. The grouting material have the potential to fill the fracture void more completely if the aperture is somewhat larger. The countermeasure, recommended in /Eriksson 2002/ would be to increase the pressure and/or grout longer in finer fractures.

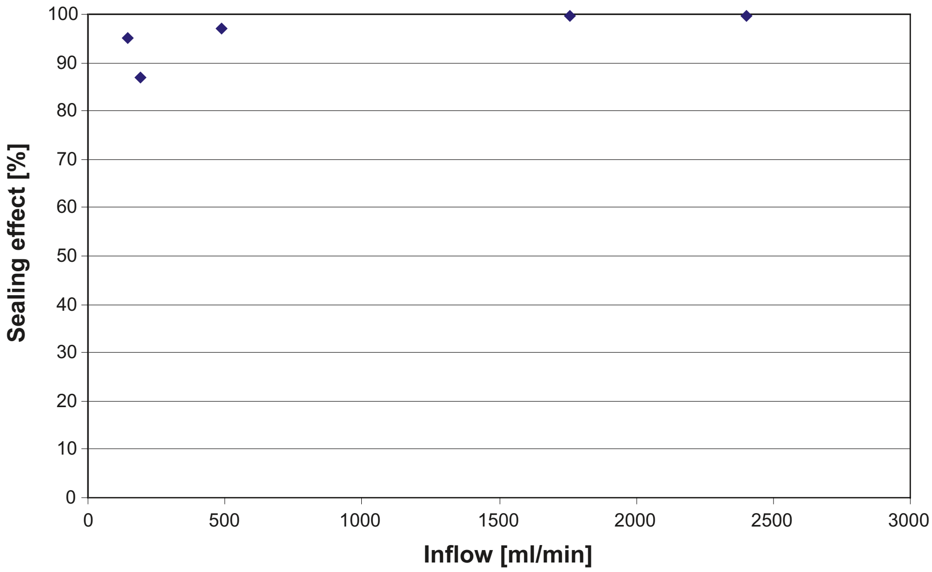

Figure 4-5. *Diagram showing the obtained sealing effect as function of inflow.*

5 Lessons learned

5.1 Dilution problem

The unsuccessful filling of the gap between the Mega-Packer and the rock wall at position 3 may be explained by the water flowing in to the actual position (490 ml/min).

The Mega-Packer was slowly filled with silica sol, which might has caused that the ground water leaking in to the gap from the fracture meant to seal diluted the silica sol extensively. It is previous shown that a dilution of the silica sol causes a longer gel time. When the dilution is too extensive, no gelling will appear at all, as was the case for position 3 the first grouting.

The water diluted silica sol is believed to float on top on the undiluted silica sol since the diluted silica sol is less dense than undiluted silica sol.

The diluted silica sol was not evacuated from the top vent as undiluted silica sol was added in the bottom vent since it was not known that silica sol could behave in this way when water leaking in to the actual position.

The lesson learned in this first grouting session is that ground water leaking in to the gap can mix with silica sol, which might cause problems. This shows that it is important to consider an improved filling technique in the further coming grouting sessions. See chapter 5.1.1.

Figure 5-1 shows the unsuccessful filling of the Mega-Packer at the first grouting session.

It is clearly seen that the silica sol not has filled the gap as expected. The top of the silica sol had a smooth and wavy look, indicating the surface of it.

Figure 5-1. *The unsuccessful filling of the gap in the Mega-Packer at position 3.*

5.1.1 Preventing dilution of silica sol by ground water leaking in

It is of importance trying to prevent the dilution of silica sol by the ground water leaking in from the actual position, which was shown in the first grouting at position 3.

Several alternatives of preventing the problem with diluted silica sol were considered:

- evacuating the diluted silica sol,
- quicker filling of the gap,
- evacuating the groundwater with help from nitrogen gas.

In the tests performed in position 2, 4 and 5 all these three techniques were applied to avoid the dilution problem.

Evacuating the diluted silica sol

Supposing that the diluted silica sol will float on top of the undiluted silica sol, the diluted silica sol can be evacuated from the top valve of the Mega-Packer.

This was applied in all grouting sessions after the first unsuccessful grouting session at position 3.

When letting the diluted silica sol out of the upper valve in the following grouting sessions it could be seen that the first volume of silica sol coming out was diluted. This is indicated by a look that is whitish-transparent, undiluted silica sol looks like milk.

When silica sol coming out from the valve had a milky look, the valve was closed and the grouting began.

Evacuating the diluted silica sol is necessary, but causes a loss of silica sol from the batch. Therefore it is important to take to account when calculating the batch size that a volume of the batch will be flushed out since it is diluted by ground water and unusable.

Quicker filling of the gap

A quicker filling of the gap means that the grouting starts earlier than if the gap is filled slowly. This means that less ground water is permitted to leak in to the gap and mix with the silica sol. By that means that less diluted silica sol has to be evacuated.

Evacuating the groundwater with help from nitrogen gas

If the ground water inflow is extensive a big amount of water will leak in to the gap before the grouting starts. This means that the dilution of the silica sol will be extensive. To counteract an accumulation of water in the gap before the grouting starts the nitrogen gas can be used to evacuate the water.

Nitrogen gas flushes the gap and will push the water out of it. When the grouting is about to begin, the valve to which the nitrogen gas is connected is closed, the hose from the Unigrout is connected to the Mega-Packer, the Unigrout starts pumping silica sol and the gap becomes filled.

5.2 Gel time

When grouting, it is preferred to have a longer gel time than a shorter gel time so that it is sure that the silica sol penetrates the rock. But a too long gel time might cause uncontrolled distribution of grouting material in the.

A longer gel time might result in a longer penetration into the rock and a higher consumption of silica sol, but may guarantee that the silica sol penetrates the rock even though the hoses are long and take time to fill.

If a shorter gel time is wished, then it’s important to consider filling the gap quickly so that the grouting can start as soon as possible.

5.2.1 Batch size

If the hoses are long it takes several litres of silica sol to fill them.

The flushing of diluted silica sol from the top valve of the Mega-Packer causes a loss of silica sol.

Since it might take time to fill the hoses and the gap, this might require a longer gel time, than if the hose is short. It is important to consider the time it takes to fill a long hose and from that known time apply the gel time so that it not becomes too short or too long.
A short gel time may cause a failed grouting session if the gelling process has gone too far as the silica sol reaches the Mega-Packer and the fracture, as happened at position 5.
A long gel time may cause a greater grout spread in the surrounding rock, which affects the grout take. A bigger grout take than expected may lead to a shortage of silica sol and a failed grouting session.

To calculate the batch size as exactly as possible the following has to be concerned:

- the length of the hoses
- the amount of diluted silica sol being flushed out from the gap
- the spread of the silica sol in the surrounding rock

Maximum batch size upper limit for the Unigrout E 22 H and for the Unigrout EH22 200-140 AWB-SS about 400 litres.

If it is estimated that the volume of grout needed to keep on grouting as designed is less than the volume left in the hoses, the container at the Unigrout might be filled with water so that there is water pressurised in the hoses instead of silica sol so that the grouting can continue.

If it is uncertain that the consumption of silica sol is quite small from that moment the shortage of silica sol is being discovered, then this method cannot be applied, because of the risk that the water in the hoses pumps all the way to the gap and dilutes the silica sol.

Another method in case of shortage of silica sol from the first batch in the grouting, is that another batch might be mixed, with a shorter gel time. This second batch should be so similar to the first batch as possible regarding to gel time, so that the two batches will gel as close as possible at the same time.

5.2.2 Mixing of water leaking in to the Mega-Packer gap and silica sol

If there is water leaking in to the gap between the Mega-Packer and the rock wall, the water will dilute the silica sol. Experiments were done to examine the impact on the silica sol when water leaks in to the gap.

The experiments were performed in the way that a determined weight of silica sol was dosed in to six different cups. A constant weight of accelerator (NaCl) was added together with ground water from the tunnel in different proportions (per cent by weight).

What can be seen from the dilution experiment is that a few per cent dilution with ground water affects the gel time remarkably. See Table 5-1. A dilution of silica sol by water leaking in to the drift causes a longer gel time the higher the concentration of ground water.

Table 5-1. Showing the gel time of the silica sol versus the concentration of ground water leaking in to the tunnel mixed in the silica sol batch.

Concentration [%]	Gel time [min]
0	43
1	48
2	62
5	83
10	139
20	> 160

5.2.3 Filling time

The time for filling the Mega-Packer with silica sol is important in several ways; if the filling time is long, it is required that the gelling time is long. Otherwise, the scenario in the first grouting session for position 5 is probable. A short grouting time might not be a problem, but if a specific distance of penetration out in the surrounding rock is required for the silica sol, then the gelling time for the silica sol must be lengthened or the filling of the hoses and the gap more effective. If the gelling time is too short, then the silica sol does not penetrate small fractures at all, which means that these small fractures remain unsealed, which in turn means that the grouting might not be complete and successful.

5.3 Measurement of grouted volumes of silica sol

In the first grouting set, it was difficult to estimate the volumes of silica sol grouted. The Logac equipment showed a low accuracy, and therefore the values delivered were not reliable.

After the first grouting, when it was realised that the Logac could not be used, another method of estimation of volumes silica sol grouted was used. This time the volume in the container at the Unigrout was estimated before grouting started and after the grouting was finished. The level of the surface before and after grouting was measured with a folding rule and the diameter of the container was measured. The volume of the hoses and the gap between the Mega-Packer and the rock wall were calculated.

The volume of the gap and the hoses were subtracted from the volume pumped from the container. This subtraction gave a rough value of the silica sol grouted.

It is important to keep in mind that this estimation is very rough and not reliable.

The second grouting at position 5 gave opportunity to another way to estimate the grouted volume. The scale system on the new Unigrout register volume grouted per beat from the piston in the pump. In this case, the fracture was almost entirely close, which means that the piston did not even beat one single whole beat, therefore the scale system did not log any grout take. The piston beat only a part of one beat during the whole grouting session. The volume and the weight silica sol in the container did not decrease at all, since it only decreases as the piston beats a new beat. What now was known was that the maximum grout take was the volume of the piston in the pump. This volume was calculated to amount to 1.15 litres.

Even though the scale on the Unigrout is a good measurement on the volumes of silica sol grouted, there is a source of error regarding to the volumes grouted; the volume of the piston in the pump. If the piston is not fully pressed, there is a volume of silica sol left in the pump, and this volume can not be measured, as in the same way as the volume of one not completed beat can be measured. Therefore there is an error in the volumes grouted amounted to the volume left in the container (can be calculated from the scale and the density of the silica sol. The volumes grouted calculated from the scale measurements in the container may amount to 1.15 litres more, depending on where in the beat cycle the piston is when the grouting stops. This is an error which is caused due to the model of the pump. To get rid of this problem another kind of pump has to be used, a pump which not have a piston concept on pumping.

5.4 The flow measurement equipment in the Logac

The Logac equipments at both of the Unigrout platforms were not able to deliver the accuracy in the measurements during the grouting sessions as required. After the second grouting session it was discovered that there was an inaccuracy in the data delivered from the Logac.

To prove that there was an accuracy issue, one hose was provided with a valve (tap) that could be opened and closed. The hose was connected to the Unigrout and the pump started to pump water to the tap which now was closed. It was checked so that there were not any inflows on the hose, at the connection between the hose and the Unigrout or at the end of the hose at the connection to the tap.

The test found out that the Logac registered a flow and a volume pumped although there were not any inflows and the tap was closed. After running the test for 10 minutes, the Logac had registered a flow of 2 litres, and after 21 minutes the logic had registered a flow of 3 litres.

This lead to the conclusion that the Logac equipment was not reliable regarding the flow measurements.

5.4.1 The older and newer version of Unigrout

The newer version of Unigrout (EH22 200-140 AWB-SS), differ in many ways from the older version of Unigrout (E 22H) used at the beginning of the experiments.

The older Unigrout was simpler in its performance and constructed for cement grouting. One disadvantage was that it was difficult to get the right proportions between silica sol and accelerator since the volumes had to be measured by hand. The volumes of the silica sol and accelerator were quite large and the vessels used to measure the right amounts were big, there might be a difference between the real volume silica sol and accelerator and the calculated volume.
The newer Unigrout is constructed for silica sol grouting and use pumps to pump the right volumes to the containers using the scale system and the computer connected to the scale system to steer it.

The scale system means a great advantage in estimating the volumes grouted. This makes the newer Unigrout preferable compared to the older one.

5.4.2 The limitations of the Water Injection Controller

There are limitations on the Water Injection Controller (WIC) used to perform the water loss measurements. The pump in the device has an upper limit in pressure on 21 bars, this means that in the case that a full ground water pressure is developed in a specific position (fracture) a water loss measurement cannot be performed.

A water loss measurement is performed with a pressure that is 10 bar over the ground water pressure measured in the pressure build up test, preformed before the water loss measurement. When a full ground water pressure is developed (approximately 21–22 bars) a water loss measurement cannot be performed due to the upper limitations on the WIC.

This was the case before the second grouting session in position 5. This was the last grouting performed and the pressure build up test showed a ground water pressure about 21 bars, therefore a water loss measurement could not be performed correctly.

A lesson to learn about this is that it is important to check the upper limit on the water loss measurement equipment and to assume that at some position there might be a fully developed ground water pressure and that the water loss measurement equipment must have an upper limit on 10 bars over the assumed existing ground water pressure.

5.4.3 Time for measurement of water loss and ground water pressure

The time for measurement of the pressure build up test was set to about 30 minutes. However, several of the measuring sessions lasted more than 30 minutes, because the pressure after 30 minutes still increased. The measurements should have been about two hours longer.

In the ideal case, the pressure build up test should be performed during one night. One test was done in this way and showed a stable curve. This was not the case for the first pressure build up test for position 2 in November 2007. The curve has an unexpected appearance, but it might have appeared in another way if the pressure build up test had lasted longer.

The water loss measurements proceeded for 15 minutes and this time seemed sufficient to get a stable flow of water out in the surrounding rock. A longer duration of water loss measurement had thus probably not changed the results.

5.4.4 The hydraulic characterisation

The characterisation should have been more extensive so that after each grouting a new hydraulic characterisation would have been done on all the other positions except from the one just being grouted. In this way it would be possible to follow the changes in ground water pressure and the water inflow in a better way to better understand what happened in the rock body. This was however not found possible due to the timetable.

For future experiments it is suggested to perform these hydraulic tests after each grouting. See 7.2

5.4.5 The time set for the experiments

To be able to perform the extended hydraulic characterisation it would have been required to have more access time to the drift for the tests, DA1619A02. During both test sets there was a limited access time to the drift. Without this limit there would have been more flexibility in changing the plan for the test as new experience at the test site was won. Because of this limited access the plan for the experiments had to be followed exactly.

5.5 Moving the Mega-Packer

The moving of the Mega-Packer in to the drift to the test position succeeded. But as the equipment was moved longer in to the drift, the problem with the steering of the device appeared. The risk of overturning was immediate and had to be counteracted as soon as possible, which was performed in loading lead weights in to the Mega-Packer to counteract the movement up on the wall. This was a temporary solution and another way of steering the Mega-Packer had to be found. During the break in the tests between December 2007 and Mars 2008 the wheels were reconstructed so that they could be adjusted and by that means the Mega-Packer could be steered and the risk of overturning was attended to.

5.6 The Mega-Packer

The status of the Mega-Packer when used in the pre characterisation, grouting and post characterisation is good. Where the Mega-Packer body has been scratched when pulling it in to the transport tube (used by the deposition equipment), there has been an extensive rust (iron oxidation).
The plugs in the Mega-Packer body that has not been used to connect valves are now impossible to remove due to an extensive rust process. The result is that these cannot be used to connect new valves in the future, which means that new connections have to be drilled in the Mega-Packer body if more valves are going to be connected.

The packer status is good, but it can be seen that the packers have been scratched superficial, approximately 0,5–1 mm deep scratches. See Figure 5-2. The scratching is not that extensive the packers are most likely usable.

In further use of the Mega-Packer it is preferred that the packers should be checked and controlled regarding to scratches in them.

Figure 5-2. *Minor scratches in one of the packers.*

6 Conclusions

The practical test using the Mega-packer has given the following results and conclusions.

The functional tests showed that the packer material was functioning as required to perform the grouting. This issue was a critical question for the method. Since it was possible to seal off the Mega-Packer the hydraulic test and the grouting could be performed. It is not tested to what pressures the packer material can seal off. It was considered a risk to increase the pressures to high, since there was a risk that the packers would blast.

For hydraulic characterisation the Mega-Packer have advantages and disadvantages. It is found to be an advantage as compared to bore hole measurements, that a "larger" contact length with the fracture is obtained resulting in a better estimate of transmissivity using the specific capacity.

It is however found complicating for the rock mass characterisation that only partial sections of a tunnel can be sealed off using the Mega-Packer. A "full hole measurement" is thus not possible. For this reason, the ground water pressure is difficult to estimate.

The actual grouting was successful and the fulfilment of the requirements can be considered as fully achieved. The results have been evaluated and certain basic relations for decision-making have been found. This concerns for instance grout take for distributions on transmissivity.

7 Future work

7.1 Modelling

Modelling work is an essential activity to demonstrate understanding and to make prediction concerning sealing effect and grout take. The test result presented in this report open possibilities for modelling work and to gain new understanding.

In principle there are two approaches to the modelling work:

- One is to apply the approach made in the pre-study and presented in /Autio et al. 2008/ where a probabilistic approach based on fracture statistics are made. This has the potential of predict sealing effect and grout take.
- Another approach is to use the empirical relations presented in this report and based on the DFN modelling make predictions on grout take.

However, the data presented in this report are considered to be state-of-art as observations on the hydraulic system in the rock and it is recommended to further explore this system. This would gain insight to grouting knowledge in general and to KBS-3H design issues in particular.

7.2 At the –220 level

There is further work to be done regarding the Mega-Packer on the –220 level.

A problem that appeared during the second grouting set was that the water loss measurement equipment used in the experiments had a limited pumping pressure of 20 bars. Since the ground water pressure at position 5 amounted to 21 bars, the water loss measurement equipment could not be used to hydraulically post characterise the drift.

So, a further work to be done at the –220 level is to post characterise the grouted positions regarding to ground water pressure and water loss. This can help to better understand the aperture, transmissivity and the permeability at the actual fractures that have not been grouted.

It has been observed that as the grouting has proceeded, the actual positions have experienced a decrease in water inflow. At the same time, fractures that not have been grouted, due to the lack of inflow from them, have become water bearing fractures in the drift.
To better understand the conditions in the rock regarding the fractures and what happens when grouting, the ground water pressure and the water loss at these new inflow positions should be measured.

It has now been shown that the Mega-Packer works for sealing off positions in the drift at the – 220 level. The next step is to prove that the Mega-Packer works for sealing off positions in a drift at the – 450 m level.

Further work at the –450 level presupposes that the packers can be inflated with ha higher pressure than 40 bars, which has been used in the performed tests described in this report. It is suggested that the packers should be inflated with ha pressure of at least 70 bar. This can be tested already at the –220 m level.

The execution of such further work presupposes that another water loss injection controller is being used. This one should have a pump that can be used up to at least 60 bars.

7.3 At the –450 level

At this level it is required that the packers can be inflated with at least 70 bar, which can be tested at the –200 m level (see 7.2).

The pressure that has to be used in grouting and water loss measurement at this level is 10 bars over the ground water pressure (45 bar), which means 55 bar if the ground water pressure is fully developed. If these requirements shall be met then there has to be a water injection controller equipment that is able to pump water in to the gap at a pressure of 55 bars.

A problem that can appear at the level of – 450 meters is that a higher ground water pressure results in a higher ground water inflow in to the drift. This is important to note since the dilution of the silica sol in the grouting may be a problem. With respect to this, it is important to know that 50–80 litres of silica sol might have to be evacuated from the gap when it is filled with silica sol before grouting starts. This affects in turn the batch size of silica sol and it is important to estimate the grout take during the grouting. If the hoses are long and it is estimated that the grout take is extensive, then it might be that the batch mixed in the Unigrout is not enough. In such cases an alternative method of getting rid of the water in the gap is necessary. As mentioned in section 5.1.3, one such method would be to flush the gap with nitrogen gas that can push the water out of the gap.

After each grouting at the – 450 level, there should be a complete hydraulic characterisation performed at each position that has not been grouted, after a grouting of a specific position. In this way, it is possible to follow the changes in the rock mass in the whole drift before and after grouting at one position. To follow these changes regarding ground water pressure and water loss can help understanding the hydraulic development in the rock mass.

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Appendix 1

Inflow Measurements

Inflow measurements in DA1619A02 before and after grouting.

Time	Leakage (l/min)	Remark
September 20 2007	4,4	
October 04 2007	4,3	
November 1 2007	4,15	
November 16 2007	4,35	
November 19 2007	-	Grouting of position 3:1
November 22 2007	-	Grouting of position 3:2
November 28 2007	2,23	Grouting of position 1
December 03 2007	2,8	
December 20 2007	2,68	
Mars 10 2008	2,4	
Mars 12 2008		Grouting of position 5
Mars 14		Grouting of position 4
Mars 17	0,69	
Mars 18		Grouting of position 2
Mars 19	0,58	
Mars 25		Grouting of position 5
Mars 26	0,42	
Mars 27	0,42	
Mars 28 2008	0,42	

Inflow per position in DA1619A02 before and after grouting.

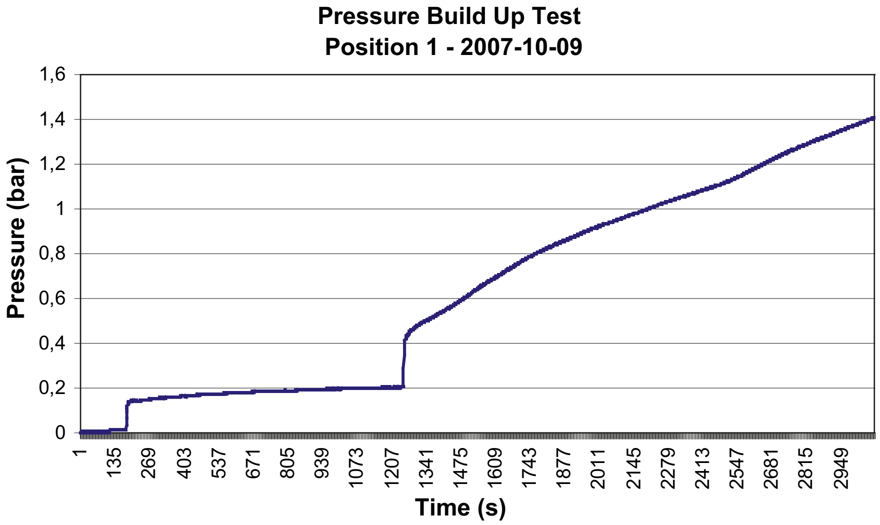
Position	November 2006	November 2007	November 2007 After the first grouting of position 3	Nopvember 2007 After grouting of position 3	Mars 2008 Before grouting of position 2, 4 and 5	Mars 2008 After grouting of position 5	Mars 2008 After grouting of position 4 and 5	Mars 2008 After grouting of all positions
1	2,960	2,400	–	2,230	–	–	–	4
2	90	25	–	–	–	–	145	7
3	870	490	485	–	–	–	–	15
4	2,240	1,470	–	–	–	1,760	–	3
5	280	148	–	–	190	–	–	25
SUM:	6,440	4,533	–	–	–	–	–	54

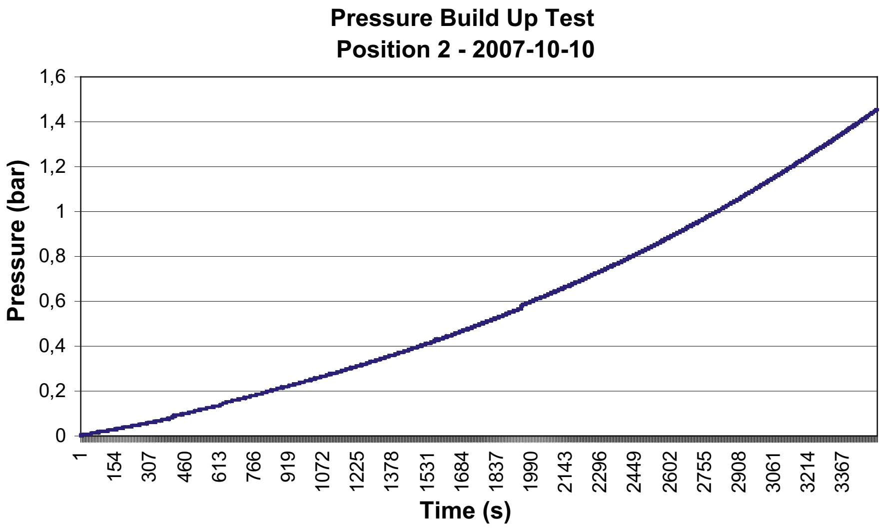
Inflow in DA1622A01 before and after grouting of DA1619A02.

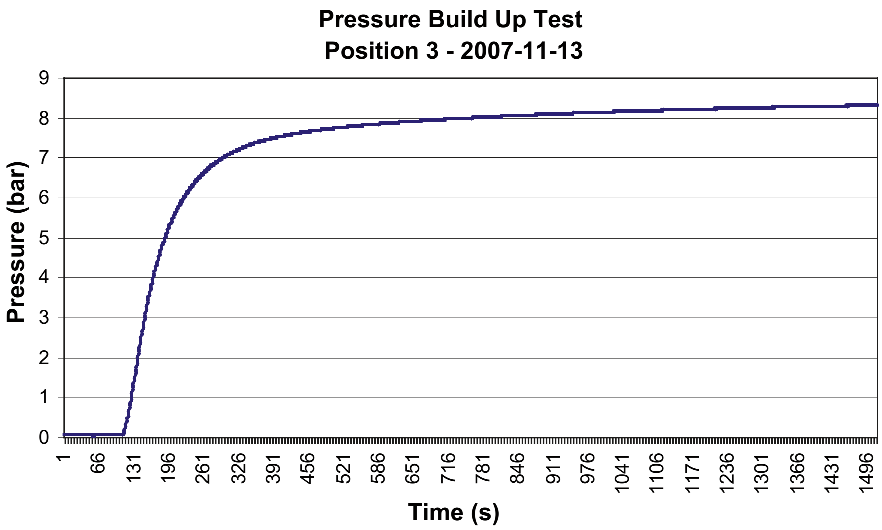
	Inflow (ml/min)	Remark
Before grouting, November 2007	65	
November 2008		Grouting of position 1 and 3
Mars 10 2008	270	
Mars 12 2008		Grouting position 5 (failed)
Mars 14 2008		Grouting position 4
Mars 17 2008	280	
Mars 18 2008		Grouting position 2
Mars 19 2008	280	
Mars 25 2008		Grouting position 5
Mars 26 2008	295	
Mars 27 2008	290	

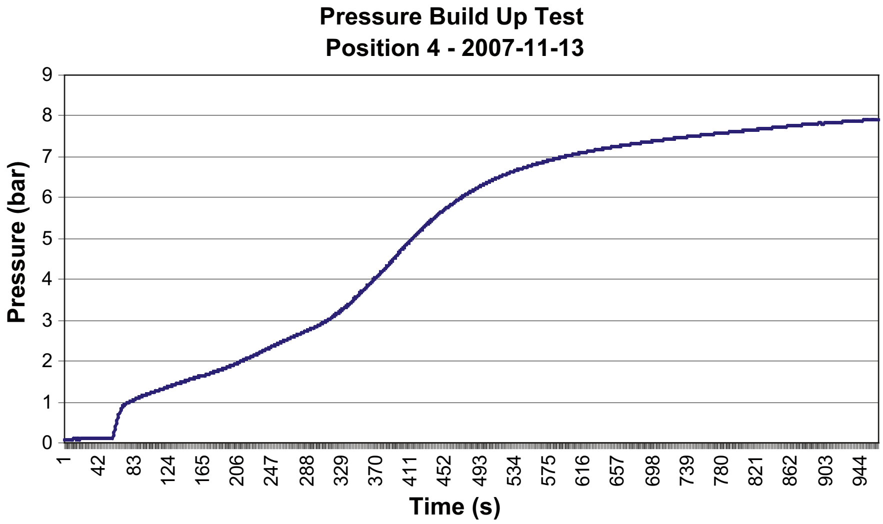
Appendix 2

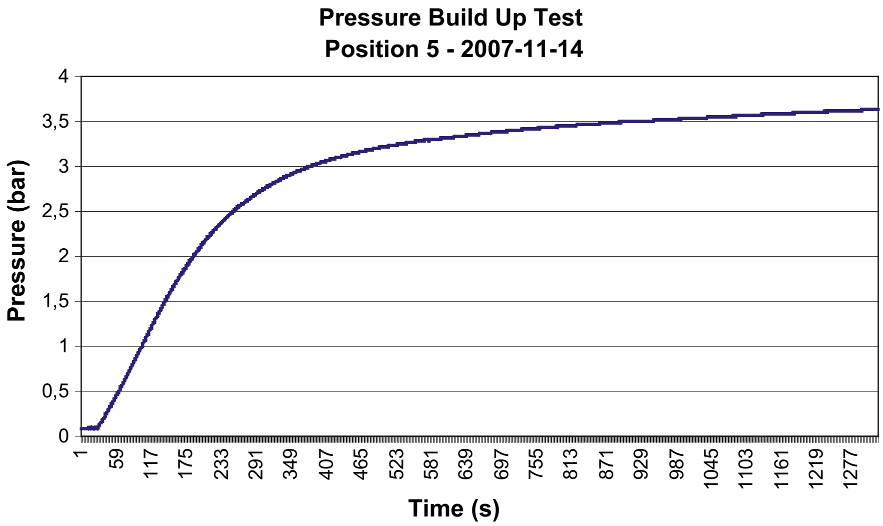
Pressure Build Up Tests

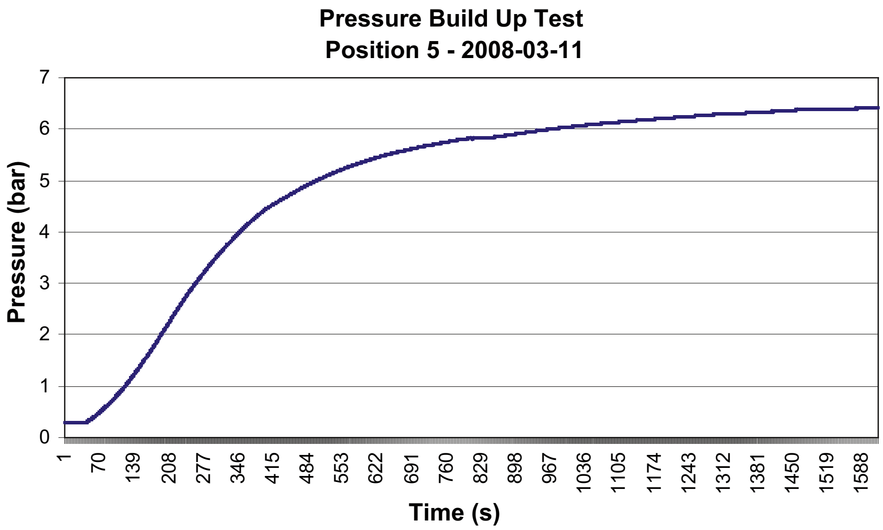


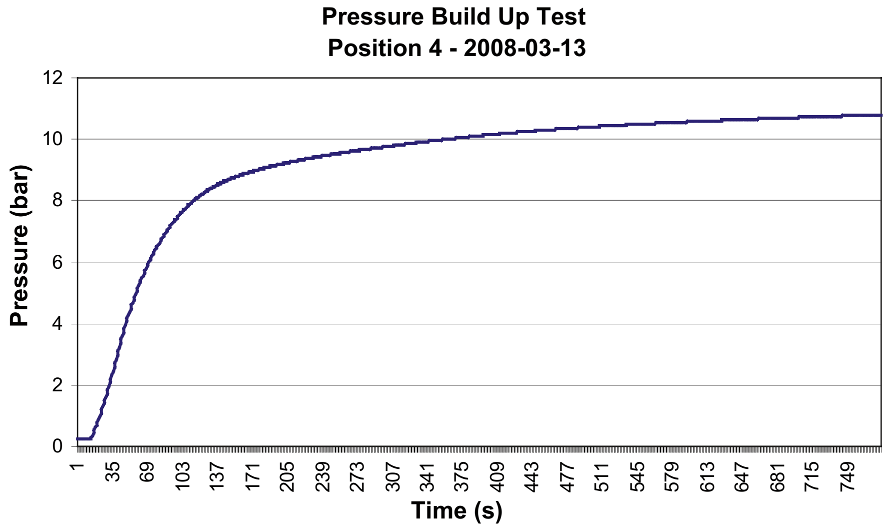


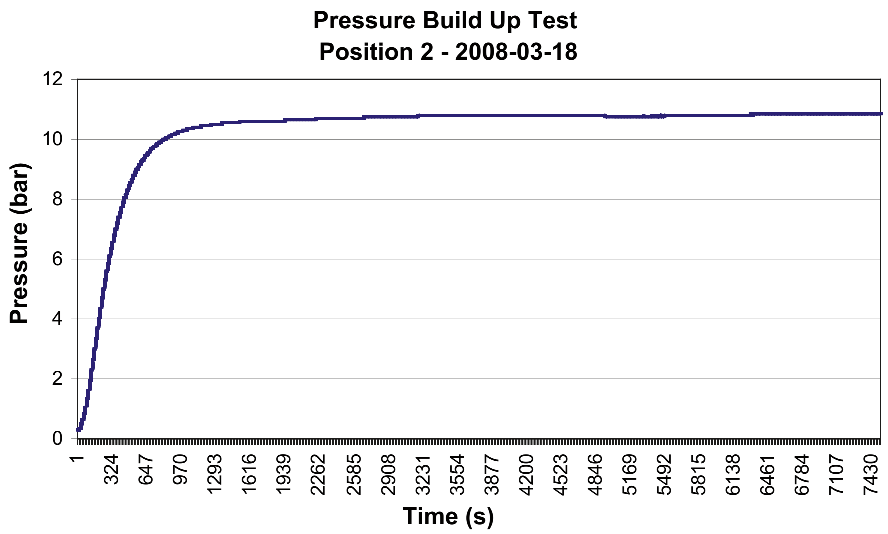



Pressure Build Up Test
Position 4 - 2007-11-13
Pressure (bar)
Time (s)


Pressure Build Up Test
Position 5 - 2007-11-14
Pressure (bar)
Time (s)


Pressure Build Up Test
Position 5 - 2008-03-11
Pressure (bar)
Time (s)


Pressure Build Up Test
Position 4 - 2008-03-13
Pressure (bar)
Time (s)
12
10
8
6
4
2
0
1
35
69
103
137
171
205
239
273
307
341
375
409
443
477
511
545
579
613
647
681
715
749


Pressure Build Up Test
Position 2 - 2008-03-18
Pressure (bar)
Time (s)
12
10
8
6
4
2
0
1
324
647
970
1293
1616
1939
2262
2585
2908
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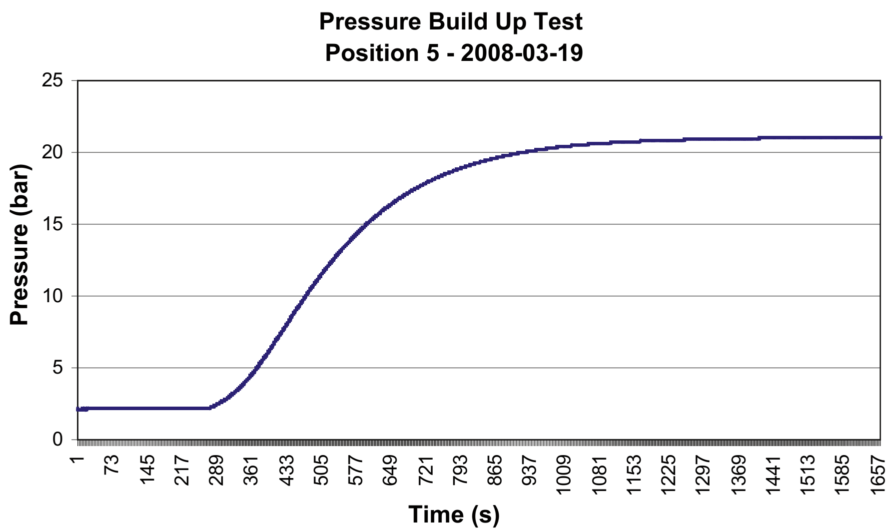
6461
6784
7107
7430


Pressure Build Up Test
Position 5 - 2008-03-19
Pressure (bar)
Time (s)
25
20
15
10
5
0
1
73
145
217
289
361
433
505
577
649
721
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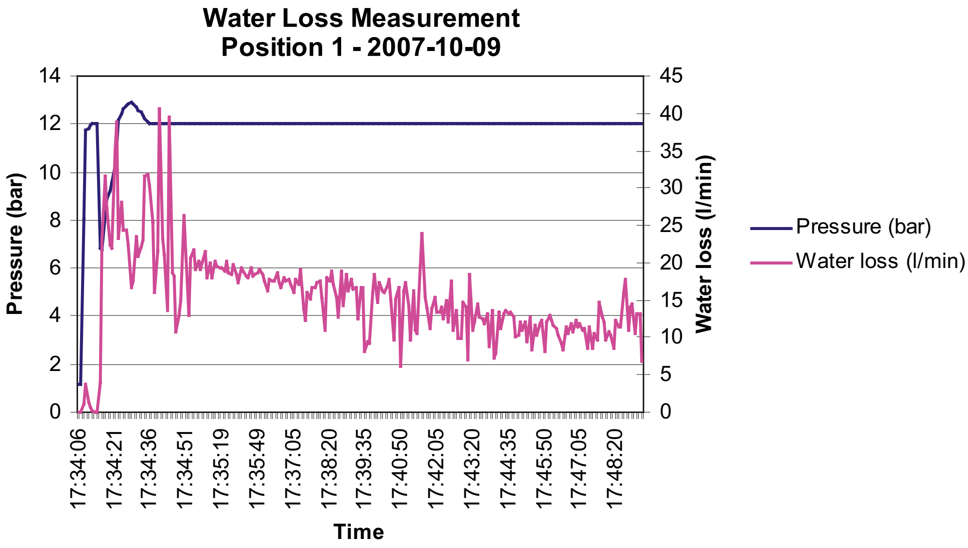
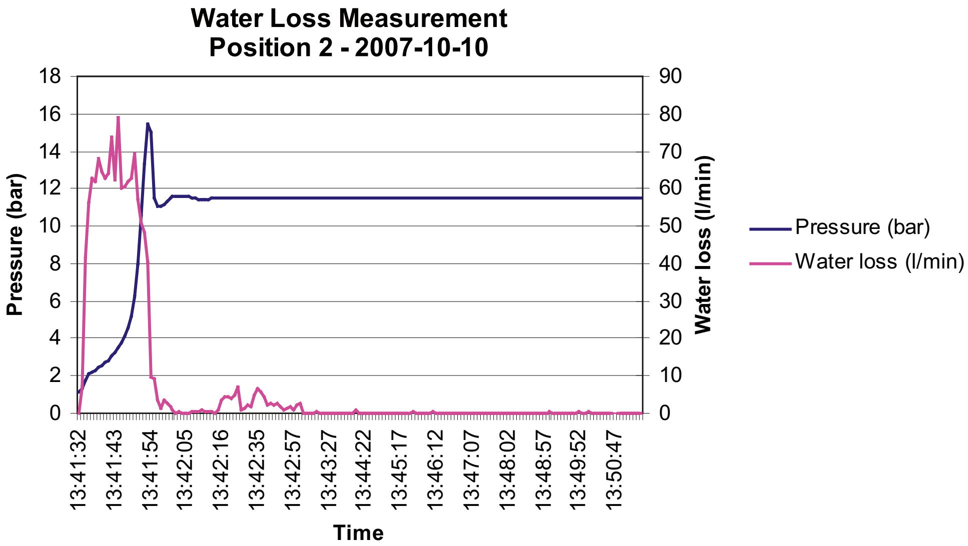
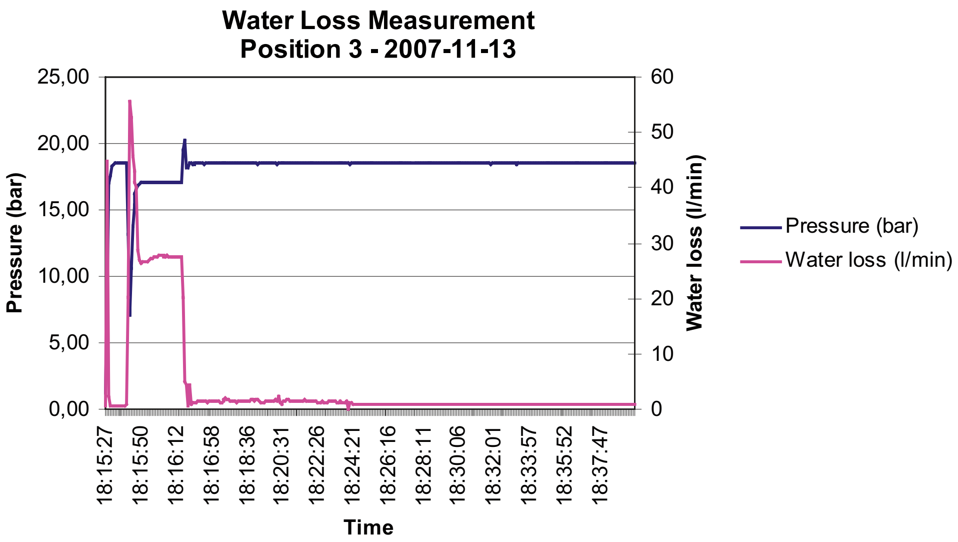
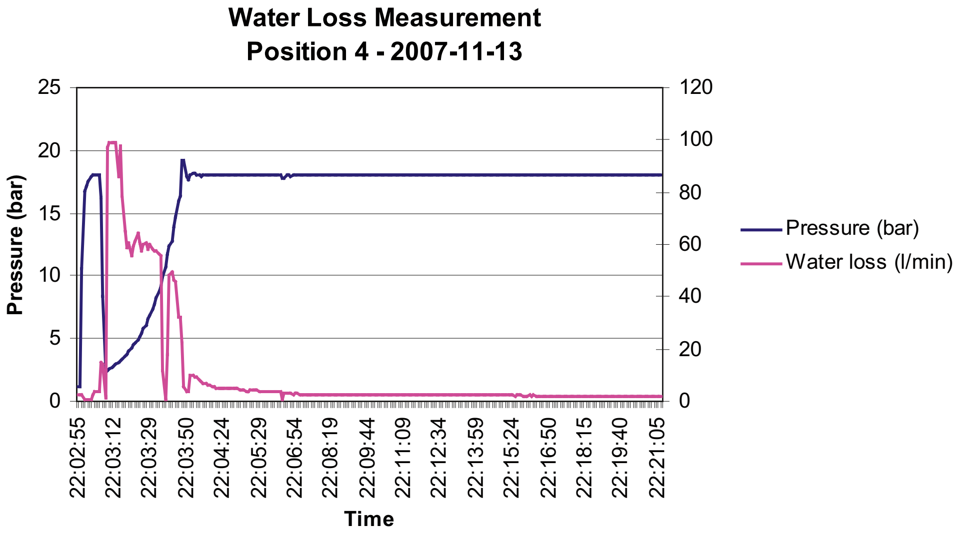
1441
1513
1585
1657

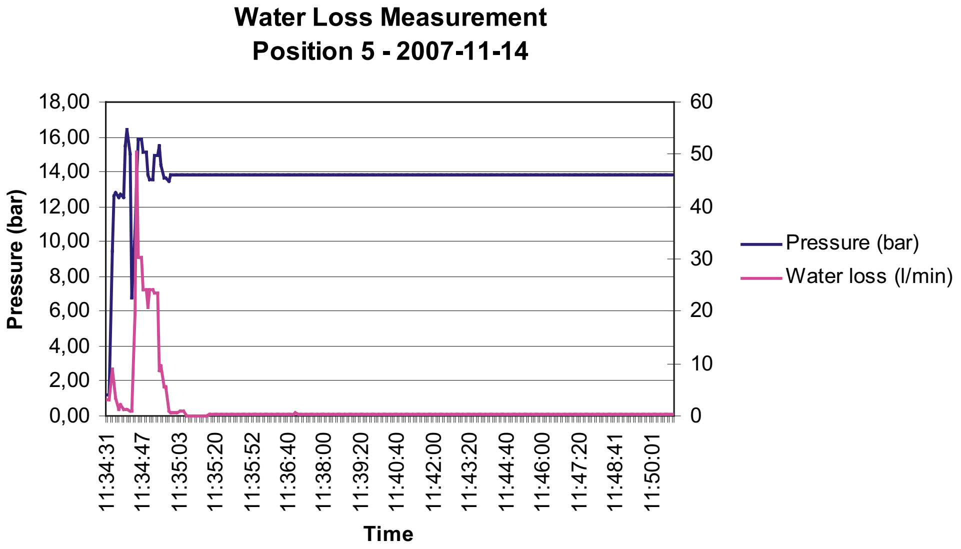
Water Loss Measurements

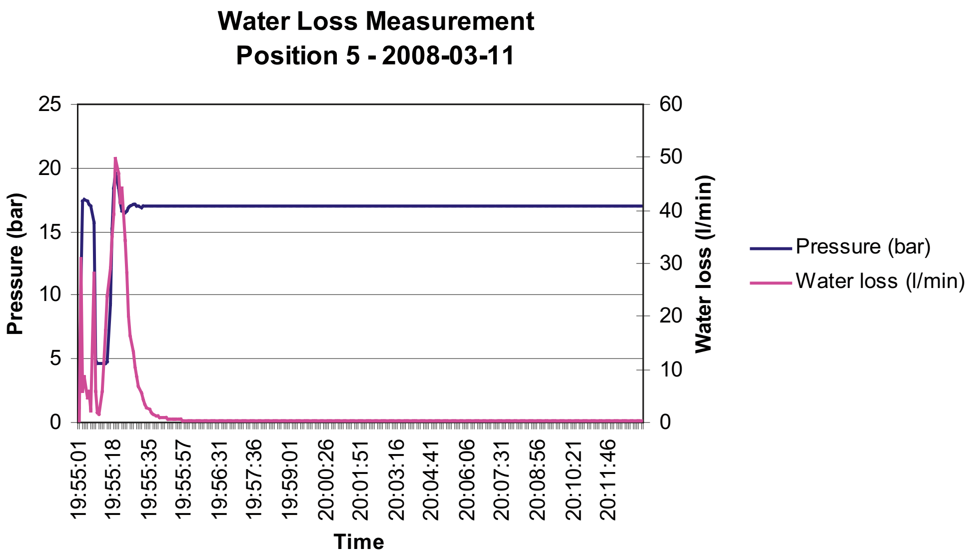


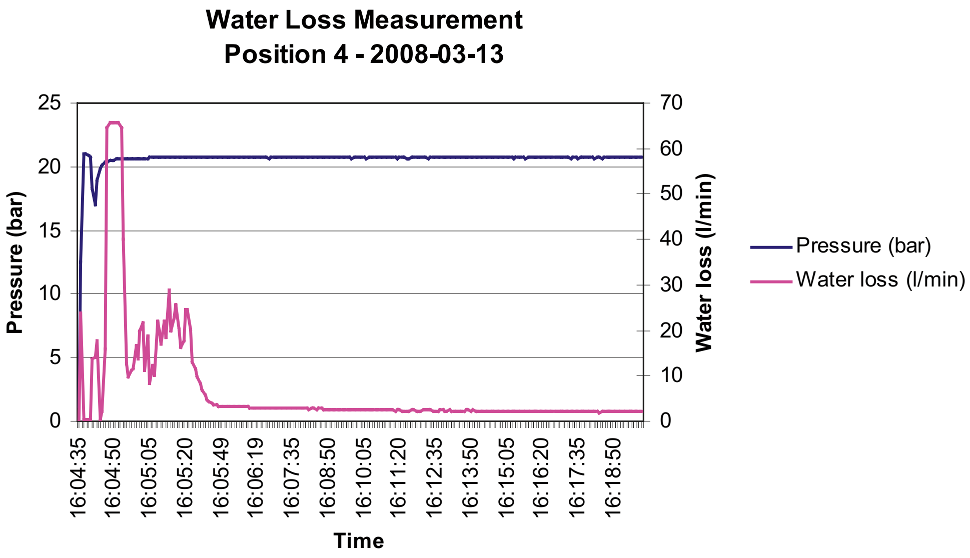


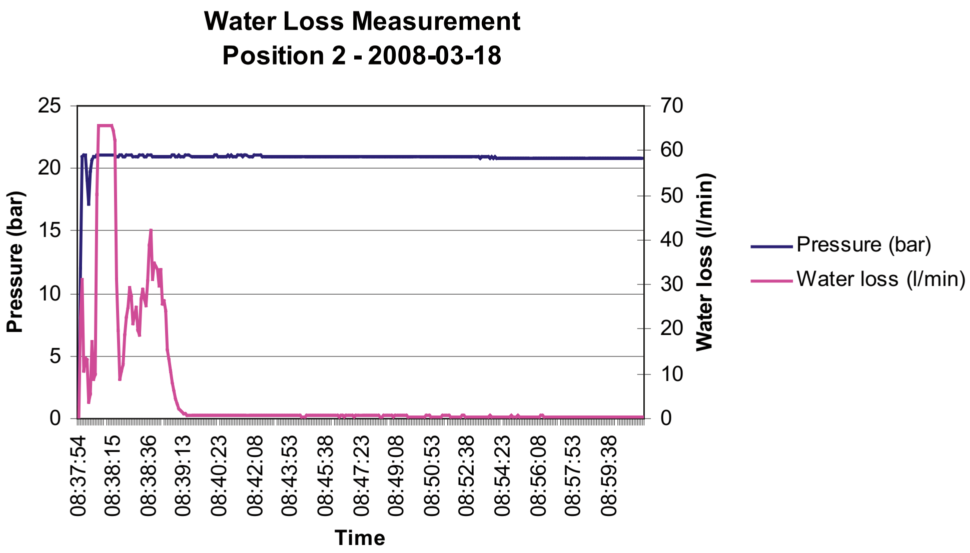


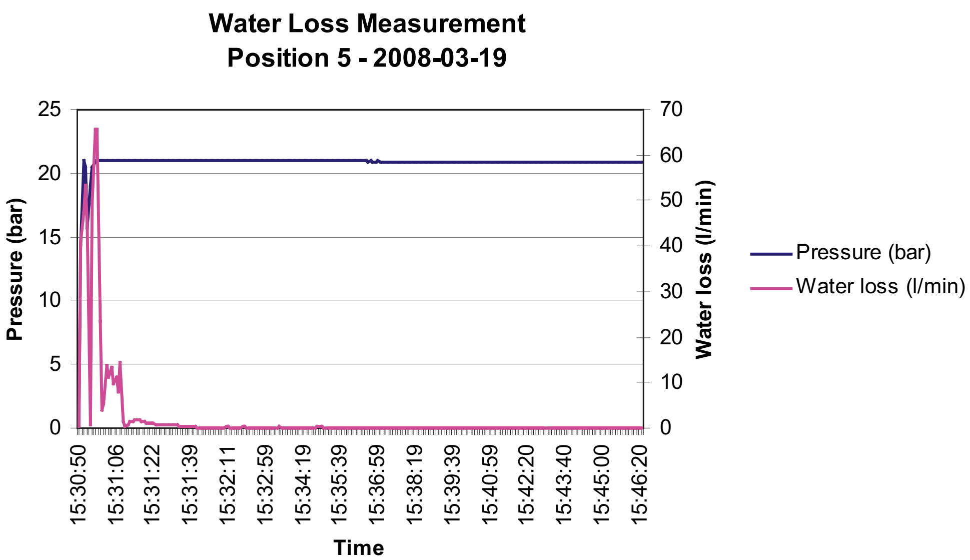

Water Loss Measurement
Position 4 - 2007-11-13
Pressure (bar)
Time
Pressure (bar)
Water loss (l/min)
25
20
15
10
5
0
120
100
80
60
40
20
0
22:02:55
22:03:12
22:03:29
22:03:50
22:04:24
22:05:29
22:06:54
22:08:19
22:09:44
22:11:09
22:12:34
22:13:59
22:15:24
22:16:50
22:18:15
22:19:40
22:21:05


Water Loss Measurement
Position 5 - 2007-11-14
Pressure (bar)
Time
Pressure (bar)
Water loss (l/min)
18,00
16,00
14,00
12,00
10,00
8,00
6,00
4,00
2,00
0,00
60
50
40
30
20
10
0
11:34:31
11:34:47
11:35:03
11:35:20
11:35:52
11:36:40
11:38:00
11:39:20
11:40:40
11:42:00
11:43:20
11:44:40
11:46:00
11:47:20
11:48:41
11:50:01

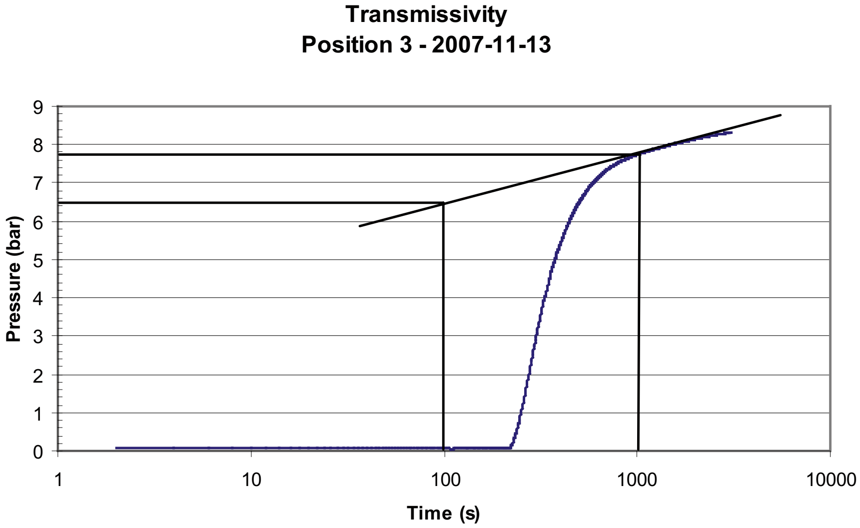

Water Loss Measurement
Position 5 - 2008-03-11
Pressure (bar)
Water loss (l/min)
Time
Pressure (bar)
Water loss (l/min)
25
20
15
10
5
0
60
50
40
30
20
10
0
19:55:01
19:55:18
19:55:35
19:55:57
19:56:31
19:57:36
19:59:01
20:00:26
20:01:51
20:03:16
20:04:41
20:06:06
20:07:31
20:08:56
20:10:21
20:11:46


Water Loss Measurement
Position 4 - 2008-03-13
Pressure (bar)
Water loss (l/min)
Time
16:04:35 16:04:50 16:05:05 16:05:20 16:05:49 16:06:19 16:07:35 16:08:50 16:10:05 16:11:20 16:12:35 16:13:50 16:15:05 16:16:20 16:17:35 16:18:50
Pressure (bar)
Water loss (l/min)


Water Loss Measurement
Position 2 - 2008-03-18
Pressure (bar)
Water loss (l/min)
Time
08:37:54 08:38:15 08:38:36 08:39:13 08:40:23 08:42:08 08:43:53 08:45:38 08:47:23 08:49:08 08:50:53 08:52:38 08:54:23 08:56:08 08:57:53 08:59:38
Pressure (bar)
Water loss (l/min)


Water Loss Measurement
Position 5 - 2008-03-19
Pressure (bar)
Water loss (l/min)
Time
15:30:50 15:31:06 15:31:22 15:31:39 15:32:11 15:32:59 15:34:19 15:35:39 15:36:59 15:38:19 15:39:39 15:40:59 15:42:20 15:43:40 15:45:00 15:46:20
Pressure (bar)
Water loss (l/min)

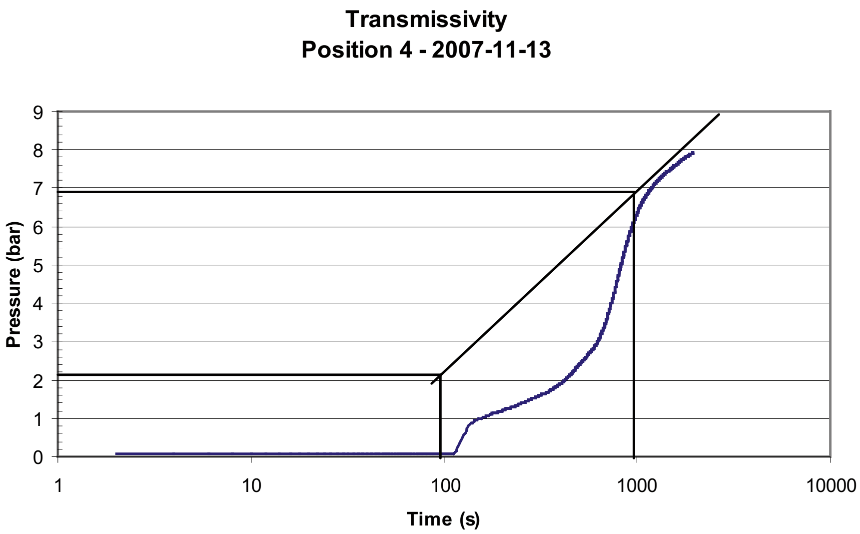
Pressure Build Up Test Evaluation – Transmissivity



dS'' = 1,2

Q = 0.49 l/min ⇒ 8.1 ∗ 10^{-6} m^3/s

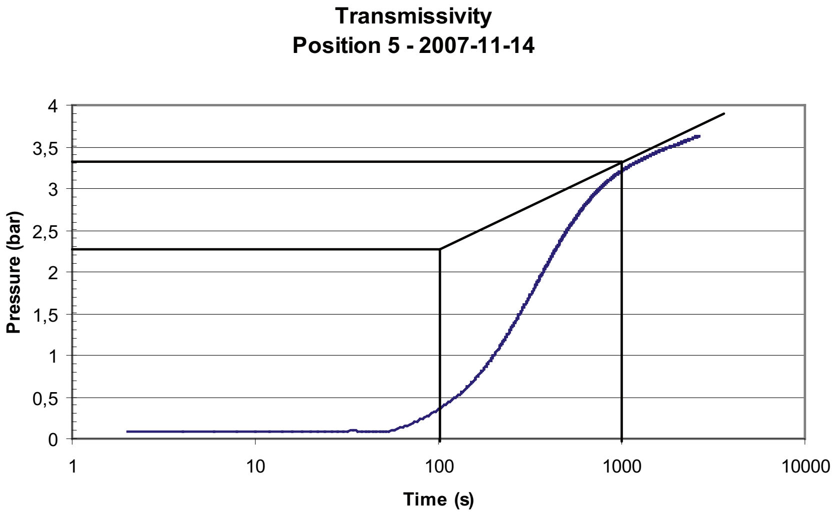
T = 1.25 * 10^{-6}



dS'' = 4,6

Q = 1,47 l/min ⇒ 24.5 ∗ 10^{-6} m^3/s

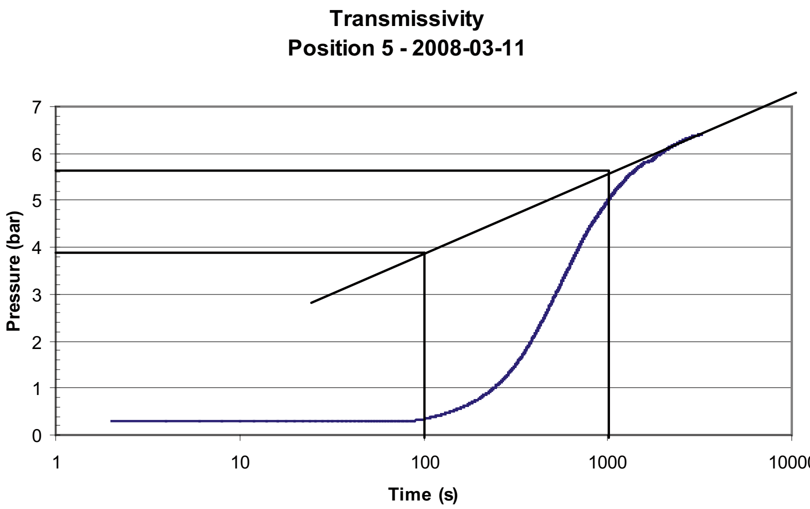
T = 9.7 * 10^{-7}



dS” = 1

Q = 0.148 l/min ⇒ 2.4 ∗ 10^{-6} m^3/s

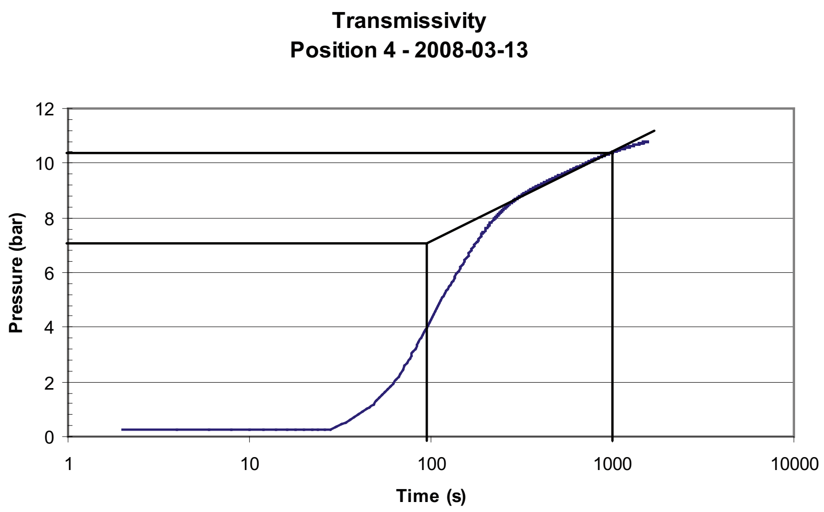
T = 4.392 * 10^{-7}



dS” = 1,8

Q = 0.190 l/min ⇒ 3.1 ∗ 10^{-6} m^3/s

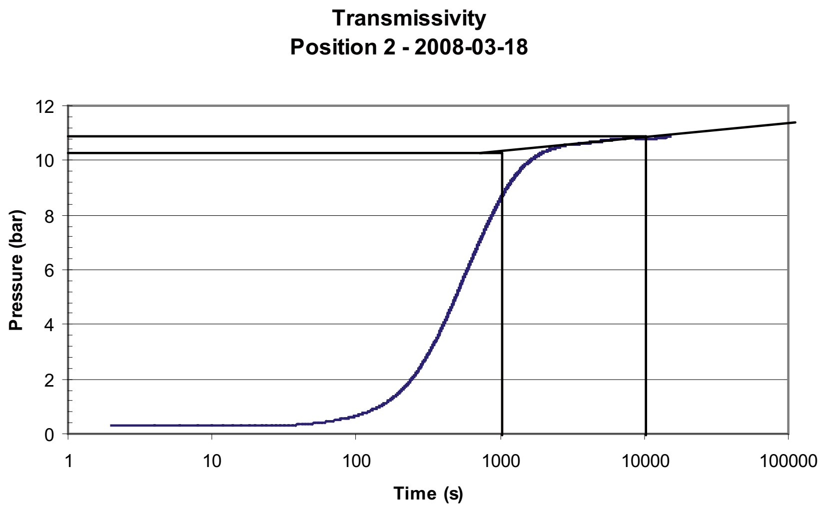
T = 3.1516 * 10^{-7}



dS” = 3,4

Q = 1.760 l/min ⇒ 29.3 ∗ 10^{-6} m^3/s

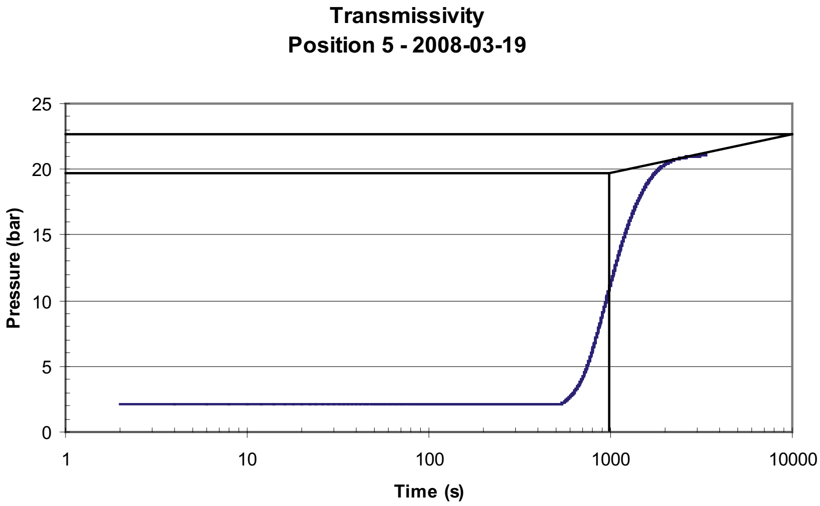
T = 1.577 * 10^{-6}



dS” = 0,8

Q = 0.145 l/min ⇒ 2.4 ∗ 10^{-6} m^3/s

T = 5.49 * 10^{-7}



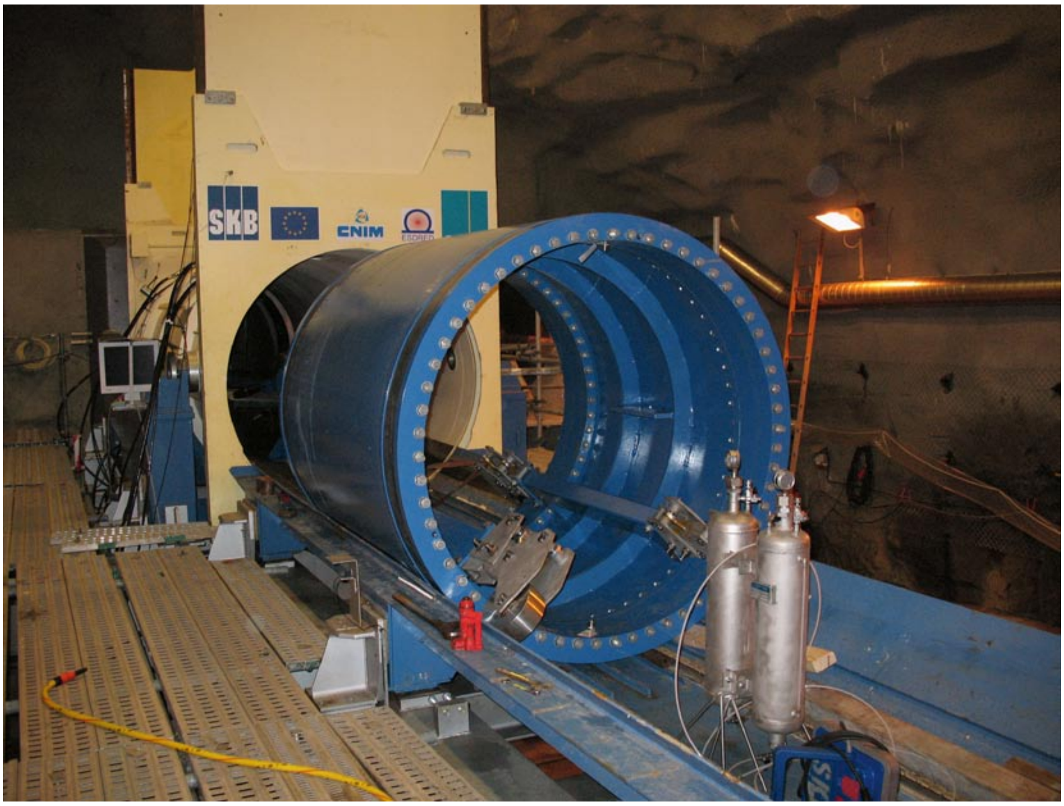
dS" = 2,8

Q = 0.190 l/min ⇒ $3.1 * 10^{-6}$ m^3/s

T = $2.026 * 10^{-7}$

Photos

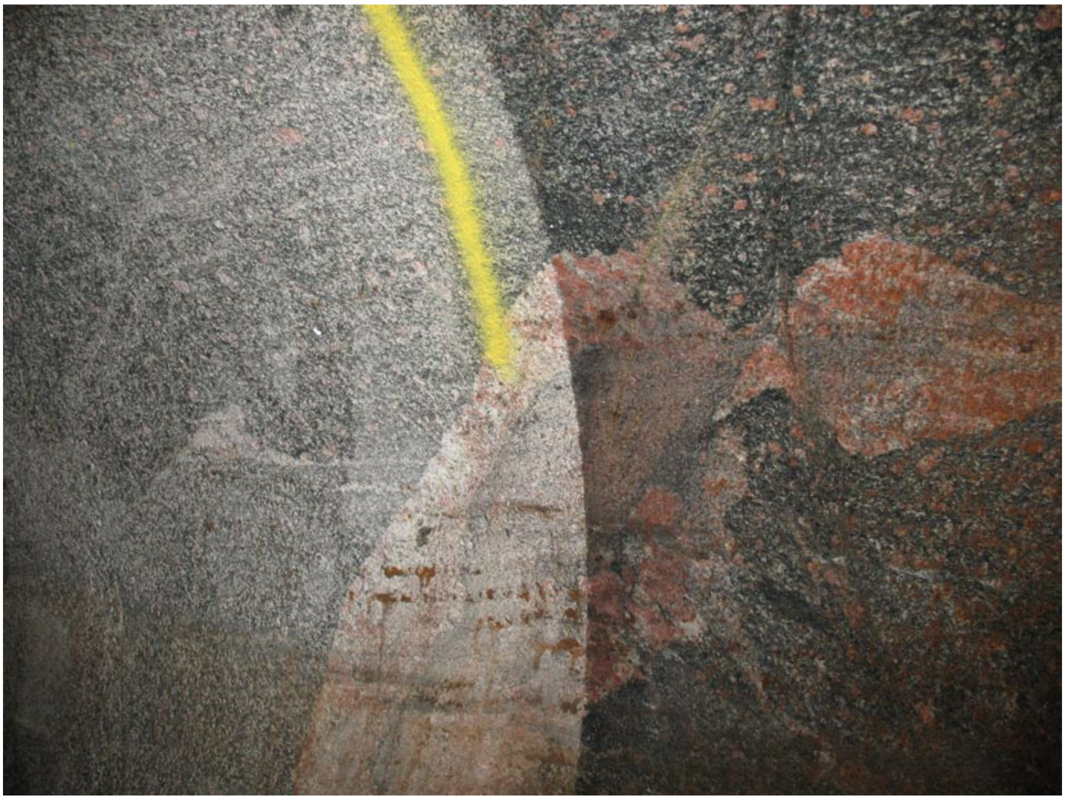
The Mega-Packer outside the drift.



The Mega-Packer connected to the pressure tanks.

Water leakage at position 1.

The rock wall after removing of the Mega-Packer showing the sealing effect.

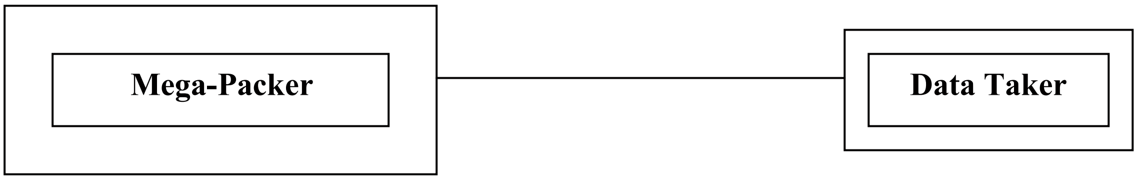


The rotation of the Mega-Packer in the drift before the wheels were adjusted.

Removing of the Mega-Packer after the first grouting session. The silica sol is left at the rock wall.

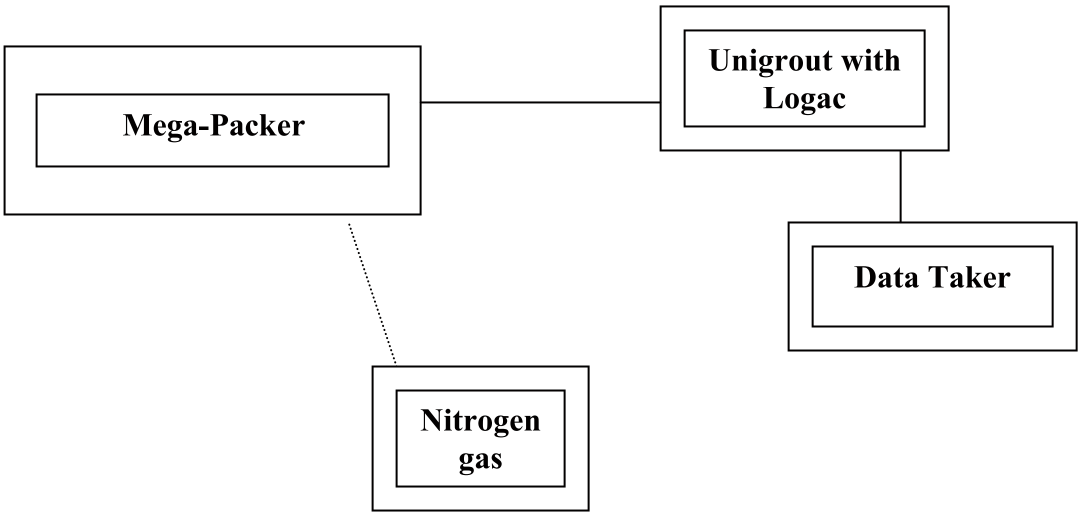
Connection between the equipment during the different steps in the experiments

Pressure Build Up Test



Water Loss Measurement

Grouting



Pressurising the packers