International Progress Report

IPR-04-57

Äspö Hard Rock Laboratory

Borehole sealing, preparative steps, design and function of plugs – basic concept

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September 2004

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Report no.	No.
IPR-04-57	F98
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Approved	Date
Christer Svemar	2006-03-21

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Keywords: Sealing, Plugging, Clearing and stabilization of the borehole, Borehole, Compacted bentonite, Copper tubes

Abstract

Stabilization and sealing of boreholes with a length or depth of up to about 1000 m must be made such that they will not serve as a continuous flow path for groundwater but be sealed to become as tight as the surrounding rock for at least 100 000 years. Where the surrounding rock has a low conductivity the sealed part must be very tight, while permeable but mechanically and chemically stable plugs can be constructed where permeable rock zones are intersected. Three main activities are required: 1) clearing and stabilization of the holes, 2) construction and placing of plugs, and 3) sealing and securing of the uppermost parts, which will be exposed to exogenic processes.

For clearing, existing techniques can be used although some development may be required; a standard procedure can not be defined. Stabilization is needed where the holes intersect fracture potentially unstable rock. This can be made by use of suitably composed quartz ballast solidified by a small amount of low-pH cement.

Construction and emplacement of plugs can be different in different parts of the holes. A concept is proposed that is based on the use of highly compacted smectitic clay where tight seals are needed and on casting cement-stabilized plugs where the holes pass through fracture zones. The length of the holes may imply practical difficulties like jointing of plug segments and erosion of the plugs in the installation phase. A very important finding is that the water in long boreholes must be replaced by low-electrolyte water before emplacement of clay seals for avoiding quick dispersion.

The uppermost part of deep boreholes must be sealed with material that can sustain the swelling pressure from below and offer resistance to mechanical impact like intrusion, erosion and glaciation. A few possible design principles have been identified and are mentioned.

Sammanfattning

I rapporten beskrivs stabilisering och pluggning av borrhål för bl a platsundersökning med längd upp till ca 1000 m. Den föreslagna principen är att ett pluggat hål inte får verka som en kontinuerlig strömningsväg utan tätas så att det får samma eller lägre genomsläpplighet än omgivande berg under åtminstone 100 000 år. Strategin innebär att där berget är tätt måste pluggen vara mycket tät medan genomsläppliga men mekaniskt och kemiskt stabila pluggar kan byggas där permeabla sprickzoner skärs igenom.

Tre operationer krävs: 1) rensning och stabilisering av borrhål, 2) byggnad och inplacering av pluggar, samt 3) tätning och försegling av hålens översta del där berget blir utsatt för exogena processer. Rensning kan göras med hjälp av existerande teknik men viss utveckling kan krävas; något standardförfarande kan inte definieras. Stabilisering erfordras där hålen skär igenom sprickzoner eller där bristningar skett som följd av höga bergspänningar och en viktig uppgift är att identifiera och karakterisera alla sådana partier innan stabiliserings- och pluggningsarbetena igångsätts. Avsikten är inte att täta zonerna utan att säkra instabila bergfragment som kan vara kvar efter rensningen. Detta kan göras med användning av gjutning av lämpligt graderat kvartsmaterial som hårdgörs med en liten mängd låg-pH cement. Ett nödvändigt villkor är att sammansättningen och anbringandet skall göras så att den allra största delen av kvartskomponenten blir kvar på plats under avsedd tid.

Konstruktion, byggnad och inplacering av pluggar kan vara olika i olika delar av hålen. Grundkonceptet innebär användning av högkompakterad smektitlera där täta pluggdelar krävs och gjutning av cementstabiliserade pluggdelar där hålen skär genom sprickzoner. Den föreslagna konstruktionen är i princip samma som tillämpats för djupa borrhål i SFR-området och som testats ingående i det internationella Stripaprojektet. Den mycket stora hållängden i det nu aktuella projektet kan innebära svårigheter såsom skarvning av pluggdelar och erosion av lerkomponenterna i appliceringsfasen. Preliminära studier för att kvantifiera och minimera problemen rapporteras i dokumentet och de visar att optimering krävs med avseende på val av metall i de perforerade rören som innehåller den kompakterade leran, perforeringsgraden och typ och densitet hos leran. Ett mycket viktigt resultat är att vattnet i djupa borrhål måste ersättas med saltfritt vatten för att undvika dispergering av leran.

Den översta delen av djupa borrhål måste pluggas med material som kan motstå svällningstrycket från huvuddelen av pluggsystemet och ge motstånd mot extern mekanisk påverkan såsom inbrytning, erosion och glaciation. Denna fråga kräver mer studium men några designmetoder har identifierats såsom fyllning med bitumen, införande av väl passade bergkroppar med silikagel eller fluorvätesyra som cement och tätning. Partiell smältning av berget kan också vara en möjlig förseglingsprincip. För djupintervallet 50-100 m är bedömningen att man kan använda bentonitpellets eller ringar av högkompakterad bentonit uppträdda på en central kopparstång, medan grundkonceptet, som beskrivs i rapporten, är lämpligt för mer än 100 m djup. Detta koncept innebär anbringande av högkompakterad smektitlera i perforerade metallrör.

Summary

The present document describes stabilization and sealing of boreholes with a length or depth of up to about 1000 m. The proposed principle is that such a hole bored for site investigation purposes must not serve as a continuous flow path for groundwater but be sealed to become as tight as the surrounding rock for at least 100 000 years. This strategy means that where the surrounding rock has a low conductivity the plug must be very tight, while permeable but mechanically and chemically stable plugs can be constructed where permeable rock zones are intersected. Three main activities are required: 1) clearing and stabilization of the holes, 2) construction and placing of plugs, and 3) sealing and securing of the uppermost parts, which will be exposed to exogenic processes.

For clearing, existing techniques can be used although some development may be required; a standard procedure can not be defined. Stabilization is needed where the holes intersect fracture zones or where failure has taken place because of high rock stresses, and an important task is to identify such parts before stabilization and plugging are initiated. The intention is not to tighten them but to secure unstable fragments in the borehole walls remaining after the clearing operation. This can be made by use of suitably composed quartz ballast solidified by a small amount of low-pH cement. A necessary condition is that the composition and placement be made such that the large majority of the quartz material remains on site during the intended time period.

Construction and emplacement of plugs can be different in different parts of the holes. A concept is proposed that is based on the use of highly compacted smectitic clay where tight seals are needed and on casting cement-stabilized plugs where the holes pass through fracture zones. The design of tight seals is basically the same as has been used for deep boreholes in the SFR area and extensively tested in the international Stripa Project. The much longer holes that are considered in the present project may imply practical difficulties like jointing of plug segments and erosion of the plugs in the installation phase. Preliminary studies for quantifying and minimizing them are reported in the present document. A very important finding is that the water in long boreholes must be replaced by low-electrolyte water before emplacement of clay seals for avoiding quick dispersion.

The uppermost part of deep boreholes must be sealed with material that can sustain the swelling pressure exerted by the main clay-dominated part of the plugged hole and also offer resistance to mechanical impact like intrusion, erosion and glaciation. This issue requires more consideration but a few possible design principles have been identified like filling of bitumen, placement of very well fitting rock columns with fluoric acid or silica gel for fixation and sealing, or partial melting of the rock.

For the depth interval 50-100 m it is estimated that bentonite pellets or rings of highly compacted clay stacked on a central copper rod may do, while deeper down, the basic design concept described in the report is suitable. This principle involves emplacement of perforated copper tubes filled with highly compacted bentonite.

Contests

1 Introduction

The report summarizes the outcome of work on borehole plugging that was initiated in 2002 for investigating how sealing of boreholes can be made based on to-days knowledge and experience and how the technique can be developed. It has involved both national and international expertise and has comprised the following activities:

1. Survey of proposed and applied borehole plugging techniques (State-of-art report dated December 2002), [1].
2. Symposium with presentation and discussion of techniques for preparation and plugging of boreholes (Seminar on borehole plugging, Äspö February 2003)
3. Definition of work plan Phase 2 during 2003- 2004.

Pursuing of the work plan will comprise the following activities:

- Listing and investigation of methods for clearing and stabilizing boreholes
- Characterization of boreholes for defining unstable parts
- Investigation of cement materials and grouting methods for hole stabilization
- Definition of basic plug concept
- Design of metal components etc with respect to placement
- Theoretical study for optimizing the design with respect to plug functions
- Laboratory testing of plugs (erosion, maturation)
- Field testing of plugs on various scales

The report will also, in general terms, define remaining questions and suggestions where and how the concept has to be examined, tested and applied in the future, and how the work should proceed in order to improve the concept.

2 Scope

Boreholes are made for investigation of a rock mass for finding out if it is suitable for hosting a repository and for characterizing it with respect to hydraulic, rock mechanical and geochemical conditions, which all need to be known for the design of a repository and analysis of its performance as well as for safety assessment. Some long (deep) holes bored from the ground surface may intersect the repository and serve as transport paths for radionuclides released from the radioactive waste by flow- or diffusive transport if they are not adequately plugged. Boreholes of any length and orientation that intersect both the near-field and conductive fracture zones can perform in the same way. Some holes will be bored from the interior of the repository in the construction and monitoring phases meaning that also horizontally and upwards directed holes have to be sealed. The performance criteria depend on the type of repository and different sealing materials can be considered. The choice of plug material with special respect to longevity is an important matter and so is the for placement method. A further, particularly important issue is how the tightness can be determined in situ for quality assurance.

The present document deals with the following major issues:

- Performance criteria for borehole plugs
- Preparation of boreholes, clearing and stabilization
- Plugging technique, materials and placement
- Performance of plugs

It describes principles for plugging boreholes of different lengths and nature and the performance of installed plugs. It also outlines required further investigation for optimizing the function and installation of proposed plug types.

3 Performance criteria

The boreholes that need plugging can be up to 1000 m deep, vertical or graded with an inclination of 45^{o} to 90^{o}. The diameter is commonly 56 or 76 mm but can be larger. For boreholes extending up to the ground surface it is required that they do not serve as continuous flow paths for groundwater but be sealed to get the same or lower conductivity than the surrounding rock for at least 100 000 years under the transient conditions with respect to temperature, rock strain and groundwater chemistry that will prevail. The tightness and hence design and construction of plugs can be different in different parts of the holes, meaning that the over the length intervals of a hole representing the distance between intersected fracture zones, the plugs need to be at least as tight as the normally fractured rock. More permeable plug parts can be accepted where the holes pass through fracture zones, where a higher conductivity of the plug can be accepted.

It will also be necessary to plug horizontal and upward-directed holes with a length of some hundred meters at different levels in a repository. The required longevity of the plugs is the same as for the repository, which, in practice, implies sufficient isolation for at least 100 000 years.

4 Procedures in borehole plugging

4.1 General

Three main procedures are required: 1) clearing and stabilization of the holes, 2) construction and emplacement of plugs, and 3) sealing and securing of the uppermost parts, which will be exposed to exogenic processes.

The preparative work required for selecting well defined techniques includes testing of plug materials and complete plugs as proposed in the report.

4.2 Preparation of boreholes for plugging

4.2.1 Field work

A basic requirement for emplacement of borehole plugs is to clear the holes by removing any obstacle and to make sure, by dummy testing, that the geometry and conditions of the borehole walls are such that plugs can be brought in. Two major activities can be defined: "Fishing" and "Clearing[1]" which precede characterization of the boreholes for identifying unstable parts from which rock fragments can fall in the course of the plugging procedure.

This subject has been treated by the Finnish deep-drilling company SMOY, which specified the following important issues [2]:

- Equipment remaining in a hole may be classified as belonging to two categories: drilling equipment, and measuring equipment. To remove the drilling or measuring equipment lost in a borehole, special techniques and professional skill must be applied.
- There are two common reasons for drill strings to become stuck in holes, 1) drilling problems like "burning" i.e. melt of bits due to failure in water flushing, and 2) rods left in the holes.
- There are several methods to remove the drill strings from a borehole, a primary one being lifting using the drill rig. If this cannot be made the next method to be tried is jacking, which is pursued until the drill string is recovered or broken.
- If the drill string breaks disconnection of the remaining rods should be tried. This is made by using rods with left-handed couplings and left-handed suitable worm pins or "carrots". The rate of disconnection varies greatly. It may be that just one rod can be removed at a time while in some cases hundreds of meters of drill strings can be extracted in one piece.
- If disconnection is unsuccessful or impractical, overcoring by use of a larger casing may be the best alternative. In overcoring it must be noticed that the clearance between the overcoring bit and the drill string to be removed must not be too large. If so, rock fragments formed may jam the casing and lock the drill string.

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[1] "Clearing" is used in this report for what is termed "rinsing" and "cleaning" in other contexts

- Equipment stuck in the hole may also be removed by drilling through it. The equipment removed will be destroyed when drilled through it. Loose equipment in the holes, like wire line cables, can cause considerable problems and drill bits stuck in holes are often so firmly held that they may have to be removed by drilling with another bit. There is a risk that drill rods and other equipment stuck in holes act as wedges and cause deviation of the hole at renewed drilling. Manufacturers provide special bits for drilling through steel. The bit must have an adequate diameter to prevent the development of wedge-shaped fragments.

- Part of the equipment stuck in a hole may be removed by drilling through it. By this, metal chips accumulate in the hole but many of them, i.e. those of steel, can be recovered by a magnet. Penetrated material will be destroyed and useless after removing and this technique is hence applicable only for removing less valuable and harmless material. Drilling through loose material, which can be made by use of coarse roughing bits in order to secure proper flushing of the bit, can cause problems and loose pieces may have to be cemented in the hole for subsequent re-drilling. Drilling a hole with a small size bit for penetrating loose pieces and making it possible to bring in a fishing tool can be an alternative technique.

- Removing measuring equipment from a hole is often demanding and time consuming. The equipment can be intended for short- and long-term surveys. For removing instrumentation of the firstmentioned type a probe is lowered in the hole using a wire line or a cable. The probe is usually centered in the hole by guiding rings with a diameter that are only slightly smaller than that of the hole. The most common instrumentation for short-term surveys are standard geophysical probes, difference flow probes, digital scanning cameras, water sampling devices, HTU-probes and down-hole seismic probes. The probes usually get stuck because a piece of rock has fallen between the probe and the borehole wall.

  As to instruments for long-term surveys, e.g. hydrogeological investigations in holes, the type most commonly being stuck is a multipacker device consisting of several plugs, support rods made of steel, and plastic tubes. For this type of instruments wedging by loose rock fragments or cementation caused by the drill slurry are the most common reasons for problems in removal campaigns.

- Some of the instruments that cannot be easily recovered may be valuable or unwanted because they contain parts (e.g. batteries) that affect the groundwater chemistry in the hole. Such parts must be removed from the holes without breaking them. Parts of the devices may be removed also after breakage.

- Normally, a drill rig and a drill string are needed in the clearing work. The drill string is attached to standard tools or special fishing tools. In practice, it is possible that, either before commencing the clearing operation or in the course of it, new fishing tools must be designed and manufactured. Quite often the lifting capacity of the rig is a limiting factor and a jack lift is needed for heavy lifting work.

- A vital part of the clearing operation is early planning. In order to make the plan and to select suitable methods it is important to know the condition of the device stuck in the hole. It is also important to know the exact depth where the equipment is located and to find an explanation of the mishap. Also, it is very important to know the correct dimensions of the device before starting the work. At least one alternative plan must be identified as back-up.

- When the plan for the clearing work has been approved, all fishing tools etc. must be manufactured. The exact position of the equipment stuck in the holes must be checked.
- In present and future instrumentation of drill holes all measuring devices should be designed so that the risk of getting them stuck can be minimized. Devices should be centered in holes with elastic material so that pieces of rock falling on the device will not cause wedging but pass it and fall to the bottom of the hole. Stone collectors on top of probes are common and useful for collecting fallen rock fragments. Further, couplings that fit standard drill rod threads at the top of the probe help fishing with normal drill rods if necessary. Also, the attachment of cables to the probe should be designed so that the cable will break at pre-determined spots if the probe gets stuck. The clearing work is thereby simplified and the cable may even be utilized in the rescue work.

4.2.2 Characterization of boreholes for defining unstable parts

The basis for identifying unstable and enlarged parts of boreholes that need to be secured and given the same diameter as the rest of the holes comprises borehole loggings including photographic, petrographic and geodetic documentation. A routine scheme for this must be developed that specifies the geometry, rock mechanical characteristics, petrography, temperature and hydraulic properties of the boreholes with specification of where stabilization or other activities are needed. Preliminary studies show large variations in the presence of fracture zones that require stabilization. In granite domes, like the Stripa granite massive, typical diagnostic fracture zones appear as shown in Table 4-1. In other areas, like the Forsmark region, the spacing of zones deemed to require stabilization is larger.

Table 4-1. Diagnostic fracture zones as interpreted from LBL deep hole data (Stripa granite, SBH1 and 2).

Hole	Depth, m	RQD	Caliper	Indication	Conductivity, m/s
SBH-1	50-60	40	>5 %	Wave form	>E-7
SBH-1	105	75	>5 %	Wave form	E7
SBH-1	180	70	>5 %	Pegmatite dike	5E-9
SBH-1	240-260	50-75	-	Acoustics	5E-9
SBH-1	315-325	55	>5 %	Temp. change	E-9
SBH-2	55-65	60-70	-	-	E-6
SBH-2	110	60-65	-	-	E-7
SBH-2	190	75	-	-	5E-8
SBH-2	270	70	-	-	5E-9
SBH-2	320	75	-	-	5E-9
SBH-2	350	75	-	-	E-9

The Stripa data indicate that fracture zones that require stabilization have a spacing of around 50 m, which fits well with the structural models developed when the research area in the granite had been excavated. This example shows that one needs to be prepared to make rather comprehensive stabilization of deep boreholes. The length of the zones in some of the holes in the table suggests that the intersected fracture zone are steeply oriented, which would naturally require stabilization over a considerable length of the holes.

For the Äspö area one finds a large spectrum of distances between water-bearing fracture zones. In many holes the spacing of zones with a higher hydraulic conductivity than E-7 m/s ranges between about 10 and more than 200 m, the average being around 50 m in some holes and much more in others.

Also in other areas of crystalline rock structural investigations have been found to show patterns of fracture zones that are not very different from those of the Stripa region although the evolution of the bedrock may have been quite different. In the Forsmark (SFR) area steeply oriented very dominant fracture zones appear with spacings of one to a couple of kilometres. Boreholes across such zones would require frequent and comprehensive sealing and stabilization over sections of considerable length. They would, however, be avoided in a repository context. Oblique or subhorizontal fracture zones with a width of up to a few decimeters appear with an average spacing of about 50 m down to one or a few hundred meters depth like at the Stripa and Äspö sites but deeper down the spacing is much larger. Some of these zones require stabilization.

Finnish bedrock shows similar features. For Roumovaara gneiss core examination in TVO studies have shown major zones and discrete water-bearing fractures with spacings similar to those at Stripa. Typically, the spacing of the latter increases from less than 3 m down to 250 m depth to twice this figure at more than 400 m depth. The ratio of the amount of fracture zones that require stabilization and minor, water-bearing fractures that do not require stabilization can be estimated at 1:10, which suggests that a steep hole would, as an average, intersect 5-10 fracture zones down to about 300 m and 2- 3 in the interval 300 to 700 m.

4.3 Practical aspects

4.3.1 General

Plugged boreholes must not serve as short-circuits for flow of possibly contaminated groundwater from the repository. They should therefore not be more permeable than the surrounding rock. Where the boreholes intersect fracture zones it is meaningless to seal them effectively over this length, while it is important to make the plugs tight in the interval between intersected fracture zones. Where fracture zones are intersected other seals like cement-stabilized silica sand can be used provided that the material remains in the holes and is not eroded and removed. The following issues are of major importance:

- It should be decided if deep holes need to be equally well tightened below as above the repository level or some hundred meters below it. It is suggested that decision on this matter should be based on the rock structure model and hydraulic performance, but it is proposed here that holes extending deeper than 300 m below the repository level should not require other seals than chemically stable material, like quartz grains physically stabilized by a very small amount of low-pH cement, that fills the holes and stays there for 100 000 years. This would make high-quality plugging much simpler and accurate than if deeper holes have to be equally well tightened over their entire length.

- Time-dependent degradation of the plugs must be accepted but the goal is to find plug materials that maintain their constitution and tightness for at least a hundred thousand years. For effective sealing the plug should have a hydraulic conductivity equal to or lower than that of the surrounding rock, which commonly corresponds to E-11 to E-8 m/s. An important sealing criterion is that the plug must be in tight contact with the rock, which can only be achieved if the plug material consists of expanding clay that exerts an effective (swelling) pressure on the borehole walls.

- From a practical point of view it is required that the technique selected for borehole plugging is feasible and that the various detailed steps in preparation of the boreholes and construction of the plugs can be documented. For the safety analysis it is required that the performance of the plugs is described and modelled.

- A number of practical issues are of importance in selection and application of suitable plugging techniques. Major tasks are:

1. Safety-related principles to be followed
2. Sealing of the uppermost part of deep boreholes that extend to the ground surface
3. Rock stabilization techniques
4. Decision of plug design for long and short holes oriented in different directions
5. Manufacturing of plugs
6. Placement of plugs
7. Cost

4.3.2 Principles

The basic criterion is that the plugged boreholes should not be more permeable in axial direction than the undisturbed, surrounding rock. It is proposed that where fracture zones are intersected, seals like cement-stabilized silica sand can be used provided that the material remains in the holes and is not eroded and removed. Where the holes intersect tight rock clay-based plugs are used.

Special quality criteria must be defined respecting the materials and emplacement techniques used. Such definitions have to be made when the plugging techniques have been decided.

4.3.3 Sealing of the uppermost part of boreholes that extend to the ground surface

This matter requires further study but it is proposed that the upper ends of deep and steeply oriented boreholes be sealed by materials that can sustain the swelling pressure of the major part of the plug and offer resistance to external mechanical impact like intrusion, erosion and glaciation. It is proposed that the uppermost 50 m long part is plugged, at least partly, by well fitting rock cylinders pressed down in precision-drilled (reamed) holes with silica gel or fluoric acid[2] as mortar or glue. Alternatively, partial melting of the rock can be considered. For the 50-100 m interval one can use bentonite pellets or compacted bentonite rings placed around solid copper rods. Alternatively, filling can be made here with artificial bitumen[3]. Below 100 m depth the holes are sealed by inserting highly compacted smectite clay contained in perforated tubes that are jointed to form continuous clay columns between sand/cement-sealed parts representing intersected fracture zones. The present report is focused on the plug design, construction and performance for depths larger than 100 m.

4.3.4 Rock stabilization techniques

The matter of selecting suitable materials has been considered based on a study made by CBI. Major issues are described below.

Materials

Various combinations of cement, ballast material and superplasticizers have been tested, the criteria being that the material must be groutable below water in deep boreholes, become strong enough to carry a clay plug of considerable length already after one day without failing, and be sufficiently fine-porous even after dissolution of the cement component to prevent clay particles from passing through it. The following major properties are valid for the proposed concrete:

- The concrete is prepared using a concept with large amounts of suitably graded quartz filler and only a small cement content. It is possible to adjust the recipe so that it may contain larger stones if required.
- The concept demands use of a superplasticizer. By increasing the amount of binder and reducing the amount of filler the amount of superplasticizer can be kept at minimum.
- The shrinkage is small due to the small amount of cement. At wetting one can observe a small swelling. This means that there will be no practically important gap between the concrete and the rock.
- The proposed material for stabilization is deemed to be stable for a considerable time but dissolution and loss of the small cement component will occur and the material will then remain as a clastic quartz fill of extreme longevity.

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[2] Great care required because of toxicity

[3] It remains to be certified that artificial bitumen is sufficiently longlived. Natural bitumen is not acceptable.

The composition of the concrete is proposed to be as given by Table 1.

Table 1. Concrete concept (CBI).

Components	Kilograms per m^3 of concrete
White cement (Aalborg Portland)	60
Water	150
Silica Fume (Elkem)	60
Finely ground α quartz (Sibelco)	200
Finely ground cristobalite quartz (Sibelco)	150
Superplasticizer (Glenium 51Modern Betong)	4.38 (dry weight)
Aggregate (ballast), (Underås, Jehanders Grus)	1679

The most important concrete properties are as follows:

- Rheology: Syrup-like flow behaviour.
- Strength: For 1 day curing the cube strength is on the order of 1 MPa at 10-20^{o}C and for 2 days curing time it is 1.9 MPa at 5^{o}C and 4.5 MPa at 20^{o}C.
- Shrinkage/Expansion: Shrinkage will take place in the first month yielding a gap between rock and concrete of less than 10 mm, but it is followed by expansion that will eventually almost close the gap.
- Pore size: The porosity is about 0.6 and the maximum void size less than a few tens of micrometers, which certifies that clay particles can not penetrate the concrete.

Techniques

Several techniques for performing injection, reboring etc have been suggested. A method that describes the principle of deep borehole grouting and is similar to the one being developed in SKB's ongoing RDT work has been suggested by Dr Craig Garden, Chevron-Texas, cf. Figure 4-1, [1]. A tool – Para Bow – is extruded from the lower end of a perforated cylinder containing grout, which is pumped out from it after expanding the tool to form a packer. After hardening of the grout re-boring with diamond cutters for removal of excess cement and steel components can be made to yield the desired diameter of the borehole.

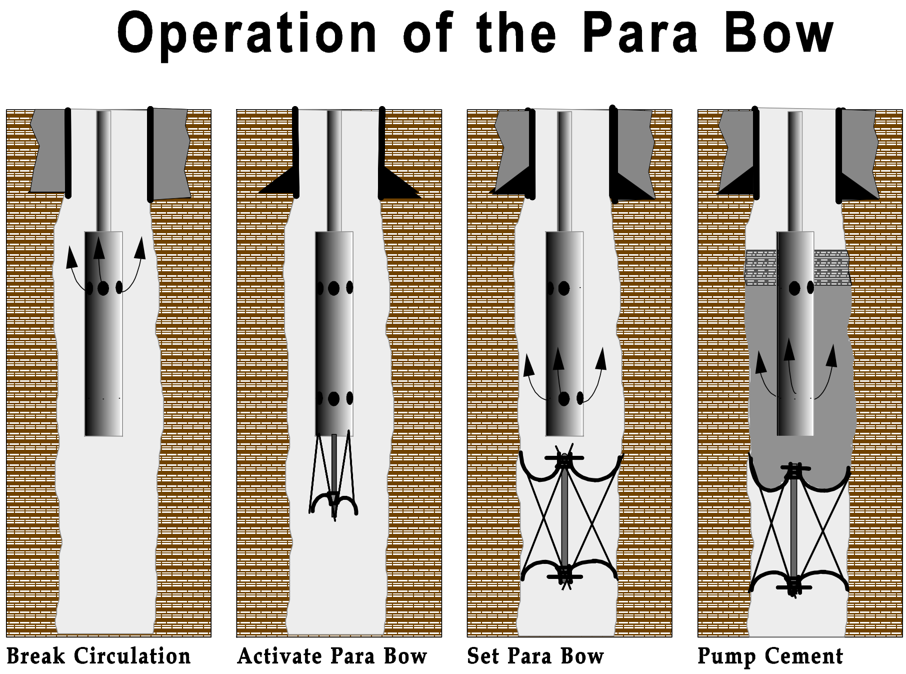

Figure 4-1. *The Para Bow method for cement grouting of boreholes. After re-boring that gives the hole the desired diameter plugging is made by using expanding clay (bentonite).*

4.3.5 Clay plug design

Working principle

Historically, the basic principle of plugging the lager part of deep boreholes by use of clay was published some 20 years ago (cf. Figure 4-2) and has been tested and applied in several contexts since then. Prefabricated perforated metal tubes are filled with tightly fitting cylindrical blocks of highly compacted smectite-rich clay like MX-80 [3, 4, 5] When the plugs are submerged into the water the clay will migrate through the perforation and ultimately embed the tubes in largely homogeneous clay. Since clay moves out rather early there will be some frictional resistance that must be overcome in the emplacement phase and the time for installation must therefore be relatively short as described in subsequent chapters.

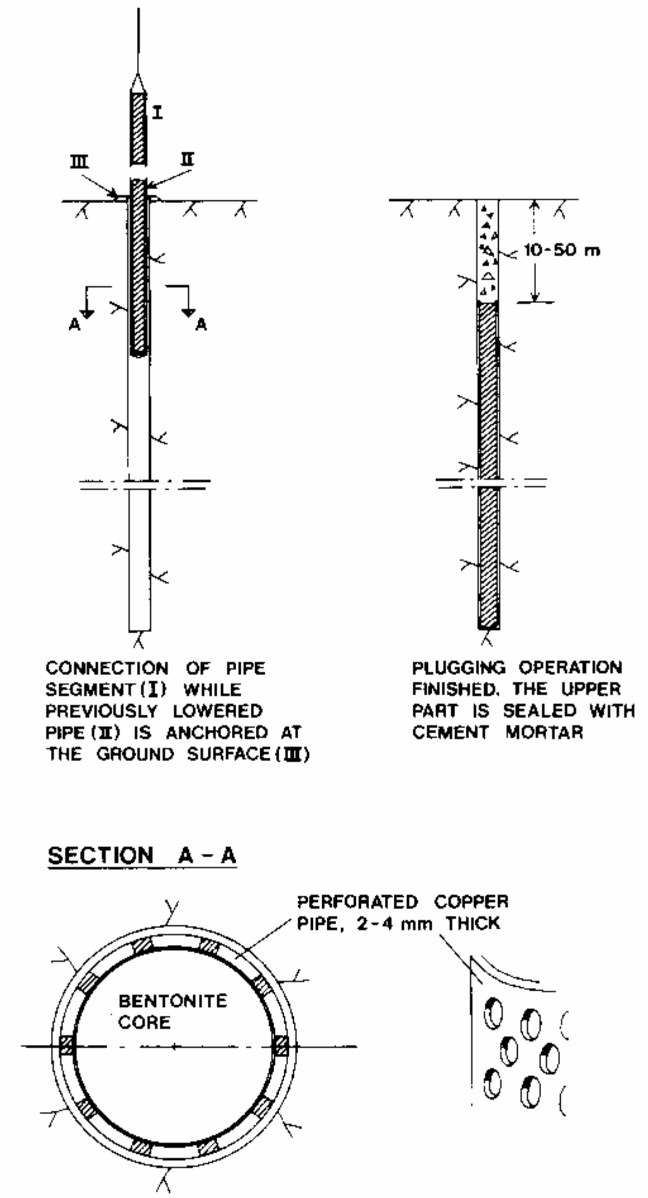

Figure 4-2. *Schematic picture of procedure for borehole plugging with precompacted clay blocks [3, 4, 5].*

Design of the confinement of the clay

The selection of tube metal and design of tubes with respect to the mechanical strength that is needed for safe handling of the clay plugs has been considered by SWECO AB. The basis of the design includes the hole diameter, the required gap between the tube and the rock, the perforation ratio, and the density of the plugs. The major issues are summarized here:

- Practical aspects, stress and strength issues, and the need for retrievability call for a concept of successively emplaced, relatively short clay plug segments. Plug elements of 3 m length jointed on the ground surface to form 24 m long segments appear to be at optimum.

- The forces and possible need for pulling up segments imply that a high-capacity drill rig be used. The jointing of the plug elements can be made by use of the rig.
- The major objective of the perforated tube is to protect the clay from being damaged in the course of the placement in the hole and to retard the expansion of the clay so that its maturation will not hinder the placement, which is estimated to require 4-8 hours for a 1 km deep hole. The stresses in the tubes in the various plug placement phases must be sustained, which determines the wall thickness of the tubes for any perforation ratio. The net density of the clay must be sufficient to fulfil the hydraulic conductivity criteria, which implies that the clay density must be high and the wall thickness small. The design is hence a compromise between sufficient strength of the tubes and sufficient density of the clay.

One of the most important tasks is to design and manufacture the joints between the plug elements. They must allow for quick connection between the elements and they must have at least the same axial and radial strength as the tubes. The proposed solution given by SWECO AB is illustrated in Figure 4-3.

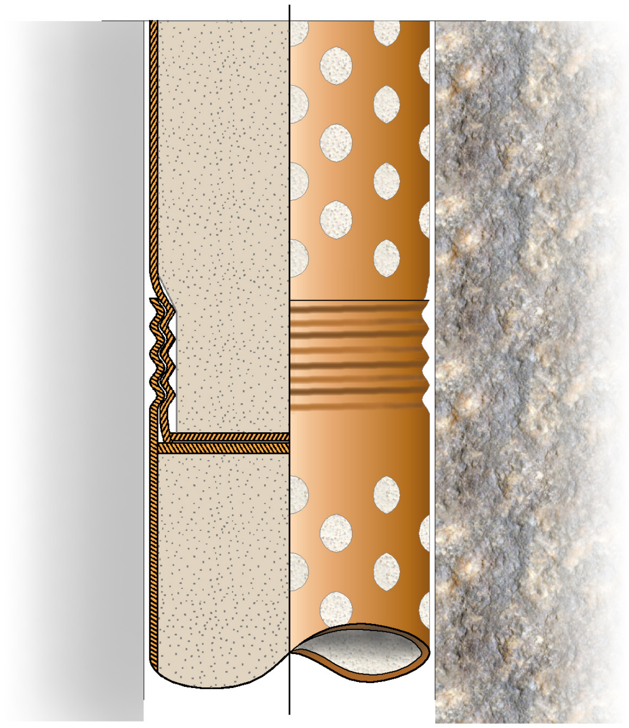

Figure 4-3. *Proposed jointing of plug elements to form 24 m long segments for emplacement in boreholes.*

The required net density of the water-saturated and matured clay plug depends on the type of clay. It needs to be on the order of 2000 kg/m^3, corresponding to a dry density of 1590 kg/m^3, for fulfilling the criterion that the hydraulic conductivity must be lower than that of the surrounding rock. This means that the clay in the tubes must be prepared by compacting clay powder under high pressure. The borehole diameter ranges between 76-100 mm and in several of the various studies underlying the present report the borehole diameter was taken as 100 mm. This range of diameters does not give significantly different results respecting the clay tightness.

The major issues in the tube design work were as follows:

- The tensile strength of the perforated tubes determines the maximum length of the plug segments.
- Copper, Navy Bronze, steel, and titanium have been considered and deemed possible as tube metal.
- A practical solution for use of copper tubes leads to 24 m long segments consisting of jointed 3 m long parts. The tensile strength is sufficient, assuming 4-fold safety and that safe attachment to the drill string can be achieved. The thickness of the tube wall will be 2-3 mm and the outer diameter about 6 mm smaller than the diameter of the hole.
- Each 24 m segment is lowered into the desired position, i.e. in the space between two stabilized fracture zones, and left there. Several segments will be placed in series without coupling them together. Their weight guarantees that they will rest on the underlying ones without moving in the axial direction.
- Before a clay plug segment is emplaced a previously cast quartz/cement plug must have hardened sufficiently much to be able to carry it. With the selected concrete recipe this shall be possible in one day.

4.3.6 Manufacturing of clay-based plugs

There is comprehensive experience from earlier projects, particularly the Stripa borehole experiments [6], and the full-scale application at Forsmark [1] of the proposed technique to make sure that the material components of the clay plug segments can be prepared on an industrial scale and that quality assurance can be obtained. Pilot experiments for manufacturing tubes of special design for tight confinement of very dense clay blocks, and perforation that directs water off from the tubes in the placement phase are under way.

4.3.7 Placement of clay-based plugs

The required hauling potential for handling and connecting plug segments can only be provided by a big drill rig. The study has not included any detailed analysis of the on-site activities but no major difficulties are expected. However, as will be shown in the subsequent chapter it is required that the preparation and placement of 24 m long plug segments down to 1000 m depth can be made in no more than 8-24 hours, requiring skilled crew and working out of detailed manuals for the work including instructions to be followed in case of technical mishaps.

Long boreholes offer difficulties with respect to straightness. Curved holes, particularly with several bends, may cause difficulties in bringing in long, stiff plugs but with only 24 m long plug segments, they are largely eliminated. The friction mobilized at the insertion of longer plugs can require high axial forces and unshielded clay plugs may break and disintegrate when forced into a borehole. An example of the deviation from straightness is a 96 m long core-drilled subhorizontal hole with 56 mm diameter in Stripa granite ("DbH2") that deviated by about 1 m from the intended direction at its end [6]. This hole was successfully plugged using the technique proposed in the present document.

4.3.8 Cost issues

Cost has not been a major parameter in the study. Thus, it has been assumed that if effective plug function requires enlargement of 56 and 76 mm boreholes to 100 mm the concept may not be disqualified considering all other costs in preparation of the boreholes for plugging.

5 Performance of clay-based plugs

5.1 General

The present study is focused on the function of the clay plugs since they will be responsible for sealing off the larger part of a hole. The processes involved in the maturation of the clay material are mentioned first in this chapter followed by a description of pilot tests that illustrate the behaviour of clay plugs placed or being placed in boreholes. The chapter also summarizes a theoretical model worked out for quantifying the maturation process and for getting a basis of optimization of tube geometries and clay densities.

5.2 Physico/chemical processes in maturing clay plugs

Highly compacted Na-smectite like SKB's reference clay MX-80 has a tremendous hydration potential and sucks water when being exposed to it [5, 7]. Figure 5-1 illustrates the maturation process of a confined element of compacted clay of granulated clay consisting of expandable clay minerals like smectite (montmorillonite, saponite etc) or mixed-layer minerals (montmorillonite/muscovite etc). When dense clay of these types is confined in a perforated tube for use as borehole plugs it expands through the perforation. The initially penetrating clay is very soft but it is followed by a denser clay paste and consolidation of the soft clay takes place by additional clay moving out through the perforation in the course of the slow wetting of the central part of the clay core. Ultimately, the tube becomes embedded by largely homogeneous clay the hydraulic conductivity of which determines the tightness of the plug. Numerous studies of smectite-rich clays show that the conductivity is lower than E-12 m/s for a density at water saturation of more than 1900 kg/m^3 almost irrespective of the porewater chemistry. This corresponds to the conductivity of the crystal matrix of granite and is hence a desired density of fully matured clay plugs.

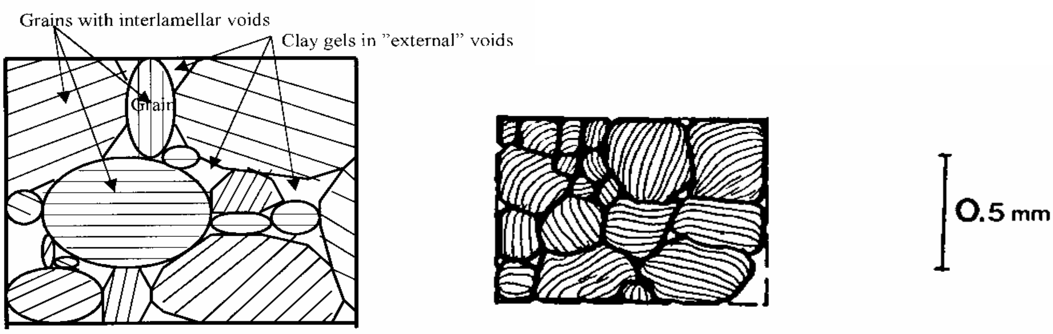

Figure 5-1. *Microstructural evolution of a dense element of compacted expandable clay minerals. Left: moderately high dry density with clay gels between expanded granules. Right: high dry density and more homogeneous microstructure. The granules contain numerous very small voids.*

The performance of the clay that has moved out through the perforation depends very much on the electrolyte content of the water surrounding the clay plug. In fresh water Na smectite of MX-80 type forms a coherent gel that moves out and rather soon forms a homogeneous paste around the tube (Figure 5-2), while in salt water, especially when Ca is the dominant cation, aggregation and settlement of clay aggregates take place yielding a heterogeneous clay embedment of the perforated tube (Figure 5-3). This coagulation process is readily explained by colloid chemistry.

The time required for clay to move out through the perforation depends primarily on the rate of water uptake of the clay core, which is determined by the hydraulic conductivity of the clay and its suction potential as well as by the water pressure.

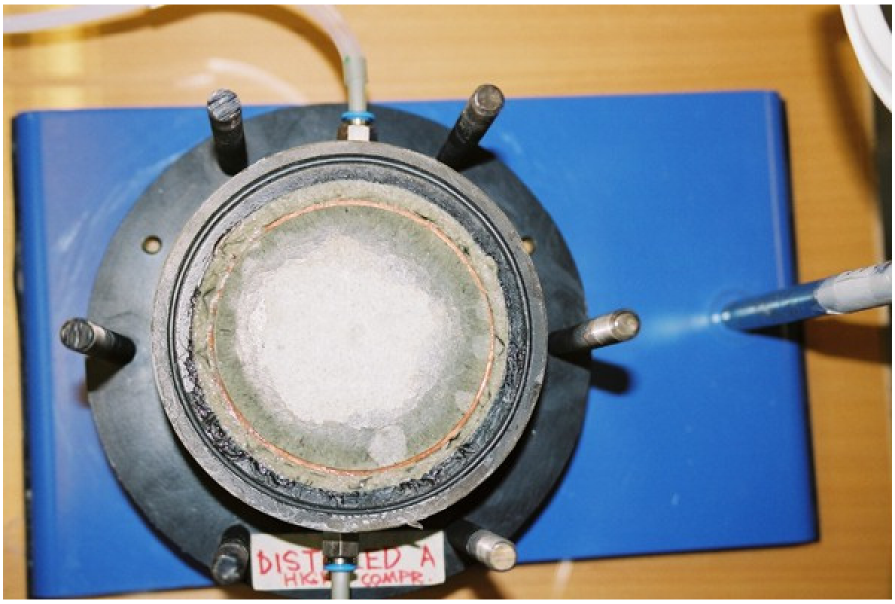

Figure 5-2. *Top of perforated copper tube confining MX-80 clay with an initial dry density of 2050 kg/m^3 in a cell with 100 mm diameter, simulating a borehole. The upper picture was taken 8 hours and the lower 24 hours after supplying the plug element with distilled water.*

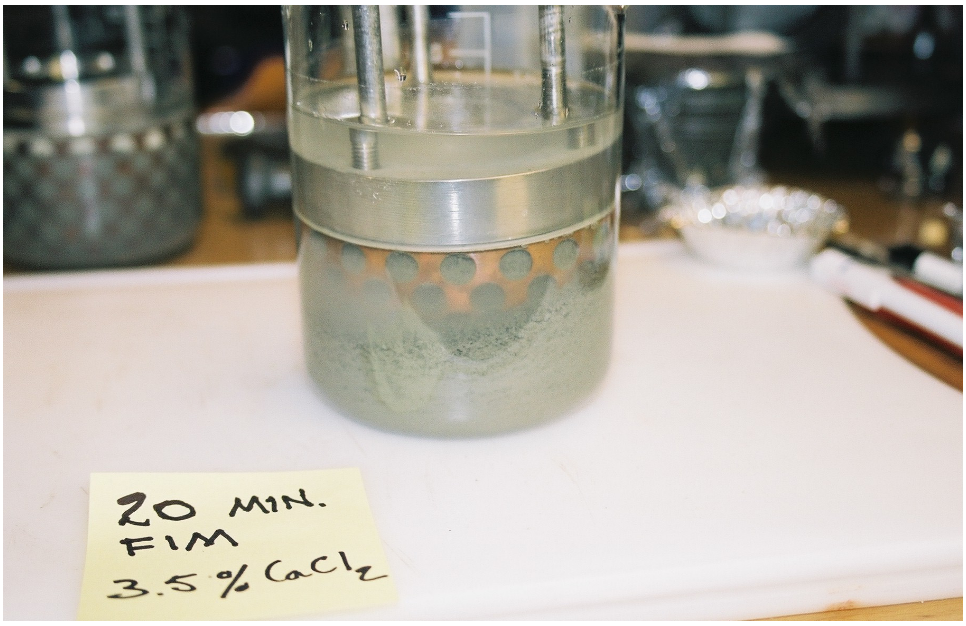

Figure 5-3. *Typical quick disintegration of compacted clay plug (FIM, dry density 2280 kg/m^3) submerged in salt solution (3.5 % $CaCl_2$). The clay formed around the tube in 20 minutes consists of large, soft aggregates that settle and are easily eroded.*

5.3 Testing and modelling of the maturation and performance of clay plugs

5.3.1 Pilot laboratory studies

Several studies have been made in the project for investigating the maturation rate of clay plugs both respecting the density and tightness of the clay formed between the perforated tubes and the rock, and of its erodability. The studies have comprised the following activities, most of them being made by Clay Technology AB and some by Geodevelopment AB:

1. Laboratory tests for studying the swelling capacity and swelling rate in order to estimate the time available for emplacement of clay plugs in deep holes with no risk of getting them stuck in the holes because of too quick maturation and generation of high friction and adhesion forces.
2. Simulation of the installation of a clay plugs for estimating the erosion of the clay caused by the water flowing along the plugs. Erosion will reduce the net density of the clay plug.
3. Prolonged tests in the laboratory for quantification of the clay maturation process. This is essential for predicting the ultimate density distribution in the matured plugs.

Maturation rate

This parameter has been investigated by determining the expansion of compacted clay elements under free and confined conditions using distilled water and 3.5% $CaCl_2$ solution, and by conducting tests of the type shown in Figures 5-2 and 5-3, including, in some tests, examination of samples extracted from the clay formed between the perforated tube and confining cell.

Scoping experiments gave results indicated in Figure 5-4 and 5-5, of which the first one demonstrates the quick growth of the density of the expanded clay gel in salt water in 48 hours and the other the difference in shear strength of plugs in fresh and salt water.

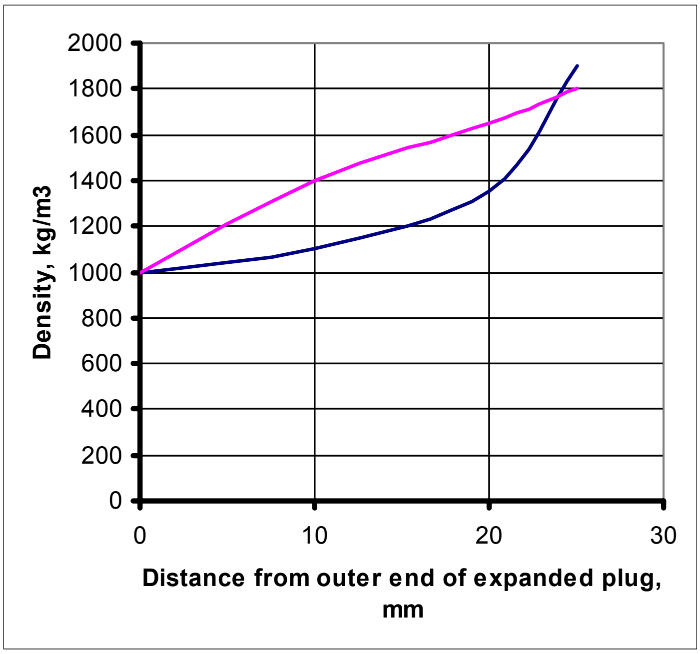

Figure 5-4. *Experimentally determined density distribution in freely expanding MX-80 clay with 2050 kg/m^3 initial dry density. Upper curve represents plug inserted in 3-5 % $CaCl_2$ solution and the lower the distilled water case. Measurements after 48 hours.*

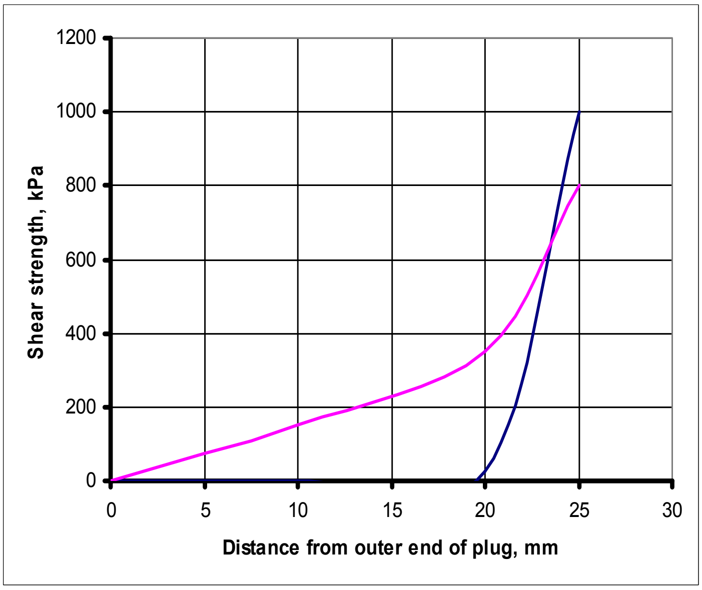

Figure 5-5. *Experimentally determined shear strength distribution in freely expanding MX-80 clay with 2050 kg/m^3 initial dry density. The curve starting from zero represents a plug inserted in distilled water and the other curve the case with 3-5 % $CaCl_2$ solution. Measurements after 48 hours.*

5.3.2 Major series of lab expeiments

The systematic experiments performed by Clay Technology AB were made by use of the following test constellations (cf. Figure 5-6):

- Steel cells simulating the hole in the rock, inner diameter 100 mm
- Perforated copper tube with outer diameter 95 mm and inner 88 mm. Perforation ratio 50 % with 10 mm hole diameter
- MX-80 clay with 9.4 % water content, block pressure up to 100 MPa
- Bentonite blocks, diameter 87 mm and height 50 mm
- Dry density of blocks 1692 and 1905 kg/m^3

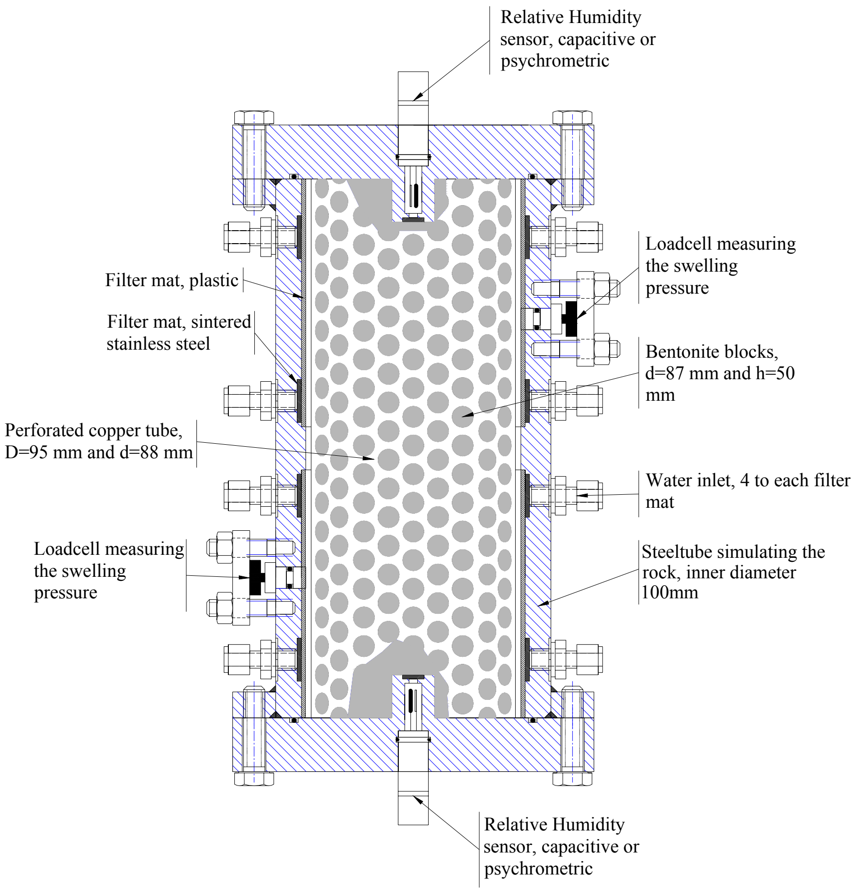

Figure 5-6. *Schematic section of the simulated borehole plug for wetting and simultaneous measuring of the evolution of the swelling pressure (load cells) and wetting ("RH" sensors).*

The major findings were as follows:

1. After 4-8 hours in low-electrolyte water clay plugs of expansive clay like MX-80 and FIM penetrate the perforation but will not form a homogeneous paste around the tube, while after 8 hours such a paste is formed.

2. The clay paste formed around the perforated tube will cause resistance to insertion of clay plugs in boreholes, which must therefore be made within a limited period of time.

3. For avoiding very rapid expansion and erosion of the clay gel formed early in the space between tube and rock the water in the borehole must be poor in electrolytes. In salt water the clay plug must be placed within one hour, while in electrolyte-poor water the corresponding time is 5-10 hours. In practice, this means that the natural water should be replaced by tap water.

4. After a few weeks the clay between the tube and the rock becomes dense and after several months the entire clay mass tends to become homogeneous and sufficiently dense for providing the required tightness. Complete homogeneity may require years or decades and it may in fact never be reached.

5. The long term tests show that swelling and homogenisation have proceeded far after 10-20 days. The measured mean swelling pressure against the rock for the initial dry density 1905 kg/m^3 of the clay plug core was 2800 kPa using fresh water and 600 kPa for salt water. Measurement of the hydraulic conductivity of the clay paste between tube and rock showed that it was lower than 9E-13 m/s for fresh water and 2E-12 m/s for salt water.

6. Only clays with Na as major adsorbed cation should be used since Ca-saturated expansive clays behave like clay in salt water.

7. Very strongly compacted clay powder of MX-80 and FIM (Friedland Ton) type migrate slower through perforated tubes than ordinary compacted clay of these types but the difference is not very large. Pressures of more than 200 MPa were used in the preparation of these blocks.

Erosion rate

A flow test that simulates the installation of a clay plug with the same density and water content as in the just described experiments was made by flushing water along the plug with a rate of 0.92 l/min for about one hour, thereby simulating emplacement of the plug in a 500 m long hole (Figure 5-7). The effect of the erosion was evaluated by measuring the clay content in the percolate and by determining the dry density of the clay contained in the tube at the end of the experiment. The results showed that 6 to 9 % of the solid clay had been eroded, which would reduce the intial dry density to about 1800 kg/m^3, corresponding to an average density of the fluid-saturated plug of 2130 kg/m^3. This finding led to the conclusion that unless the density of the clay blocks can be increased steps may have be taken to retard the expansion or to increase the solid clay content to yield a higher net density. The matter is discussed in Section 6.

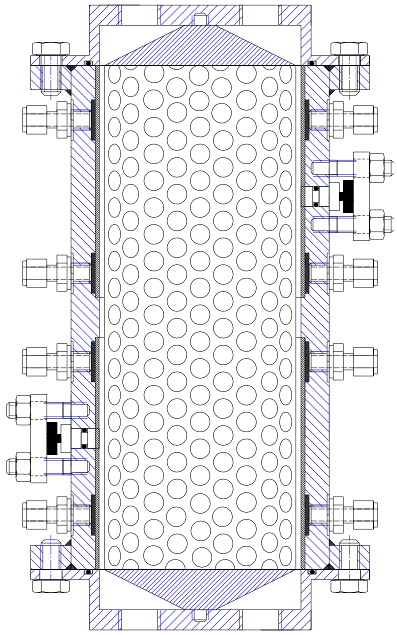

Figure 5-7. Schematic cross section of the equipment used by Clay Technology AB for the flow tests. Water was forced into the space formed by the cone at one end, flowed along the perforated tube and was discharged through the opposite end.

5.3.3 Theoretical studies

Theoretical modeling of the bentonite swelling through the holes and into the space between the copper tube and the rock wall has been made by Clay Technology AB for predicting the swelling pressure and the density of the clay surrounding the copper tube and maintained in the tube. This work is ongoing.

Geometry of perforation

A model was developed by for determining the optimum diameter of the perforation hole diameter for reaching best homogeneity and highest density of the clay. It was found to be 10 mm for 50 % perforation ratio provided that all holes are equal and that the distribution is symmetric with a half hole shift.

Pressure prediction

Equilibrium equations were formulated for forces in the clay in axial and radial directions, the forces representing swelling pressures in the system with internal friction as moderating factor. Isotropic and anisotropic swelling conditions were assumed and different friction angles (8 to 22.4 degrees) were considered. The influence of the friction angle was found to be significant, which makes the selection of a representative value for modelling important.

Stepwise calculation had to be made because of the impact of the swelling pressure onthe friction angle. The iterative procedure is that a low swelling pressure is assumed initially for representing the initial penetration of a clay gel through the perforation. The gel then consolidates from the expansion of the clay inside the perforated tube yielding a higher density and therefore a higher friction angle. Using these new values the swelling pressure can be calculated giving new density and friction angle data etc. Equilibrium is finally obtained yielding the swelling pressure and related density.

Mean pressures were predicted for fresh water and found to be in good agreement with recordings while those representing salt water deviated substantially from the recorded pressures.

Major conclusions of lab experiments and theoretical work

- A theoretical model of the swelling of MX-80 clay has been developed and applying it to the experimental case with highest initial dry density gave an optimum hole diameter of the perforation of 10 mm for 50 % degree of perforation. The *minimum* theoretical swelling pressure against the rock was 1.96 MPa for fresh water and 0.95 MPa for salt water.

- The long term tests showed that complete swelling and homogenisation is obtained after 10-20 days. The measured *mean* swelling pressure against the rock was 2.8 MPa for fresh water and 0.6 MPa for salt water. This is in good agreement with the predicted *mean* pressure for fresh water but not for salt water.

- Measurement of the hydraulic conductivity of the clay paste formed between tube and rock after maturation gave 5-9E-13 m/s for fresh water and 2E-12 m/s for salt water. Both are below the earlier mentioned typical conductivity ranges values for the surrounding rock E-11 to E-8 m/s.

5.3.4 Measures to minimize erosion

The tests referred to in Section 5.3.2 suggested that steps should be taken to reduce the impact of erosion on the clay plug and the following improvements are being investigated:

- The clay cores should fit tightly in the tubes so that water flow along the inside of the tube is prevented. In the flow tests 1 mm space was used and significant flow along the clay can have taken place.

- The density of the clay shall be very high, both for reducing the erodability and for providing an extra amount of clay for replacing eroded material. Experiments have shown that maturation of strongly compacted clay (200-250 MPa) gives dry densities of more than 2200 kg/m^3 and a delay in maturation.

- The perforation holes of the metal tubes should be oriented so that water flowing along the tube surface is suitably oriented. The matter to be investigated is the flow nature of the water (turbulent or laminar).

- The perforation ratio and the size of the holes in the tube should be further studied. Hence, a grid-type tube with closely placed smaller holes may provide better protection against erosion while still giving, ultimately, the required homogeneity and density of the matured plug.

- Protection of the tubes by application of a film consisting of a chemically compatible substance like silica gel or suitable cement should block the holes in the tubes in the insertion phase. The amount of such a film would represent a negligible fraction of the clay mass.

Pilot testing of several of these improvements are under way including a small-scale field experiment in which the maturation rate and adhesion to the rock of clay plugs in very deep holes will be simulated.

5.4 Long-term performance

Processes that can cause degradation and less good performance of clay-based borehole plugs are primarily:

- Mechanical disruption by thermally or tectonically induced shearing or tension.
- Piping generated by thermally induced high porewater pressures and pressure gradients.
- Chemical alteration, leading to dissolution and mineral changes yielding an increased porosity and hydraulic conductivity and loss of contact with the borehole walls.
- Gas formation yielding high pressure and risk of channelling.
- Freezing under permafrost conditions
- Erosion caused by meltwater flow in late-glacial time

The firstmentioned degrading factor is largely eliminated by constructing clay plugs only between fracture zones since significant displacements are confined to these zones. Piping of installed clay plugs is hardly an issue since no significant hydraulic gradients will prevail. Gas production may take place by using steel tubes while use of copper and Navy Bronze eliminates this risk.

However, in the placement the clay plug is exposed to water that is flushed along it and this may cause some erosion and loss in clay material. Preliminary tests suggest that the loss of solid matter may be on the order of 5-10 %, which is acceptable if the net ultimate density of the clay plug is deemed to be sufficient.

Chemical alteration can be estimated by applying the same model as used for predicting the degradation of canister-embedding buffer clay. Since the temperature is significantly lower for the borehole plugs than for the buffer and the latter will perform well even after hundreds of thousands of years the same is valid for the clay in the plugs provided that the metal tubes are made of copper or possibly Navy Bronze or titanium. The incompletely known chemical interaction between smectite clay and steel should rule out the latter.

Freezing of smectite clay with the intended density of borehole plugs is largely eliminated for the reason that interlamellar water, which makes up the majority of the porewater, is in a special energy state.

Erosion by meltwater flow can take place in the rock to a depth of some tens of meters in conjunction with rapid retreat of glaciers. Since the uppermost hundred meters of the boreholes will not contain clay the risk of erosion is only real if unexpectedly deep flow is generated.

6 Proposed sealing concept

6.1 General

The concepts and materials specified in this chapter are proposed for borehole sealing. Design of plugs in holes extending downwards from the ground surface requires consideration not only of their performance deep down in the rock but also in their shallow parts. Thus, the uppermost part cannot consist of clay material since it would expand upwards and soften and be eroded very quickly. It is therefore necessary to seal off the upper 100 m part of the boreholes with non-clay material that can resist swelling pressure from clay plugs below and that provides sufficient protection to them considering exogenic impact like erosion by water, glaciation and sabotage. The composition of plugs extending downwards from the ground surface are proposed to be as follows:

On the ground surface: Filling of 3 m well compacted moraine.

0-50 m: Well fitting rock cylinders pressed down in the precision-drilled (reamed) uppermost part of the hole. Silica gel or fluoric acid[4] is used as mortar or glue. Alternatively, it may be possible to melt the rock [8] or to pour down molten rock or a suitable non-precious metal. The heat-affected recrystallized rock is not expected to be very tight but to be able to serve as a mechanically strong top seal.

50-60 m: Fill of well compacted morain. It constitutes a hydraulic and mechanical buffer between the effective underlying ductile clay seal and the overlying stiff borehole plug.

60-100 m: Fill of smectite pellets of Na bentonite applied and compacted layerwise. Alternatively, plugging over this distance can be made by use of highly compacted bentonite rings placed around a central jointed solid copper rod. A third alternative is to use artificial bitumen[5].

Below 100 m: Plugging by use of highly compacted clay confined in suitably designed perforated tubes to perform as described earlier. Clay plugging is made only between fracture zones, where the holes will be filled with suitably graded quartz with a small amount of low-pH cement. There may be alternative methods for bringing in the clay into deep holes, and the matter is further investigated.

Within the repository: A number of shorter holes with 56 to 76 mm diameter will be drilled down in the repository for structural characterization and hydraulic, rock mechanical and geochemical measurements. These holes are not expected to affect the general groundwater flow pattern or the engineered barriers and can therefore be sealed by use of simple techniques, like filling with bentonite pellets. For horizontal and upward-directed holes the same plugging technique as for long holes is proposed.

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[4] Great care required because of toxicity

[5] It remains to be certified that artificial bitumen is sufficiently longlived. Natural bitumen is not acceptable.

6.2 Materials

6.2.1 Material for sealing of boreholes intersecting fracture zones

The principle is to use the same substance for stabilizing borehole walls and filling boreholes that intersect fracture zones. The proposed substance is a mixture of suitably graded quartz and a small amount of low-pH cement. Experiments made by CBI have shown that a suitable fluidity and strength regain can be obtained but the exact composition of the primary candidate material still requires confirmative tests and geochemical modelling.

6.2.2 Clay material

Smectite-rich clay equivalent to SKB's reference clay MX-80 clay (American Colloid) is proposed for constructing clay plugs for sealing of deep holes. The clay has Na as major adsorbed cation and the chemical composition given by Tables 6.1 and 6.2 [7]. For sealing boreholes that do not extend to the ground surface or intersect the near-field, very strongly compacted mixed-layer FIM clay (Friedland Industrial Minerals) may be used. For sealing short downward-directed boreholes strongly compacted pellets of either type are suitable. FIM can be considered for use where the clay has to be in contact with Portland cement since it appears to be less attacked than MX-80 [9, 10].

Table 6.1. Chemical composition in weight percent of the solid substance of MX-80 bentonite and Friedland Ton (FIM).

Clay	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	K_2O	Na_2O	S
MX-80	65	20	6	5	1.8	1.8	0.3	0.1
FIM	57.2	18.0	5.5	9.0	-	3.1	0.9	0.3

Table 6.2. Mineral composition in weight percent of MX-80 bentonite and Friedland Ton (FIM)

Clay	Smectites	Quartz	Feldspars	Mica	Chlorite	Carbonates
MX-80	70	12	7	1	2	4
FIM	45*	18	8	12	2	2

- mixed-layer montmorillonite/muscovite

6.2.3 Preparation of clay blocks

A compaction pressure of 100 to 300 MPa gives dry densities on the order of 1850 to 2150 kg/m^3 (2170 to 2350 kg/m^3 after water saturation under confined conditions) if the grain size distribution is suitable (Figure 6.1). Too small grains make it difficult for air enclosed in the voids to dissipate in the compaction process, but a size distribution like the one shown in Table 6.3 largely eliminates this problem.

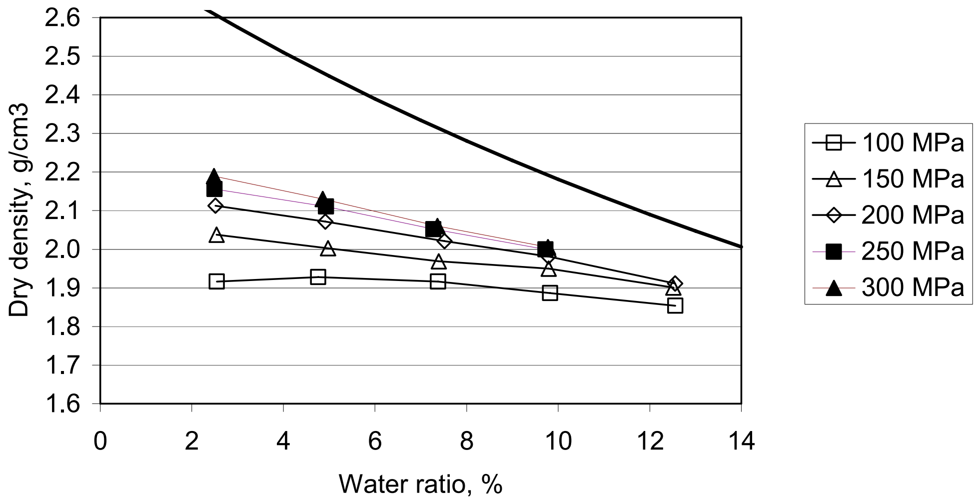

Figure 6.1. *Dry densities obtained by compacting MX-80 clay powder with different water contents using compaction pressures of 100 to 300 MPa (Clay Technology AB).*

Table 6.3. Suitable grain size distribution for achieving high block densities.

Fractions, mm	**Percentage of grain size representing the respective fraction**
2-8	20.0
1-2	20.4
0.1-1	42.4
<0.1	17.2
Total	100

6.2.4 Preparation of clay pellets

Highly compacted pellets are proposed to be used for filling the (drained) boreholes from 60 to 100 m depth. They can be compacted by use of augers to reach highest possible dry density, which is estimated at about 1700 kg/m^3.

6.2.5 Achievable densities of clay plugs

For the special case of a clay block with a dry density of 2100 kg/m^3 the solid clay mass is 1750 kg/m^3. Assuming that it reduced by erosion of the plug by 10 % the net average dry density will be 1900 kg/m^3, yielding a density at saturation of more 2200 kg/m^3. If blocks are prepared with a dry density of 2150 kg/m^3 the net average density at fluid saturation will be about 2275 kg/m^3.

The possibility of filling holes with a thixotropic smectite mud for reducing friction against the rock in the plug placement phase and for retarding expansion of clay through the holes of the perforated tubes has still not been called off. Earlier estimates have shown that if the hole contains a smectite mud with a bulk density of 1200 kg/m^3 and the tube with clay is submerged in it the net density will not be very much higher, i.e. 1920 kg/m^3. Hence, such soft slurries do not contribute very much to the density but serve to prevent the clay migrating through the perforation from settling in the gap between tube and borehole wall.

6.2.6 Physical properties of clay plugs

Hydraulic conductivity

The hydraulic conductivity of smectite clays has been determined in numerous test series, typical data being shown in Table 6.4. These and other physical data are available in handbooks like [7].

Table 6.4. Hydraulic conductivity in m/s of MX-80.

Bulk density, kg/m^3	Distilled water	2 % NaCl	10 % NaCl	2 % $CaCl_2$	10 % $CaCl_2$
2130	5E-14	9E-14	E-13	2E-13	3E-13
1850	5E-13	2E-12	8E-12	5E-11	7E-11
1570	5E-12	E-9 to E-8	E-7 to E-6	E-7 to E-6	E-6 to E-5

The relatively insignificant influence of salt water on the conductivity of FIM clay, which is due to the lower gel formation potential and hence insignificant gel coagulation, is illustrated in Figure 6-1.

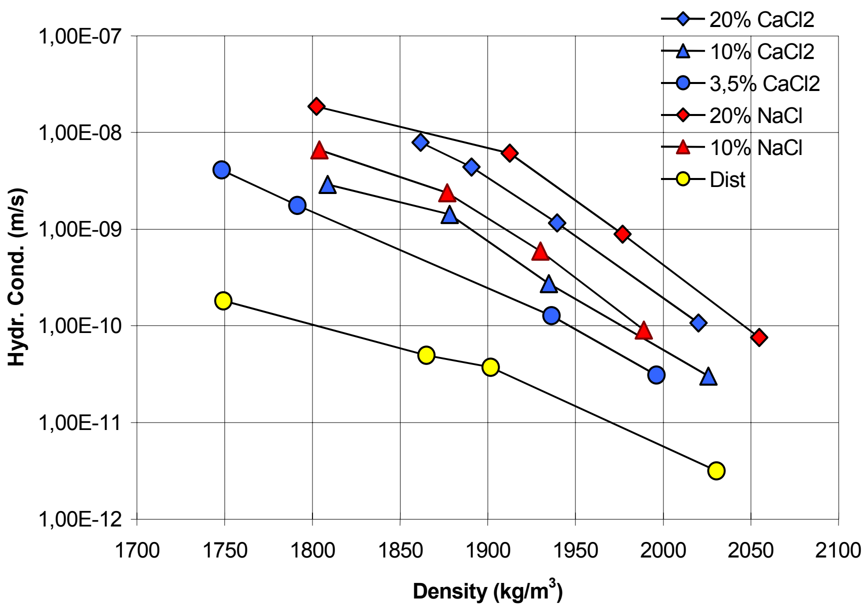

Figure 6-1. *Impact of salt water on the hydraulic conductivity of FIM clay (After Clay Technology AB).*

Even for very salt, Ca-rich water one finds that matured clay plugs of MX-80 and FIM with densities of 2100 kg/m^3 have an average hydraulic conductivity that is significantly lower than the value E-11 m/s that is typical of fracture-poor rock.

Gas conductivity

A number of experimental studies have shown that gas penetration is initiated in a limited number of channels formed in the clay and widened in the course of the gas penetration when the pressure exceeds a critical value, which is the sum of the swelling pressure and the piezometric pressure. When this pressure is reached and kept constant gas makes its way through the clay in a finger-like manner, usually in a peristaltic fashion without desiccating the clay if the water pressure (”backpressure”) is sufficiently high. If the pressure drops, the channels tend to be closed if the water pressure and the density of the clay are sufficiently high, leaving compressed gas bubbles locked up in the former paths. They will be dissolved and the clay will ultimately be as homogeneous as from the beginning. The gas pressure has to rise to the previous level before gas can get through again [11].

The gas conductivity depends on the number and aperture of the micro-channels in the clay and on the clay density and water pressure. A general estimate is that the gas conductivity is about 1/1000 of the hydraulic conductivity.

Swelling pressure

Testing of MX-80 clay with saline solutions have given the approximate data in Table 6.5.

Table 6.5. Swelling pressure in MPa of MX-80.

Bulk density, kg/m^3	Distilled water	0.5 % NaCl	3.5 % NaCl	0.5 % $CaCl_2$	3.5 % $CaCl_2$
2100	15-20	11-15	8-10	7-8	6-7
2000	3-4	3-4	3-4	3-4	3-4
1800	1	0.3	0.2	0.5	0.4

The relatively insignificant influence of salt water on the swelling pressure of FIM clay, which is due to the lower gel formation potential and hence insignificant gel coagulation, is illustrated in Figure 6-2.

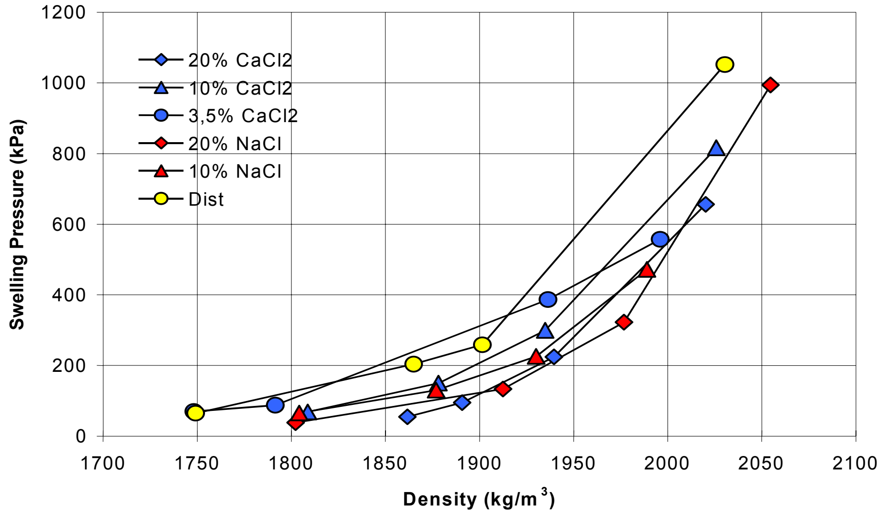

Figure 6-2. *Impact of salt water on the swelling pressure of FIM clay (After Clay Technology).*

The swelling pressure is of importance in two respects: 1) It should be at least about 100 kPa to guarantee tight contact between the clay and the borehole walls, and 2) It should be on the megapascal level for resisting extrusion of the entire plug by high water or gas pressures. The firstmentioned criterion is fulfilled by MX-80 clay with a density at saturation of at least 1800 kg/m^3. The latter requirement implies that the matured clay material should have a density of at least 1900 kg/m^3. For FIM the required density is somewhat higher.

Shear strength

The shear strength is of importance for two reasons, firstly it determines the wall friction (adhesion) that controls the resistance to extrusion of the plug, and secondly it determines the sensitivity to earthquakes. The shear strength of the rock/clay contact is the product of the effective pressure, which is taken as the swelling pressure, and the friction angle, which is in the interval 10-15^o. The adhesive strength as determined in field experiments reported in Chapter 7 of this document (Case 3) was found to be on the order of 100 kPa, after a few months, which means that the axial force to extrude a plug with 56 mm diameter and 100 m length is about 350 tons. This corresponds to a gas pressure of 1000 MPa, which is far more than the critical gas pressure at which gas is released through channels in the plug without extruding the entire plug.

7 Reference test cases

7.1 Examples

Table 7-1 summarizes borehole plugging tests that are described in available documents and they have been examined and commented in a previous paper [1]. In the present document we will only give short comments on the outcome of the tests.

Table 7.1. Generalized conductivity values in m/s of MX-80.

Case no	Plug material	Site	Project	Number of holes	Length, m/diameter, mm
1	Clay	Stripa	Stripa Project	2	1/56 vertical
2	Clay	Stripa	Stripa Project, DbH2	1	100/56 horizontal
3	Clay	Stripa	Stripa Project	2	4/76 vertical
4*	Clay	Forsmark	Construction of SFR	5	(10-15)/76
5	Clay	Stripa	Stripa Project, packer type	3	5/76 vertical
6	Clay	Ranstad	Ranstad	5	(10-15)/(80-115) vertical
7	Clay	Freiberg	NAGRA	1	0.62
8	Clay	Grimsel	NAGRA	1	2/80
9	Clay	California	Oil hole sealing	2	3/100 and 30/100
10	Cement	Stripa	Rock sealing, Stripa Project	2	2/76

*Full-scale sealing of boreholes for geological and geophysical investigations at sea

Case 1 SKB, Stripa Project (Pilot test)

A pilot test for validating the conceptual model of maturation of clay plugs contained in perforated copper tubes was made in the early eighties using a 2.5 m long plug submerged in a 6 m deep core-drilled hole with 56 mm diameter extending downwards from the floor of a blasted tunnel. The copper tube had an outer diameter of 35 mm and an inner diameter of 32 mm with a perforation of 11 mm holes that occupied about 50 % of the surface. The cylindrical blocks of MX-80 bentonite with 10 % water content had a bulk density of 2150 kg/m^3 and an outer diameter of 30 mm. The ultimate density at complete water saturation, which was not achieved in the 6 month tests, would have been 1780 kg/m^3 and the water content 43 %. The upper 0.5 m length of the borehole was filled with cement mortar. Overcoring 6 months later showed that the clay had swelled out through the perforation and embedded the copper tube by homogeneous, stiff clay. Determination of the water content showed that it was uniformly distributed in the clay, the average value of the upper half, located in the fracture-rich floor of the drift being 37 %, while it was 35 % in the lower half. The estimated degree of saturation was 75 to 85 %, the low values being explained by poor access to water in the rock due to low water pressure caused by drainage of nearby tunnels and drifts.

Case 2 SKB, Stripa Project (DbH2)

An almost horizontal core-drilled hole with 56 mm diameter and nearly 100 m length in normally fractured granite was plugged by use of the earlier described method with precompacted clay blocks confined in perforated copper tubes as in Case 1.

The perforated tube consisted of 39 segments of 2.5 m long units with 54 mm outer and 50 mm inner diameter. The perforation of 11 mm holes occupied about 50 % of the surface. The segments were jointed by use of copper cylinders (Figure 7-1). The cylindrical bentonite blocks were made by uniaxial compaction of MX-80 bentonite powder with 11 % water content under 120 MPa pressure to a bulk density of 2110 kg/m^3. The blocks had an outer diameter of 48.7 mm and a central hole with 18.3 mm diameter for a copper pipe in which tubings were contained for testing the tightness of the plug about 30 m from the outer end of the hole. This end was sealed by cement through which the tubings from the test segment extended.

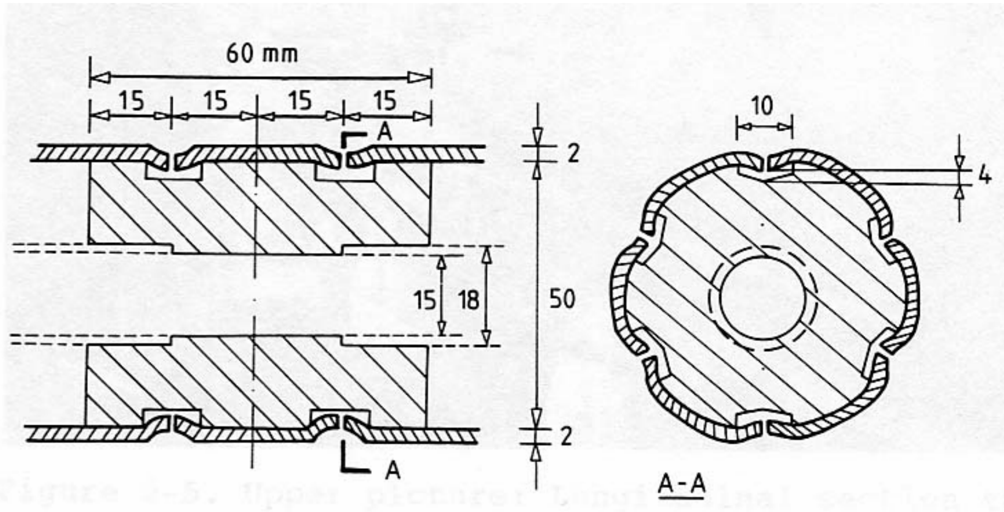

Figure 7-1. *Connection of pipes.*

The plug segments were jointed in conjunction with pushing them into the hole until the tip of the completed plug had reached the inner end of the hole. A hydraulic jack with 10 kN capacity was used for this purpose. The process took 2.5 hours, the long time being due to difficulties in overcoming the successively increased friction between the copper tubings and the inner pipe. The time required to install a 100 m long plug with no instrumentation in a horizontal 56 mm hole under real conditions is estimated at no more than 1 hour. The clay extracted from the plug after 2.5 years was completely water saturated and had a water content of about 33 % and a density of 1950 kg/m^3.

A different technique must be used in the forthcoming development of the method since the axial tension force developed in long plugs in the application phase requires strong connections between the unit segments of 3 m length for speeding up the plug application, and is also called for, if it is required to pull the 24 m long plug segments up again.

Case 3 SKB, Stripa Project

Two vertical core-drilled holes with 76 mm diameter and 14 m length in normally fractured granite were plugged by use of the earlier described method with precompacted MX-80 clay blocks confined in a perforated copper tube and in a net of stainless steel, respectively. The perforated copper tube had an outer diameter of 68.6 mm and an inner diameter of 65 mm. The perforation of 11 mm holes occupied about 50 % of the surface. The net of 1 mm steel threads had a mesh size of about 8 mm. The cylindrical bentonite blocks were made by uniaxial compaction of MX-80 bentonite powder with 11 % water content under 120 MPa pressure to a bulk density of 2110 kg/m^3. The blocks had an outer diameter of 65 mm and a central hole with 20 mm diameter for a copper pipe in which tubings connected to the filters and pressure cells were located. The clay plugs were confined between mechanical packers. The water content at complete water saturation should be 40 % and the density 1820 kg/m^3.

The adhesive strength, i.e. the maximum shear stress that can be mobilized at the plug/rock contact, is a measure of the shear strength of the clay and hence also of the water content. For determining the adhesive strength the plugs were extruded by use of a hydraulic jack. Both plugs required an axial force of 9 tons to be pushed out, which means that the adhesive strength was 100 to 120 kPa at large strain. The peak shear strength of MX-80 bentonite with the same density as the clay in the plugs, i.e. about 1850 kg/m3, was found to be in the interval 150-180 kPa in laboratory tests, while the residual strength corresponding to the large strain that the plugs experienced was about 120-145 kPa. This indicates that the clay had reached a high degree of homogeneity at a density 1750-1800 kg/m^3 and a water content of 35-45 %.

Case 4 Plugging of boreholes drilled at sea for geological and geophysical investigations for SFR, SKB

The plugging was made by use of the earlier described technique with perforated copper tubes in five 76 mm diameter boreholes with a length of up to 160 m. The work, which was made at sea from a drilling rig, comprised cement sealing of the lower and uppermost parts of the holes with 10-15 m long clay plugs in between. The clay plugs were located where rather little water flowed into the holes. One of the holes was vertical and the others inclined with a dip of about 60^o.

Case 5 SKB, Stripa project (3D experiment)

The “3D experiment” at Stripa was performed in the eighties for identification of flow paths in a large rock mass by injecting tracer solutions from selected parts of three 76 mm boreholes with 70 m length extending vertically from the roof of a blasted tunnel. The injected rock segments contained water-bearing fractures and were separated by use of packers with bentonite as sealing material. They consisted of rings of highly compacted bentonite (MX-80) that were placed around a 25 mm central steel tube that contained tubings for saturating the clay packers, which were confined between steel flanges with rubber seals, and for injecting tracer solutions in selected parts of the boreholes. A 40 m long packer system consisting of bentonite units was pushed into each hole and anchored to the rock at the lower end. The application was made in relatively strongly water-bearing rock and could be completed in a few hours without difficulties. The density of the saturated clay plugs was about 1800 kg/m^3, yielding a swelling pressure of about 800 kPa for saturation with the electrolyte-poor Stripa groundwater.

Case 6 Boreholes in abandoned uranium ore area at Ranstad (SKANSKA)

Five vertical 80-115 mm boreholes with a depth of 42 to 48 m for groundwater observations were sealed in the early nineties by use of cement and clay. The lower parts of the holes were filled with cement slurry and also the uppermost 7 meters. The remaining 5 m length was sealed by use of plugs of highly compacted MX-80 bentonite.

Each plug consisted of a central 25 mm steel rod surrounded by rings of clay blocks with a water content of about 10 % and a density of about 2100 kg/m^3, the outer diameter being 105 mm for the wider holes and 70 mm for the slimmer ones. The theoretical ultimate density was about 1900 kg/m^3 for the 80 mm holes and 1950 kg/m^3 for the 115 mm holes, yielding a hydraulic conductivity of about 5E-13 m/s to E-13 m/s and a swelling pressure of about 2 MPa for the assumed low-electrolyte groundwater.

Case 7 Borehole in sandstone, NAGRA

The principle was to fill 92 mm boreholes in sandstone blocks with pellets of MX-80 clay in which a slurry of Friedland Ton with 500 % water content was injected while confining the pellet filling by use of a mechanical packer. Two injection tubes extending to the base of the hole and a ventilation tube ending just below the packer passed through it. A pressure gauge for recording the pressure build-up was placed in the lower part of the filling with cable connection up through the packer.

A first test was made with 10-16 mm pellets applied by hand, yielding a dry density of 1329 kg/m^3, the injected slurry giving the clay mixture a dry density of 1390 kg/m^3 (1875 kg/m^3 at saturation) and a porosity of 49.57 %. The pressure rose to 0.8 MPa after 5 days and to the ultimate pressure 1.2 MPa was reached after about 14 days. A second test was made with with 10-16 mm pellets applied by hand, yielding a dry density of 1278 kg/m^3, the injected slurry giving the clay mixture a dry density of 1400 kg/m^3 (1885 kg/m^3 at saturation) and a porosity of 49.11 %. The pressure rose somewhat quicker in this experiment and reached about 1.2 MPa after 20 days.

The procedure is slow; it is estimated that plugging of a 1000 m long hole would require several weeks. The holes must be dry, which means that the method can hardly be used in holes longer than a few tens of meters; since water will otherwise flow into the voids between the pellets before they can be injected with slurry. It is probable that the clay plug will not be homogeneous since there is an initial variation in density and the injected slurry may not fill all the voids uniformly.

Case 8 Borehole in crystalline rock, NAGRA

Tests have been made in the laboratory and in field by use of “pneumatic sealing”, i.e. introducing bentonite pellets in holes by use of a conveying pipe with 32 mm diameter and a length of more than a hundred meters. The borehole diameter was 100 mm in all tests. The MX-80 bentonite pellets had a size of 4-10 mm – larger grains caused blocking of pipes and pumps – and a density of 2100 kg/m^3, the water content being a few percent by weight. Lab tests gave a bulk density of 1365-1491 kg/m^3 and subsequent field tests a density of 1274 to 1471 kg/m^3 (up to 1880 kg/m^3 after water saturation) of the freshly applied material. A separate laboratory test with blowing of the pellets upwards in a simulated borehole with 40^o dip gave a significantly lower density. It was evaluated as a dry density of 961 kg/m^3 (1605 kg/m^3 at water saturation).

A first experiment was made using a 3 meter long casing with 100 mm diameter equipped with pressure gauges. Tap water was introduced after which the clay pellets were applied and the casing closed. The bentonite was allowed to hydrate for 18 hours whereafter air pressure was applied to the top flange of the casing. The pressure was increased in three steps, 0.7, 1.4 MPa for two minutes and 2.1 MPa for 6 minutes without any observed flow. Air pressure of 0.7 MPa was then applied to the lower flange of the casing and flow started immediately. Thereafter, an air pressure of 0.7 MPa was applied at the upper end for 15 minutes without observing flow.

7.2 Conclusions

The major conclusions from the lab and field experiments on clay plugs can be summarized as follows:

- Clay plugs of compacted blocks in perforated copper tubes can be inserted in boreholes, the expected maximum depth being more than a kilometer depending on the plug design and strength of the tubes and connections. Hydration of the clay takes place parallel to its expansion and ultimately yields complete embedment of the tubes and filling of the boreholes. A swelling pressure will be exerted on the borehole walls provided that the density at water saturation exceeds about 1600 kg/m^3.

- The technique of plugging boreholes with prefabricated units of compacted blocks in copper tubes that are jointed in conjunction with bringing them into the holes is feasible even for slim holes of the type used in the test (56 mm core-drilled) holes.

- Clay plugs of compacted blocks in copper tubes have been inserted in upward oriented boreholes with 40 m length and a diameter of 76 mm. It is estimated that the such plugs can be forced into much longer boreholes of this type

- Theoretically, the maturation is slow, up to several weeks or even months if there is no water pressure but it is expected to be quick under real conditions at depth, especially if the groundwater has a high salinity.

- The time for inserting clay plugs of compacted blocks in copper tubes into boreholes determines the applicability of this method. Thus, if it is very long the hydration process may cause problems by generating too high adhesion forces. Application of a 100 m long instrumented plug was made in a horizontal 56 mm boreholes in a couple of hours, which suggests that much longer plugs without instrumentation can be brought into much deeper boreholes in the same amount of time.

- Clay plugs in boreholes without liquid water hydrate by adsorbing water from moist air in the hole. This gives very slow maturation.

- The achievable net density at saturation of the clay component of a plug with prefabricated compacted blocks in metal tubes is 1900-2000 kg/m^3. This means that the hydraulic conductivity for strongly brackish Äspö water is about E-12 m/s and the swelling pressure 0.6-2 MPa.

- Bentonite pellets can not be used for constructing homogeneous, dense clay plugs in very deep holes or holes oriented upwards. However, they are believed to be suitable for plugging boreholes of less than 100 m depth provided that the holes can be kept dry during the filling operation. It is estimated that section-wise application and compaction can give a density that is around 1900 kg/m3 after water saturation, i.e. about the same as for clay plugs of compacted blocks in copper tubes.

8 Main conditions for applying the proposed borehole plugging method

8.1 Clearing and stabilization of the holes

A very important prerequisite for successful plugging is that the boreholes have been cleared and stabilized. Where fracture zones are intersected and rock fall has taken place or may occur, stabilization is required, preferably by grouting of a mixture of very finely ground quartz powder cemented together by a small amount of low-pH cement. The quartz is largely inert and the small amount of cement is not estimated to be of concern for the chemical stability of the plug material. The cement may be dissolved and the elements lost but the remainder will stay on site preventing clay particles from adjacent clay plugs to migrate into the fracture zone.

8.2 Required clay constitution

Referring to the requirements respecting hydraulic conductivity and contact between plugs and boreholes as well as longevity in a long-term perspective, it appears that smectitic clay of sufficient density will perform well. The minimum net density for matured clay plugs to be less permeable than the surrounding rock is estimated at about 1900 kg/m^3 and this density is also required to resist extrusion when high water or gas pressures prevail at one end of the plug while the opposite one is unsupported. It yields a hydraulic conductivity of less than E-11 m/s for MX-80, and E-10 m/s for FIM clay. Higher densities of matured plugs are easily obtained by using very dense clay blocks in the tubes and for a net clay density of 2000 kg/m^3 the respective conductivity of MX-80 and FIM clay will be about E-13 m/s and E-11 m/s almost irrespective of the salt content in the water. These values are lower than or about equal to the average bulk conductivity of the rock between fractures zones

8.3 Required water conditions

A major condition for safe insertion of the clay plugs is that the water in the borehole has a low electrolyte content since dispersion of clay will otherwise be too quick and lead to soft flocculated clay gels in the space between the tube and the wall of the borehole. They may settle and accumulate lower down in the hole. The original water therefore has to be replaced by pumping in tap (drinking) water through the drilling rods before the plugging operation starts and it may have to be repeated several times in the course of plugging a very deep hole.

8.4 Confinement of plugged holes

The expandability of dense smectite clay means that clay plugs must be confined at open ends of the boreholes. This is particularly important for the upper end of deep boreholes; they need to be sealed by materials that can sustain the swelling pressure exerted by the plug and that can offer resistance to external impact like erosion and glaciation. It is proposed that the uppermost 0-50 m part is plugged by well fitting rock cylinders pressed down in the precision-drilled (reamed) uppermost part of the holes with silica gel or fluoric acid as mortar or glue. For the 50-60 m interval moraine can be filled and compacted layerwise and for the 60-100 m interval bentonite pellets filling and compaction can be under drained conditions, i.e. by pumping out inflowing water, is feasible. Below 100 m depth the holes are suitably sealed by inserting highly compacted smectite clay contained in perforated metal tubes that are jointed to form about 24 m long columns, which do not need to be coupled. While this plug constitution is recommended alternative methods may be considered as well.

8.5 Placement conditions

A major condition for inserting clay plugs of the basic concept type, i.e. jointed elements of perforated, clay-filled tubes, is that they must be brought down to the intended depth in no more than 8-24 hours for avoiding too quick expansion of the clay. Special measures for retarding the expansion and hence offering longer time for the placement are being considered. In its present form the concept implies that the equipment and staff used for placement of the plugs must have sufficient capacity to perform the operation in a limited number of hours.

9 Remaining questions to be answered in future study

The proposed borehole plugging method based on insertion of prefabricated elements of perforated tubes containing dense clay is a robust and safe method that has been applied on full scale at SFR, where the plugging was made down to about 50 m from a drill rig at sea, and in several other cases including plugging of a 100 m long horizontal borehole at Stripa. Still, a number of questions remain to be answered, most of them concerning jointing of plug elements to form the 24 m segments. It may appear that simpler and cheaper but sufficiently safe alternative clay plug concepts can be found.

Separate and major issues are the clearing and stabilization of boreholes that precede the plug installation.

9.1 Borehole stabilization

It is required that the tools and procedures for borehole clearing and grouting be examined and tested on various scales. Development of a suitable grout for stabilization of weak zones is of particular importance. In the present document it is suggested that suitably graded quartz and a small amount of low-pH cement is used and this should be the starting point for the work. The important properties of tested combinations are 1) Fluidity, 2) Hardening time, 3) Strength of hardened grout, 4) Erodability of hardening grout, 5) Fracture penetrability, and 6) Degradation time of the cementing component. This requires laboratory, bench-scale and full-scale experiments. A major question is the selection or development of suitable grouting tools, i.e. packers etc. The Para Bow method is proposed here as the primary candidate that is available today.

9.2 Design of borehole plugs

For the plug types down to 100 m depth, assessment has to be made respecting the practicality in placement considering difficulties with inflowing water and possible problems with making these upper seals sufficiently homogeneous. A special problem is the presence of steel liners in some boreholes; they need to be removed by cutting and piece-wise removal by pulling, or by overcoring.

For short boreholes in the repository the following issues should be considered:

- Can cementation materials be used?
- Can already developed clay plugging techniques be used with or without improvement?
- Can plugging of downward directed holes be effective by use of strongly compressed clay pellets?

For the main clay plugs deeper down the following important questions remain to be answered:

- What is the best procedure for manufacturing and preparation of the plugs?
- Which is the most suitable metal in the tubes with respect to strength and corrosion and chemical interaction between clay and metal?
- What density of the clay is needed and preferable?
- What is the optimum degree of perforation of the tube for different diameter ratios of tube, clay, and borehole?
- How can erosion of the clay be minimized or practically avoided?
- How should the jointing of plug elements to form 24 m long segments best be made?

9.3 Emplacement of borehole plugs

A suitable operation plan should be defined for application of the plugs with focus on:

- How can water in the boreholes be exchanged by tap (drinking) water?
- What is the best method and equipment for installation of plugs? What is the weight and handability of plug segments of different size? What types of drilling rigs or crane types are required?
- Is mud in the holes needed or beneficial before inserting the plugs below 100 m depth?
- What can go wrong in the placement phase and what steps can be taken to avoid mishaps or to save a plugging project that fails? How can possibly appearing critical situations develop and be coped with?
- How should the upper plug components in deep holes be designed and constructed?

9.4 Performance of borehole plugs

The performance of borehole plugs should be modelled conceptually as well as theoretically for predicting the various maturation phases and for the long-term operation. This should be made with respect to:

- Hydration and homogenization processes in the clay plug with respect to the groundwater chemistry, water pressure and temperature for different clay densities.
- The influence of groundwater chemistry on the hydration, migration, and consolidation of the clay in the plug.
- The rate of corrosion of the metal tubes.
- The influence of cation exchange in the clay from Na to the cations given off from the tubes (Cu, Fe or Ti) in the corrosion phase.

9.5 Need and technique for testing of borehole plugs

It is anticipated that laboratory-scaled, bench-scale and full-scale tests of short plugs will be made for validation of plans for application and performance of all the clay components in deep holes. As to longer holes it is difficult to make relevant tests in the field and definition must be made of what sort of validation or confirmation that is really needed. The placement phase will naturally be investigated once the plug design has been decided and one can think of plugging three holes of different length for determining the practicality in the finally worked out plug application manual, both for clay blocks and clay pellets.

Experience from the Stripa borehole sealing project shows that clay plugs mature in a few weeks or months and reach such a dense state that piping or other disturbances can no longer threaten their integrity. For plugs matured to this state no meaningful measurements can be made over even short plug lengths to determine the hydraulic conductivity. However, the same procedure as used for the DbH2 hole at Stripa can be applied for determining the maturation rate, i.e. by equipping the clay with filters at suitable length intervals and connecting them to tubings that reach out of the hole. Application of a hydraulic gradient across adjacent filters for creating piping at different time intervals makes it possible to determine the maturation rate. Such tests can preferably be made in relatively short holes for systematic testing of various plug designs (Figure 9-1). After complete maturation of a clay plug the force required to extrude it can be determined by removing the packer supporting the clay in its hole and in applying pressure in the other one.

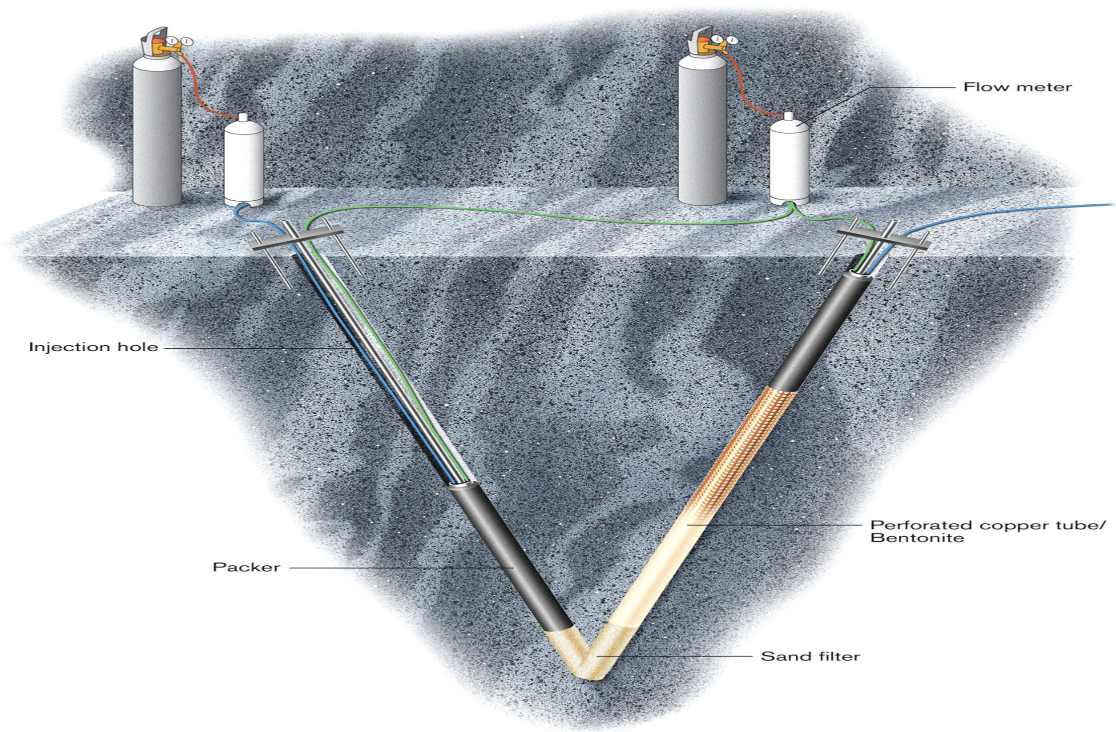

***Figure 9-1** Schematic test arrangement for determining the maturation rate and the pressure required for extruding the ultimately matured clay plug*

Direct study of the physical and chemical states of cement and clay plugs at suitable occasions can be made by plugging holes that are accessible for sampling like the Stripa DbH2 hole Placing the holes relatively close to the tunnel walls one can extract rock were cement and clay plugs are located for detailed analysis. This is planed to be made at Olkiluoto (borehole K24)

9.6 General Phases for the Borehole Sealing Project

The Borehole Sealing Project consists of three main phases, divided into a number of sub-phases as described below. Phase 1, was a pre-study ending in 2002. Phase 2 involved definition, specification and recommendation of methods for borehole sealing, resulting in the present document. Phase 3 comprises continuation of the projection involving optimization of the clay plug concept and development of techniques and, in particular, practical demonstration through small- and large-scale field tests of the applicability and practicality of the proposed sealing methods.

Phase 1 is the pre-study resulting in the report "Borehole plugging-State-of-art Dec.2002"

Phase 2 2003-2004

Phase	**2003 4th Quarter**	**2004**
Phase2a: Identification, assessment, recommendations of materials and techniques for preparation of boreholes	* Sealing/stabilization of intersected fracture zones * Packer techniques * Injection methods * Identification and development of cement materials for minimum impact on smectite clay * Re-drilling	
Phase 2b: Selection of candidate plugging materials and methods	* Identification, development and lab testing of cement and clay materials that fulfil the criteria respecting hydraulic conductivity, shrinkage, phys. and chem. stability * Search for other materials than clay and cement that fulfil the criteria	
Phase 2c: Selection of method for construction and application of plugs	* Definition of controlling parameters * Concepts * Design of plugs w.r.t. borehole geometry, sealing rate, and longevity	
Phase 2d: Performance assessment	-	* Conceptual modelling of short and long-term perf; optimization. * Theoretical modelling * Planning of field tests (planning, prediction of performance, instrumentation, testing program, quality assurance)
Phase 2e: Cleaning of borehole	* Definition of equipment left in the hole and characterisation of the situation * Identification of equipment needed	* Application of methods and equipment in cleaning the hole
Phase 2f: Reporting		Definition of Basis of R&D for 2005-2006 year period by Sept.24 2004

9.7 Proposed program for continuation of the Borehole Sealing Project

General plan, Phase 3, 2005-2008

Subproject	2005	2006	2007	2008- ????
Subproject 1:	Design, conceptual modelling, Continuation of lab tests from Phase 2	Design, conceptual modelling, Continuation of lab tests	Design, conceptual and theoretical modelling, Continuation of lab tests	
Subproject 2	Preparation of plugging of 5 m deep holes at Äspö	Construction and testing of plugs in 5 m deep holes at Äspö	Evaluation and reporting of of tests in 5 m deep holes at Äspö	
Subproject 3	Preparation and construction of plugs of deep hole (KR-24) at Olkiluoto	Maturation phase.	Maturation face	Extraction and lab testing of clay and cement/quartz plugs at Olkiluoto Evaluation and reporting of of testing of clay and cement/quartz plugs at Olkiluoto
Subproject 4	Planning of plugs in large-diameter holes at Äspö	Construction of plugs in large-diameter holes at Äspö	Testing of large-diameter holes at Äspö	
Subproject 5	-	-	Planning of boring and plugging of deep holes at Äspö	Plugging and testing of deep holes at Äspö

Subproject 1

Activity	Detailed work	Responsible organization	Time period
1. Design of plug	Conceptual model of the performance of clay plugs	SKB	4th quarter of 2005
2. Design of plug	Conceptual of cement/quartz plug	SKB	4th quarter of 2005
3. Modelling of clay/cement interaction	Geochemical modelling of clay contacting cement/quartz	SKB	1st and 2nd quarter of 2006
4. Modelling of maturation of clay plug	Physico/chemical evolution of clay plugs	SKB	3rd to 4th quarter of 2006
5. Reporting		SKB	1st quarter of 2007

Subproject 2

Activity	Detailed work	Responsible organization	Time period
1. Characterization of 5 m holes	Structural and hydrological modelling	SKB	1^{st} to 4^{th} quarter of 2005
2. Design of plugs	* Development of different clay plug concepts * Detailed design of concepts to be tested at Äspö	SKB	1^{st} and 2^{nd} quarters of 2006
3. Prediction of performance	Evolution of plugs, physically and chemically	SKB	1^{st} and 2^{nd} quarters of 2006
4. Construction of equipment	Manufacturing and placement of plugs	SKB	2^{nd} and 3^{rd} quarters of 2006.
5. Testing and evaluation	* Collection of data * Evaluation * Further development of plug concepts	SKB	3^{rd} and 4^{th} quarters of 2006, 1^{st} quarter of 2007
6. Reporting		SKB	2^{nd} quarter 2007

Subproject 3

Activity	Detailed work	Responsible organization	Time period
1. Planning and preparation of plugging of OL-KR24 at Olkiluoto	* Characterization of hole * Rinsing of hole * Stabilization of hole	POSIVA POSIVA POSIVA/SKB	1^{st} to 2^{nd} quarters 2005
2. Construction of plugs	* Manufacturing of plug materials: cement/quartz, and clay * Placement of plugs	SKB SKB/POSIVA	3^{rd} and 4^{th} quarters 2005
3. Planning of testing	* Detailed test program	SKB	3^{rd} and 4^{th} quarters 2005
4. Testing	* Retrieval of cement/quartz and clay plug components * Laboratory testing	POSIVA SKB	? ?
5. Reporting		SKB/POSIVA	?

Subproject 4

Activity	Detailed work	Responsible organization	Time period
1. Selection of plug types	* Definition of function	SKB	2nd and 3rd quarters 2006
2. Preparation of large-diameter holes at Äspö	* Characterization of holes * Rinsing of holes * Preparation of holes (reaming etc)	SKB SKB	3rd and 4th quarters 2006
3. Prediction of performance of plugs	* Impact on rock * Scale issues	SKB	3rd and 4th quarters 2006
4. Construction of plugs	* Manufacturing of plug materials * Placement of plugs	SKB SKB	3rd and 4th quarters 2006 1st quarter 2007
5. Planning and performance of tests	* Detailed test program * Excution of tests	SKB	1st quarter 2007
6. Evaluation and assessment	Data collection and evaluation	SKB	1st and 2nd quarters 2007
7. Reporting		SKB	2nd and 3rd quarters 2007

References

[1]. Pusch R, Ramqvist G, 2003. Borehole plugging – State of art. Technical Document TD 03-05.

[2]. Rautio T, Alaverronen M, Lohva K, Mikkola P, Teivaala V, 2004. Cleaning of boreholes, Posiva Oy. 29p. Working report 2004-39.

[3]. Pusch R, 1981. Borehole sealing with highly compacted Na bentonite. SKBF/KBS Technical Report 81-090. SKB, Stockholm.

[4]. Pusch R, 1983. Borehole sealing for underground waste storage. J. of Geotechnical Engineering, Vol.109, ASCE Proc. No. 17601.

[5]. Pusch R, 1994. Waste Disposal in Rock, Developments in Geotechnical Engineering, 76. Elsevier Publ. Co (ISBN: 0-444-B89449-7).

[6]. Pusch R, Börgesson L, 1987. Final report of the borehole, shaft and tunnel sealing test – Volume 1: Borehole Plugging, TR 87-01.

[7]. Pusch R, 2002. The Buffer and Backfill Handbook. Part 2. Materials and techniques. Technical Report TR-02-12. SKB, Stockholm.

[8]. Gibbs F G F, 2000. A new scheme for the very deep geological disposal of high-level radioactive waste. J. Geological Society, London. Vol.157 (pp.27-36).

[9]. Pusch R, Zwahr H, Gerber, Schomburg J, 2002. Interaction of cement and Friedlan Ton – theory and practice. Int. Workshop Clay Microstructure, Lund, October 2000. Applied Clay Science No.

[10]. Huertas F et al, 2000. Effects of cement on clay barrier performance, Ecoclay. Final report of Contract F14W-CT96-0032 Nuclear Science and Technology.

[11]. Horseman S T, Harrington J F, 1997. Study of gas generation in MX-80 buffer bentonite. British Geological Survey, WE197/7.

Appendix 1

Concrete for plugging of deep bore holes.

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August 2004

Contents

1 Introduction

In Sweden radioactive waste will be stored in underground repositories in granitiod rock formations. To find a proper place the geology of the rock formation must be investigated, which demands a large number of drill cores. In the rock formation the drill holes will act as conductive transport channels and must thus be sealed of. The choice of material and application technique will be important both for the function, durability and interaction with the repository.

The drill holes normally have a diameter of around 75-100 mm and the length can be up to 1500 meters. The inclination normally varies between 45 and 90 degrees but in some sections the drill holes can even be horizontal.

The life length of the plugs must be as long as that of the repository, i.e., they must hinder water transport for more than 100 000 years. During this period the hydraulic conductivity shall be lower than that of the surrounding rock and the properties of the plug shall be such that no water flows in the contact zone between the plug and the surrounding rock.

The suggested basic concept is to use bentonite clay for the sealing. Compacted bentonite in perforated cupper tubes will be placed in the drill holes and the swelling of the bentonite will seal the drill holes. In some places and as a complementary material concrete will be used.

Concrete will presumably also be used to stabilise the drill holes so that the tubes with compacted bentonite can be put in place.

This report treats the concrete and its applications. The concrete must, however, have such properties that the function of the bentonite is not jeopardized

1.1 Concrete for the bore hole plug

In the borehole-plugging process concrete will be used in two different ways. Firstly the borehole must be stabilized to allow the application of the bentonite tubes. How to stabilize the boreholes is investigated in another project “low alkali mortar for selective stabilization of deep drill holes" in the PLU programme. One of the concepts here is to enlarge the damaged section of the borehole and fill it with ultrahigh strength low alkali fibre concrete (Vogt et al 2004). When this concrete has hardened a new hole will be drilled with the same diameter as the original hole. This will result in a “tube” in the rock that will stabilize the drill hole. Other concepts are also being investigated.

The borehole plug will be casted at the desired position where it shall fill the section and hinder water movement. The technique to get the concrete in place is being developed in the other project (se above). Basically a special canister with fresh concrete will be lowered to the desired depth where it will be emptied. The geometry of the canister will put a limit to D-max of the aggregates. As the geometry is not fully developed the concrete recipe must be designed in such a way that it will be possible to adjust.

The casting technique, spacing, and chemistry put special demands on the concrete, both the fresh and hardened concrete.

1.1.1 Demands on the concrete

1. The geometry of the application canister and the diameter of the borehole restrict the largest size of aggregates. The D-max is around 1/3 of the diameter of the opening in the canister. A D-max of 4 mm is set for the basic recipe.
2. The concrete shall be self-compacting, i.e. there shall be no need for vibration to get the fresh concrete compacted.
3. The shrinkage shall be at a minimum.
4. The fresh concrete may be placed in an area with peculating water. Thus the concrete must have a good cohesion.
5. The concrete will be subjected to leaching. Thus the concrete shall have high resistance to leaching
6. The concrete shall have a good stability also after leaching.
7. The concrete will be in direct contact with bentonite. A high pH will reduce the swelling capacity of the bentonite. Thus the concrete shall not contaminate either the bentonite or the surrounding ground water. Preferably the concrete shall not increase the pH of the surrounding groundwater to more than 11.

2 Concept for the bore hole concrete

The special and demanding requirements are to get a low pH when leached, make it self-compacting and to minimize the amount of cement paste.

2.1 Chemical composition and leaching.

The cement paste of hardened concrete is water-soluble. How fast the leaching goes and the effect on ground water depends on the composition of the cement paste. The mechanism of leaching is complicated and will only be briefly described here. A more detailed description can be found in Lagerblad (2001).

Basically cement paste is porous and the pore water is in contact with ground water. If a chemical component is removed from the pore water the solid phases of the cement paste will requilibrate and solid phases will dissolve or change composition. Submerged in water the ionic transfer from the pore solution to the ground water will be by diffusion processes, which is controlled by concentration gradient, transport distance through leached concrete and porosity. Thus to control the effect on ground water the focus must be on the pore water composition. If the pore water has a pH of less than 11 the concrete will presumably not give a pH of above 11 to the ground water.

The pore water composition is controlled by the composition of the cement paste phases and residual ions from the cement hydration. The bulk effect comes from hydration phases. Thus to control the effect on the ground water the composition of the cement paste must be regulated.

Pure Portland cement mixed with water gives crystalline portlandite (CH, calciumhydroxide), semi crystalline calcium silicate hydrate (C-S-H), crystalline ettringite (AFt, calcium aluminate sulphate), crystalline monosulphate (AFm, calcium aluminate sulphate), remaining cement clinker and residual alkali hydroxide in the pore solution. The amount of the different phases depends on the composition of the cement and the degree of hydration. Each of the crystalline phases gives a specific pH when in contact with water. The C-S-H dissolves by releasing CH, i.e. lowering its CaO/SiO_2 ratio.

The pore solution of ordinary concrete is above 13. This is due to residual easily soluble alkali hydroxide. The amount of alkali ions is limited, but to get a low pH concrete low alkali cement must be chosen. Of the different types of cement available on the Swedish market Aalborg A/S white cement contains least alkalis, around 0.2 wt. % alkalis when recalculated to pure Na_2O.

Of the solid phases CH gives the highest pH, around 12.4 in pure water. Thus this phase must be eliminated. This can be achieved by mixing the cement with reactive silica (puzzolana) that will give more C-S-H.

$Ca(OH)_2 + SiO_2 = \text{C-S-H}$

The most reactive silica is silica fume that is extremely fine-grained amorphous silica. To eliminate all CH around 15 wt. % silica fume is needed in the binder (cement + silica fume).

This C-S-H will, however, give a C-S-H with a CaO/SiO_2 ratio of around 1, 6 and it will give a pH of above 12 when leached. To lower the pH further more silica fume is needed. To get a pH of less than 11 the CaO/SiO_2 ratio must be less than 1, 1 (Stronach and Glasser 1997, Fig 1). The effect on pH diminishes with the ratio. One must, however, also to consider the composition of the ground water, as this will effect the composition of the pore water, equilibrium with the hydrate phases and thus the pH.

SiO_2 + C-S-H (1) = C-S-H (2) where C-S-H (2) has a lower CaO/SiO_2 ratio than C-S-H (1)

To get a C-S-H with a CaO/SiO_2 ratio of 1.1 around 30 wt. % silica fume is needed in the binder (Lagerblad 2004). One must, however, consider that fine-grained quartz also reacts with the Ca and thus will lower the CaO/SiO_2 ratio further.

In a concrete with this large amount of silica fume AFm will not form, as it requires a pH of 11.6 to form. The ettringite is stable at a pH above 10.6. Thus with enough silica fume there will be no solid phase that can dissolve and give the ground water a pH of above 11.

For the basic recipe a mix with 50/50 white cement and silica fume was chosen to be certain to get a pH of below 11.

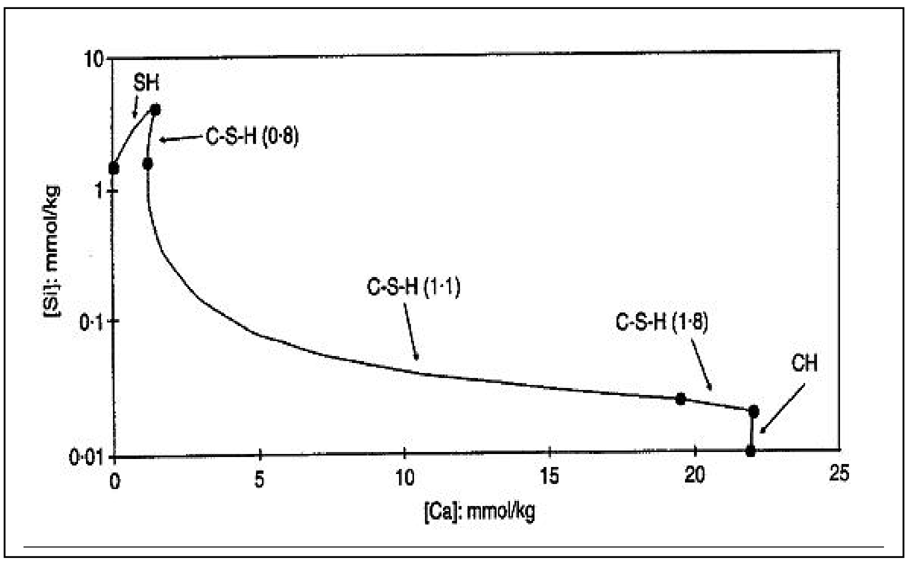

Figure 1. Relation between Ca and Si in solution and composition of C-S-H. The values in ( ) marks the CaO/SiO_2 ratio. Figure and data from Stronach and Glasser 1997. The contents of Si and Ca in solution define the pH. SH is a silica gel.

2.2 Concrete mix.

The concrete shall be cohesive, contain a minimum of cement/binder and it shall be self-compacting. The two first demands can be met with large amount of filler. To reduce the amount of binder part of the filler shall be ultrafine. This concept has been developed and is described in Lagerblad & Vogt 2004. Fillers are particles with a size of less than 63 µm and ultra filler are particles with a size of less than 10 µm.

The ultra filler shall be of quartz as this mineral will react with the cement paste and thus lower the Ca/SiO_2 ratio of the C-S-H. The fine ground types of quartz chosen for the mixes were fine ground α-quartz (M300) and fine ground cristobalite quartz (M6000). They are both commercial products from Sibelco. M300 has a size similar to cement and thus allows the amount of cement to be lowered without disturbing the particle packing. The M6000 is much finer than cement and will thus act as ultra filler and can thus replace cement without reducing the strength or increase the porosity (Lagerblad & Vogt 2004).

The concrete shall be self-compacting. This can be achieved by having a large amount of filler in the mix.

2.3 Concrete recipe

Based on the concept of silica fume and ultra fine filler a sequence of mixes was tested. The goals were to minimise the amount of Portland cement and maximise the amount of silica fume. Earlier experience has shown that to large amounts of silica fume can give a mix that is difficult to mix and a concrete with large shrinkage. On the other hand small amounts of binder will diminish shrinkage. It is thus a balance.

Based on a sequence of mixes and preliminary tests the recipe below was chosen for further testing.

Components

Components	Kilograms per m^3 of concrete
White cement (Aalborg Portland)	60
Water	150
Silica Fume (Elkem)	60
Fine ground α-quartz (Sibelco)	200
Fine ground cristobalite quartz (Sibelco)	150
Superplasticizer (Glenium 51 Modern Betong)	4,38 (dry weight)
Aggregate 0-4 mm (Underås, Jehanders Grus)	1679

The concrete was mixed in a forced mixer. Other mixers will also be tested.

3 Results

3.1 Rheology

The concrete composed according to the recipe was self-compacting, i.e. it flows by itself as can be seen in Fig. 2. To measure the ability to self-compact a flow set measurement is normally used. It is based on a normal set cone but instead of measuring the set the spread is measured. The flow set (Fig. 2) was 650 mm, which is enough to define it as self-compacting. Compared to ordinary concrete it was fairly viscous, i.e. it flows slowly (like syrup). The concrete had a good adhesion. This can be noticed at the edge of the spread (Fig. 2) where no water separation can be noticed. The rheological properties indicate that it can be applied and casted at position in the borehole, but it must be verified.

Figure 2 Picture of flow for the borehole plug concrete. This concrete is self-compacting in a borehole.

3.2 Strength

There are demands both on stiffening, strength development, and final strength. Thus the strength was tested at different ages. The basic aim was to get cube strength of above 10 MPa. The strength and strength development is dependent on temperature. Thus the mix was tested both at 5 and 20 °C curing temperature. The temperature in the borehole depends on depth and is assumed to be between these two temperatures.

Table 1. Strengths development. Cube strength.

Curing time in days	5°C Cube strength in MPa	20°C Cube strength in MPa
2	1.9	4.5
3	4	6.6
7	7.5	10.6
28	14	40
72	32.9	55.2
91	35.4	57.4

The demands on strength are low for this application. The strength is, however, linked to porosity which in turn is linked to leaching and is thus of importance. The strength development is relatively slow presumably due to the low amount of cement. It is slower at lower temperatures. The strength development can be increased by adding $CaCl_2$ to the mix. Normal concrete for building purposes normally has strength of somewhat above 30 MPa after 28 days. This means that the borehole concrete by time is very strong. It was rather surprising that a concrete with this low amount of cement could get this high strength.

3.3 Shrinkage

In the borehole the concrete will never dry out. Thus drying shrinkage can be neglected. Only autogeneous shrinkage and shrinkage with surplus water has to be considered.

3.3.1 Autogeneous shrinkage

This is shrinkage under sealed conditions, i.e. water is not added or removed. In the test the concrete was put in a flexible plastic tube and the length change was measured over time. The results are shown in Fig 3. The measurements started when the concrete was hard enough to handle the tubes. The shrinkage before this is of no importance as the concrete in the borehole will compact itself before stiffening.

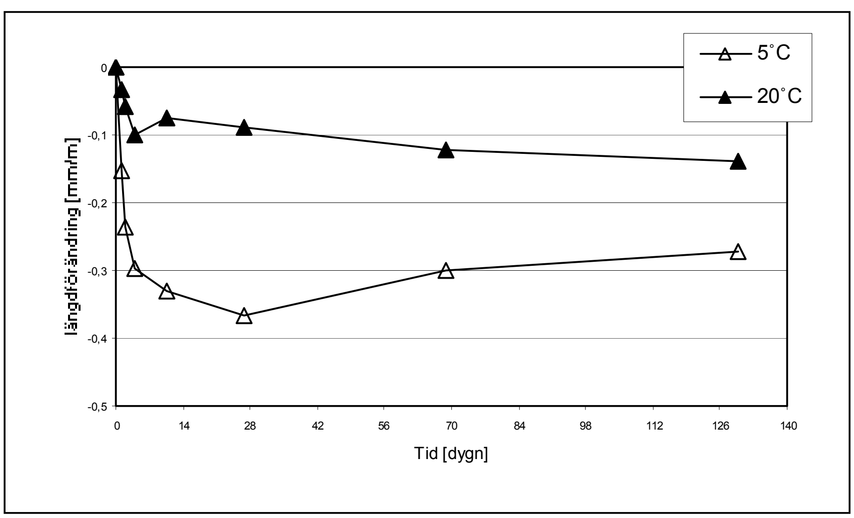

Figure 3: Autogeneous shrinkage of bore hole concrete.

The results show that, as expected, there is shrinkage at both temperatures. The reason for the difference is not known, but the shrinkage is fairly low and will only produce a neglible gap between the concrete and the rock.

3.3.2 Shrinkage in water

In water there was a small initial shrinkage. After the initial period, however, the concrete started to expand. The final results after 125 days show a small swelling. This indicates that there will be no gap between the concrete and rock. The swelling will increase the sealing capacity.

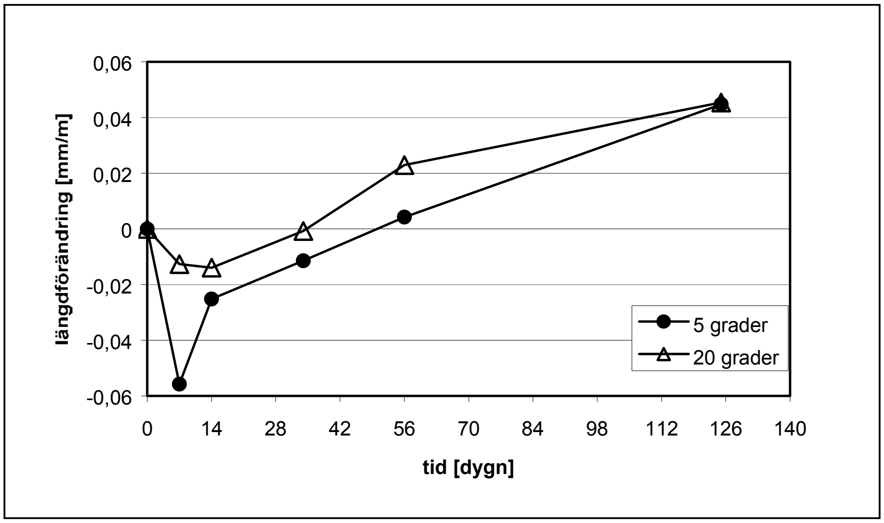

Figure 4: Shrinkage of bore hole concrete submerged in water.

3.4 Concrete texture and porosity

The porosity has been analysed in thin sections. A thin section is a specimen that has been polished so thin that light can penetrate is. This means that the concrete can be analysed in a polarising microscope. The thin sections was impregnated with epoxy containing fluorescent dye. When analysed with UV light one can estimate the porosity. A porous material will absorb more epoxy/dye. Normal concretes with different water/cement ratios are used as reference.

The results (Fig. 5) show that the borehole concrete has porosity similar to common concrete with a water/cement ratio of around 0.6. This is interesting as the porosity is linked strength and the strength of the borehole concrete is similar to that of a normal concrete with a w/c of 0.6. Normal concrete contains around 300 kg cement and 150 kg of water. The borehole concrete contains 150 kg of water, 60 kg cement and 60 kg Silica Fume. As the amount of free/excess water decides the porosity this porosity is reasonable.

The effect is presumably due to the ultra filler that gives a dense structure. This can be better observed in scanning electron microscope (SEM) that gives a greater enlargement. Pictures from SEM are shown in Fig. 6. In these photos one can observe a texture dominated by fine quarts grains, grains finer than cement. In the sample stored a 5 °C we can observe a remaining cement grain. This remain cement will react with time and give a more dense texture.

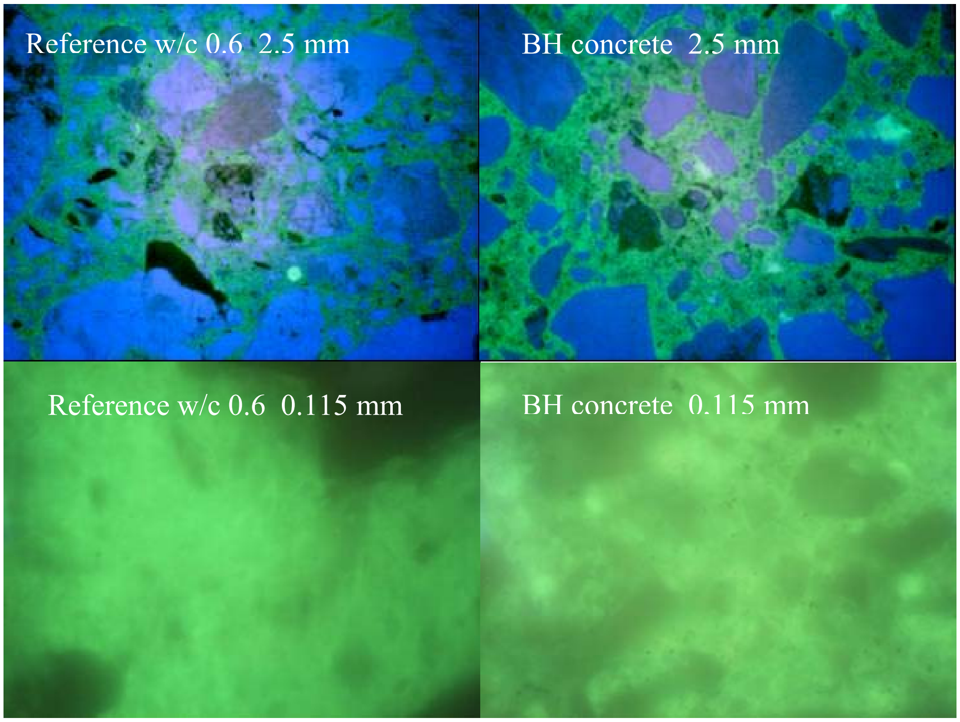

Figure 5: Thin section of bore hole concrete cured for 14 days in water compared to ordinary concrete with a water/cement of 0.6. Fluorescence pictures in petrographic microscope. The blue or dark grains are non porous aggregates while the yellow colour comes from fluoresces dye absorbed by the porous cement paste.

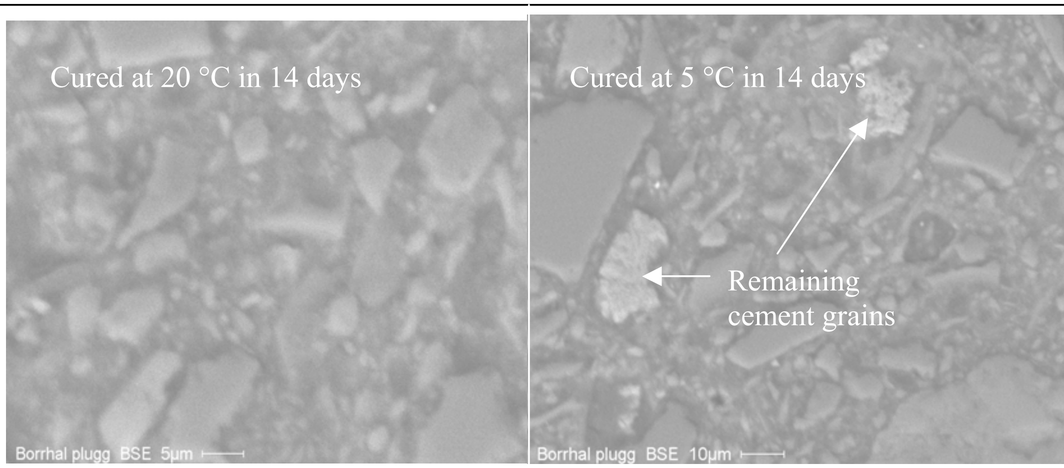

Figure 6. Scanning electron microscope image of flat polished surfaces in backscatter mode of bore hole concrete. The small lighter grains that emerge from the surface are quartz filler.

3.5 Chemical composition of the cement paste.

In SEM the chemical composition in a small area (spot) can be analysed by energy dispersive analysis. This technique was used to analyse the cement paste. It was, however, difficult to find a god spot away from the quartz filler due to the small amount of paste. Thus a large number of spots was analysed and those with the highest amount of Ca was chosen as representative of the paste. The paste contains water and thus the analyses where normalised to 100 % oxides. Representative analysed are presented in table 2.

Table 2 Chemical composition of cement paste in bore hole concrete. The analysis of the cement grain (belite, Ca_2SiO_4)) can be used as reference for accuracy on the Ca/Si ratio. It shall be 66/33 (2.0). In the table are also included compositions of white cement and silica fume (company declared compositions). In the cement the content of alkalis are put together as Na-equivalent.

Oxide	Cement	6ºC age 14 d	6ºC age 14 d	20ºC age 14 d	20ºC age 125 d	20ºC age 125 d	White cement	Silica Fume
	Belit (C_2S)	Close to cement	In matrix	In matrix	In matrix	Close to cement	Bulk composition	
CaO	64,18	36.1	17,18	15,80	18,72	24,36	69.28	0,5
SiO_2	33,31	52,29	72,09	75,99	70,84	66,71	24.9	93,8
Al_2O_3	0,38	5,90	6,60	3,62	4,06	3,50	1.91	1,2
TiO_2	1,59	0,28	0,25	--	--	--	--	--
Fe_2O_3	0,33	2,40	1,33	1,58	3,07	2,87	0.33	0,5
Na_2O	--	0,49	--	0,37	0,33	0,21	0.15	0,27
K_2O	0,2	0,55	0,35	0,78	0,94	0,83		1,04
MgO	--	1,05	1,31	0,68	1,15	0,86	0.58	0,6
SO_3	--	1,29	0,89	1,17	0,68	0,45	2.11	0,4
LOI							0,7	2,1
CaO/SiO_2	1,93	0,69	0,24	0,20	0,26	0,37		

The analysis shows a paste dominated by silica and calcium and with small amounts of Al, Fe, Mg, and S. No CH could be detected. This indicates a paste dominated by C-S-H. The Al, Fe, Mg and S are either contaminants in the C-S-H or minute crystals of ettringite or some other crystalline phase. The CaO/SiO_2 ratio is very low. The highest ratio was found close to a remaining cement grains and was only 0.69 but the mean value is between 0.2 and 0.4. In the older concrete the difference is less probably due to homogenisation. This is basically not a C-S-H but a silica gel with Ca ions. This may explain why the contents of the other ions are higher than in normal C-S-H. According to the amount of cement and silica fume the CaO/SiO_2 ratio should be around 0.55. This indicates that part of the quartz fillers has reacted with the cement paste or that the paste contains were minute quartz grains that cannot be identified. This low ratio should give a pH of distinctly less than 11.

3.6 Leaching experiments

Some simple leaching experiments were done to confirm the effect of silica on the composition of the paste. The problem with leaching is that it is a slow process and that carbon dioxide from the atmosphere can interact with the leaching water. Carbon dioxide will dissolve to carboniferous acid that will react with the calcium hydroxide and lower the pH of the fluid. Thus interaction with carbon dioxide must be hindered.

The device that was set up for the test consists of 800 ml Teflon beakers with Teflon lids. In the lid of the beaker a 10 mm sawn slab is hung in platinum treads. The slabs are 70x 80 mm, i.e. the slab has a volume of around 56 cm^3 and an area of 142 cm^2. The surface liquid area is around 1.8 cm^2/ml. In the bottom a Teflon coated magnetic stirrer keep the liquid in motion. To avoid carbon dioxide contamination the beakers are modified in such a way that the empty space is filled with argon gas and the argon gas is used to squeeze out the sample water (Fig.7). The samples were water cured for 48 days. After this period they were sawn and the slabs were water cured (tap water) for 2 days. Following this they were put in the beakers. The first pH measurement was taken after one day in the beakers. The leaching process is fairly slow and is linked to water turnover. Thus four experimental series was set up. In one of them the water was continuously replaced while in other the concrete slabs were kept in the water. A glass electrode calibrated with a buffer solution at pH 10 measured the pH.

When leached there is first a surface reaction, which gives the highest pH. As the test slabs were sawn there may be some cement grains at the surface. This will not be the case with casted concrete, as it will get a surface skin. Thus the slabs were first put in water to hydrate these cement grains. The last 40 days was during summer holiday. During this period no Argon gas was added which increases the risk for carbon dioxide contamination.

Table 3. Influence on deionised water of borehole concrete. The pH is measured by glass electrode calibrated at pH 10 (buffer solution). pH measurement followed by *exchange of water.

Days	1	4	7	10	12	14	17	19	21
Serie 1	*10.3	*10.43	*10.28	*10.24	*10.14	*10.15	*10.23	*10.29	*10.08
Serie 2	10.21		*10.18			*10.30			*10.13
Serie 3	10.23					10.23			
Serie 4	10.22			10.25			10.14		

24	27	31	33	35	38	40	42	82
*9.94	*9.90	*9.97	*10.01	*10.06	*9.99	*10.16	*10.17	8.98
	*10.32			*10.37			10.36	9.49
	10.38	*10.37					10.38	10.30
	10.02						9.88	9.51

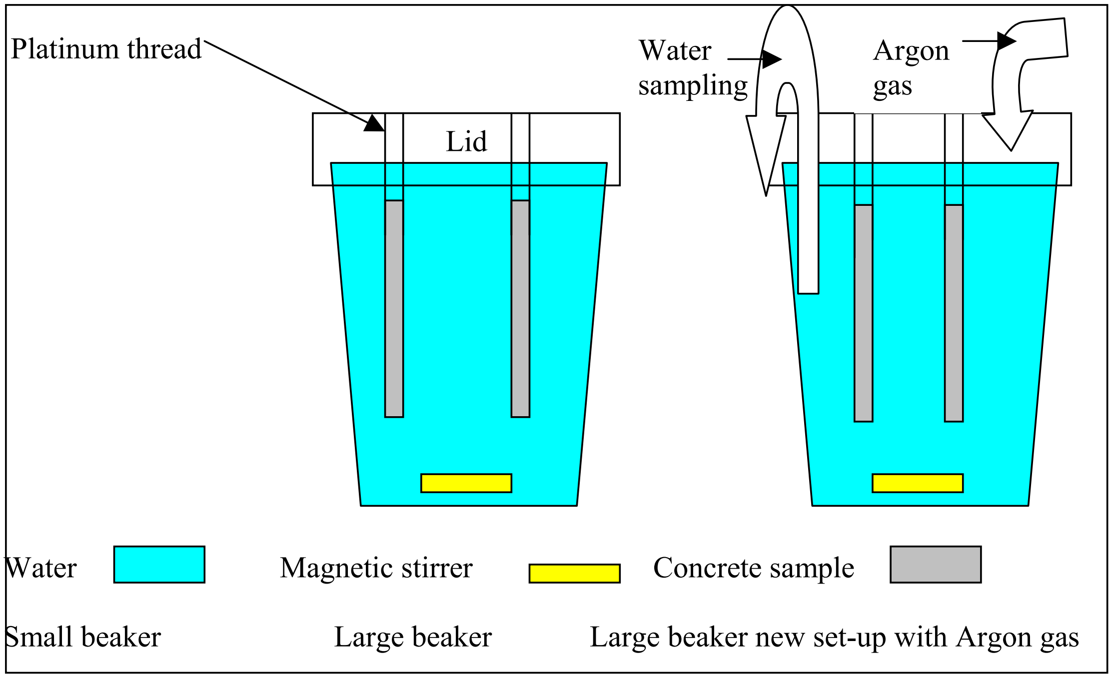

Figure. 7. Set-up of leaching devices.

3.6.1 Discussion of leaching results.

Leaching is a complicated process. To start with it is a chemical reaction between the surface and the water. Later leaching is a diffusion-controlled process between the pore water of the concrete and the surrounding water. Moreover the cement paste changes as the concrete becomes older. It will take some time before the cement clinker is totally consumed and has reacted with the silica fume and especially with the less reactive fine-grained quartz and the C-S-H will polymerise or crystallize with time. In the leaching experiments the concrete is fairly young and the sawn surface is fresh. In all of the four experimental series the pH was less than 10.5. The data from experimental series 1 show that the pH declines somewhat with every water change. This indicates that it takes a certain time for the leaching process. In series 4 the pH remains fairly constant. There is a small decline in pH over time. This is not logical and indicates some minor leakage of carbon dioxide. With time and more mature concrete the pH will presumably decline somewhat.

In none of the beakers the pH was above 10.5. This is in accordance with the low CaO/SiO_2 of the C-S-H.

4 Discussion

The tests show that it is possible to make a low pH concrete with very low content of cement to fill boreholes. The strength is sufficient to fulfil its purpose. The pH will be below 11

Earlier unpublished experiments give that the pH of leaching declines with the salt content of the ground water. Thus this is a conservative value. More accurate experiments in a closed glove box and with different types of water are needed to make a more absolute statement of the effect of pH in ground water. As the Ca/Si ratio is low in the paste and agree with the leaching results it is fairly certain that the borehole concrete will give a low pH, a pH below 11.

The cement paste mainly consists of C-S-H. The CaO/SiO_2 ratio, however, is very low, less than 0.4. This is presumably due to that the fine-grained quartz filler has reacted and formed more C-S-H. This is very much less than in normal cement paste. Thus we must consider the stability of this phase. As the paste is in equilibrium with a pore solution with a content of CaO less than 2 mmol/kg liquid it will leach very slowly. The problem is how the paste will change over time and what the final aging product will be. The C-S-H is a cryptocrystalline phase formed rapidly during the hydration process. It will not be long-time stable. This problem is partly treated in (Lagerblad et al 2004). The C-S-H will by time try to crystallize to lower its energy. In normal concrete cement paste the backbone of the C-S-H are short silica chain bond together by CaO and $Ca(OH)_2$. The C-S-H can due to the high contents of CaO only lengthen in the silica chains. With lower content of CaO, however, the chains can become longer and with low enough content of CaO it can cross polymerise and form a sheet structure. Thus in a long time perspective we can assume that the C-S-H in the borehole concrete will crystallise. One of the possible phases is Tobermorite (14-Å). It has the composition $Ca_5Si_6(O,OH)$ x 5 H_2O. The CaO/SiO ratio in the borehole concrete C-S-H is however, even lower than in the Tobermorite (0.83). With a CaO/SiO_2 ratio around 0.5 there is a whole range of natural minerals like okenite ($Ca_5Si_9O_{24}$ x $9H_2O$) or Gyrolite ($NaCa_{16}(Si_{23}Al)$ O_{60} x 14 H_2O). These mineral are normally found in hydrothermally altered volcanic rocks in nature.

Of the different compounds in the borehole concrete it is only the Ca ions that leach out. When totally leached the cement paste will be dominated by silica gel, and metal hydroxides. The concrete contains 60 kg of cement per m^3 of concrete. The cement contains 69 % CaO, which shows that the concrete may lose 41.4 kg CaO. The CaO will be bound as $Ca(OH)_2$ with a weight of 54.7 kg in the C-S-H. If we assume that all CH will be leached out and that the C-S-H will shrink with the same volume, the concrete will lose 23.8 dm^3 of paste. This gives a volume reduction or increased porosity of 2.4 %. This assumes that the remaining silica gel will shrink according to the amount of removed CH, which probably is not the case. In any case with a volume loss of around 2.4 % the concrete will still be fairly intact. It will consist of aggregates glued together with a silica gel.

5 Conclusions

The produced and examined concrete has properties which makes it a candidate for the borehole plugging.

The concrete is based on a concept with large amounts of quartz filler. It is possible to adjust to adjust the recipe so that it may contain larger stones (D-max). The concept demands the use of superplasticizer. By increasing the amount of binder and reduce the amount of filler the amount of superplasticizer can be lowered.

The shrinkage is low due to the small amount of cement paste. In wet conditions one can observe a small swelling. This means that there will be no gap between the concrete and the rock.

5.1 Remaining questions and uncertainties.

The data indicates that the pH during leaching will be less than 11 but this must be verified by more precise methods (glove box) and with water with relevant compositions.

The C-S-H of the cement paste is not a typical C-S-H, i.e. it is a silica gel with Ca and other ions. This type of product is not examined in the cement chemistry literature. Thus research concerning the stability of silica gel need to be done

The variability of the basic concrete and its rheological properties needs to be examined more closely to find the variability and the effect of changes of the variables

The borehole concrete demands superplasticizer. A series of test needs to be done to find out the effect of lowering the amount of superplasticizers.

Field test and tests in the application canister is needed to verify the results.

6 References.

1 **Leaching performance of concrete based on samples from old concrete constructions**, SKB TR-01-27, Lagerblad, B., Report series of Swedish Nuclear Fuel and Waste Management CO 2001

2 **Modification of cement paste with silica fume-A NMR Study**, *Lagerblad, B., Jennings, H.M., Chen,* J.J., Nanotechnology In Construction, Eds Bartos, Hughes, Zhu, The Royal Society of Chemistry, Special Publication No. 292, p. 123-131, 2004.

3 **Ultrafine particles to save cement and improve concrete properties,** *Lagerblad, B., Vogt, C.,* CBI report, 1:2004, 2004

4 **Optimization of UHPC for selective stabilization of deep boreholes**, *Vogt, C., Lagerblad, B., Hugo-Persson, T.*, Accepted for publication, International Symposium on Ultra High Performance Concrete, Sept 13-15, 2004, Kassel Germany.

5 **Modelling of the impact of abundant geochemical components on the phase stability and solubility of the CaO-SiO2-H2O system at 25 ºC**, *Stronach, S.A., Glasser, F.P.,* Advances in Cement Research, Vol 9, No 36, 167-181, 1997.

Appendix 2

SKB, Äspölaboratoriet

SKB, BOREHOLE PLUGGING

Report concerning design of borehole plugs with perforated copper tubes and highly compacted bentonite.

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Report
Stockholm 8 October 2004

Project No. 5535032

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SWECO

Summary

Carrying out site investigations for future deep repository, a number of investigation holes in the rock are drilled which results in boreholes down to the repository level. (500 m)

These holes must be sealed in order to not be a flow path for ground water in all directions. A basic principle is that the conductivity for the installed plugs will be lower than the surrounding rock.

The proposed approach is to fill perforated tubes with bentonite clay and place these in the boreholes were they swell and thereby seals the holes in the same degree as surrounding rocks do.

SWECO's assignment is to propose appropriate design and material of the plug tubes to achieve a practical solution that meets the requirements of sealing.

The conditions are that the holes has a diameter of 76 mm, is up to 1500 m deep and can be placed in all directions, i.e. vertical up/down as well as horizontal. To achieve necessary sealing, the bentonite clay has to have an average density of at least 1900 kg/m^2 when wetted and swelled. Furthermore, the tubes have to be perforated to at least 50% for the bentonite to swell in the right way.

Recommended design is a 3 m long perforated plug tube with an outer diameter of 74 mm and a thickness of material of 2 mm. The material suitable for the tube is copper. The tube is provided with round threads in both ends and jointed at site to 24 m long "strings". With a conventional jig, these "strings" are then placed at the bottom of the boreholes. The plug "string" is grabbed by a tool, which is attached to a regular drill string.

A future development of the concept is to include the production of the prototype and performing strength tests of the tubes and its joints.

Sammanfattning

Vid platsunderökningar av det tänkta framtida slutförvaret används ett antal undersökningshål i berget vilket resulterar i borrhål ner till och kring förvarsnivå (500 m).

Dessa hål måste tätas för att inte utgöra en strömningsväg för grundvattnet i alla riktningar. Grundprincipen är att pluggarnas konduktivitet inte skall vara lägre än omkringliggande berg.

Föreslaget tillvägagångssätt är att fylla perforerade rör med bentonitlera och föra in dessa i borrhålen där de sväller fast och tätar i minst lika hög grad som kringliggande berg.

SWECOs uppdrag är att föreslå lämplig utformning och material på pluggrören för att uppnå en praktisk lösning som uppfyller kraven på tätning.

Förutsättningarna är att hålen har 76 mm diameter, är upp till 1500 m djupa samt kan vara belägna i alla riktningar dvs. vertikalt uppåt/nedåt och horisontellt. När bentonitleran blötts och svällt ut skall denna ha en genomsnittsdensitet av minst 1900 kg/m^2 för att ge erforderlig tätning. Vidare skall rören vara perforerade till minst 50% för att bentoniten skall svälla ut på rätt sätt.

Rekommenderad utformning är 3 m långa perforerade pluggrör med 74 mm ytterdiameter och en godstjocklek på 2 mm. Materialet i rören väljs lämpligen till koppar. Rören förses med rundgängor i båda ändar och skarvas på plats ihop till 24 m långa ”strängar” som förs till borrhålens botten med hjälp av en konventionell borrigg. Pluggsträngen greppas av ett verktyg som i sin tur är fäst vid en vanlig borrsträng.

En fortsatt utveckling av konceptet föreslås omfatta prototyptillverkning och hållfasthetsprovning av rören och dess skarvar.

Table of Contents

1 Project Definition

At site investigations for a future deep repository for spent nuclear fuel in the Swedish rock, deep investigation holes are being drilled. These holes will be sealed when the examination phase is completed or when a deep repository is built. During the execution of the repository, both horizontal and upwards oriented boreholes for detailed examination will be drilled from the level of the repository.

The proposed principle is that a plugged hole must not serve as a continuous flow path for groundwater but be sealed to get the same or lower conductivity than the surrounding rock for at least 100 000 years.

The basic conditions involves utilization of perforated tubes filled with highly compacted bentonite in units which will be jointed when placed in maximum 1500 meter long investigation holes or shorter holes on the level of repository.

Two main issues will be included within the project: Stabilizing of crack zones and design of clay based borehole plugs. The concept means that the holes will be filled to approximately 100 meters distance from the rock surface. The upper of the 100 meters should be sealed with material that is capable of holding clay plugs in place and give adequate protection to erosion, frost and sabotage.

This report describes the design of the clay plugs regarding the perforated tubes and the joint system that connects the tubes, as well as how the handling above ground at installations are being performed. The report also includes how to achieve efficient manufacturing of the tubes and the joint system. Furthermore, the report provides a basis for developing a room-sized prototype for tensile tests of tubes, joints, etc.

The report comprises a part of a project report which will result in a complete borehole concept and that will be completed by October 2004.

2 Conditions

Following conditions applies for the design and calculations of the borehole plugs:

- Vertical boreholes from the surface of the rock with a maximal length of approximate 1500 meters and a slope between 45 and 90 degrees.
- Horizontal boreholes from the repository with a length of a couple of hundred meters.
- Upwards oriented boreholes from the repository with a length of a couple of hundred meters.
- The reference diameter for boreholes is chosen to 76.0 mm.
- The vertical boreholes are considered to be water filled when plugged.
- The plug segment is made suitable in the lengths of 3 or 6 meter.
- The plug segments joints to suitable length, considering the strength of material of the perforated tube.
- The strength of material of the plug is calculated with adequate security, as the plug will tolerate additional forces if it is wedged up in the borehole
- The basic concept is perforated tubes made of copper. The material navy-G-bronze and titan has also being studied.
- The grade of perforation of the tube will be 50%.
- Suitable diameter for the hole for perforation in the tubes is 10 mm.
- The initial density for the clay core is 1900 kg/m^3
- The final density for the clay core in the plug will be at least 1900 kg/m^3

- The results and lessons learned from the laboratory test ”PILOT STUDY OF BOREHOLE PLUG MATURATION” will be considered.

3 Calculations of necessary Tube Dimensions for Plugs

The value in the showed calculations concerns only the chosen geometry and not the base optimization that resulted in the values.

3.1 Data and Terms

Given values and features:
$\rho_{DryBentonite}$ = 1900 kg/m^3 = Initial density for bentonite
ρ_{Cu} = 8930 kg/m^3 = Density for copper
ρ_{H2O} = 1000 kg/m^3 = Density for water
$d_{Borehole}$= 76 mm = Borehole diameter
N_{Perf} = 50% = Grade of Perforation of the tube
g = 9.82 m/s^2 = Acceleration of Gravity
d_{Tube} = 74 mm = Diameter of the copper tube (i.e. the gap between the hole and the tube is 1 mm radial)
$\sigma_{Tensile}$ = 60 MPa

0.5 mm = Gap between the tube and the bentonite

Assumed values:
t_{Tube} = 2 mm = Thickness of the tube material
l_p = 24 m = Length of the plug
b_{Cont} = 10 mm = Width of the plug’s contact surface against the rock at horizontal emplacement.
s = 200 = Slip line, i.e. the horizontal deposition drifts’ depth, at horizontal installation.
$k = 1 \cdot 10^{-4}$ Abrasion factor for rock-copper.

Other features:
$d_{Bentonite}$ = Diameter of the bentonite core
$\rho_{WetBentonite}$ = Density for wet, pressed bentonite which has not swelled.
$\rho_{SwelledBentonite}$ = Density for wet, swelled bentonite
p = Surface pressure in the plug’s contact surface against the rock at horizontal deposition.
K_{Stress} = 5.7 = Stress concentration factor for hole in tubes at tension, see Attachment 1

3.2 Calculations

Density of Bentonite

$$\rho_{WetBentonite} = \left(\left(0.63 \cdot \frac{\rho_{DryBentonite}}{10^3}\right) + 1\right) \cdot 10^3$$ = 2197 kg/m^3 (Equation referred by R.Pusch)

Cross section area of the Bentonite Core

$$A_{Bentonite} = \frac{d_{Bentonite}{}^2 \cdot \pi}{4}$$ = 3.794·10^{-3} m^2

Cross section area for the outer gap, borehole-tube

$$A_{OuterSlot} = \frac{(d_{Borehole} - d_{Tube})^2 \cdot \pi}{4}$$ = 2.356·10^{-4} m^2

Cross section area for the Copper Tube

$$A_{Tube} = \frac{(d_{Tube} - (d_{Tube} - 2 \cdot t_{Tube}))^2 \cdot \pi}{4}$$ = 4.524·10^{-4} m^2

Cross section area for the inner gap, tube-bentonite

$$A_{InnerSlot} = \frac{((d_{Tube} - 2 \cdot t) - d_{Bentonite})^2 \cdot \pi}{4}$$ = 5.478·10^{-5} m^2

Volume of the Bentonite Core

$$V_{Bentonite} = A_{Bentonite} \cdot l_p$$ = 9.106·10^{-2} m^3

Volume for swelled bentonite

$$V_{Swelled} = A_{Swelled} \cdot l_p = \left[A_{OuterSlot} + (A_{Tube} \cdot N_{Perf}) + A_{InnerSlot} + A_{Bentonite}\right] \cdot l_p \Rightarrow$$

$\Rightarrow$ 1.034·10^{-1} m^3

Density for Swelled Bentonite

$$\rho_{SwelledBentonite} = \frac{V_{Bentonite} \cdot \rho_{WetBentonite}}{V_{Swelled}} = \frac{A_{Bentonite} \cdot \rho_{WetBentonite}}{A_{Swelled}}$$ = 1934 kg/m^3

Weight of the Copper tube in water

$$m_{Tube} = A_{Tube} \cdot l_p \cdot N_{Perf} \cdot (\rho_{Cu} - \rho_{H2O})$$ = 43 kg (48 kg in air)

Weight of the Bentonite Core in water

$$m_{Bentonite} = A_{Bentonite} \cdot l_p \cdot (\rho_{WetBentonite} - \rho_{H2O})$$ = 109 kg (173 kg in air)

Weight of the Plug String in water

$$m_{Plug} = m_{Tube} + m_{Bentonite}$$ = 152 kg (221 kg in air)

Tensile Stress in the hanging Plug String

$$\sigma_{Tensile} = \frac{(m + m_{Bentonite}) \cdot g}{A_{Tube}} \cdot K_{Tensile}$$ = 19 MPa

Abrasion of the Plug Tube at Horizontal Deposition Drifts

$$p = \frac{((A_{Tube} \cdot \rho_{Cu} \cdot N_{Perf}) + (A_{Bentonite} \cdot \rho_{Bentonite})) \cdot l_p \cdot g}{b_{anl} \cdot l_p}$$

$f = k \cdot p \cdot s$ = 0.7 mm (Depth of Abrasion)

3.3 Conclusions of the Calculations

When calculating backwards with the yield stress ($\sigma_{Tensile}$ = 60 MPa) the plug string's length is 77 meters. This stress is in essence independent of the tube's diameter. To consider the loads that occur during the handling, the safety factor should be ~3-4, as this gives a suitable length for the plug string of 24 meters.

The usage of another material, as Titan or Navy-G-bronze, gives admittedly a possibility to increase the length of the plug string to more than double, but the Copper material's long-time features is better documented in this context. Therefore, the advantages of the Copper material overweigh the Titan and Bronze materials.

With the supposed dimensions on the Copper tube, a density for the swelled bentonite that fulfils the minimal requirements of 1900 kg/m^3 is obtained.

Rough estimations of the tube's abrasion at horizontal installation shows that the depth of the abrasion is 0.7 mm. This estimation should be considered as a rough estimate, as the abrasion factor is a parameter that has to be measured under realistic circumstances for the materials in consideration. If the plug is rotated during the insertion, this abrasion will be divided over the whole shell, instead of concentrated to a line.

Thus, the proposed outer diameter of the plug is 74 mm and 2 mm thickness in the tube material. For handling and strength reasons, the plug tubes should not be made longer than 3 meters and the plug tubes should be joined (to strings) in lengths of 24 meters. (i.e. 8 parts). Furthermore, the holes in the tube should be placed in a straight line pattern (0-90°) as this gives the origin to the least possible stress concentration at tension, see pattern 2 in attachment 1. However, it has become apparent that this pattern has certain disadvantages, as the bentonite will swell and fill out the gaps. Therefore, pattern 3 could be an alternative.

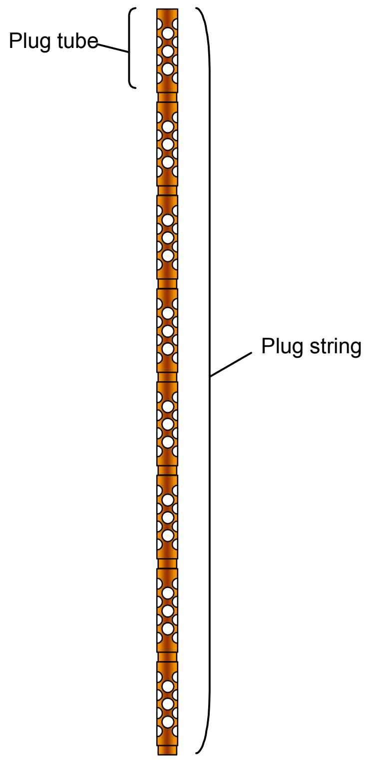

Figure 1, Plug string consisting of eight plug tubes

4 Description of the Joint System

4.1 Thread System

This design is based on that the plug tubes joints with threads, see Figure 2. In the gap between the plug strings, the threads are not used however and the strings are only being lead into each other, which is enabled by the below described “nose cone”.

On the bottom tube in the drill string, a type of “nose cone” is threaded on, see Figure 3. The function of this section is to fill out the cavity inside the uppermost threads on the earlier installed plug string, partly to function as a bottom plug and partly to prevent that parts of bentonite will loose and drops down into the hole.

The threads are milled/rolled in the material of the tube and are given a round thread equal to the thread profile according to Swedish standard SMS681 to be able to tolerate mechanical strain.

The advantages with this type of joint are that no tooling of the plugs is necessary when installing the plugs in the boreholes. Furthermore, it is easy to disassemble.

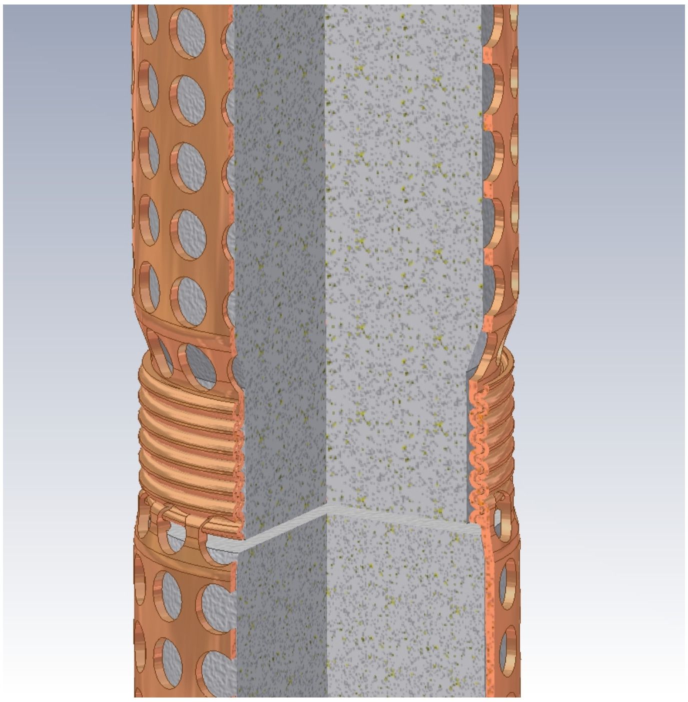

Figure 2, Threaded joint connection between the tubes.

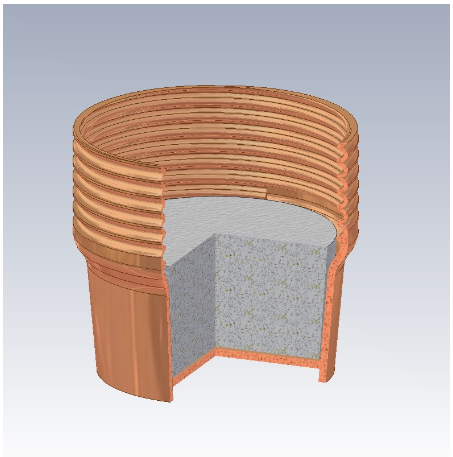

Figure 3, The bottom plug (the nose cone).

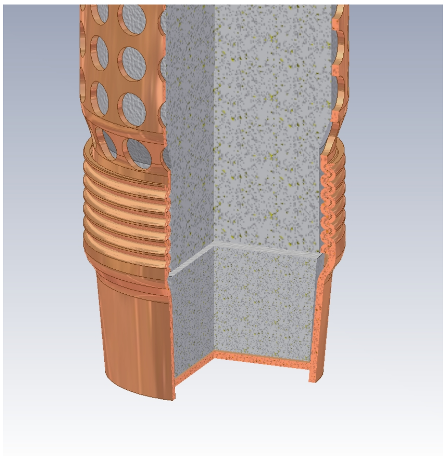

Figure 4, The bottom plug assembled on the lowest tube.

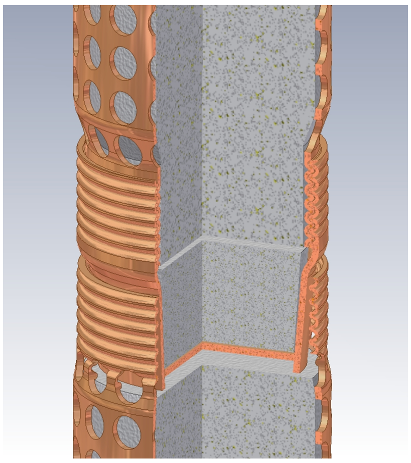

Figure 5, The bottom part of the plug string in place in the uppermost section of the earlier assembled plug string.

A possible option of this joint connection is to make the bottom and the uppermost threads (i.e. the joint between the plug strings) into a conical thread, instead of using the nose cone. The joint would then be threaded together instead and thereby an axle locking and sealing against the borehole's walls will be obtained, which could be an advantage. The part with the female thread should be slotted to be able to expand at the contractions, see Figure 6. This design is however more expensive and complicated to produce and is therefore only an option if axial locking is desired.

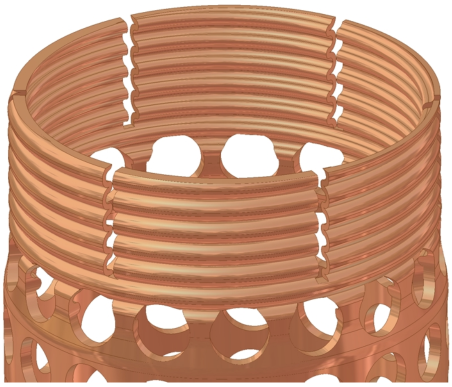

Figure 6, Option with a slotted conical thread in the uppermost section.

The assembly of the plug string should be made by providing the plug tube with shearing waist/shearing peg in Copper, which are being pulled off when the right torquehas been achieved, see Figure 7.

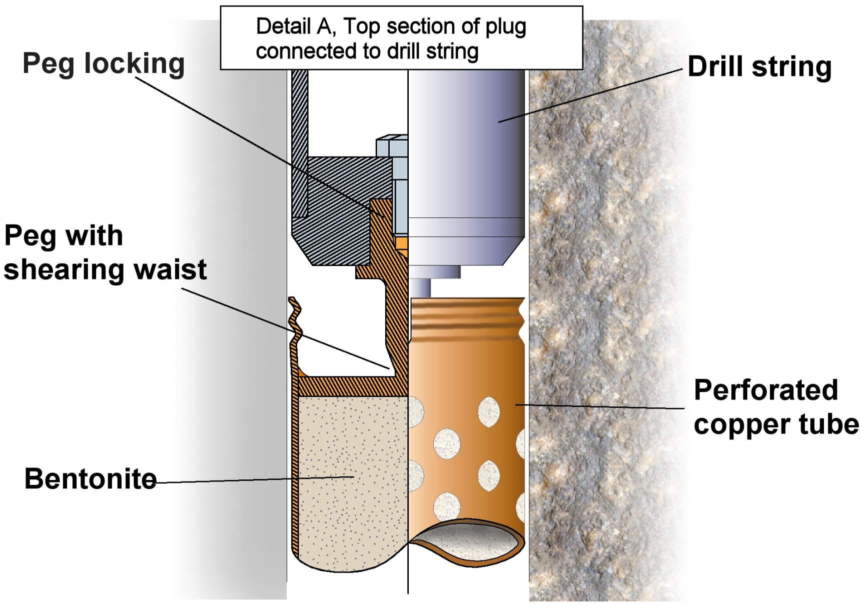

Figure 7, Assembly of an alternative joint design.

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4.2 Press Joint

The press joint is achieved when a copper case with a head or steps on the inside, is positioned over the plug tube and pressed together over the gap. The steps as well as the friction between the pressed parts, prevents the plug tubes from sliding apart. The copper case can most likely not be perforated since the steps become discontinuous and therefore risk hitting the hole in the plug tubes. This type of joint method requires pressing to be performed on location in correlation with descending on the plug string. A disadvantage of the method is that the disassembly gets complicated if a plug string has to be picked up.

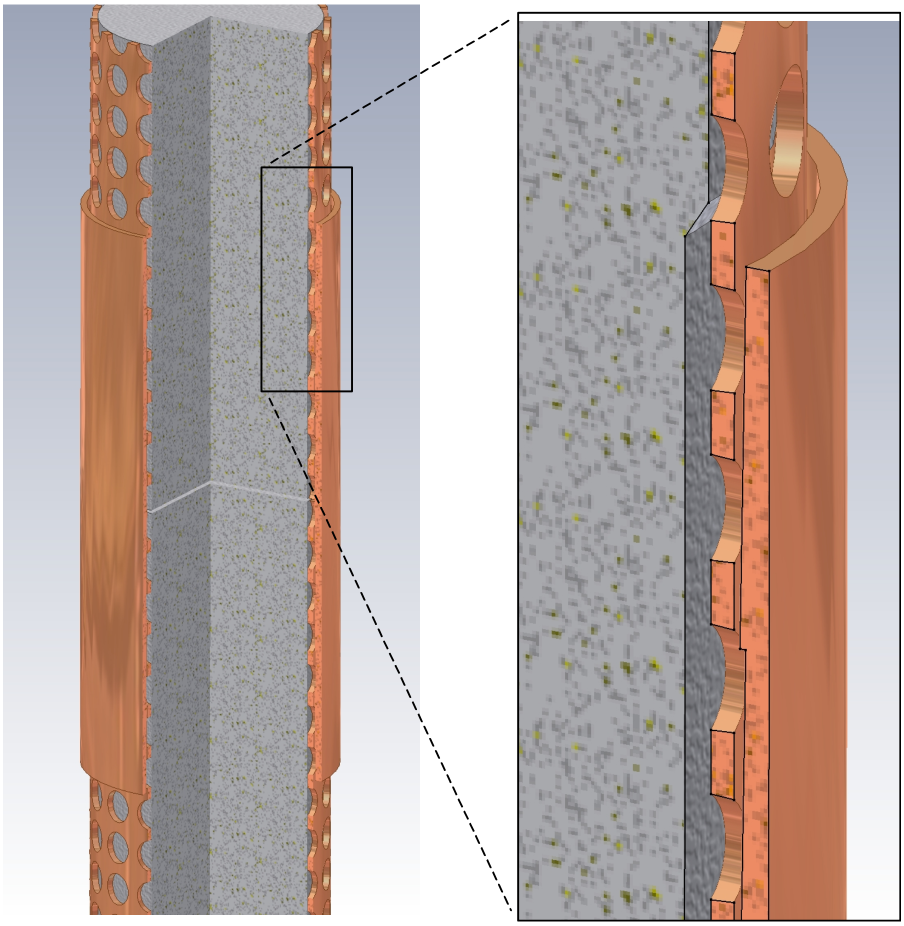


Figure 8, The tubes with the copper case before pressing.

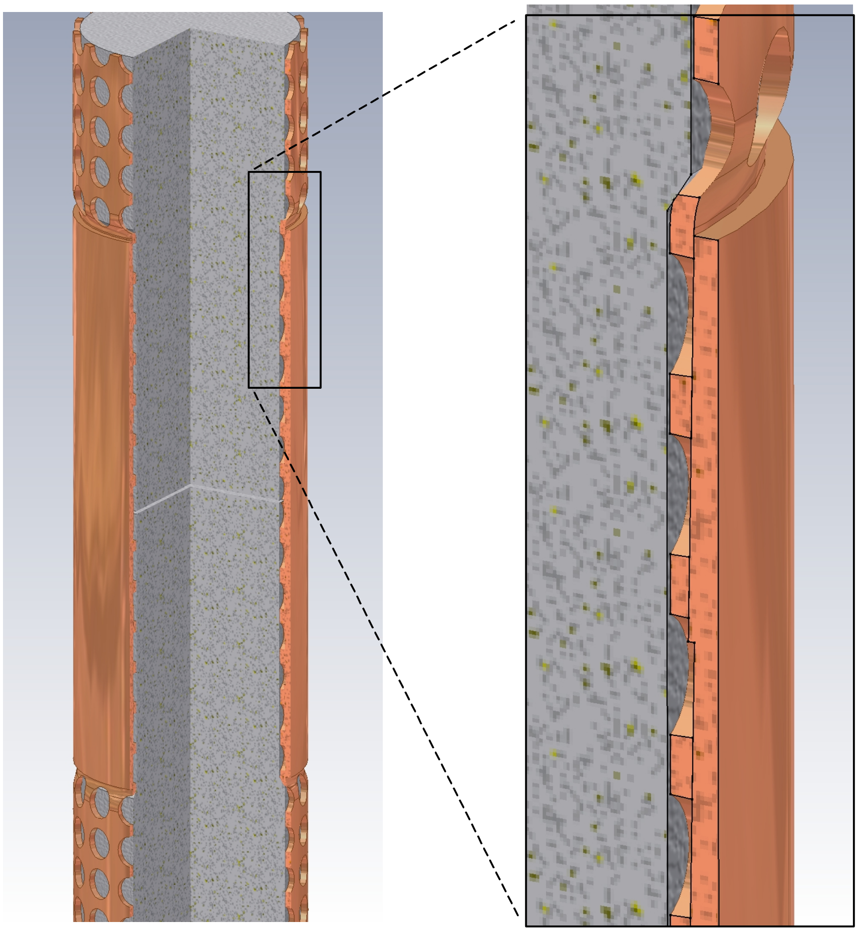


Figure 9, After pressing is performed

5 Installation in a Borehole

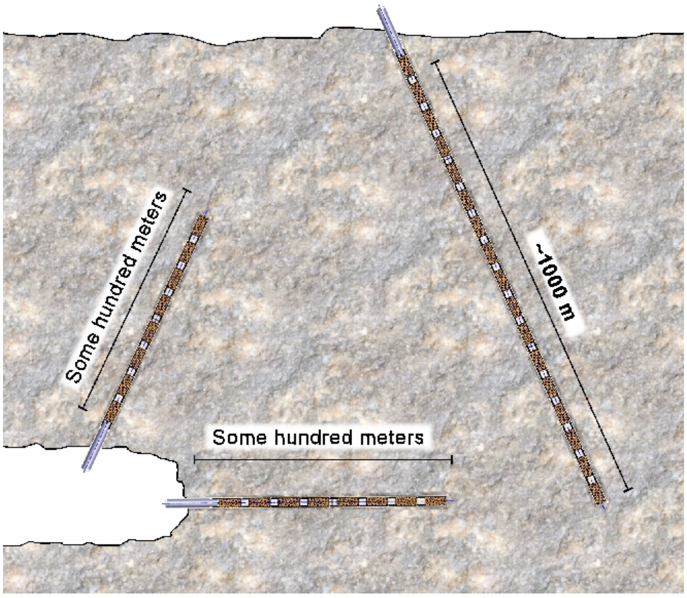


Figure 10, Different configurations of the boreholes

There are three types of installation configurations, see Figure 10. At the two lowest (latter) types, the boreholes start from the deep repository. The lengths on the boreholes vary, but the plug solution should work for all types without larger modifications. The plug string is grabbed in the top threads by a tool that can extend or pressed when the mid section is pulled up/down, see Figure 11. This is an existing and dependable type of tool.

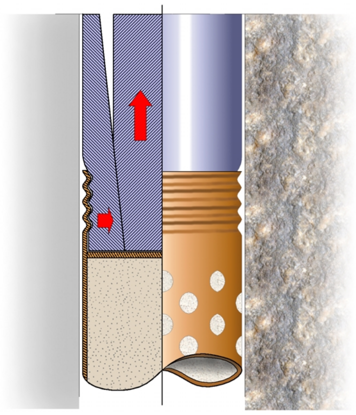


Figure 11, The function of the gripping tool when loosing the plug string.

5.1 Vertically

This type should be the most common, and the largest amount of these boreholes assumes to be filled by water at the plugging process. The plug tubes is jointed in lengths of 24 meter and descended to bottom where the grabbing tool releases and the drill string is pulled up and again jointed with new bore tubes. To avoid that the water gets a high impact on the bentonite, the descending should be done reasonably fast.

For instance, the bentonite should be able to start dissolving and be washed away by the water that passes through the plug tubes' shell during descending.

5.2 Horizontally

The application of the plugs in horizontal holes is identical to the vertical assembly. The only difference is that one have to take into consideration that the plugs are dragged toward the rock surface during the whole insertion. A certain rotation during the insertion would distribute the abrasion over the whole shell, which would be an advantage. The purpose of this is that the asymmetry in the geometry otherwise would give an uneven swell or piping (channels)

5.3 Under-up

The number of holes that are upwards oriented is assumed to be limited in number, which results in that the process of installation can be done in a more extensive way, which is necessary in this case. When every plug string is installed, the gap between the borehole and the drill string is filled with water by a sealing sleeve is pressed to the opening of the boreholes and the water is sprayed in. Next, the plug string is kept in place until it has swelled enough to be fixed in the borehole. Additional tests should answer required swelling for the tubes to be kept in place.

6 Manufacturing Aspects

Estimated appropriate material for the perforated tubes is copper according to standard ISO R1337 Cu DHP (formerly Swedish Standard SS 5015) containing 99,9% copper. The tubes are preferably manufactured by cold drawing after which the tubes are perforated by stamping. An alternative is to role and length-weld a sheet metal that are perforated. Nevertheless, the alternative is marked as less suitable as the sheet metal is less homogeneous in its material structure than a cold drawn tube. Furthermore, the alternative results in a material attenuation in the weld zone, where there is a risk cracking.

The copper tubes are manufactured according to dimension standard EN 1057, which is a norm for Europe. The chosen dimensions according to shown calculations are an outer diameter of 74 mm and a materials thickness of 2 mm. These dimensions differ from common standard but can be obtained from a manufacturer on request.

The copper tubes are delivered in the lengths of 3 meters, after which it's perforated through stamping. The stamping of the approximately 10 mm large holes is performed with a stamp and a holder-on inside the tube. Another method that can be used for making holes is water cutting. With water cutting the design of the hole can be chosen without restraint, but the method will be more expensive than stamping.

To perform de inner and outer thread on the copper tube's top and lowest part, hydro pressing can be used. In the method, the threads are formed with liquid pressure that results in a thread with high precision. Soft copper is suitable to hydro form. Hard copper could possibly crack. Where the limit is between hard and soft has to be verified in practical tests. The alternative is that the threads are formed by rolling or pressing. This method is somewhat craftsman like and thus more suitable for one-of-a kind production.

At a batch production of perforated copper tubes with round threads in a production line, an investment of approximately 2 MSEK for machines is required.

The price on finished goods for 3 meter long copper tube is estimated to 3000 SEK apiece.

After pressing and possible machining of the bentonite core, these are installed in the perforated copper tubes where the lower thread already is formed.

Due to the minimal gap between the tube and the bentonite core the thread in the upper section on the copper tube is formed after the bentonite is installed. After that, the plug is packed and sealed in plastic film. The plugs are delivered tentatively in a box containing 8 plugs that correspond to a plug string of 24 meter.

7 Handling above Surface at Installation

To obtain the most efficient and safe handling, the equipment should be automatic in the highest degree possible. One way is to use a box, containing plug tubes functioning as a magazine and next use one tube at a time for assembly on the drill string. This box should furthermore work as a protection during transportation and be designed to make handling by a forklift truck possible.

The box is raised to a vertical position with help from hydraulic cylinders. When completed, a winch wheel is assembled on the first plug tube, which is then lifted to the borehole with a winch wheel with rotational capability. Once on place above the tool, the gripping tool fixes the tube, keeps it until a more powerful winch wheel takes over the grip and lowers it slightly into the borehole. Once again, a holding devise grabs and keeps the tube, and the lifting devise can be unloaded. The procedure is repeated again and a new tube is lifted into position above the earlier lowered tube.

The two tubes are now jointed and can be lowered together a bit further. The procedure is repeated until a whole plug string has been assembled and the lowering of the string to the bottom of the hole can begin.

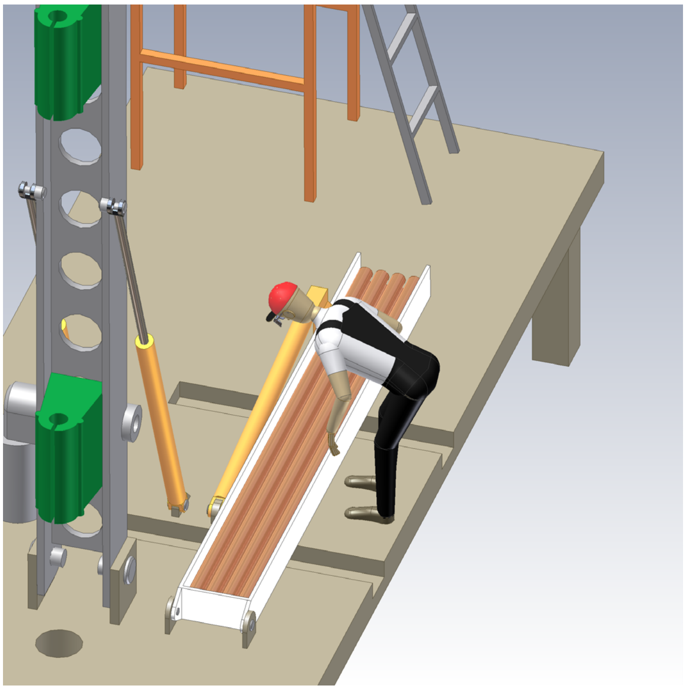


Figure 12, The plug tubes is delivered to the rig in a box containing 8 plug tubes, i.e. a plug string. This box is raised to a vertical position with hydraulics.

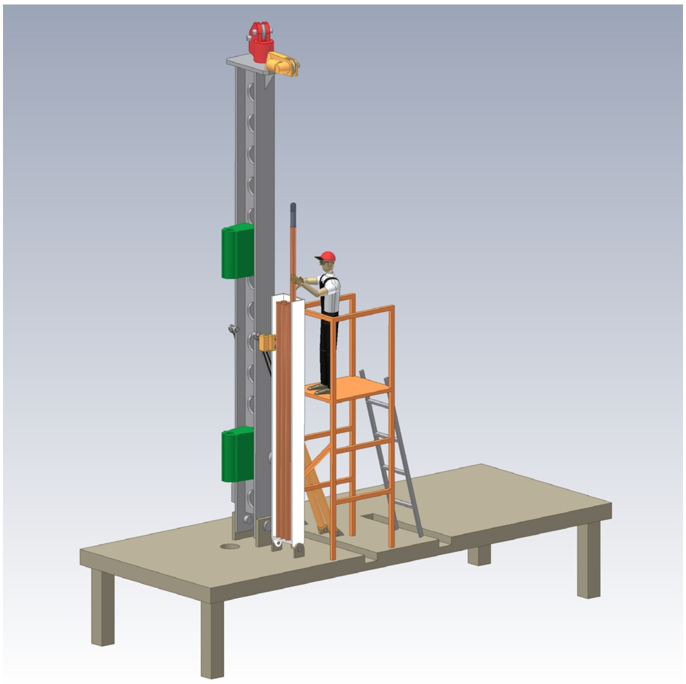


Figure 13, When the box is in a vertical position the winch wheel in the top (yellow) will be able to lift the plug tubes with the help of a lifting devise which has been assembled on the tube from the platform.

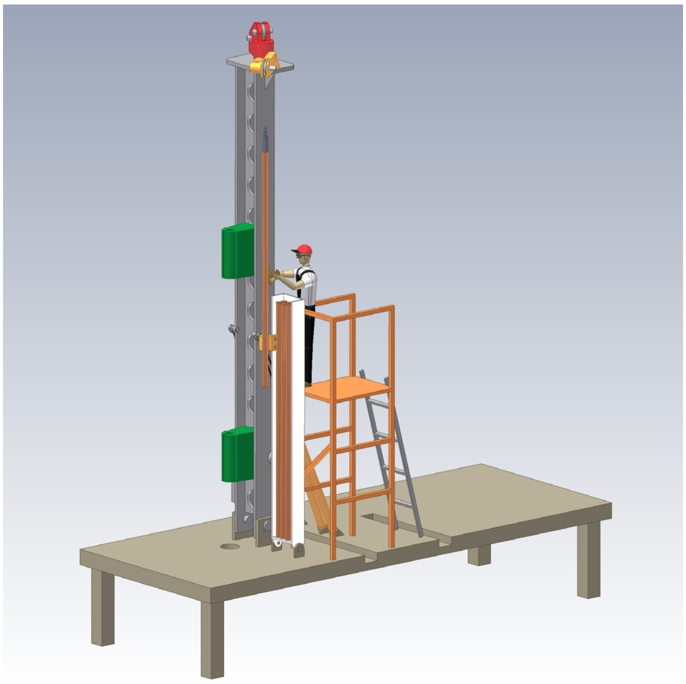


Figure 14, The plug tubes is lifted on position above the hole with a winch wheel and can be gripped by a gripping devise. (green)

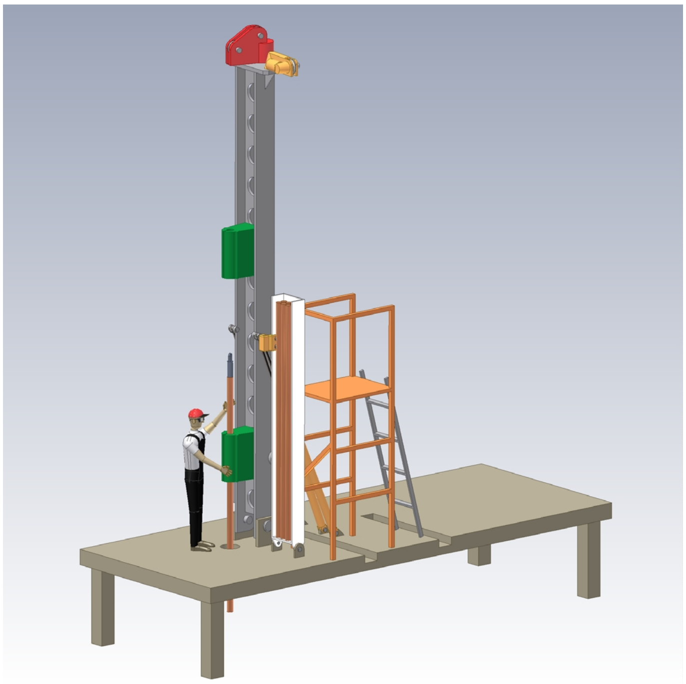


Figure 15, The plug tube is lowered down into the hole with the stronger winch wheel in the top of the rig (red)

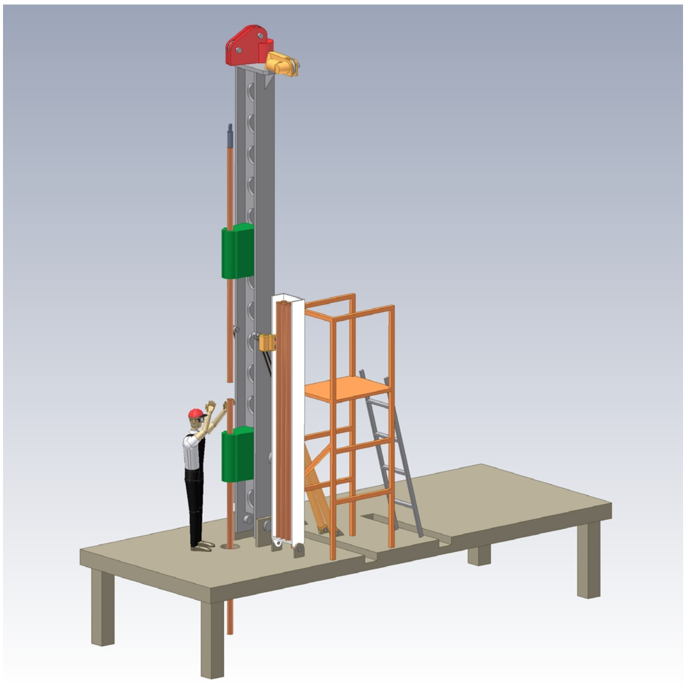


Figure 16, Jointing of the tubes, the upper tubes is threaded onto the lower.

8 Developing a Prototype

To verify the calculated dimensions and function of the plug and also the chosen thread profile for the joint system, some practical tests is recommended. For this purpose a suggested is to manufacture 2 plugs. Tests of a prototype should answer following:

- Do the perforated tubes manage the tensile stress that can occur at installation?
- Do the chosen thread profile for the joint system also manages these tensile stresses?
- Can the threaded section of the copper tube also be perforated?
- How much time is needed to get the plug to swell enough to hold its own weight (see under-up installation)?

As copper tubes does not have an outer diameter of 74 mm as a standard dimension, the tests should be performed with the closest standard dimension, which is 70,0 mm with a materials thickness of 2 mm RSK-nr.1752117 alternatively 2,5 mm.

The joints and the perforation of the copper tubes are made on a handicraftsman like way through rolling/pressing of the round threads as well as drilling of the holes.

Suitably a tensile test is first performed on the two jointed tubes to current standard load corresponding to a plug string's dead weight.

Then, the tubes should be loaded with an overload, as a suggestion 2,0 x the dead weight of the plug string. The joint of the tube can thereby be perforated with holes, after which the tension tests are repeated. Finally, to find out which practical strength the construction has, the tubes can be loaded until a fracture occurs.

In the next phase, the manufacturing aspects should be illustrated at line production and the choice of material for manufacturing, tools for hydro forming, blanking tool for the perforation work should be manufactured next. Furthermore a test series of tubes should be developed.

Complemented with highly pressurized bentonite, these plugs can be handled as one or more plug strings. Under field-like conditions, the different installation configurations provide valuable experience.

9 Recommended Concept

As a basic concept the plugs is suggested to be designed with an outer diameter of 74 mm, a materials thickness of 2 mm and a length of 3 meter. Due to reasons of strength, the perforation should be drilled in pattern 2 or 3 according to appendix 1.

Next, eight plug tubes joints to 24-meter long plug strings that are lowered down into the borehole.

The joints are designed with round profiled threads that have been pressed forward in the material of the tubes. The lowest plug tube in a plug string is supplied with a bottom plug that moves past the head and unevenness on the surface of the boreholes and also fills out the female-thread in the earlier assembled plug string.

When lowered, the plug string's top thread is gripped from the inside by a tool and the tool can then contract when released.

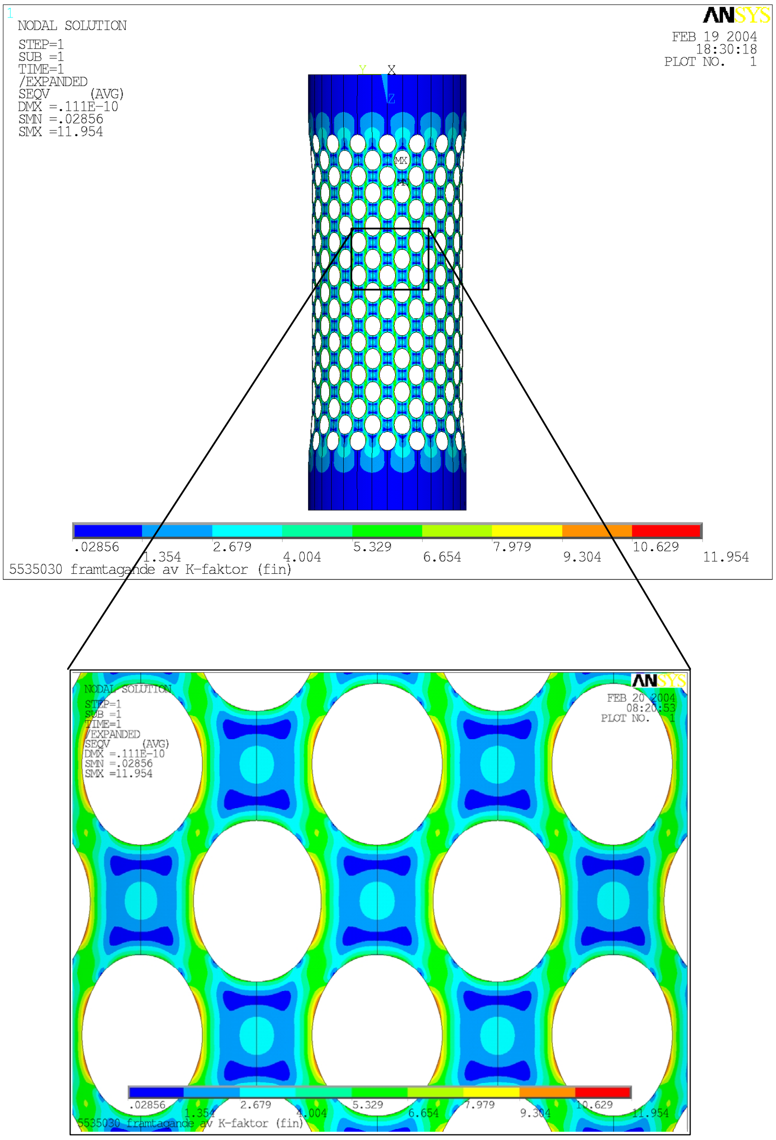
10 Appendix

10.1 Appendix 1, K-factors for different types of hole pattern in the plug tube.

The figures below illustrates the distribution of stress for three different types of hole patterns with 50% grade of perforation and circular holes with the diameter ~8.5 mm.

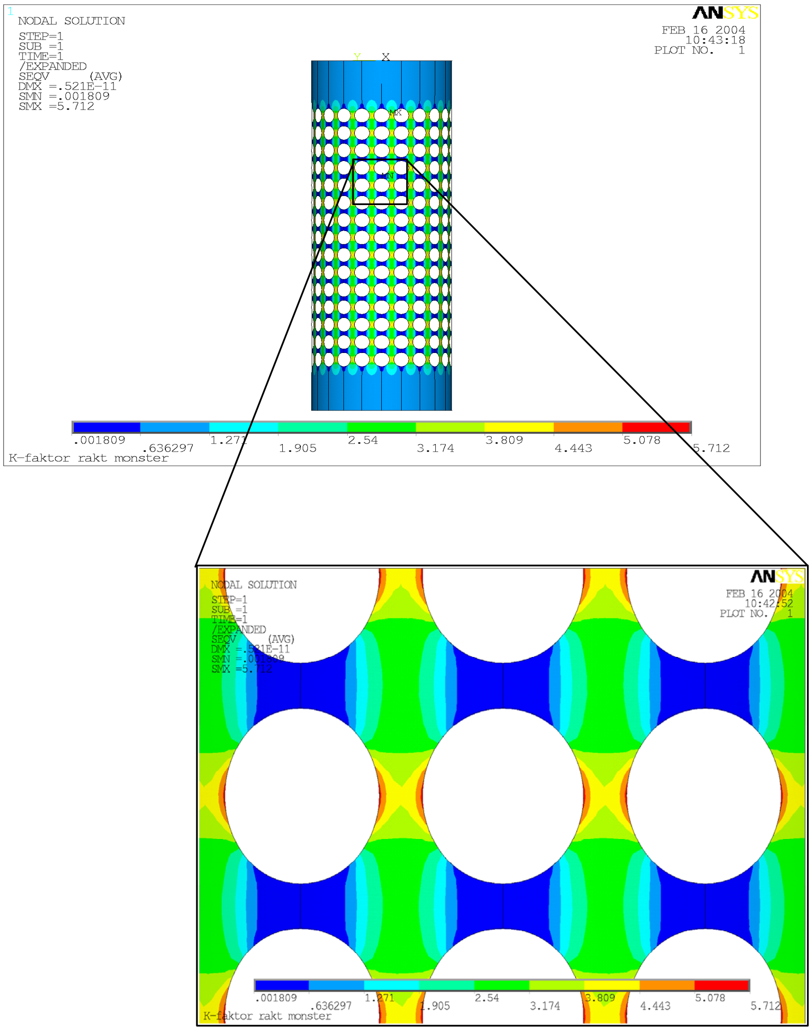
Hole Pattern 1

Factor of Stress Concentration, K = 12.0



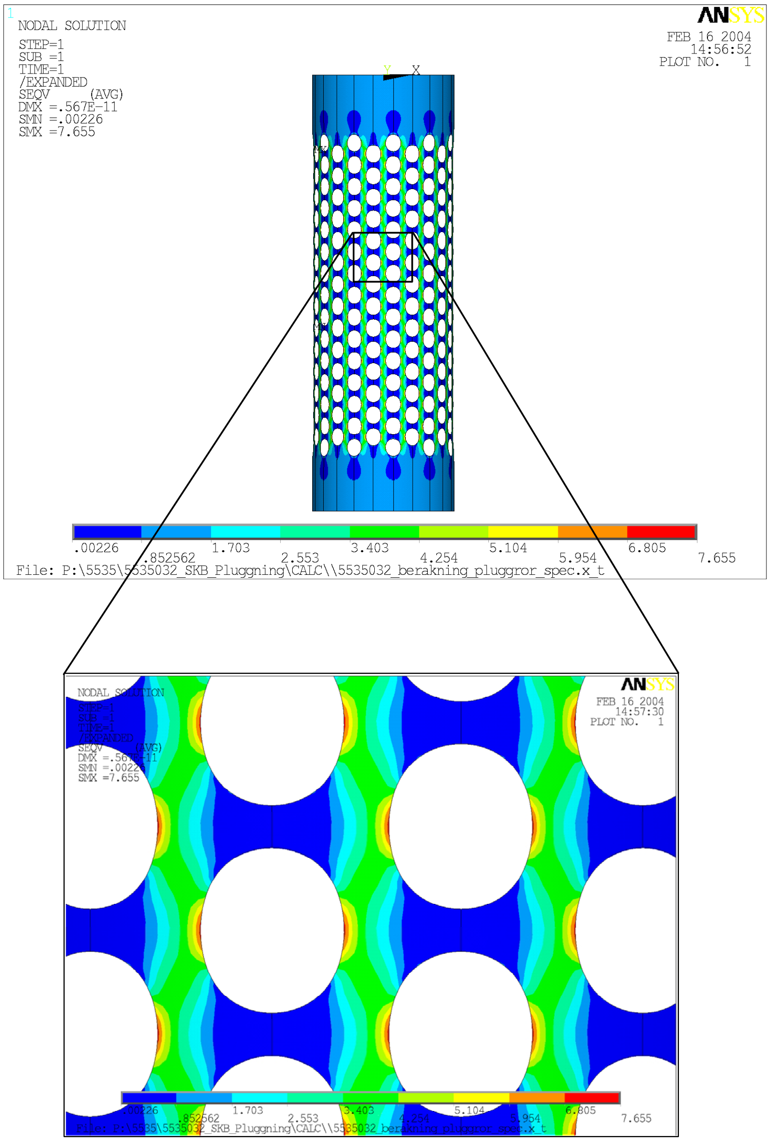
Hole Pattern 2

Factor of Stress Concentration, K = 5.7


NODAL SOLUTION
STEP=1
SUB =1
TIME=1
/EXPANDED
SEQV (AVG)
DMX =.521E-11
SMN =.001809
SMX =5.712
ANSYS
FEB 16 2004
10:43:18
PLOT NO. 1
.001809
.636297
1.271
1.905
2.54
3.174
3.809
4.443
5.078
5.712
K-faktor rakt monster
FEB 16 2004
10:42:52
PLOT NO. 1

Hole Pattern 3

Factor of Stress Concentration, K = 7.7



Appendix 3

GEODEVELOPMENT AB
IDEON RESEARCH PARK, LUND

PILOT STUDY OF BOREHOLE PLUG MATURATION

Objectives

A systematic series of laboratory tests of the maturation (saturation and homogenization) of borehole plugs of the type shown in Figure 1 will be performed in summer this year. The experiments reported here represent two pilot studies of bentonite clay cores that were free to expand in distilled water and 3.5 % $CaCl_2$ solution as a preparation of the firstmentioned study.

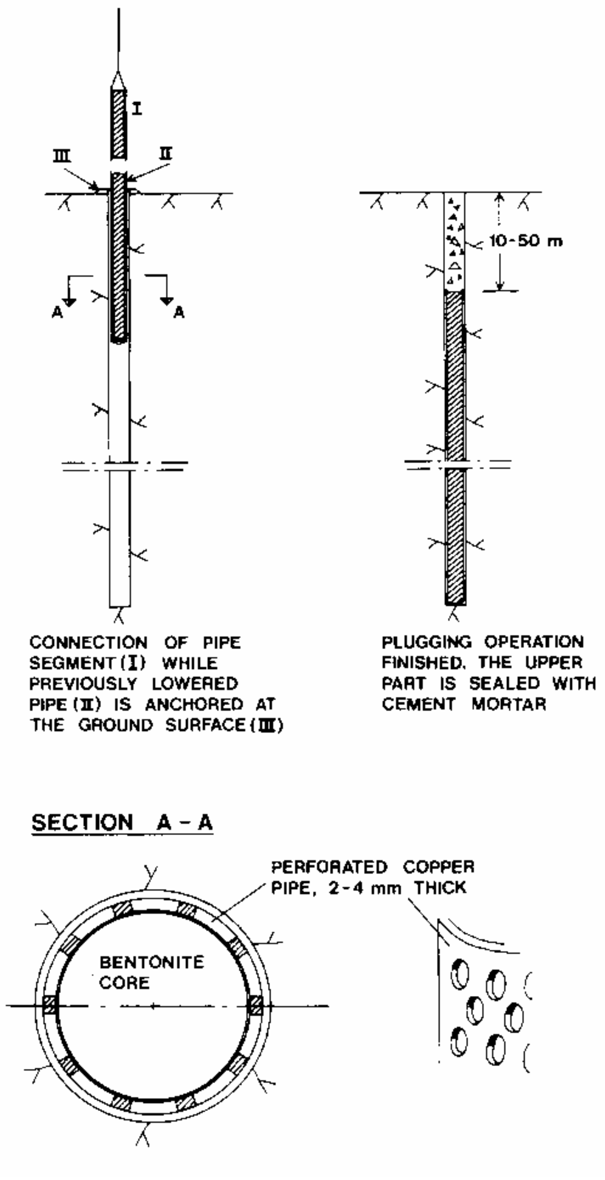


Figure 1. *Principle of borehole plugging using compacted smectite clay in perforated tubes.*

A reference case has been defined for performing the studies. It specifies a representative borehole geometry and plug data as follows:

- Hole diameter 100 mm.
- Hole length 1000 m
- Perforation ratio of tubes 50 %,
- Outer diameter of perforated tube of copper 95 mm.
- Inner diameter of perforated tube 88 mm.
- MX-80 type clay
- Outer diameter of clay core 87 mm.
- Dry density of clay core 1800 kg/m3.
- Water content of clay core 10 %.
- Distilled water and $CaCl_2$

Pilot test I

Glass tubes with 10 mm diameter were equipped with well fitting 12 mm high cores of highly compacted Greek bentonite with a smectite content of at 80 % converted to Na form by soda treatment (Figure 2). The dry density was 1650 kg/m^3 and the water content 10.0 %, The tubes were filled with distilled water in one of the tubes and with 3.5 % $CaCl_2$ solution in the other. This caused uptake of fluid by the clay and rise of the upper end of the clay core and also formation of a soft gel emanating from the dense clay. The rise of the firstmentioned and of the upper level of the soft gel were measured as a function of time. Both rose quicker in the Ca solution than in distilled water (Figure 3). Samples were taken after 48 hours and the density determined, showing that the expanded clay had a higher density in the calcium chloride solution.

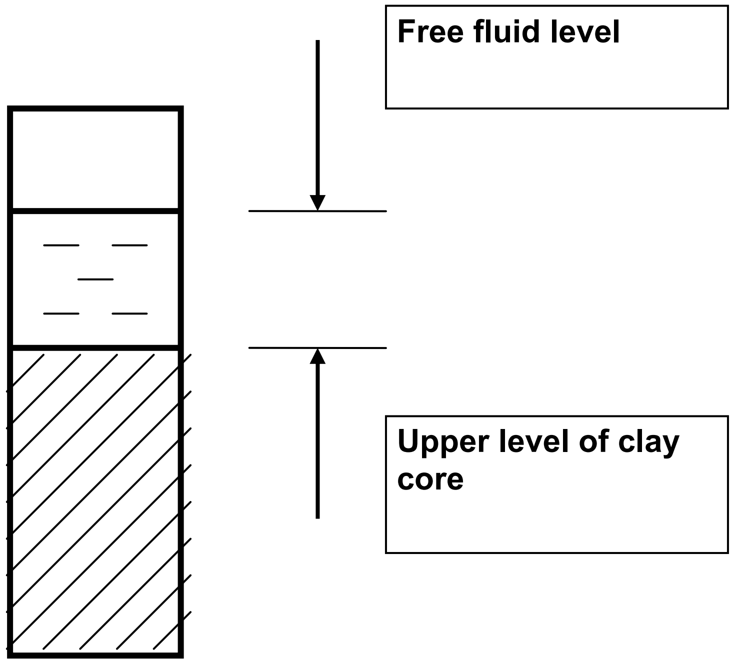


Figure 2. *Test arrangement with 12 mm dense clay covered with fluid.*

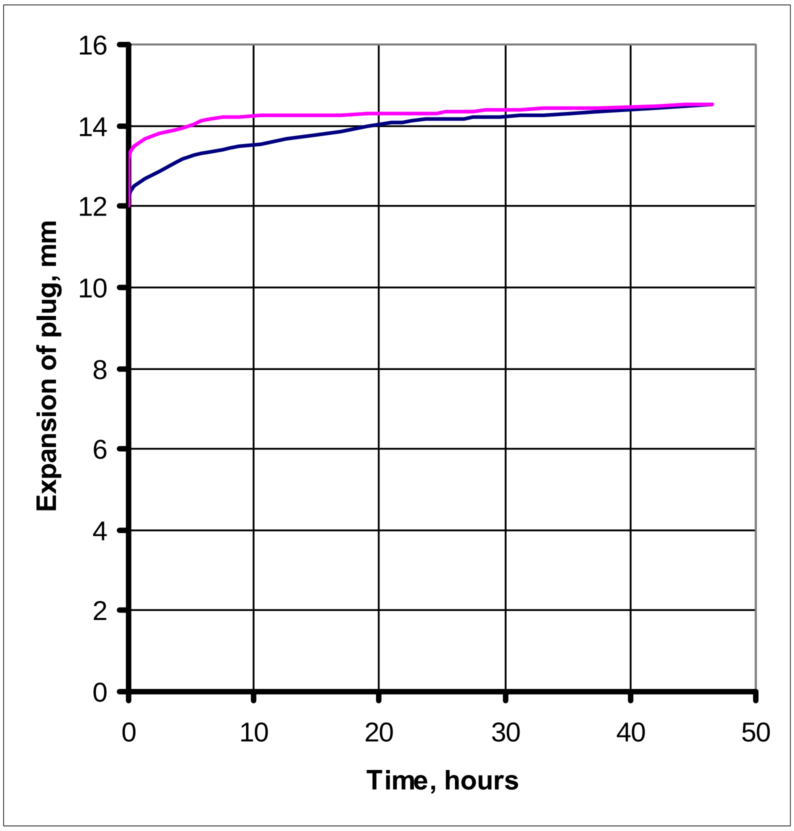


Figure 3. *Rise of the top of the dense clay as a function of time. Upper curve represents salt solution.*

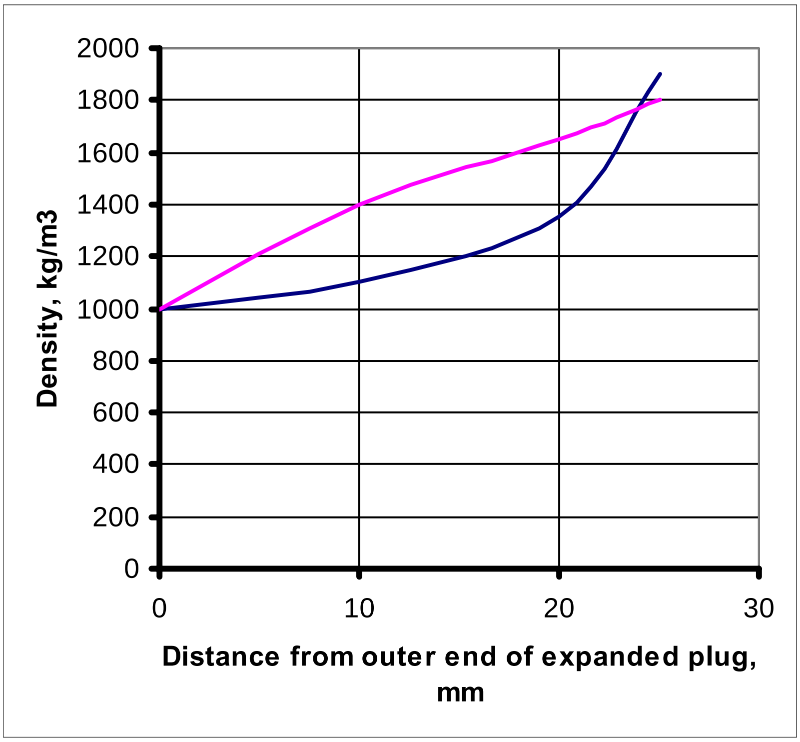


Figure 4. *Density distribution at different distances from the top of the expanded clay after 48 hours. Upper curve represents salt solution.*

One concludes from this study that the clay will expand quicker in salt Ca-dominated water than in electrolyte-poor water. Applying this to a borehole plug of dense clay it would be expected that clay will expand to come in contact with the rock within less than 8 hours in Ca-dominated salt water. In low-electrolyte water the expansion is slower and clay will not reach the rock until after in 15-20 hours. This study suggests that the boreholes should be filled with fresh-water before the plugs are put in for minimizing the risk of too rapid maturation of the clay.

Pilot test II

Test arrangement

Oedometers with 100 mm diameters and 60 mm height and with water inlets in the walls were used for determining the rate of maturation of clay plugs confined in copper tubes with a perforation ratio of 50 % and 10 mm hole diameter. A 100 μm filter of acid-proof stainless steel was fit to the oedometer walls for distribution of incoming water and for hindering clay particle migration and loss from the oedometers. The outer diameter of the copper tubes was 95 mm and the inner diameter 88 mm. The outer diameter of clay core was 87 mm. As in Test I the clay was highly compacted Greek bentonite converted to Na form by soda treatment. The initial dry density was 1650 kg/m^3 and the water content 10 %. Distilled water and $CaCl_2$ solution were filled in the gap between the tubes and the oedemeter walls in separate tests. The components are shown in Figure 5.

Figure 5. *Oedeometer cell with perforated copper tube, steel filter and compacted clay core. Teflon coating gave the dark colour of the cell.*

Test procedure

The experiments comprised ocular inspection by removal of the lid after 4, 8, 16, 24, 48 and 96 hours and taking millilitre-sized samples of expanded clay for determination of the density at some of these occasions. Estimation of the shear strength was made at certain instances by using a small penetrometer that was loaded in steps for determining the bearing capacity. The main results are summarized below.

Results

<u>*Plug in distilled water*</u>

4 Hours

The clay had expanded to reach the outer surface of the copper tube, i.e. by about 4 mm from the original position of the periphery of the clay core, but not entered the space between the tube and the filter attached to the cell wall. No sample was taken and no penetration test made.

8 Hours

The clay had expanded to form columns that reached out to the filter, i.e. about 6.5 mm from the original position of the periphery of the clay core (Figure 6). No samples were taken and no penetration test made.

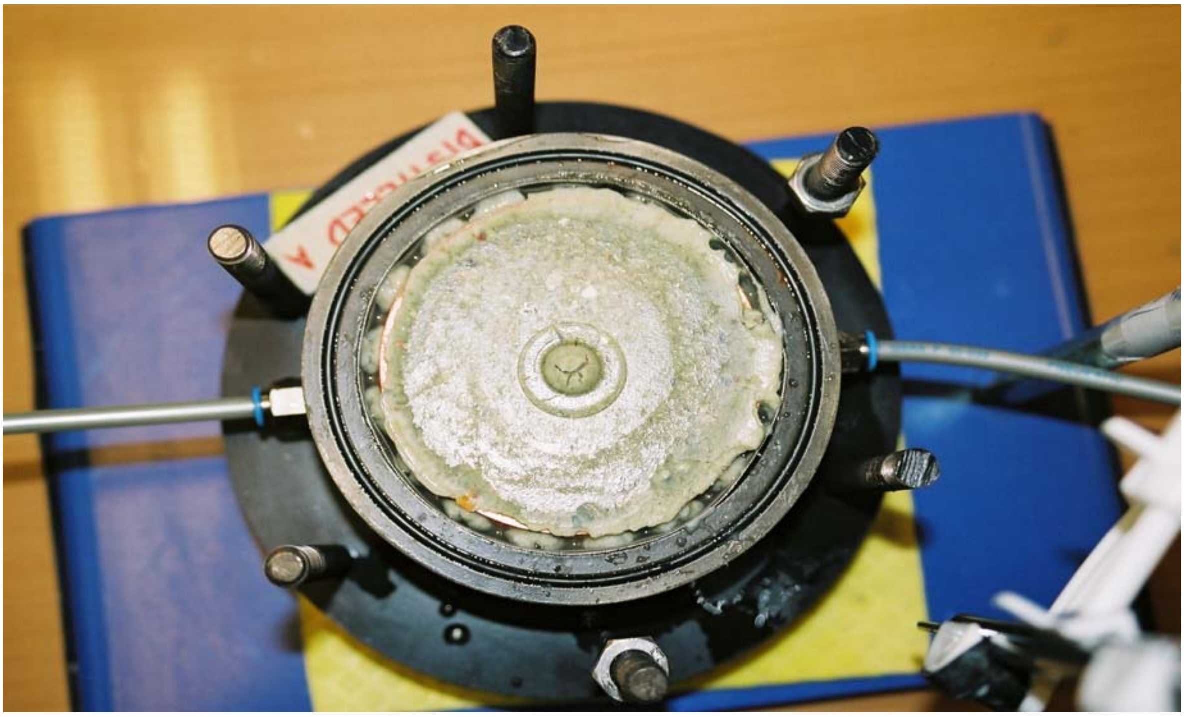


Figure 6. *Appearance of the clay plug after removal of the lid 8 hours after start.*

16 Hours

The clay columns had started to expand sideways and the space between them had become filled with very soft clay gel expelled from them. Penetration tests were made by putting a 2.5 mm diameter rod in contact with the upper surface of the densest and softest parts of the expanded clay. Breakthrough in the denser clay took place at a load of a few grams, which indicates a shear strength of less than 10 kPa.

24 Hours

The expanded clay had become largely homogeneous (Figure 7). The density of this clay was found to be 1090 kg/m^3 in its upper part and 1125 kg/m^3 in its lower, indicating that the expansion into the gap was associated with a tendency of the earliest clay to settle. This process must have become less important at later stages. Penetrometer testing gave failure at about 1-10 g, corresponding to an undrained shear strength of about 1.5 to 15 kPa.

Figure 7. *Appearance of the clay plug after removal of the lid 24 hours after start.*

48 Hours

The expanded clay had become homogeneous. The density of this clay was found to be 1150 kg/m^3 in its upper part and 1200 kg/m^3 in its lower, indicating that homogenization had taken place. Penetrometer testing gave failure at about 30 g, corresponding to an undrained shear strength of about 50 kPa.
96 Hours

Sampling of the expanded clay in the gap and at different distances from the copper tube in the clay core gave the data in Table 1. Penetrometer tests gave failure at about 300 g load, indicating an undrained shear strength on the order of 500 kPa, i.e. about 25 % of that of fully water-saturated clay of this type.

Table 1. *Densities determined for different parts of the clay plug 96 hours after start.*

Part of the core	**Water content, %**	**Density at water-saturation, kg/m^3**
Expanded clay in the gap	141	1450
Clay from tube to 5 mm (inside tube)	48	-
Clay 5-10 mm from tube	35	-
Clay 10-15 mm from tube	31	-

Plug in $CaCl_2$ solution

4 Hours

The clay had expanded to reach the filter at the oedometer wall but was not altogether homogeneous. Penetrometer testing showed that the shear strength was insignificant.

8 Hours

The expanded clay gave a very homogeneous impression. Penetrometer testing showed that failure took place at about 10 g load indicating an undrained shear strength of about 15 kPa.

24 Hours

The expanded clay was apparently completely homogeneous. Penetrometer testing gave failure at a load corresponding to an undrained shear strength of about 150 kPa.

Conclusions from Pilot Test II

The main conclusions from this test series are:

- The rate of water uptake of the dense clay core and the corresponding expansion of clay through the perforation of the copper tube are much quicker in salt water dominated by calcium than in fresh water

- If the boreholes contain fresh water significant resistant to emplacing clay plugs will not appear until after 18-24 hours, while this condition may be reached after about 8 hours in Ca-dominated salt water. Still, the shear strength of the clay formed around the copper tube in salt water may not cause severe problems until after 16-24 hours.

General conclusions from the pilot tests

Both test series show that the expansion of dense smectite clay is initially much quicker in salt Ca-dominated water than in electrolyte-poor water. Applying this to a borehole plug of dense clay in 100 mm diameter boreholes it would be expected that clay will expand to come in contact with the rock in 4-8 hours in Ca-dominated salt water, while in low-electrolyte water the expansion is slower meaning that the clay will not reach the rock until after 24 hours. This suggests that the boreholes should be filled with fresh-water before the plugs are put on site for minimizing the risk of too rapid maturation of the clay implying unacceptable resistance to emplacement of the plugs.

The density and shear strength of a clay plug of the investigated type will be considerable in both fresh- and salt water after 2 to 3 days, after which the plugs can not be retrieved. The maturation of the plugs after this time will continue and ultimately yield a completely homogeneous clay medium embedding the perforated tube. The corresponding density at saturation is expected to be at least 2000 kg/m^3.

Appendix

A preliminary model for estimating the maturation of the considered type of plug in low-electrolyte-water has been worked out. It is based on the assumption that the expansion process is one of diffusion involving both water migration into the dense clay core in the perforated copper tube and migration of clay particles from the core into the space between the tube and the rock. Uptake of electrolyte-poor water in perfectly confined very dense clay is known to be characterized by the diffusion coefficient D=3E-10 m^2/s and considering that this process is associated by clay expansion a diffusion coefficient of D=3E-11 m^2/s is assumed for the coupled process.

The resulting maturation is illustrated by the Table 2, from which it is seen that the predicted and recorded evolution of the expanded clay in fresh-water agree well.

Table 2. *Evolution of density of expanded clay in fresh-water.*

Time after exposure of the clay plug ro water, hours	Distance from tube towards the rock, mm	Predicted density of expanded clay, kg/m^3	Actual density, kg/m^3
0	0	0	0
4	1.5	1025	<1050
8	2	1050	1050
16	2.5	1075	1125
24	3	1100	1070

April 9, 2004

Geodevelopment AB
Roland Pusch

Appendix 4

APPENDIX 4

PILOT TESTING OF BOREHOLE PLUGS OF PREWETTED MX-80

Introduction

Air-dry compacted smectite-rich clay exposed to water is quickly wetted on its surface and gives off a soft gel that grows in conjunction with continued penetration of water with the suction of not yet moistened clay as driving force. This process was particularly obvious in borehole plugging tests described in the Final Report and was assumed to cause resistance to placement of plugs in deep boreholes and loss of clay from the plug by erosion in the placement phase. It was therefore decided to take steps to minimize these effects for which a number of possibilities are specified in the Final Report. One option is assumed to be prewetting of the clay plugs since this would cause less quick release of clay particles and slower formation of gels. This hypothesis, which turned out to be valid, was tested as described in this Appendix.

Technique for prewetting

Prewetting of the clay confined in perforated tubes must be made in a simple, rational and cheap way, the proposed technique being to place the 3 m long plug segments or possibly complete 32 m long plug segments in a slightly wider steel tube and fill the gap with quartz silt/sand that is kept water saturated by injecting water in a few perforated pipes placed in the gap. The silt/sand prevents the clay to migrate out through the perforation. The required time for saturating the outer centimeter of the clay is about one week after which the plug is pressed out from the outer tube and remaining silt/sand scraped off whereafter the plug is ready for placement in the borehole. This principle was followed in the pilot test series described here.

Pilot tests

Two perforated copper tubes with 1 cm wide holes and about 50 % perforation ratio, 2 mm thickness and an outer diameter of 90 mm, were equipped with well fitting highly compacted Na bentonite clay and placed in an oedometer ring with 102 mm diameter. The dry density of the clay was 1900 kg/m^3 and the initial water content 10 %. The 4 mm radial space between the perforated tube and the oedometer ring was filled with finely ground quartz that was kept water saturated by connecting radially oriented nozzles of the oedometer with a vessel filled with tap water.

After one week the tubes were pushed out from the oedometer ring and quartz sand sticking to the clay that had moved to the outer periphery of the tubes was scraped off. One of the tubes was then coated twice with a silica solution containing sodium and potassium ("vattenglas") with a density of 1250 kg/m^3. Preceding tests by CBI had indicated that such coatings shrink by loosing water to clay with about 50 % degree of water saturation and hence fail in isolating the plug from water. The high initial degree of saturation of the presently investigated plug was assumed to eliminate this difficulty.

The plugs were placed in tap water and lifted up after 4, 8 and 24 hours for examination and sampling.

Results

Figure 1 shows the two plugs before submerging them in water.

Figure 1. *The plugs before submerging them in water. Plug A to the left has still some very minor amounts of quartz powder in the holes after scraping it off the tube. The basal surfaces of Plug A and all surfaces of Plug B were coated with silica solution.*

Figure 2. *The plugs after 4 hours in water except for the uppermost parts. The clay columns in Plug A protrude by about 2 mm. Very soft clay gel was formed outside Plug B.*

Figure 3. *The plugs after 8 hours in water except for the uppermost parts. The clay columns in Plug A protrude by about 4 mm. Very soft clay gel was formed outside Plug B.*

Figure 4. *The plugs after 24 hours in water except for the uppermost parts. Most of the clay columns in Plug A protrude by about 6 mm and by 8-10 mm in Plug B. A very soft clay gel reaching out to about 10 mm from the tube tended to flow down along the tube in Plug B.*

Sampling

Samples were taken from the clay moved out through the perforation after 8 and 24 hours for estimating the friction resistance at placement of plugs of the two types. The density, shear strength data and force required to move a 24 m long plug segment with by pushing or pulling are given in Table 1. The force after 8 hours in case A is calculated by assuming that the contact area rock/clay is 50 % of the theoretical area because of incomplete clay filling.

Plug	Density of penetrated clay after 8 h, kg/m^3	Density of penetrated clay after 24 h, kg/m^3	Shear strength of penetrated clay after 8 h, kPa (estim)	Shear strength of penetrated clay after 24 h, kPa (estim)	Force required to move 32 m plug after 8 h, N	Force required to move 32 m plug after 24 h, N
A	1190	1070	5	2	20000	16000
B	1100	1090	3	2	11000	16000

The weight of a 24 m segment of A- and B-type is about 250 kg hence giving a gravitational force of 2500 N meaning that the required force for moving the segment after 8 and 24 hours is on the order of 1-2 tons. In the first 4-8 hours a segment of A-type will sink in water under its own weight.

Discussion and conclusion

The following major conclusions were drawn from the pilot study:

- The expansion of prewetted clay through the perforation of Plug A was much slower than of plugs with air-dry Na-smectite with the same dry density, thereby validating the hypothesis that formed the basis of the study.

- Coating with Na/K silicate solution is not suitable since the gel formation is quicker than for untreated plugs. The reason for the quicker gel formation is that the electrolyte content of the coating has the same effect as when clay plugs are submerged in salt water. The density of the clay gels formed around coated plugs is lower than of uncoated plugs and they would be more easily eroded in the placement phase.

- Clay moving out through the perforation of plugs of prewetted dense Na smectite clay will, as an average, not reach the borehole wall in 4 hours and would undergo very little erosion. After 8 hours such contact is established but the density is so low that the force required to push down a 24 m long plug segment is not more than 1-2 tons, which is much lower that what can be provided by ordinary drill rigs. The outermost part of the clay protruding through the perforation is expected to be easily eroded after 8 hours.

- Prewetting of dense Na smectite clay appears to be a useful technique for retarding expansion of clay through the perforation of tubes and it also means that the clay fully occupies the tube so that no erosive water flow takes place inside the plug tubes.

- Although the pilot tests of prewetted clay plugs were successful additional tests on a larger scale are required for final assessment of the method.

Lund 2000-10-20

Roland Pusch
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Appendix 5

CLEANING OF BOREHOLES

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ABSTRACT

For the long-term safety it is a risk that the boreholes can eventually function as short-circuits between the repository and ground surface. Therefore sealing of investigation boreholes is an important issue for the long-term safety of high-level nuclear waste repositories.

In order to seal a borehole properly, the conditions of the borehole have to meet certain predetermined requirements. One of the requirements is that no instruments or materials endangering the plugging operation or the long-term function of the sealing materials, are allowed to be left in the borehole. Sometimes drilling equipment will be left in the hole or it cannot be recovered from the hole in spite of attempts. Further various measurements may be carried out in the holes after the drilling has been completed and measuring devices may get stuck in holes. Consequently cleaning of the borehole is carried out as a preoperational activity before sealing can be implemented.

There are two common reasons identified for the drill strings to get stuck in holes. First the drill string may get stuck due to acute drilling problems. The second case is where rods are left as casing in a hole either based on the structure of the upper part of the hole or in order to support the hole.

Numerous various surveys are carried out in holes after the drilling has been completed. Experience has shown that it is quite likely that some measuring devices may get stuck in the holes during these surveys.

To remove the drilling or measuring equipment lost in a borehole, special techniques and professional skill must be applied. Removing measuring equipment from a hole is often demanding and time consuming work. A vital part of the cleaning operation is planning the work in advance. In order to make the plan and to select the suitable methods it is important to know the condition of the stuck material. It is also important to know the exact depth where the equipment or drill strings are stuck and to have an estimate of the reasons why they have got stuck. It is very important to know the correct dimensions of the device or drill string before commencing the cleaning work.

Keywords: borehole, plugging, cleaning, drill string, measuring device, stuck material, drilling, drill rig.

CLEANING OF BOREHOLES

ABSTRACT

CONTENTS

CLEANING OF BOREHOLES

1. INTRODUCTION

Sealing of investigation boreholes is an important issue for the long-term safety of high-level nuclear waste repositories. There is a risk involved that the boreholes can eventually function as short-circuits between the repository and ground surface. For the long-term safety it is therefore required that the boreholes will be sealed in such a way that the hydraulic conductivity of the borehole is lower than the conductivity in the bedrock over a time period, which is needed for the safe disposal.

In order to seal a borehole properly, the conditions of the borehole have to meet certain predetermined requirements. One of the requirements is that no instruments or materials endangering the plugging operation or the long-term function of the sealing materials are allowed to be left in the borehole. Cleaning of the borehole is carried out as a preoperational activity before sealing can be implemented.

Cleaning operation can include various techniques depending on instruments or materials left in the borehole during the history of the borehole. Apart from drilling equipment or instruments used for borehole investigations, the borehole wall, often covered with a coating, need cleaning or brushing.

The cleaning techniques must be applicable in various borehole sizes (diam. 56-76 mm) and depths down to about 1000 metres, that is, in all boreholes that have been drilled in the site.

2. REMOVING OF DRILLING EQUIPMENT FROM HOLES

2.1 Why is equipment left in holes

During drilling holes there are situations, when drilling equipment is left on purpose or is forced to be left in the hole. In acute problematic situations the drill string gets stuck in the hole and its removing will be carried out in connection to the ongoing drilling work. However, in many cases rods are left in a hole according to a plan either due to the structure of the upper part of the hole or for supporting the hole. Such equipment is e.g. casing rods used in DTH drilling.

There are many ways to remove rods from holes. Rods can be removed by lifting them with a drill rig. If the pulling force of the rig is insufficient a separate jack lift can be used. Rods can be taken apart by using break up rods with left handed couplings and lifted one by one from the hole. Further rods may be removed by overcoring the rods with bigger diameter bit and rods.

2.2 Various types of fishing tools

Manufacturers of drilling equipment supply industrially manufactured fishing tools for removing drilling equipment from boreholes. These tools are routinely used for various rescue work.

Various fishing tools are available for catching drill strings that have remained in holes. Some of these tools are screwed to the end of the rods to be rescued. After this the rods are lifted from the hole. The fishing tools may be attached either inside the lost rods, fishing tap, or outside, recovery bell tap. Further there are fishing tools for wire line equipment, which are inflated inside the lost rods. When the fishing tool has been attached to the lost rods it can be used for lifting the lost equipment. Figure 1 shows fishing pins and sockets and Figure 2 a wire line fishing tool.

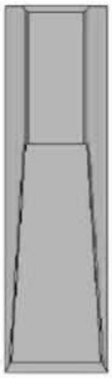
Fishing tools 1(1)

TERRA-TEAM OY

Recovery taps

Product no:	Description:	Working range Ø
3080	Recovery tap right handed R42	Ø15 – Ø40
3105	Recovery tap right handed R42	Ø36 – Ø54
3070	Recovery tap right handed R33	Ø20 – Ø34
3115	Recovery tap right handed 72/57	Ø56 – Ø72
3090	Recovery tap left handed R42	Ø15 – Ø40
3106	Recovery tap left handed R42	Ø36 – Ø54
3134	Recovery tap left handed 68/47-R32	Ø41 – Ø59
3120	Recovery tap left handed 72/57-R32	Ø56 – Ø72
3135	Recovery tap left handed R38	Ø63 – Ø89
3136	Recovery tap left handed 121/95	Ø59– Ø120

Recovery bell tap



Product no:	Description:	Working range Ø
3190	Recovery bell tap right handed g 35	Ø25 – Ø40
3170	Recovery bell tap right handed R42	Ø30 – Ø35
3200	Recovery bell tap left handed R32	Ø30 – Ø48
3210	Recovery bell tap left handed R38	Ø36 – Ø58

Fishing tools for aluminium drill rods

Product no:	Description:	Working range Ø
3040	Recovery tap for Alu drill rod coupling M20, right handed	Ø14 – Ø28
3060	Recovery rod L=3m M20 pin/pin	
3050	Coupling R42 box / M20 box	

Figure 1. Fishing tap and recovery bell tap

Special Craelius wire line rods fishing tool **Miscellaneous**

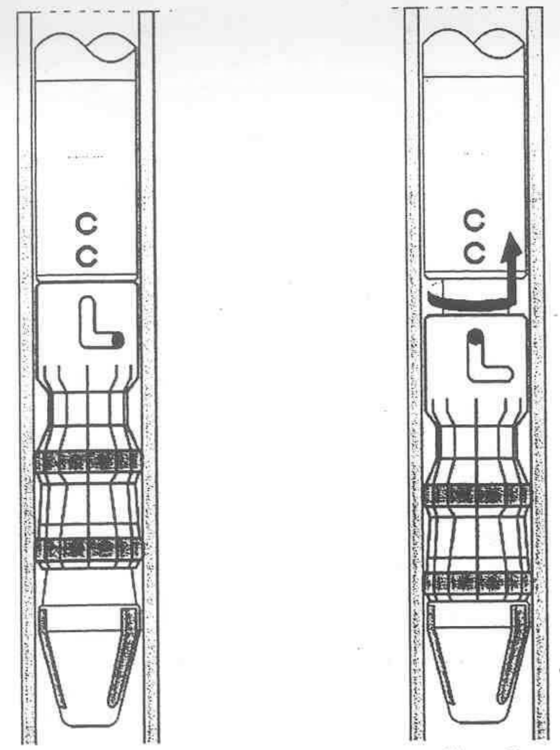


Figure 1 Figure 2

Technical data

Type	Suitable for rod	Suitable for casing	Thread to rod	Max.force applicable ton	lb	Product number
A	AK, AQ rod		EW	4.2	9 260	3742 0025-13
AGM	AGM rod		EW	3.5	7 720	3742 0025-14
B	BK, BQ rod		AW	6.0	13 230	3742 0025-15
BGM	BGM rod		AW	4.2	9 260	3742 0025-16
N	NK, NQ rod		BW	10.0	22 000	3742 0025-17
NGM	NGM rod	BW casing	BW	10.0	22 000	3742 0025-18
NR	NR, CHD76 rod		BW	15.0	33 000	3742 0025-27
H	HK, HQ rod		NW	14.0	30 900	3742 0025-19
NW		NW casing	NW	14.0	30 900	3742 0025-26
P	GEOBOR P rod		HW	14.0	30 900	3742 0025-20
HW		HW casing	HW	14.0	30 900	3742 0025-25
PW		PW casing	HW	25.0	55 125	3742 0025-24
SW		SW casing	HW	30.0	66 000	3742 0052-53

Figure 2. Fishing tool for wire line rods.

In wire line drilling the core barrel is lifted from the hole using a wire line. The wire line may also be used for making orientation marks to the core samples. A worn-out wire may break in the hole and it has to be caught. Equipment manufacturers provide fishing tools for wire lines. One example is shown in Figure 3.

BOART LONGYEAR — Wireline Coring System — NQ

Wireline Cable Recovery Tool

Features:
- Cable fisher housing is connected to the inner tube, after removal of the core lifter case, and is lowered with the inner tube assembly and overshot.
- Reduces instances of having to pull the rods, and complications which occur when broken wireline cable has to be cut while pulling the rods.
- Reduces amount of scrap wireline cable through recovery.

Application:
- Recovering (fishing) wireline cable when breakage has occurred in the rod string.

Wireline Recovery Tool			kg	lbs
1	61733	NQ Cable Fisher	1.2	2.6

NOTE: Refer to ITHT Product Manual for additional operating information.

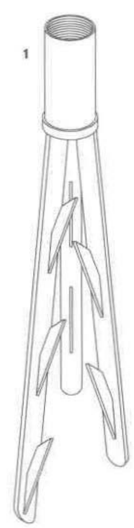


Figure 3. Wire line cable fishing tool.

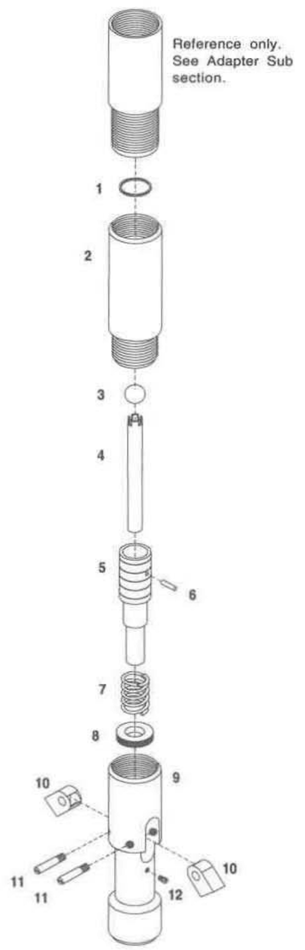
If the amount of rods to be lifted from the hole is very large and it is too heavy to be lifted either with a rig or a jack lift, the drill string may be cut to several pieces using a casing cutter. Casing cutter is lowered with the rescue drill string inside the stucked rods. The cutting blades are opened with water pressure and the cutter is rotated by the rescue drill string. The eccentric blades cut the drill string into small pieces i.e. lighter loads, which may then be lifted more easily. A casing cutter is presented in Figure 4.

BOART LONGYEAR — Conventional Coring System — LTK60

Casing Cutter

Features:
- Used for cutting BW casing at any point in a drill hole when the entire string can not be retrieved.
- BQ rod box connection.

Operations:
Upon lowering the assembly, the cutting lugs are retracted inside the body by the spring. With low rotation (25 rpm) initially, the cutting lugs are forced out using water pressure, 1 380 kpa (200 psi). A drop in pressure indicates that the cutting operation is complete.



Assembly			kg	lbs
1-12	52775	BW Casing Cutter Assembly	5.4	12.0

Parts			Qty
1	61265	Retaining Ring	1
2	52776	Plunger Case	1
3	21837	Stainless Steel Ball, 15/16"	1
4	14520	Water Tube	1
5	14519	Plunger	1
6	15260	Shear Pin	1
7	14522	Spring	1
8	14521	Spring Rest	1
9	14517	Body	1
10	14523	Casing Cutter Lug	2
11	14587	Casing Cutter Pin	2
12	44663	Set Screw	1

NOTE: Refer to the ITHT Product Manual for additional operating information.

Figure 4. Casing cutter.

2.3 Drilling through metal objects

In some cases part of the equipment stuck in the hole may be removed by drilling through it. The equipment may consist of either drilling equipment, sampling tools or measuring equipment. The equipment stuck is most often made of metal; either aluminium or steel and eventually small amount of organic material. The equipment drilled through will be destroyed.

Drilling through loose material, e.g. wire line cable, causes extra problems. Loose and moving material may break the drilling bit, which in turn may jam the rescue equipment in the hole. Therefore the material to be drilled through should be fastened in the hole. In drilling through there is a risk that the equipment stuck in the hole acts like a wedge and drilling will deviate from the original hole. Equipment manufacturers supply special bits designed for drilling through metal objects. Bits used for drilling through must have an adequate diameter. Otherwise there is a risk that wedge-shaped pieces may be formed and they may jam the rescue equipment in the hole.

Drilling through metal object produces metal chips that should be removed from the hole. This can be done by effective flushing or by e.g. a magnet.

2.4 Jack-lifting

If equipment stuck in hole cannot be recovered with a rig, the next step is normally jack-lifting. In jack-lifting the rods are pulled with a special hole jack as long as the rods are released or the rods break at some point. It is important that the platform under the jack is steady and strong. Further the jack must be accurately aligned with the rods, because even a smallest angle causes an asymmetrical load on the rods. The tensile strength of the rods is essentially reduced under asymmetrical load.

Safety aspects must carefully be taken into account during jacking. The rods are under considerable tension and in the case of breakage the rods may be released fiercely. No one should be in the line of the hole during jacking. The hydraulic hose from the power pack to the jack must be so long that it is safe to operate the jack from a safe distance.

The behaviour of the rods during jacking must be observed continuously from the safety point of view. If the stuck drill string is long and the jamming point is at the depth, the rods may stretch considerably before breaking. In such a case it is a good practice to stop lifting and to release the tension in order to find out if the rods have actually moved or do they return to the start position. Sometimes it is good to keep the rods under tension and follow the hydraulic pressure of the jack.

2.5 Disjoining the drill string

If the drill string is broken as a consequence of jacking the next step may be disjoining the rods. Disjoining is carried out using recovery rods with left handed threads and with left handed thread tap i.e. with a carrot fishing tool. Aluminium drill rod breaks normally in the centre part of the rod. In such a case a tap at the end of a thin shaft will be used. The tap will be attached through the broken rod to the steel coupling at the lower end of the rod. The work needed in disjoining the drill string varies greatly. Sometimes each rod has to be disjoined separately sometimes hundreds of meters may be recovered at one lift.

Disjoining is carried on according to the actual situation. It is often useful to attempt to recover the core barrel. If the core barrel coupling can be disjoined also the inner tube will be recovered. If the outer tube of the core barrel remains in the hole, it should be considered case by case, if the disjoining will be continued or if it would be useful to drill through the objects in the hole. The risk of getting the left-handed fishing tap stuck in the hole should be avoided, as it will be difficult to recover.

2.6 Removing rods by overcoring

Removing of drill rods by overcoring is a normal procedure in drilling work. In its simplest mode overcoring is usual core drilling without removing the sample from core barrel. When rods are removed by overcoring one step bigger bit and rod size is utilized. However, the difference of the outer diameter of the rods to be removed and the inner diameter of the overcoring bit must be very small in order to avoid making a thin rock slice while overcoring. The rock slice may easily wedge the overcoring rods, which in turn would get stuck in the hole. So e.g. removing of 76 mm rods may be carried out using 86/77 equipment in other words the outer diameter of the bit is 86 mm and the inner diameter 77 mm. The outer diameter of the rods to be removed is normally about 72 mm. If overcoring is carried out in an inclined hole the rods to be removed lay on the lower side of the hole and the overcoring bit moves along the upper edge of the rods. In such a case a 5 mm rock slice may be produced on the lower side of the hole. This slice may wedge the overcoring rods so that they can possibly get stuck in the hole. This can be avoided by using a specially made overcoring bit with an inner diameter of 73 mm.

If the rods to be removed do not extend to the ground surface and there is empty space in the upper part of the hole, the overcoring drilling must be guided in the upper part of the hole. This is done by using a guide tap with the calliper of the hole in the reamer tool.

Securing the flushing water circulation during reaming and overcoring is important. It may be necessary to plug up the hole below the borehole section to be reamed or over cored for securing the flush water circulation. The plug will also prevent the sludge (drill cuttings) produced by the overcoring from flowing deeper in the hole.

2.7 One selected case history

During the drilling of hole OL-KR24 fractured zones at depths of 94 and 115 metres were intersected. The rock material dropping from these zones disturbed both rock stress measurements and directional drilling operations. The hole diameter was 77 mm. In order to eliminate the dropping pieces of rock the hole was reamed to the depth of 120 m. A 84/77 casing pipe was installed in the hole till this depth. After completing the hole these pipes were to be lifted with the rig, but it was noticed that the casing was stuck in the hole. The reason for the sticking was thought to be sludge sedimented (accumulated) between the casing and the wall of the hole and collapsing of the hole against the casing. It was decided to leave the casing in the hole until all the geophysical and groundwater flow surveys had been carried out. It was decided that even the 114/99 and 98/89 casings extending to the depth of 20.13 m would be removed simultaneously with the 84/77 casing. The 114/99 casing was injected with cement to the bedrock.

When the 84/77 casing was attempted to lift, the pipes broke at the depth of 63 m. Taking the casing apart could not be done because the threads did not open. When the casing was taken apart with left handed 43 mm rescue rods they got stuck to the 84/77 casing. The string of the rescue rods had to be taken apart using right handed rods. At the end of taking the string apart a fishing carrot and six meters long string of left handed rods remained in the hole. The fishing carrot was attached to the end of the 84/77 casing at the depth of 63 m.

It was decided that 84/77 pipes would be over cored with 98/89 mm size. The 84/77 casing would act as a guide for the overcoring equipment. Before loosening the 84/77 casing the 98/89 casing set for supporting the drilling rods had to be removed. The drill cuttings accumulated in the space between 114/99 and 98/89 casings were cleaned by pumping water with high pressure through 98/89 casing. The 98/89 casing sat tight and it was tried to lift the casing with a jack lift. When jacking the casing broke at the base of the male thread at the depth of 0.5 m. This casing sat tightly with the others and the outermost casing was injected in the bedrock. Therefore it was decided that they would be loosened by overcoring with 128/118 equipment. The special bit with an inner diameter of 116 mm was used..

The hole was plugged at the depth of about 120 m before the commencement of overcoring in order to avoid flushing water flowing deeper in the hole and to boost the flushing effect in the upper part of the hole.

Overcoring with 128/118 mm equipment was finished at the depth of 20.32 m and both casings (114/99 and 98/89) were lifted from the hole.

The 114/99 casing was reinstalled in the hole. When this was done the hole was reamed to the depth of 63 m with 98/89 equipment. A centralizer ring was used in the reaming. The inner diameter of the reaming bit was 85.5 mm. After the reaming six metres of left handed 42 mm rescue rods were removed from the hole. The “carrot” fishing tool remained at the end of the 84/77 casing. Overcoring was continued at the depth of 63 m after the centralizer ring had been taken away. Flushing water circulation ceased at the depth of about 95.5 m. Drilling was continued till the depth of 119.87 m and the casings were lifted from the hole.

3. REMOVING OF MEASURING EQUIPMENT AND PACKERS FROM HOLES

3.1 Why is equipment left in holes

Numerous various surveys are carried out in holes after the drilling has been completed. Experience has shown that it is quite likely that various measuring devices may get stuck in the holes during these surveys. Many of the holes are drilled in order to investigate fracture zones, which increase the probability of the equipment getting stuck in the holes. From the cleaning point of view the measurements may be divided into short-term and long-term surveys. In the short-term surveys the equipment is lowered into the hole and lifted up immediately. In long-term surveys devices may be installed into the hole for long time periods . In addition tools etc. needed in the work may be dropped accidentally in the hole.

3.2 Devices stuck in hole

In short-term surveys a measuring probe is lowered into the hole by a cable or a wire line. If the gap between the probe and the wall is small the risk of the probe being stuck increases. Quite often the probe is as large as possible and the gap is very little. Often guidance rings are used to centralize the probe in the hole. The most common of probes of this type are sensors used in standard geophysical logging, difference flow measurement sensors, digital cameras, water sampling devices, HTU sensors and in-hole seismic geophones etc. Most often the jamming of the probe is caused by a piece of rock falling between the probe and the borehole wall. Cutting the cable or wire line attached to the probe should be avoided during the rescue operations. It is often advantageous if the cable is cut under control or it is used in pulling the equipment from the hole.

Typical long-term investigations are e.g. hydro geological studies. These investigations are used to get detailed information e.g. of hydraulic properties of fractures, their correlation to fracturing and groundwater composition. Further these are used for getting information for eventual flow and safety analysis. For making these investigations multipacker devises are installed in holes. These devices consist often of a number of packers, support rods of stainless steel and plastic tubes for inflating the packers and for test pumping. The packers are coated with rubber and their body is of stainless steel. The packers are connected by support rods of stainless steel. In long-term investigations the equipment may be stuck due to malfunction of equipment, loose rock pieces or due to sedimentation of slurry (drill cuttings ?).

3.3 Various types of tools

Removing of measuring equipment from hole is often demanding and time consuming work. Due to the diversity of equipment many types of tools are needed in the rescue work. In most of the cases these tools are not commercially available but they have to be designed and to be made specially for each rescue task. Some of the devices stuck in hole are valuable and it is tried to rescue them undamaged. Sometimes the devices are invaluable and it may be useful to break them before taking them from the hole. Some devices may contain parts that are harmful for the hole if broken. E.g. batteries must be removed unbroken to avoid disturbing water chemistry in the hole.

In accurate work the weight of the drill string may be reduced by plugging the bottom of the string and tightening the couplings. In this way the floating effect of the rods reduces the weight. In accurate lifts the lifting may be carried out using a weighing machine for resolving the accurate lifting force.

In removing equipment from holes drill rig and drill string are utilized. Tools used at the end of the drill string may be of standard type designed for removing drilling equipment or tools modified specially for this purpose. Further various fishing tools like “spruce”, “harpoon” etc. may be made before the rescue work and during it. Figures 5a and 5b show some tools used in realized rescue operations.

Figure 5a. Various fishing tools; “spiral”, “skirt”, inner cone.

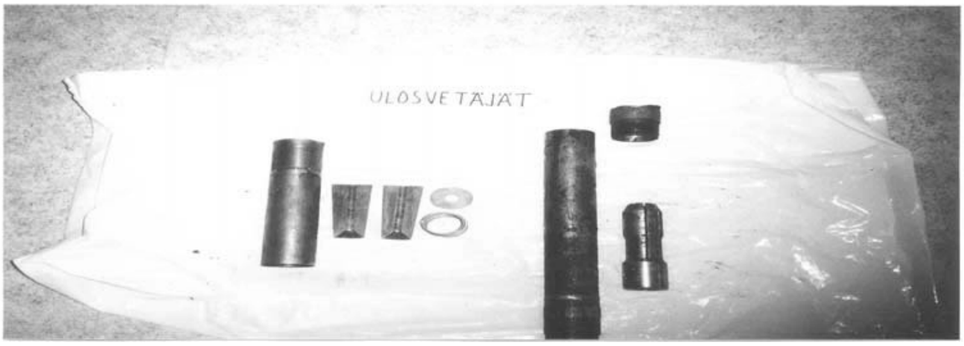


Figure 5b. Various fishing tools; “harpoon”, “Christmas tree”, pulling devices

3.4 Drilling through metal objects

Some of the equipment stuck in the hole may be rescued by drilling through it. In this method the equipment to be removed will be destroyed. Therefore this method is used in cases when the equipment to be removed is not valuable or harmful. Drilling through loose material involves, however, certain risks. If material made of steel can move while it is being drilled there is a risk that this will break the drill bit and the drilling equipment used for the rescue work may get stuck in the hole. Soft materials like plastic, rubber and wood are not suitable for drilling with a standard diamond bit. The reason for this is that the soft material is not grinded enough and it will not be flushed from the hole effectively. If this is the case the water slots in the bit may be jammed and the bit will not be flushed and it will burn and get stuck in the hole with the drill string. Loose material in the hole should be cemented so that it will not move while drilling. Even in doing so there is a risk that the material will act as a wedge and the drill bit will deviate from the original hole and a new branch will be made by accident. Sometimes soft material should be drilled with a coarse crushing bit, which reduces the risk of burning the bit in the hole.

Drilling in the equipment to be removed can be used also so that a smaller auxiliary hole is drilled in the equipment to be removed. Then a fishing tool may be attached to this auxiliary hole.

3.5 Opening of the hole

Drill rig and drill string are needed in removing the equipment from the hole. Often the lifting force of the rig is the limiting factor. Therefore a separate lift jack should be available for jobs demanding big lifting force.

Before starting the work the equipment to be used must be checked. Broken and undersized rods will be discarded. The drill rig will be serviced and cleaned before taking to the site and eventual malfunctions will be repaired. The fishing tools eventually needed, will be made before commencing the work. The situation in the hole will be analyzed: the description of the equipment to be rescued, the condition of the equipment, depth of point where the equipment is stuck and eventual reason for the equipment getting stuck. The 0-point or reference point for measuring the depth to the point where the equipment is stuck must be checked. A rescue plan will be prepared and it will be given to the client for comments and approval. If it will become necessary to deviate from the original plan an optional plan will be made. Also the optional plan will be given to the client for approval.

3.6 Two selected case histories

Case 1
Posiva’s Flow Log tool probe used for electric conductivity logging got stuck in hole HH-KR3 in Hästholmen, Loviisa in November 2000. This device had been used in detailed site investigations in several holes and areas. The measuring organisation tried to loosen the probe stuck in the hole with the aid of a hammering sond. While lifting the measuring probe also the hammering sond got stuck in the hole. In addition to these probes also a spectacle case including spectacles was dropped into the hole during the rescue operations.

It was estimated that the upper end of the measuring probe was at the depth of 277.35 m counted from upper end of the casing pipe. This depth includes the

estimated 35 cm strain of the cable. The uppermost part of the probe was a stone collector, which was centralized in the hole with a 54 mm centralizer ring. The stone collector has a female thread of a Alu 43 drill rod. The total length of the probe is about 2.70 m (Figure 6). The probe consists of following parts (length in parenthesis):
- stone collector (35 cm)
- probe tube (60 cm)
- cover tube (40 cm)
- upper sealing ring (16 cm)
- spiral (50 cm)
-lower sealing ring (about 30 cm)
- centralizer and cover (about 40 cm)

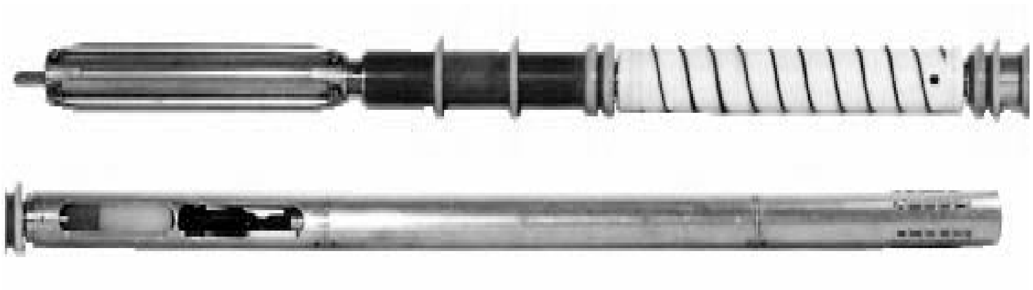


Figure 6. The sensor of the difference flow measuring device.

Further below the probe there were two extra weights with a total length of 2.2 m including the adapter piece. There was a 6 mm wire line connected to the device.

The hammering sond is made of 50 mm axel steel, which is split in the middle. The length of the probe is 117 cm. The wire line length to the upper end of the probe from the upper end of the casing tube is 233.45 m. At the upper end of the probe there is a pin with a length of 400 mm and diameter of about 10 mm. There are four chain rings attached to this pin. The total length of the chain rings is 80 mm. The chain rings were taped with ventilation tape. The wire line loop was attached to the uppermost chain ring.

The difference flow measuring probe got stuck when it was lowered into the hole. After getting stuck it was attempted to get loose with the hammering sond.

The measuring probe had been hammered for six or seven times with the hammering sond when the hammer probe got stuck in the hole while up lifting. The hammering sond was probably stuck to the wall of the hole and not to the sensor cable. Further it was possible that measuring cable and the wire line were wrapped around each other 1 or 2 turns. The measuring probe had been under the tension of 200 kg's before and after the hammering and it had moved up almost not at all. The breaking of the safety breaking point between the probe and the cable during the lifting trial was however avoided.

The rescue work was carried out with a drill rig and a drill string. The aim was to get the equipment out of the hole undamaged. Therefore great forces were avoided when fastening to the probe. In order to lighten the drill string the lowermost rod was plugged watertight and all rod couplings were tightened with hemp. In this way it was tried to prevent the probe from getting loose and dropping to the bottom of the hole, which would have made the rescue work even more difficult.

At first stage the spectacles with their case were tried to be removed from the hole by using a magnet. The spectacles or the case did not stick to the magnet. Therefore a fishing tool of 110 mm plastic water pipe was constructed. The aim was to get the spectacles case lifted up inside the plastic pipe. This did not succeed and the spectacles were left in the hole to be lifted up with other material.

Then the hammering sond was loosened by pushing it downwards with an eccentrical rod fixed to a drill string of Alu 43 rods (Figure 7). The diameter of the rod was 20 mm. The position of the rod was changed by turning the drill string manually with pipe wrench until the rod met the upper end of the hammering sond. As a consequence of pushing the hammering sond it was loosened and lifted from the hole. Apparently a piece of rock had remained between the probe and borehole wall and had wedged the probe in the hole.

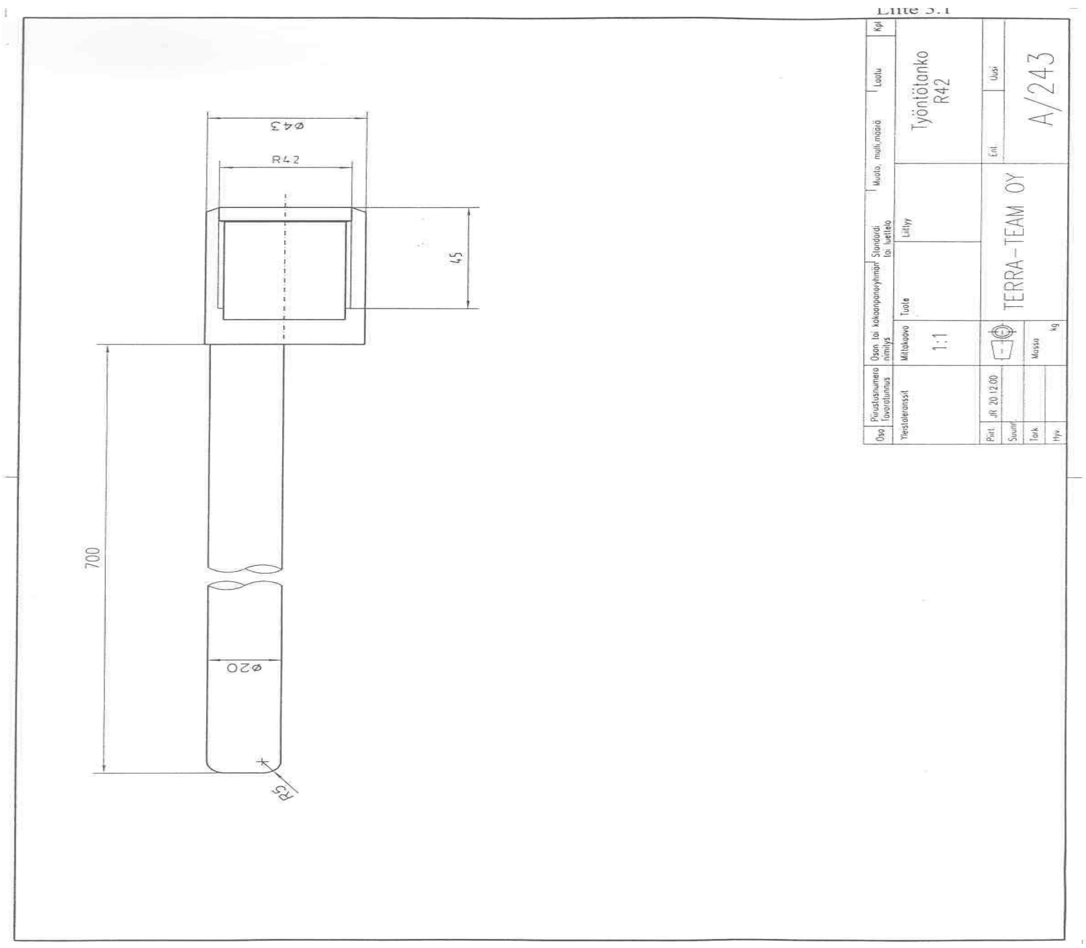


Figure 7. Eccentric rod.

The next step was to get attached to the measuring probe with a wire shuttle fixed to the lower end of the drill string (Figure 8). This shuttle had a male thread corresponding to the female thread of the stone collector in the measuring probe. As the cable line was still at its place it was threaded through the shuttle so that the cable came outside the drill string diagonally upwards through a hole in the side of the shuttle. The drill string was lowered about two meters above the probe using the drill rig. A rod lock was attached to the drill string and it was carefully lowered down along the rods using a hoist. After several trials it was managed to screw the drill string together with the probe. Then the probe was lifted about one meter with the hoist. The force needed was 650 to 700 kp. After this the equipment was lifted with the hoist 10 metres and the force needed was 400 to 800 kp. By the end of this phase the equipment advanced with steady force and the lifting was continued using the drill rig. The equipment was rescued undamaged judging visually. A piece of the spectacles case and plastic tube with a diameter of 8 mm joined to a connecting socket came up with the equipment. The plastic tube and socket had apparently been left in the hole during earlier investigations.

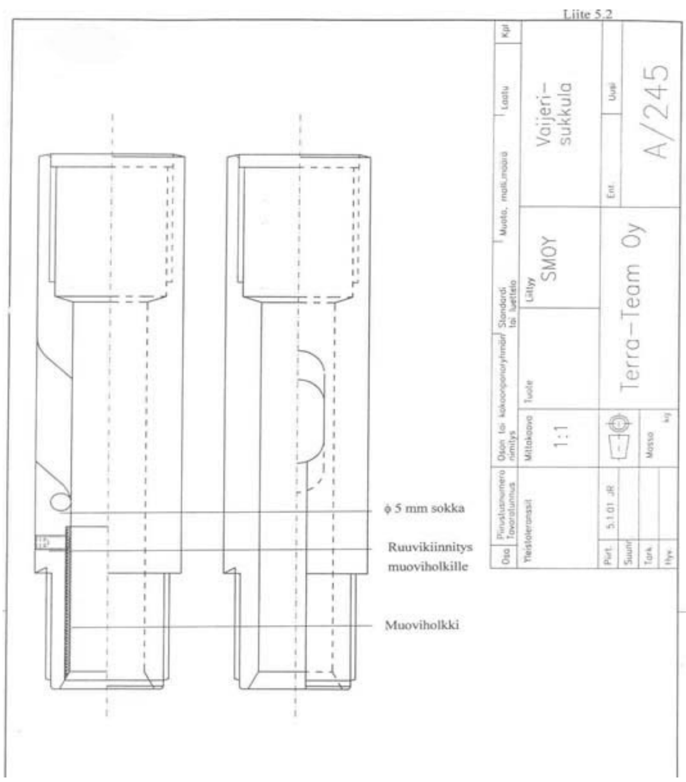


Figure 8. Wire line shuttle.

Case2

A multipacker equipment was installed in hole HH-KR3 in the autumn of 1999. The aim was to investigate eventual hydraulic connections between holes during the test pumping of hole HH-KR3. The multipacker equipment consisted of 15 inflatable packers, the length of each was 1 m. Further the equipment consisted of supporting rods of stainless steel between the packers and of nylon tubes leading to survey intervals and packers. The packers are covered with rubber and their bodies are of stainless steel. The diameter of the supporting rods is 8 mm and the length of each rod five metres. Further there were the 8/6 mm nylon tubes connected to the seven measuring intervals and to the packers. The client lifted the equipment with a tripod and wire line in November. In this way the equipment was lifted about 372.6 metres before it got stuck. The equipment remaining stuck in the hole consisted of five packers and all the material connected to them. A sketch of the location of the packers before the lifting work and at the beginning of the cleaning work is presented in Figure 9.

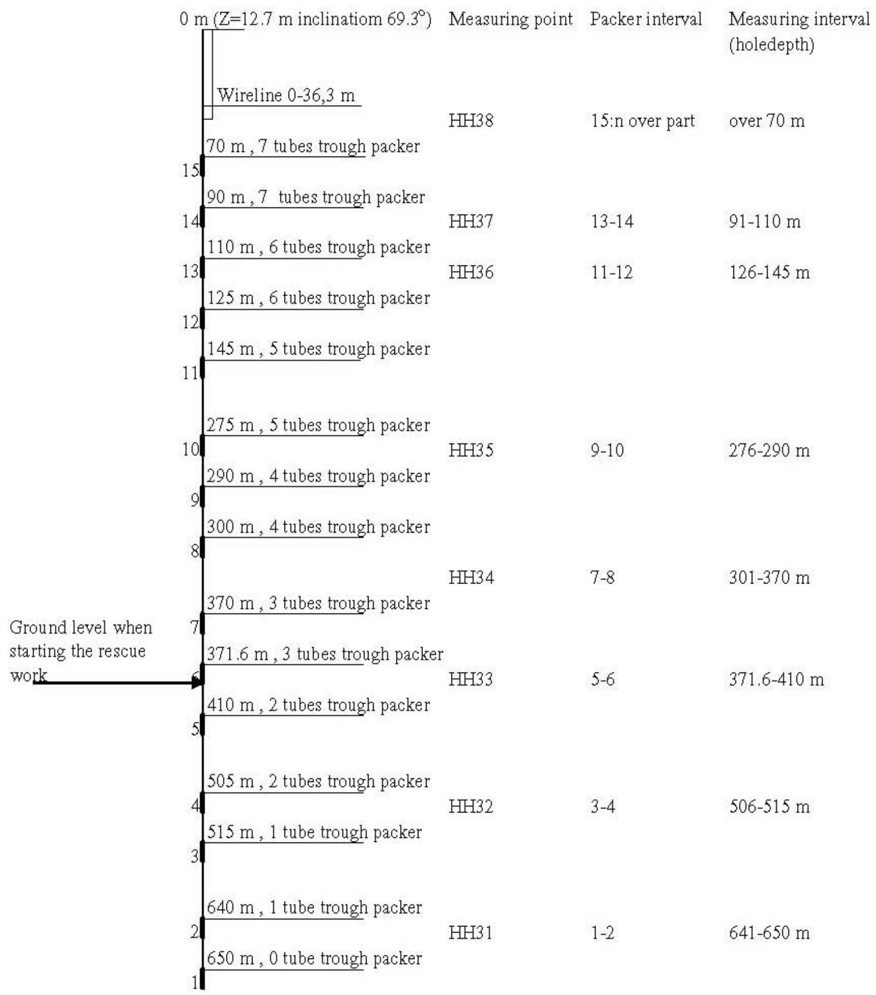


Figure 9. Situation in the borehole before the rescue work.

The opening work was carried out using a drill rig. The rig was fastened to a supporting rod and the equipment was lifted about five metres when it got stuck again. It was decided that 64/57 casing tubes would be installed in the hole from surface to the depth of 203 m. While the casing was lowered the supporting rods and the nylon tubes were threaded through the casing tubes. When the casing tubes were installed it was noticed that the packer equipment was loosened. In addition to the uppermost packer all supporting rods and nylon tubes were removed from the hole. Also the casing pipes were lifted from the hole. The supporting rod was broken at the threads in the lower cover of the packer.

In the next phase various specially made fishing tools were used to catch the supporting rods. By pulling with the rig and the jack lift two packers and nylon tubes and supporting rods attached to them were managed to be removed from the hole. The rubbers of both packers removed had turned twofold.

In order to remove the second lowest packer a hole was drilled to the upper cover of the packer with T 36 bit. There were two through tubes for the nylon tubes at the upper end of the packer. These were removed before the drilling using a shell spiral. In order to reduce the vibration of the drill string 64/57 casing pipes were installed in the hole from surface to the depth of 203.10 m. After the drilling a fishing pin was attached using Alu 53 rods to the hole in the packer. When the equipment was pulled up with the rig the supporting rod below the packer broke. The packer was removed from the hole. Also the rubber cover of this packer had turned twofold.

There were ten meters of steel rods and a nylon tube remaining in the hole above the lowermost packer. The rods were removed using a falciform hook. Most of the nylon tube came up with the rods. The rest of the nylon tube and the through tube used for inflating the packer were removed with several various fishing tools. When this was done a hole was drilled to the cover of the packer with T 36 bit. A fishing pin was attached in this hole with Alu 53 rods. The equipment was loosened by pulling with the rig and the packer was removed from the hole. The rubber of the packer had been ripped and most of the rubber and two binding bands stayed in the hole. In addition a 15 cm steel cover of the valve in the bottom of the packer and several pieces of nylon tube were still in the hole.

The steel cover was removed by pushing it to the bottom of the hole with the drill string. Catching the small loose pieces of the nylon tube was difficult. The hole was drilled 46 cm deeper in order to catch the loose material in the core barrel. In this way pieces of rubber, pieces of binding bands, cover cone and pieces of steel were lifted together with the core sample.

4. WASHING THE HOLES

4.1 Why are holes flushed and washed

It has been noticed when inspecting holes with video cameras or by digital scanning that the borehole walls gradually become covered with a coating so that visibility has been decreased. Such a cover prevents and disturbs many investigations that should be carried out in holes. Sometimes it may become necessary to clean holes. Sometimes the holes may contain some sludge (drill cuttings) remaining after the drilling.

Washing of hole is carried out using drill rig and drill string. The duration of the washing operation depends essentially of the length of the hole. Further the diameter of the hole has some influence on the duration. Handling of large diameter rods is difficult and time consuming. According to Smoy's experience some 300 metres of hole may be washed in an eight hour shift in normal conditions. Some 3 to 5 m^3 of water would be consumed. Erecting and dismantling of the rig at the hole is often hard and takes several shifts. Fractured zones need special attention in the washing operation. These zones must be washed very carefully so that all loose material, which would eventually fall in the hole with time, will be removed and dropped to the bottom of the hole.

4.2 Cleaning the hole by washing

The washing of holes is carried out with water and steel brushes (Figure 2). The brush has steel threads, which brush against the wall of the hole when moved in the hole. The brush is connected to the drill string with an adapter. There are holes in the bottom of the adapter so that water can be conducted and directed to the borehole wall. Another option is that the holes are in the brush instead of the adapter. When washing the drill string is slowly rotated in order to boost the washing effect.

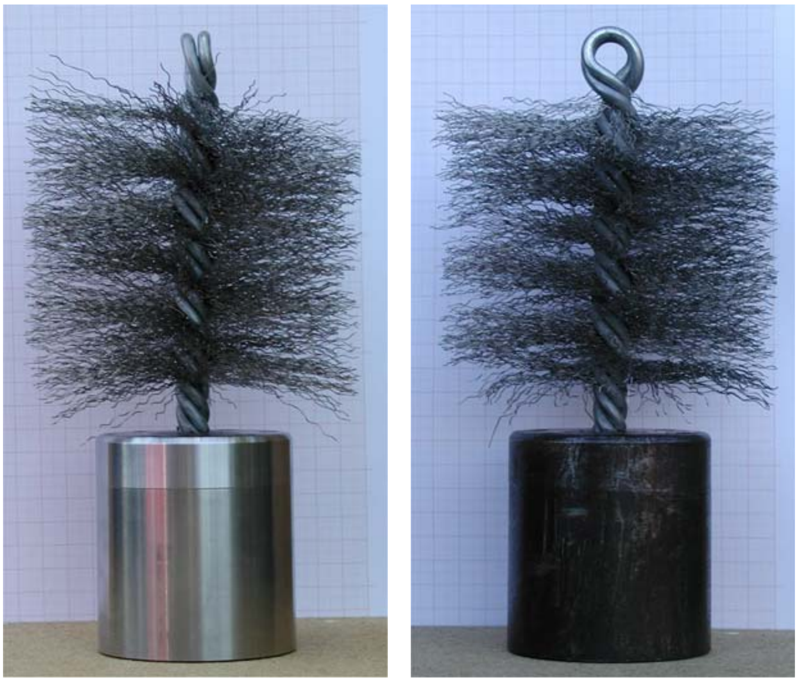


Figure 10. The 125 mm brush before and after use.

Brushes are available for various hole diameters. According to Smoy's experience most effective are brushes, which are slightly oversized. Smoy has used 80 or 90 mm brushes in 76 mm holes and respectively 145 mm brushes in 115 mm holes. The benefit of steel brushes compared to nylon brushes is better durability.

Some test work has been carried out in Olkiluoto. The brushes were weighted and photographed at the start of the work and again at the end of the work. The biggest brush was of the size of 125 mm. Its weight was at the start 241 grams and at the end 238 grams. The 90 mm brush weighted at the beginning 218 grams and at the end 212 grams. There were no noticeable changes in the size or form of the brushes during the work.

4.3 Washing experiences

The experiences of washing the holes with brushes are positive. The washing has cleaned the borehole walls and the usability of the holes for e.g. digital imagining and other investigations has been increased.

5. SUMMARY

Sometimes drilling equipment will be left in the hole or it cannot be recovered from the hole in spite of attempts. Further various measurements may be carried out in the holes after the drilling has been completed and devices used in the measurements may get stuck in holes. Equipment remaining in a hole may be classified in two categories: drilling equipment and measuring equipment. To remove the drilling or measuring equipment lost in a borehole, special techniques and professional skill must be applied.

There are two common reasons identified for the drill strings to get stuck in the holes. First the drill string may get stuck due to acute drilling problems. The most common situation where the drill string may get stuck is when the drill bit “burns” i.e. the bit melts due to failures in water flushing and looses its form and gets stuck to the borehole walls. The second case is where rods are left as casing in a hole either based on the structure of the upper part of the hole or in order to support the hole. Examples of these are e.g. casings used in the overburden drilling carried out with DTH techniques or casing set through a fractured section intersected by the hole. When the drill string gets stuck drill rods or core barrels may remain in the hole. The core barrels contain bearings and sealings including some organic material, i.e. grease. Casing left in the hole may be either standard or stainless steel type.

There are several methods to remove the drill strings from a borehole. They can be lifted using the drill rig. If this cannot be done the next stage is often jacking. Jacking will be continued until the drill string is recovered or the drill string is broken.

If the drill string breaks the next phase may be disjoining the remaining rods. Disjoining is done using rods with left handed couplings and left handed suitable worm pin or “carrot”. The speed of disjoining varies greatly. Sometimes each rod must be disjoined separately and sometimes hundreds of metres of drill string may be disjoined in one piece.

If disjoining is unsuccessful or it is unpractical for some reason, overcoring the drill string with a bigger diameter casing equipment may be the best alternative. In overcoring it must be noticed that the clearance between the overcoring bit and the drill string to be removed must not be too big. If the clearance is too big a falciform slice of rock formed may jam the casing and the drill string together.

Equipment stuck in the hole may be removed also by drilling through it. The equipment removed will be destroyed when drilled through. Loose equipment, e.g. wire line cable, stuck in hole is quite problematic. Drill bit stuck in hole is often so firmly stuck that it may be drilled with another bit. Loose material must be cemented so that it could be removed by drilling. There is a risk that drill rods and other equipment stuck in hole act as wedges and make the borehole to deviate from the original direction during drilling. Manufacturers provide special bits for drilling through steel. The bit must have an adequate diameter to prevent the development of wedge-formed pieces.

Drilling through metal objects generates metal chips in the hole. Most of the metal chips may be recovered from the hole using effective water flushing. In addition some of the steel material may be recovered by a magnet.

Removing measuring equipment from a hole is often demanding and time consuming work. From the cleaning point of view the hole measurements are either short-term surveys or long-term surveys. In short-term surveys a probe is lowered into the hole and immediately lifted from the hole, while in long-term surveys measuring equipment is installed for a long period in the hole.

In short-term surveys a probe is lowered in the hole using a wire line or a cable. Often the probe is centralized in hole with centralizing rings with a diameter only slightly smaller than the hole. The most common equipment of this type are standard geophysical probes, difference flow probes, digital scanning cameras, water sampling devices, HTU-probes and down hole seismic probes. The probes get stuck mostly due to a piece of rock that falls between the probe and the borehole wall.

Considering long-term surveys e.g. hydrogeological investigations in holes, the most common device getting stuck in holes is a multipacker device consisting of several plugs, support rods made of steel and plastic tubes. In long-term surveys the reason for getting equipment stuck may be malfunction of the equipment, wedging by loose rocks or cemented by drill slurry (cuttings).

Some of the stuck devices may be valuable or may contain parts (e.g. batteries) that disturb e.g. groundwater chemistry in the hole. Such parts must be removed from the holes without breaking them. Some parts of the devices may be removed also after breaking them.

Normally a drill rig and a drill string are needed in the cleaning work. The drill string is attached to standard or tools specially made for fishing lost equipment. In addition it is possible that either before commencing the cleaning work or during the cleaning work various fishing tools must be designed and manufactured. Quite often the lifting capacity of the rig is a limiting factor and a jack lift is needed for heavy lifting work.

Part of the equipment stuck in the hole may be removed by drilling through it. Material drilled through will be destroyed and useless after removing. Therefore drilling through material is applicable only in removing less valuable and harmless material. Drilling through loose material involves certain risks and consequently the loose material must be cemented in the hole. Drilling soft materials is done using coarse roughing bits in order to secure proper flushing of the bit. Drilling a hole with a small size bit in the stuck equipment for the fishing tool can also be used as an alternative technique.

A vital part of the cleaning operation is planning the work in advance. In order to make the plan and to select the suitable methods it is important to know the condition of the stuck device. It is also important to know the exact depth where the equipment is stuck and to have an estimate of the reasons why the equipment has got stuck. It is very important to know the correct dimensions of the device before commencing the cleaning work. The plan must be considered and approved by the client. If the plan cannot be followed an alternative plan must be made. Also the alternative plan must be considered and approved by the client.

When a plan for the cleaning work has been approved all fishing tools etc. must be manufactured. Also the reference or zero point for depth value of the stuck equipment must be checked.

All measuring devices should be designed so that the risk of getting stuck would be minimized. Devices should be centralized in holes with elastic material so that pieces of rock falling on the device would not wedge the device but could instead pass the device and fall to the bottom of the hole. Stone collectors on top of probes are a common and useful way to collect falling pieces of rock. Further a coupling with standard drill rod threads at the top of the probe helps fishing with normal drill rods. Also the attachment of the cable to the probe should be designed so that the cable would break at a controlled place if the probe gets stuck. In this way the cleaning work is easier and the cable may even be utilized in the rescue work.

6. REFERENCES

Niinimäki, R. 2004. Removing of casings from deep borehole OL-KR24 at Olkiluoto in Eurajoki. Posiva Oy. 11 p. Working Report 2004-15.

Rautio, T. 1999. Cleaning of the borehole HH-KR3 at Hästholmen in Loviisa in 1991. Posiva Oy. 11 p. Working Report 99-63.

Rautio, T. 2001. Cleaning of the borehole HH-KR3 at Hästholmen in Loviisa in 2001. Posiva Oy. 9 p. Working Report 2001-04.