Technical Report

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Boring of full scale deposition holes at the Äspö Hard Rock Laboratory

Operational experiences including boring performance and a work time analysis

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December 2002

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Abstract

Thirteen experimental deposition holes similar to those in the present KBS-3 design have been bored at the Äspö Hard Rock Laboratory, Oskarshamn, Sweden. The objective with the boring program was to test and demonstrate the current technique for boring of large vertical holes in granitic rock. Conclusions and results from this project is used in the planning process for the deposition holes that will be bored in the real repository for spent nuclear fuel. The boreholes are also important for three major projects. The Prototype Repository, the Canister Retrieval Test and the Demonstration project will all need full-scale deposition holes for their commissioning.

The holes are bored in full scale and have a radius of 1.75 m and a depth of 8.5 m. To bore the holes an existing TBM design was modified to produce a novel type Shaft Boring Machine (SBM) suitable for boring 1.75 m diameter holes from a relatively small tunnel. The cutter head was equipped with two types of roller cutters: two row carbide button cutters and disc cutters. Removal of the cuttings was made with a vacuum suction system. The boring was monitored and boring parameters recorded by a computerised system for the evaluation of the boring performance.

During boring of four of the holes temperature, stress and strain measurements were performed. Acoustic emission measurements were also performed during boring of these four holes. The results of these activities will not be discussed in this report since they are reported separately.

Criteria regarding nominal borehole diameter, deviation of start and end centre point, surface roughness and performance of the machine were set up according to the KBS-3 design and were fulfilled with a fair margin. The average total time for boring one deposition hole during this project was 105 hours.

Summary

Thirteen experimental deposition holes similar to those in the present KBS-3 design have been bored at the Äspö Hard Rock Laboratory, Oskarshamn, Sweden. The objective with the boring program was to test and demonstrate the current technique for boring of large vertical holes in granitic rock. Conclusions and results from this project is used in the planning process for the deposition holes that will be bored in the real repository for spent nuclear fuel. The boreholes are also important for three major projects. The Prototype Repository, the Canister Retrieval Test and the Demonstration project will all need full-scale deposition holes for their commissioning.

The holes are bored in full scale and have a radius of 1.75 m and a depth of 8.5 m. To bore the holes an existing TBM design was modified to produce a novel type Shaft Boring Machine (SBM) suitable for boring 1.75 m diameter holes from a relatively small tunnel.

The cutter head was equipped with two types of roller cutters: two row carbide button cutters and disc cutters. After rebuilding of the cutter-head a total number of 19 cutters were used. Cuttings were removed from the cutter head by a vacuum suction system. Between the vacuum pump and the boring machine there was a container connected to collect the main part of the cuttings. The finest grained particles followed the air stream, passed the main collection container and were filtered in the vacuum pump. The furthest distance the cuttings were transported was approximately 100 m.

During boring different boring parameters were constantly monitored and recorded with a computerised system. When boring some of the holes, test series were carried out with the objective to determine how changes in the boring parameters effected the performance of the boring machine. After completion of boring of each deposition hole it was surveyed to make sure that the geometrical criteria were fulfilled.

Analysis of monitored boring parameters indicated that the penetration rate became higher as the thrust was increased and it seemed that the penetration rate became lower as the rate of rotation was increased. One reason for this might be that the crushing of rock functioned well but the removal of cuttings did not work well at higher rates of rotation. There was also a trend towards a lower rate of penetration in the second half of the holes. No connections between the rate of penetration and changes in the geology were found.

The probable reason is that the vacuum suction system cleans the borehole more efficiently at an upper level than deeper down in the borehole.

The criterion for the maximum bending was set to 16 mm. Bending is the largest distance between the borehole wall and a theoretical line connecting the start and end centre point. The average bending for the thirteen deposition holes is 8 mm.

The effective average rate of penetration was 0.45 m/h. If the total time for boring of the holes is included the average rate of penetration drops to 0.08 m/h. The maximum rate of penetration achieved during a short period of time was approximately 1.1 m/h. If the time for measurements is excluded the average time for completion of one hole is 105 hours. The most time consuming activities in the boring cycle and their part of the total time are listed in Table 1 below:

Table 1. The most consuming activities during boring of the holes.

Activity	Part of total time [Percent]
Transport	11
Set up	19
Boring	18
Repair and Maintenance (R&M) of boring machine	18
R&M of vacuum system	10
Handling of casings	11

It has earlier been stated from SKB that one canister per day shall be deposited in the future repository during regular operation. Approximately 220 deposition holes have to be bored each year during 20 years. If the average time for boring is reduced to 30 hours, it will still take approximate 4 different boring machines working simultaneously to be able to complete the task. In this perspective efforts made in making the boring cycle more effective and hence reducing the time for completion of each hole is needed. The utilization degree of the boring equipment could be increased significantly by planning the maintenance work beforehand and carrying out as much of the repair and maintenance work as possible during transport and set-up.

A photograph of a finished deposition borehole is presented in Figure 1.

***Figure 1.** Photograph of a finished deposition borehole.*

Sammanfattning

Vid Äspölaboratoriet i Oskarshamn har tretton deponeringshål borrats i forskningssyfte i enlighet med nuvarande KBS-3 design. Målsättningen med borrningsprogrammet var att utvärdera och demonstrera befintlig teknik för borrning av stora vertikala hål i kristallint berg. Slutsatserna och resultaten från detta projekt kommer att användas i planeringsprocessen för de deponeringshål som skall borras i det verkliga djupförvaret för använt kärnbränsle. Borrhålen är också viktiga för tre större projekt: Prototypförvaret, Återtagsförsöket och Demonstrationsprojektet vilka behöver deponeringshål i fullskala för sina respektive genomföranden.

Hålen är borrade i fullskala och har en diameter på 1,75 m och ett djup på 8,5 m. För att kunna genomföra borrningen i en relativt liten tunnel modifierades en Tunnelborrmaskin (TBM) till en Schaktborrmaskin (SBM).

Kutterhuvudet var utrustat med två typer av kuttrar: stiftkuttrar och diskkuttrar. Efter ombyggnaden av kutterhuvudet användes totalt 19 kuttrar. Borrkaxet avlägsnades från borrhålsbotten med ett vakuumsystem. Mellan vakuumpumpen och borrmaskinen fanns en container som samlade upp huvuddelen av borrkaxet. Det finkornigaste materialet följde luftströmmen förbi containern och filtrerades i vakuumpumpen. Uppskattningsvis transporterades borrkaxet som längst 100 m.

Under borrningen registrerades och dokumenterades olika borrparametrar av ett datoriserat system. Under borrningen av vissa hål genomfördes testserier för att kunna fastställa hur förändringar i borrparametrarna påverkade borrmaskinens prestanda. Efter borrningen av varje deponeringshål kontrollerades att de geometriska kriterierna var uppfyllda. När sedan alla deponeringshål färdigställts genomfördes ett omfattande karakteriseringsprogram.

Analyser av registrerade borrparametrar indikerade att indriften ökade då matningskraften ökades. Det fanns även en indikation på att indriften minskade då rotationshastigheten ökades. En orsak till detta kan kanske vara att bergavverkningen fungerade bra, men att avlägsnandet av borrkax inte fungerade bra vid högre rotationshastigheter. Det noterades även en tendens mot en lägre indrift i den andra halvan av hålen. Ingen korrelation mellan indrift och variationer i geologin kunde göras. Den troliga orsaken är att vakuumsystemet fungerade effektivare i den övre delen av borrhålet än i den undre.

Kriteriet för hålens maximala krökning sattes till 16 mm. Krökning motsvarar det största avståndet mellan borrhålsväggen och den teoretiska linje som förenar start- och slutmedelpunkten. Genomsnittskrökningen för de tretton hålen är 8 mm.

Medelvärdet för indriften vid borrningarna var 0,45 m/h. Indriften sjunker till 0,08 m/h om den totala tiden för färdigställande av hålen divideras med den totala borrningslängden. Den största erhållna indriften under en kort tidsperiod var uppskattningsvis 1,1 m/h. Om tiden för mätningarna utesluts är genomsnittstiden för genomförandet av ett deponeringshål 105 h. De mest tidskrävande aktiviteterna i borrningscykeln och deras del av totaltiden är listade i tabell 1 nedan:

Tabell 1. De mest tidskrävande aktiviteterna under borrningen av deponeringshålen.

Aktivitet	Del av totaltiden [Procent]
Transport	11
Uppställning	19
Borrning	18
Reparation och underhåll (R&M) av borrmaskinen	18
R&M av vakuumsystemet	10
Hantering av casings	11

Tidigare har SKB framfört att en kapsel skall deponeras dagligen vid den ordinarie driften av det framtida djupförvaret. Uppskattningsvis kommer 220 deponeringshål att behöva borras årligen under en 20-årsperiod. Om genomsnittstiden för borrningen reduceras till 30 h, kommer det då att behövas fyra parallellt arbetande borrmaskiner för att uppfylla målsättningen. Sett ur denna synvinkel är insatser för att effektivisera borrningscykeln och därmed reducera tiden för borrningarna önskvärda. En möjlig förbättring är att låta servicegrupper sköta allt underhåll vid sidan av själv borrningen samt bytet av casings.

Figur 1. *Färdigborrat fullskaligt deponeringsborrhål.*

Contents

1 Introduction

1.1 The Äspö Hard Rock Laboratory

The Äspö Hard Rock Laboratory (HRL) is located in the area of Simpevarp in the northeastern part of the municipality of Oskarshamn. The geographical location of the Äspö HRL is given in Figure 1-1.

The Äspö (HRL) constitutes an important part of the work of developing a deep repository and testing methods for investigating and licensing a repository site. The Äspö HRL has been designed to meet the needs for the planned research, development and demonstration activities. The underground part takes the form of a tunnel from the Simpevarp peninsula to the southern part of the island of Äspö. Below Äspö, the tunnel runs in two turns down to a depth of 450 meter, see Figure 1-2. The first part of the tunnel was excavated using the drill-and-blast technique. A tunnel-boring machine (TBM) with a diameter of 5 meter excavated the last 400 meters.

One objective with the Äspö HRL is to demonstrate technology for and function of important parts of the repository system. This implies translation of current scientific knowledge and state of the art technology into engineering practice applicable in a real repository. It is important that development, testing and demonstration of methods and procedures, as well as testing and demonstration of repository system performance, is conducted under realistic conditions and at appropriate scale.

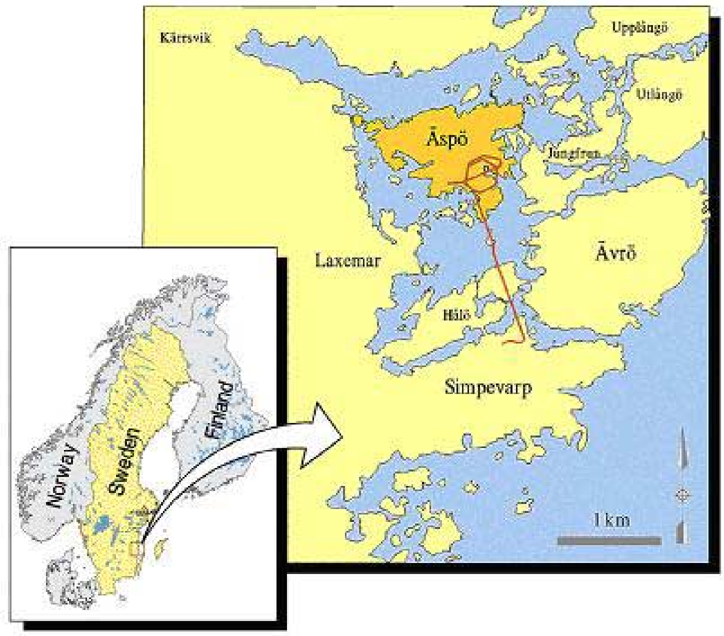


Figure 1-1. *Geographical location of Äspö HRL. The red line is the planar view of the tunnel layout.*

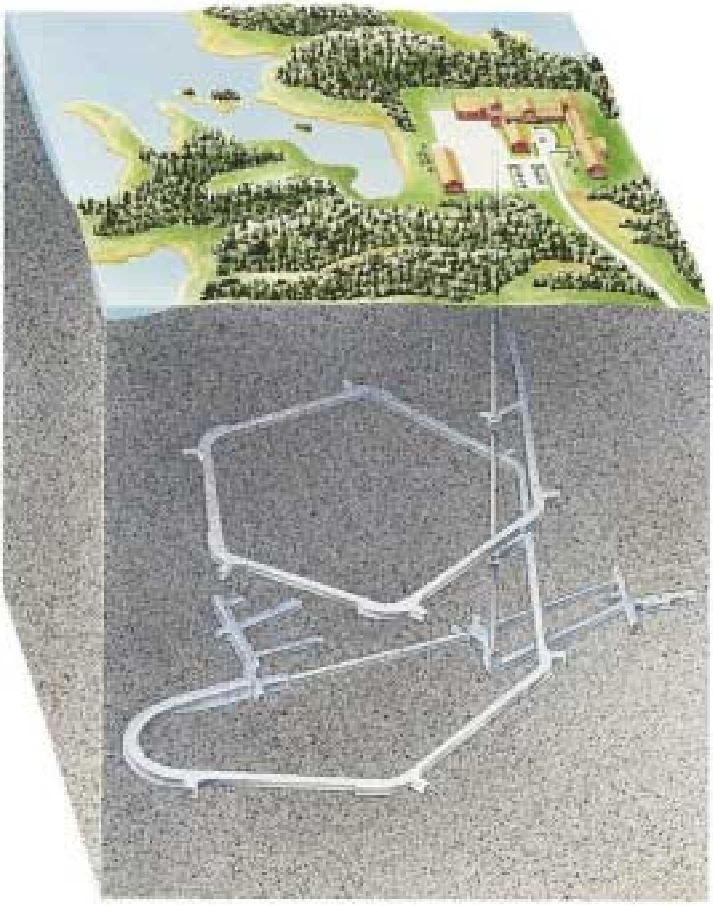


Figure 1-2. *General layout of the Äspö HRL facilities.*

1.2 Objectives

The objective with the boring program was to test and demonstrate the current technique for boring of large vertical holes in granitic rock. Conclusions and results from this project will be used in the planning process for the deposition holes that will be bored in the real repository for spent nuclear fuel. The boreholes are also important for three major projects. The Prototype Repository, the Canister Retrieval Test and the Demonstration project will all need full-scale deposition holes for their commissioning.

Machine parameters have been measured to evaluate the boring performance and to compare the performance with particle size distribution. There has also been a work time analysis based on daily reports from the contractors and from time investigation made by SKB personnel on the site during boring of all thirteen experimental deposition holes.

Another important objective with the boring of large deposition holes at Äspö is to determine the degree of fracturing in the rock wall caused by the mechanical tools during excavation as a function of the force acting on the cutter head in contact with the rock wall. In a nuclear waste repository, rock in the excavation-disturbed zone adjacent to the walls of a deposition of holes for waste canisters is one potential pathway for the transport of corrosive agents and radionuclides. Laboratory tests have shown that the propagation and shape of cracks can be systematically related to the properties of the rock and the machine parameters. Based on earlier work with penetration of indenters into different types of rock a conceptual model for crack propagation for single tools have been proposed. This model has been further developed with respect to propagation into hard rock and mathematical expressions for the different relationships have been proposed in an Indentation Crack Model /Zhang, 2001/. This model has been compared with some laboratory tests by means of numerical and analytical as well as by neural network fitting. During boring of one of the deposition holes two of the cutters were measuring the acting forces on the rock wall together with machine parameters for evaluation of the crack distribution. The evaluation was made by Luleå Technical University and is reported separately, see section 4.6.

1.3 Location of experimental deposition holes

Thirteen experimental deposition holes were bored at two different levels at Äspö HRL during 1998 and 1999. The first seven of them were bored at the 420 m level and the remaining six boreholes were bored at a depth of 450 m. The locations of the different holes in the facility are displayed in Figure 1-3. The order of the boring is presented in Table 1-1.

The ID codes for the holes are based on the following information:

- The first letter indicates the type of hole, in this case D – for Deposition hole.
- The second letter indicates in which of the tunnels the hole is bored.
- The four numbers indicates at which tunnel chainage the centre of the hole is bored.
- G01 indicates that it is the first hole bored in the tunnel floor at the specified chainage.

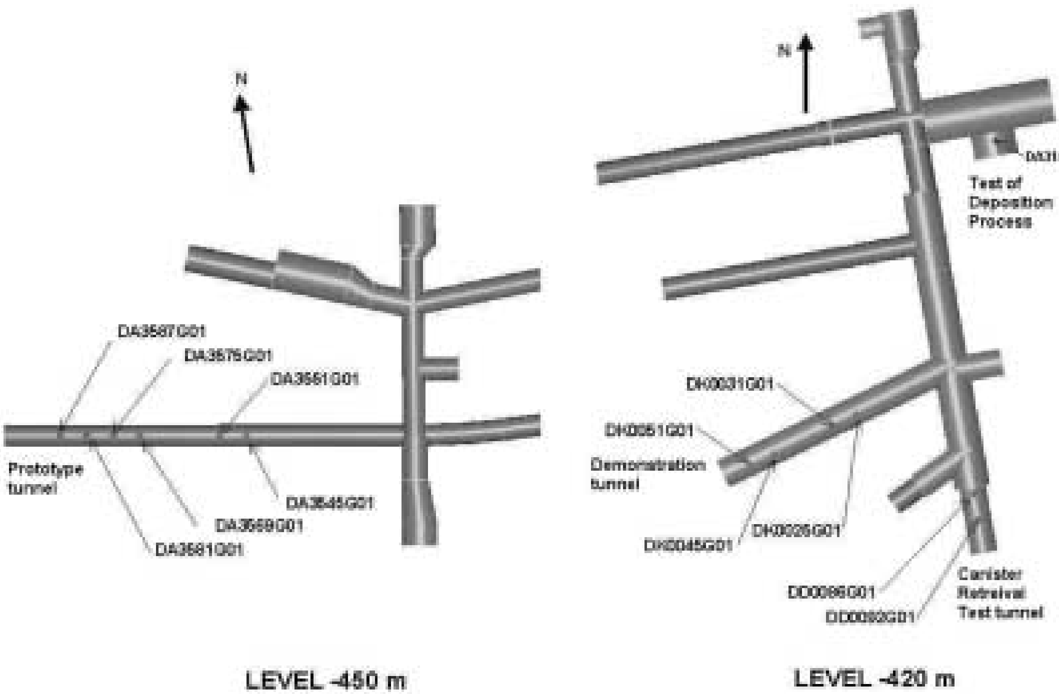


Figure 1-3. Locations of the different experimental deposition holes at Äspö HRL.

Table 1-1. The experimental deposition holes were bored in the following order.

ID codes	Description
1. DA3147G01	Test hole
(DA3156G01)	Only approximate 2 meter was bored to test the vacuum suction system, see section 2.7.
2. DK0051G01	Demo 1
3. DK0045G01	Demo 2
4. DK0031G01	Demo 3
5. DK0025G01	Demo 4
6. DD0092G01	Retrieval 1
7. DD0086G01	Retrieval 2
8. DA3587G01	Prototype 1
9. DA3581G01	Prototype 2
10. DA3575G01	Prototype 3
11. DA3569G01	Prototype 4
12. DA3551G01	Prototype 5
13. DA3545G01	Prototype 6

1.4 Future use of the deposit holes

The first seven holes were bored at the 420 m level. The first hole bored was used as a test site for full-scale tests of the deposition process, see Figure 1-3. The second to fifth boreholes were bored in the Demonstration tunnel and are used to illustrate the deposition process. Holes number six and seven are used in the Canister Retrieval Test. The Canister Retrieval test project has the objective to demonstrate the possibility to retrieve a copper canister embedded in saturated bentonite clay. To make it as realistic as possible the two canisters will be equipped with electrical heaters that shall simulate the heat generated by the declining fission processes in the used nuclear fuel.

The last six deposition holes bored at the 450 m level will be used in the Prototype Repository Project. The objective with this project is to simulate a repository for spent nuclear fuel. This will be done by depositing canisters equipped with electrical heaters in the deposition holes embedded in by compacted bentonite clay. The entire Prototype Repository tunnel will then be back-filled with a mixture of bentonite clay and crushed rock. Finally the tunnel will be sealed with a plug of concrete, see Figure 1-4.

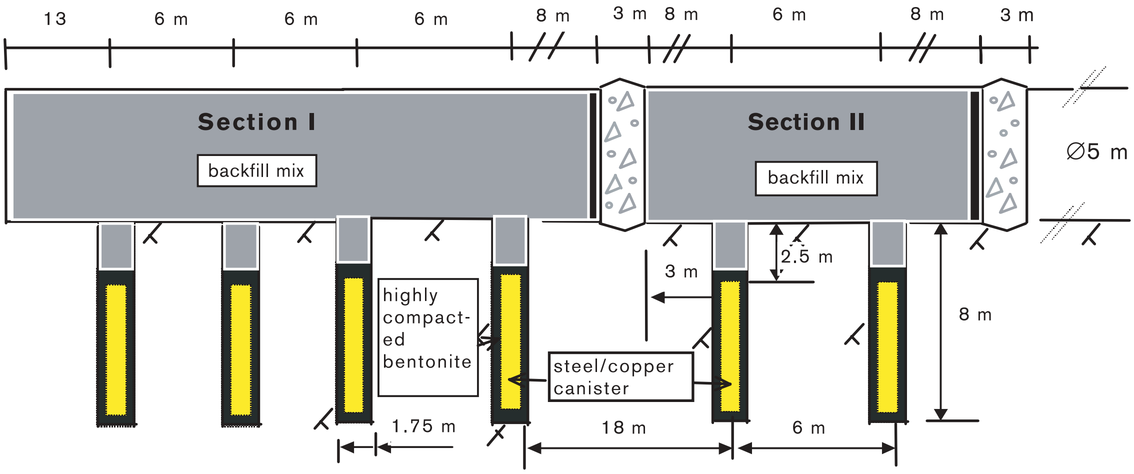


Figure 1-4. Layout of the Prototype Repository.

1.5 Criteria

1.5.1 Geometrical criteria

The general geometrical criterion is that each borehole should be able to host a column of bentonite blocks with an outer diameter of 1.65 m in such a way that the slot between the blocks and the rock wall has a minimum width of 25 mm. The following criteria have been set up in order to fulfil the general criterion:

1. The nominal diameter of the hole shall be 1750 mm –5 and +50 mm.
2. The starting centre point of the hole shall divert no more than 25 mm from the theoretical starting point measured perpendicular to the tunnel axis. The deviation parallel to the tunnel axis may be no more than 50 mm.
3. Borehole alignment. The measured centre point in the bottom of the hole shall not divert more than 25 mm from a vertical projection of the starting centre point.
4. Straightness. A measured centre point of the borehole at any depth shall not divert more than 16 mm from a theoretical line drawn between the starting and bottom centre point. This criterion includes deviation due to re-gripping.
5. Re-gripping or any other operational activity may not result in an instant horizontal displacement of the centre point that is more than 10 mm.
6. The borehole wall surface should not have larger irregularities than 10 mm.

No criteria have been set up for the bottom shape of the hole.

1.5.2 Boring cycle criteria

The criterion for the total boring time was that it should take no more than 40 hours to bore one hole, remove all the casings and make the boring machine ready for transportation to the next experimental deposition hole to be bored.

1.6 Bedrock properties

The dominant rocks on Äspö belong to the 1700–1800 million-year-old Småland granite. Four main rock types: Äspö diorite, Småland granite, greenstone and fine-grained granite make up most of the rock mass in Äspö HRL.

The *Äspö diorite* is usually grey to reddish grey, medium grained, and contains more or less scattered, large crystals of potassium feldspar.

The *Småland granite*, compared with the Äspö diorite, is mostly richer in quarz and potassium feldspar, and the amounts of dark minerals, such as biotite, is lower. Amphibole is often missing totally and the amounts of sphene, which is a very characteristic mineral for diorites, are much lower.

The greenstone – fine grained and medium to coarse-grained greenstone is easily distinguished from the granitoid rock by their very dark greenish or greyish black colour. As a rule they occur as minor inclusions or irregular, often elongated bodies within the granitoids and dioriteoids. They may be of different age and origin but the majority of them are probably connected with the Småland granitoid magma evolution. The major minerals in the greenstone are plagioclas, amphibole and biotite. According to IUGS classification most of the greenstone are andesites to basalts.

Fine-grained granites occur rather frequently, both on the surface of the Äspö island and its surroundings, as well as in the tunnel. The fine-grained granites vary in colour from reddish grey to distinct red. They are in most cases rich in quartz and potassium feldspar and can be classified as true granites /Rhén et al, 1997/. Figure 1-5 presents an overview of the rock types in different part of the tunnels.

The holes have been bored in Äspö diorite with veins of fine-grained granite and minor veins of greenstone, see Figure 1-6. The geology is similar in all holes.

Rock mechanics properties for Äspö diorite are presented in Table 1-2 /Staub et al, 2002/. Young's modulus for the rock mass is around 50 GPa.

The magnitude of the major horizontal stress is approximately 25 MPa at 450 m depth. The magnitudes of the minor horizontal stress and the vertical stress at this level are 10 and 12 MPa respectively. The values of the stress distribution are mean values from the Äspö database SICADA.

After boring of the large experimental deposition holes the water inflow into the holes has been measured. The holes in the Canister Retrieval Test and in the Demonstration tunnel are dry. Hole number DA3587G01 had an inflow of approximate 100 litres per 24 hours and the other five holes in the Prototype tunnel had a water inflow of approximate 5 litres pro 24 hours.

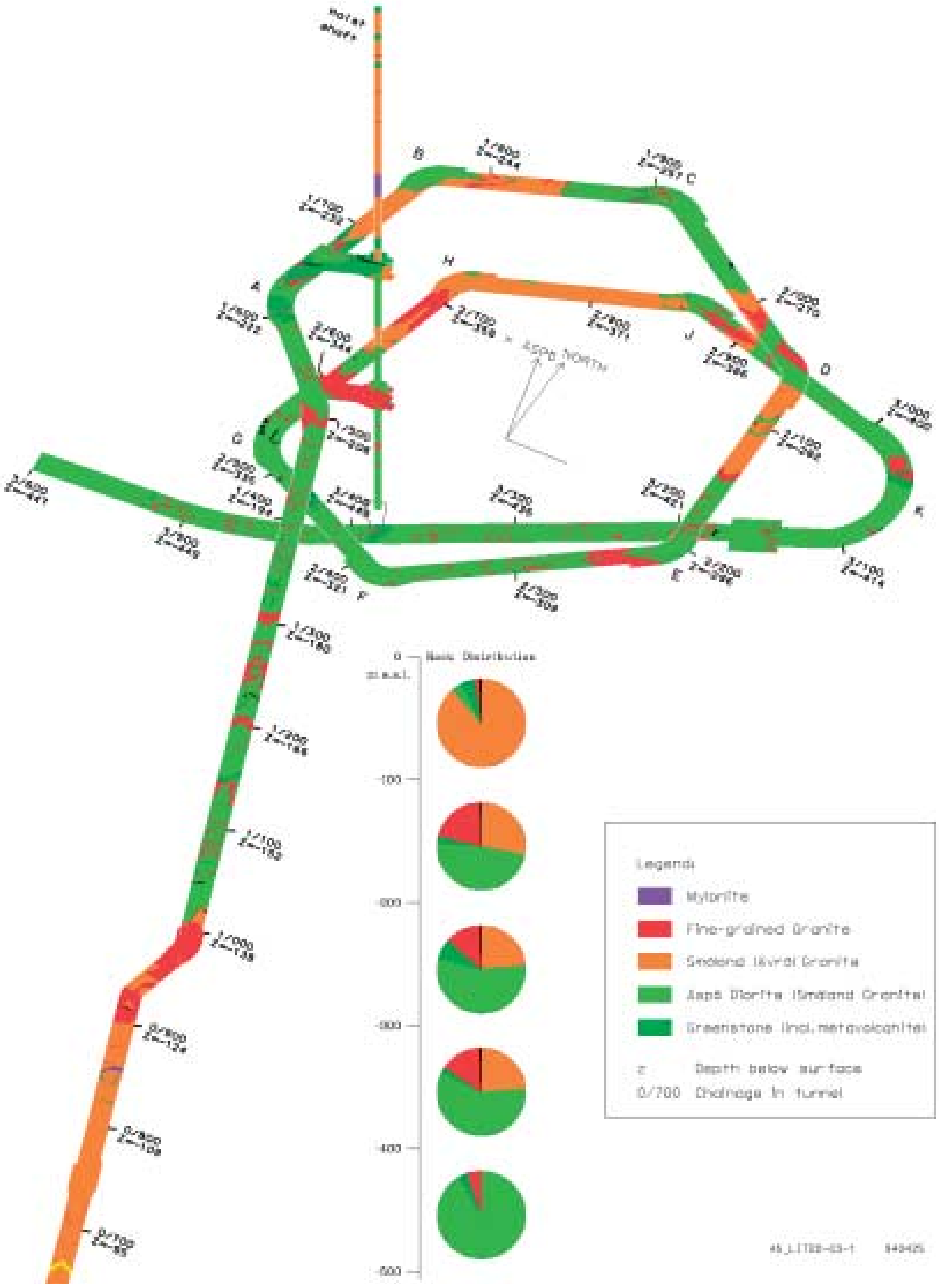


Figure 1-5. Overview of the rock type mapping and rock type distribution at different depths.

Figure 1-6. Borehole wall.

Table 1-2. Rock mechanics properties for Äspö diorite /Staub et al, 2002/.

Parameter	Value
Uniaxial compressive strength	214 MPa
Tensile strength	14.8 MPa
Young's modulus	73 GPa
Poisson's ratio	0.27
Cohesion	31 MPa
Friction angle	49 degrees

2 Technical description of boring machine

2.1 General

The Robbins Company in the USA has redesigned and rebuilt a full-face tunnel boring machine to suit SKB's purpose for demonstration of boring vertical holes for deposition of spent nuclear fuel according to the current KBS-3 design. The boring machine is named SBM 1.8 TBM where SBM stands for Shaft Boring Machine, 1.8 for the approximate diameter in meters of the hole being bored and TBM stands for tunnel boring machine. The boring equipment consists of a TBM boring machine, casings, a transport/launch assembly and a vacuum suction system. Figure 2-1 presents the installation of the boring machine into the transport assembly.

2.2 Boring machine

The machine was designed as a portable boring system with a transport assembly to transport the SMB unit in an upright position from one location to another. The SBM was mounted in a transport launch trailer 11.1 meters long by 2.5 meter in width and 3.2 meter high, see Figure 2-2.

Figure 2-1. *Installation of boring machine into transport assembly.*

Figure 2-2. *Transport launch trailer 11.1 meters long by 2.5 meter in width and 3.2 meter high.*

The boring system was designed to fit into the transport tunnels made by a TBM with a diameter of 5 meters. The tunnel height is though reduced to 4.5 meters by a road construction.

The front frame, see Figure 2-3, is the main mounting structure at the front end of the SBM. The front frame mounts the bearing and seal assembly, the four cutter head drive units and the four front stabilizers. The inner telescopic shield carries the cutter head and the rear stabilizers.

The thrust force was applied to the cutter head by four hydraulic cylinders in the boring machine. Four hydraulic motors in the boring machine achieved the rotation of the cutter head. The hydraulic power pack was mounted in the rear of the transport trailer and the machine was equipped with 20 cutters, carbide button cutters and steel disc cutters. The total maximum thrust of the thrust cylinders was 350 tons but the total maximum thrust utilised was approximately 200 tons.

The thrust applied on the cutter head is in most cases in this report presented as the thrust on each of the four thrust cylinders. The cutter head rotation varied from 0 to 23 rpm but a practical maximum rate of rotation notified when boring was 10 rpm.

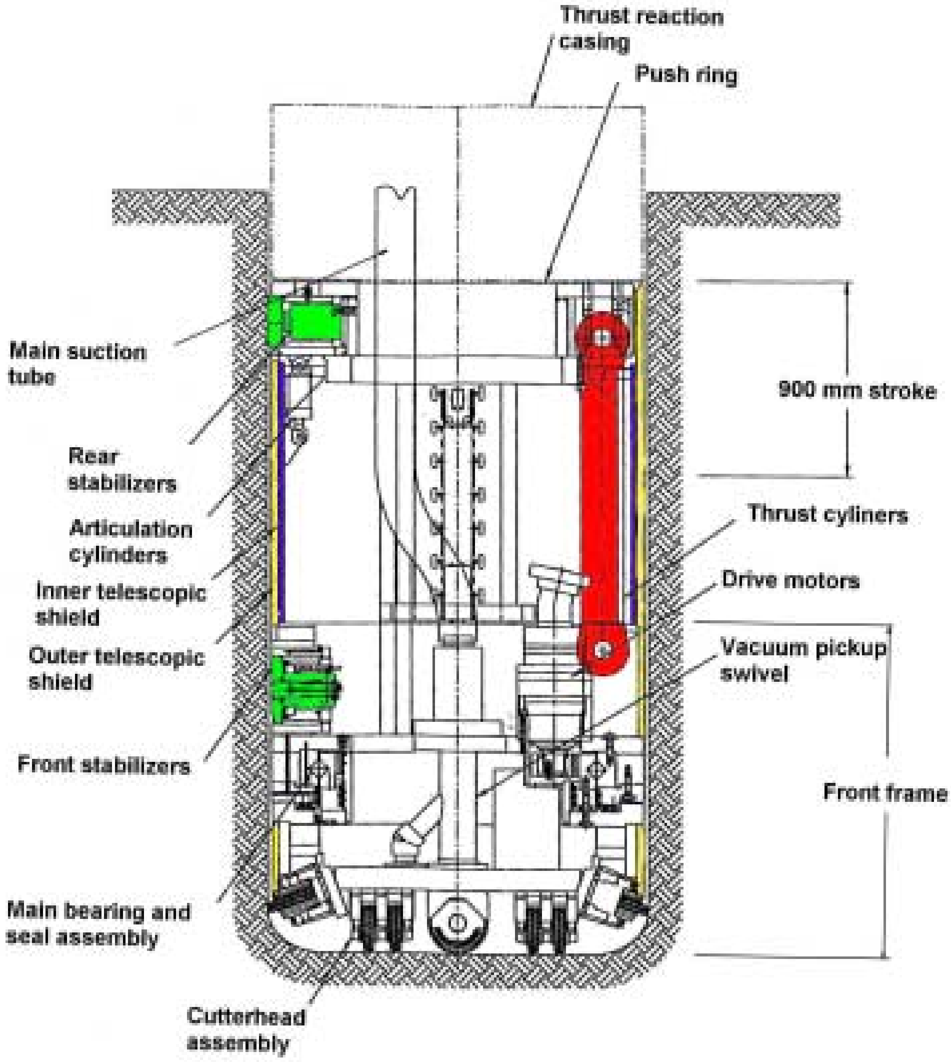


Figure 2-3. *Section through the boring machine.*

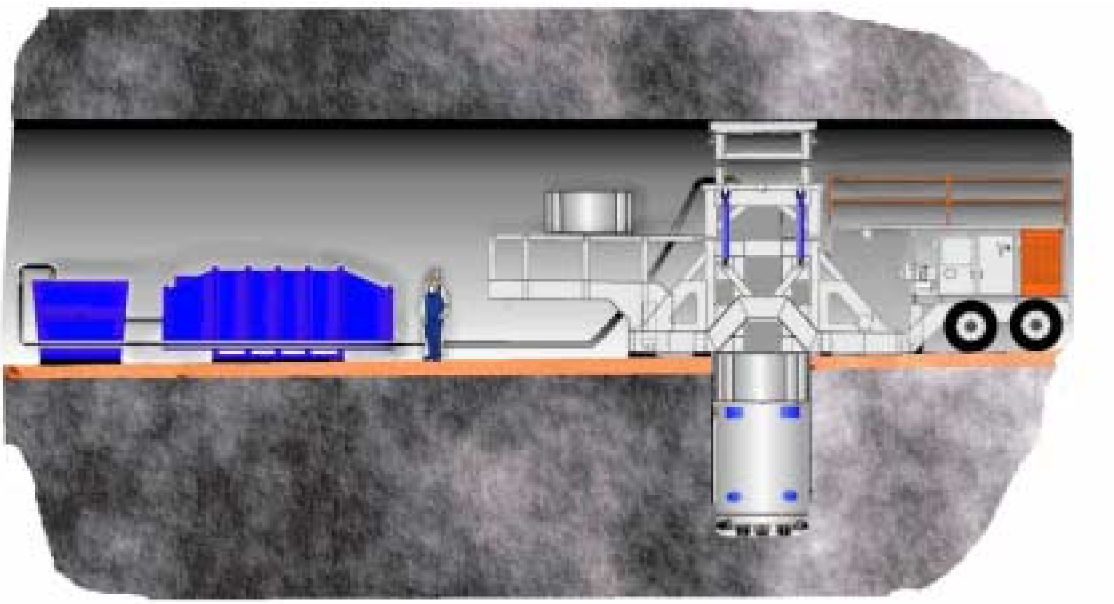


Figure 2-4. *Trailer with the boring machine. The blue containers are the vacuum pick up system.*

2.3 Cutter-head and cutters

The cutter head was of flat design with raised gage corners and totally equipped with 20 cutters, see Figure 2-5. There were four twin disc cutters mounted in the central position. Twelve face cutters were used in the face and gauge positions. The outermost two cutter rows were "double tracked" (17A and 17B, and 18A and 18B). The double tracking helps to maintain the cutter head stability and maintains the correct borehole diameter. The cutter type at any position may be steel disc or a two-row carbide button cutter.

When dressed with disc cutters in the outermost positions the borehole diameter was 1,755 mm. When dressed with carbide button cutters the hole was slightly larger with a diameter of 1,764 mm. As the cutters wore down the borehole diameter decreased.

The design of the cutter head and the vacuum system caused problems with the penetration rate, torque and surface smoothness when boring the first hole. The system for removal of cuttings was therefore rebuild and some of the button-cutters including the double tracked ones was changed into disc-cutters, see section 2.7 "Test of boring".

For all holes except DD0086G01, the outermost cutters were disc-cutters. For DD0086G01 Luleå University of Technology had one outermost two row carbide button cutter instrumented with strain gauge wiring to measure the acting forces on the cutter during boring, see section 4.6. The corresponding double tracked cutter was also changed into a button cutter.

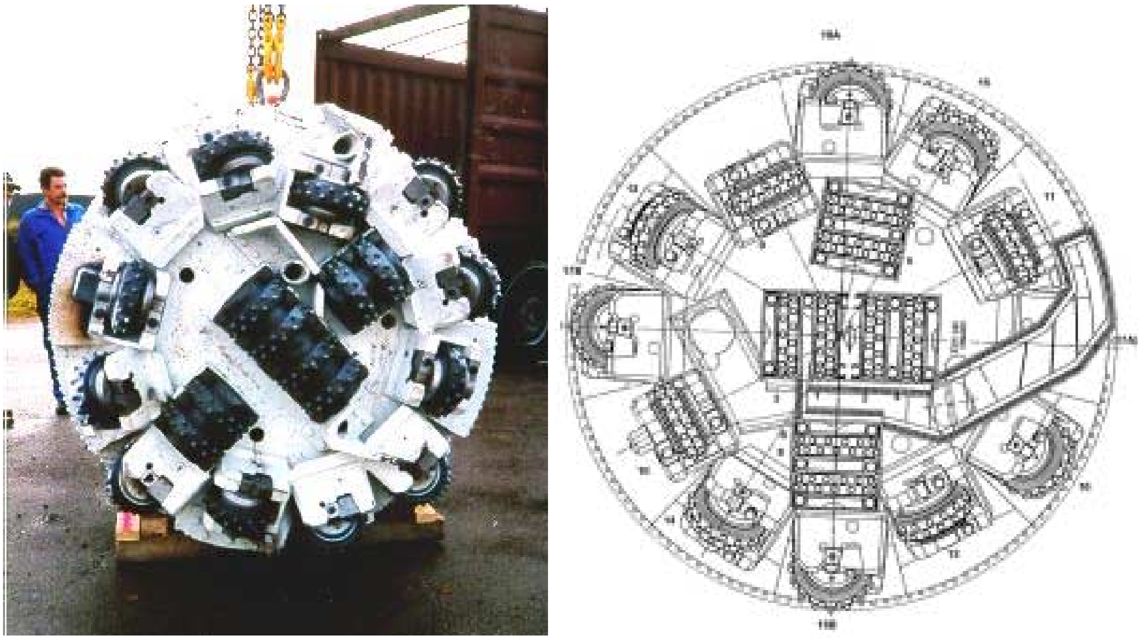


Figure 2-5. *Photograph of, and a schematic drawing of, the cutter head.*

2.4 Removal of cuttings

Cutting was removed from the cutter head by a vacuum suction system. The cutter head was at the beginning equipped with four 75 mm vacuum suction tubes designed to provide a relative even distribution of nozzles in the cutter head. Care had been taken to design as large passage area for the cuttings as possible to eliminate or reduce clogging. It was shown, when boring the first hole, that the size of the tubes in the cutter head was too small and resulted in almost constant clogging of the tubes, see 2.7 "Test of boring". Two new nozzles, each with a diameter of 150 mm, were therefore constructed to replace the four smaller tubes.

The cuttings were transported from the face through pipes in the cutter head. These vacuum pipes were connected to a swivel mounted in the centre of the cutter head, see Figure 2-3. To this swivel the main suction tube with a diameter of 150 mm was connected and the cuttings were transported through the boring machine in this main tube. Outside the boring machine the tube was connected to a 200 mm steel piping for transportation of the cuttings to the container and the vacuum suction unit, see Figure 2-4 and Figure 2-6. The furthest distance the cuttings were transported through the tubes was approximately 100 m when boring DA3387601.

The vacuum system consisted of a Disab Vacuum pump LN 200, 235 kW. The vacuum pump was diesel driven with a maximum airflow of 8,600 cubic meter per hour and a maximum pressure of 20 kPa. Approximate 70% of the capacity was used during boring to minimize the wear of tube and pipes. The pressure in the system was then 50 kPa, approximately half the normal air pressure. Between the vacuum pump and the boring machine there was a container connected to collect the main part of the cuttings, see Figure 2-7.

Figure 2-6. *Vacuum system with container for larger cuttings (blue) and Disab Vacuum pump (white).*

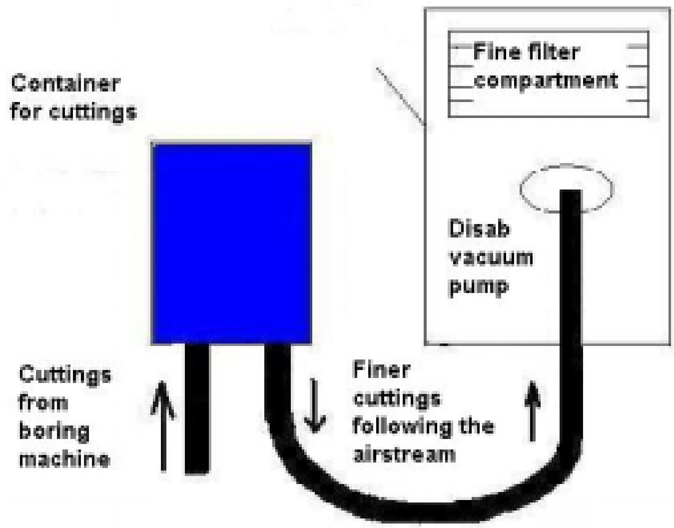


Figure 2-7. Schematic drawing of the vacuum system.

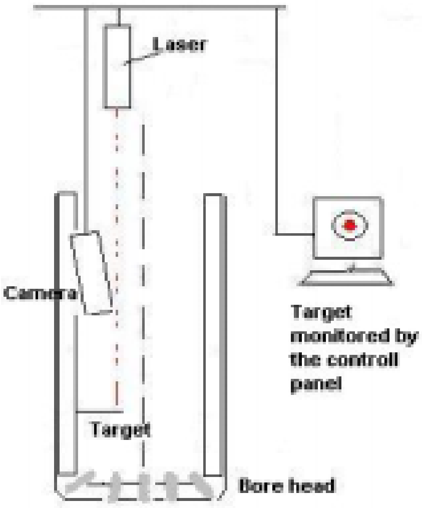
The container for large cuttings (main part) was standing on a scale with an accuracy of +/– 10 kg. The weight of the cutting was measured during boring. The finest grained particles followed the air stream, passed the main collection container and were filtered in the vacuum pump.

2.5 Guidance system

The tolerance of the starting point for the boreholes was 25 mm from the theoretical starting point measured perpendicular to the tunnel axis. The deviation parallel to the tunnel axis could be no more than 50 mm.

The guidance system when boring composed of a laser mounted in the tunnel roof and a target system mounted in the front shield of the SBM, see Figure 2-8. The target was monitored with a camera inside the front shield and a monitor at the control panel. The target was also controlled visually during boring.

To be able to return to the same boring position after adding a new casing the extension of each stabilizer was noted after boring of each casing. Before the start of boring of a new casing the stabilizers were adjusted to the same position as they were at the end of the last casing. This was made to improve the straightness of the hole and reduce the buckling of the borehole wall after changing casings.



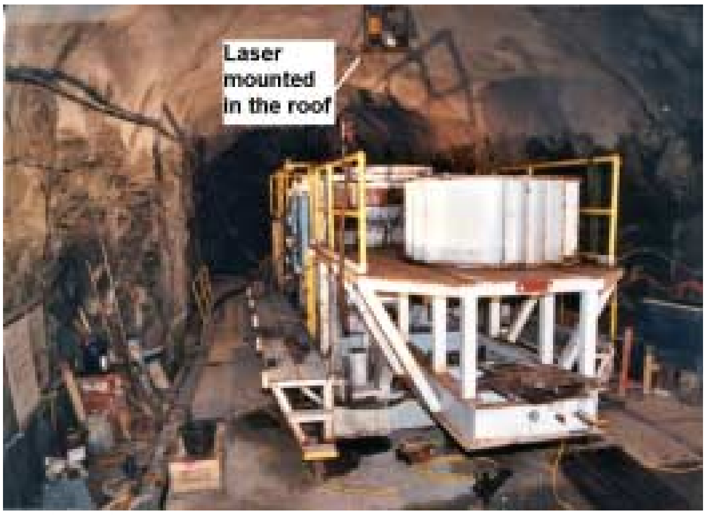


Figure 2-8. *Guidance system. Laser in the roof of the Canister Retrieval tunnel.*

2.6 Casings

The casing assembly was a series of tubular flanged steel structures, see Figure 2-9, with a build in ladder to provide access into the SBM, see Figure 7-3. The standard casings were 800 mm long and there was also a 400 mm long casing supplied to be used if it was necessary to bore a 9.3 meter deep hole.

There were three types of casings. The starter casing consists of two parts. The first part was constructed for the vacuum tube and cables to be led from the inside of the cutter head to the outside of the casing string. On the outside of the other casings there was a niche for the vacuum tubes and cables.

Figure 2-9. *The standard casings were 800 mm long.*

2.7 Test of boring

This chapter will discuss the major problems that arose when boring the first experimental deposition hole DA3147G01 and the actions taken to solve them.

Almost all of the major problems with the boring of the deposition holes were encountered while boring the first deposition hole, DA3147G01. Before the boring could commence there were rather big problems to get the boring machine functional. Most of these problems were due to bad electrical installations that had to be replaced. These problems will however not be discussed in this chapter since after they had been taken care of they did not effect the boring. Some of the data acquisition was though affected due to problems with the transducers. The major problem areas when boring DA3147G01 were:

- The hydraulic system
- The vacuum system with nozzles
- The cutter type and cutter position
- The laser guidance system

2.7.1 Hydraulic system

When the force on the thrust cylinders exceeded approximately 35 tons per cylinder the safety release valve frequently released the oil pressure to the rotation engines in the cutter head. To solve this problem some of the hoses from the hydraulic engine were shortened to reduce vibrations in them. The settings regarding the accumulator tank were tuned and the entire tank was finally replaced.

None of these actions completely solved the problem. It was then suspected that the vacuum system was not able to remove the cuttings from the borehole bottom efficiently enough and that accumulation of cuttings on the borehole bottom dramatically increased the torque needed to revolve the cutter head. This thesis is supported by the fact that the nozzles in the boring head often were clogged. Long steel wires had to be used to remove clogged cuttings in the tube from the nozzles to the swivel in the cutter head.

2.7.2 Vacuum system with nozzles

The first action regarding the vacuum system was to improve the design of the nozzles in the cutter head. At the beginning the four nozzles consisted of a tube that almost reached to the borehole bottom. This design did not concentrate a high velocity air stream radial to the borehole. It was therefore only the cutting in the immediate surroundings of the nozzles that was transported to the container. To increase the speed of the incoming air around the nozzles steel boxes was made and placed around them. The steel boxes were rectangular in shape and directed towards the periphery of the deposition hole. The only larger opening for incoming air was at the end of the box in the holes periphery. The long sides of the box were equipped with steel brooms that should let cuttings pass but stop the air from flowing free into the box from the sides. The action had some effect but the nozzles still became clogged and the safety release valve kept on releasing the pressure.

The second attempt to improve the vacuum system was to try to increase the capacity of the vacuum machine. The so far 90 kW vacuum pump used was connected in series with a 60 kW vacuum pump. The effect of the extra pump on the suction performance could though not be noticed. The nozzles continued to get clogged and it was decided to re-design the cutter head.

What finally solved the problem with the vacuum system were two things. The cutter head was removed from the boring head and the design with four 50-mm tubes from the cutter head to the swivel was changed. Two 150-mm tubes were instead mounted from the cutter head to the swivel. The nozzle to these tubes was designed quite similar to the first ones but instead of steel brooms, stiff rubber edges were used, see Figure 2-10. When the rebuilding of the cutter head was finished the two vacuum pumps were replaced with a 235 kW Disab pump. This new pump was then used for boring the rest of the holes.

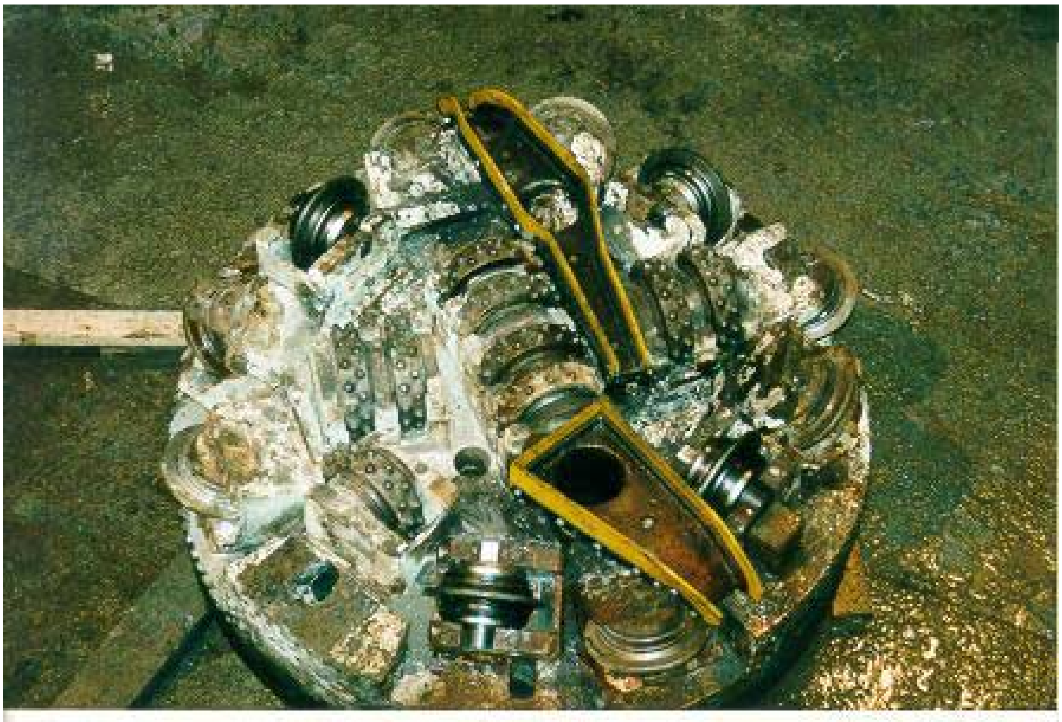


Figure 2-10. *New cutter head design.*

2.7.3 Cutter type and cutter position

When boring DA3147G01 the cutter head was equipped with 20 two-row carbide button cutters. Equipped with carbide button cutters in the outermost positions of the cutter head the button cutters produced deep grooves in the borehole wall, see Figure 2-11.

The most probable reason for the grooves was wrong spacing between both the individual cutters and the spacing of the buttons on each cutter. If the button spacing is too large when boring in rock with high compression strength the rock does not fracture all the way between the neighbouring cutters. Instead craters are created. Since the buttons does not hit the exact same spot for every revolution in the walls the crater becomes extended into a groove.

To solve the problem with the grooves the two outermost cutters were changed from carbide button cutters into disc cutters. Rebuilding of the removal system for cuttings included changing of the two outermost cutters (18A and 18B) into disc-cutters. This action was successful and the borehole walls turned out to be very smooth and the penetration rate was increased. Nine of the front cutters were also changed to disc cutters to improve the penetration rate.

When the rate of revolution reached 12 rpm and more, the rig started to vibrate heavily. The effect of the vibrations on the hole surface has not been investigated in detail but there are no obvious changes in the hole wall quality.

Figure 2-11. *Grooves made by carbide button cutters on the borehole wall.*

2.7.4 Laser guidance system

The bore machine was equipped with a laser guidance system at deliverance. The system consisted of two laser pointers mounted in the bore head in height with the front stabilizers. Two plexiglass targets were mounted at the top of the bore machine. If the bore head deviated from a vertical boring line the laser point would miss the target. The operator could then steer the bore head with the stabilizers back to correct boring position. This system was abandoned for two reasons:

- It was difficult to see the targets properly from the panel.
- The vibrations in the boring head also made the laser pointers to vibrate heavily, which made it very difficult to see if the laser points moved on the targets due to a deviation from the centre line or not.

To solve this problem a vertical laser was mounted in the tunnel roof above the deposition hole to be bored. The laser pointed on a target mounted in the bore head. The target was controlled via a video camera that was connected to a small monitor above the steering panel. The system worked out fine and the laser in the roof was also used when positioning the bore machine over a new boring site.

3 Boring cycle

3.1 Transport and set-up

The trailer with the boring machine was transported into the tunnels with a truck. The trailer was then released from the truck and moved into a more exact position using skids. When moving the boring machine from the Canister Retrieval Test tunnel to the Prototype Repository tunnel, it had to be transported between two levels, from the 420-meter level down to the 450-meter level. That transport was partly performed by a specialized company for heavy transportation and lifting.

To provide guidance when moving the trailer into the right position and to assure that the centre of the cutter head was above the theoretical starting point of the borehole a laser system was set up in the tunnel. By using a parallel displacement of the centre line of the tunnel and a rotating laser, the trailer with the boring machine could be located with good accuracy across the tunnel. The positioning parallel to the tunnel axis was performed with a vertical laser mounted in the tunnel roof and a laser target in the cutter head, see Figure 2-8. When the cutter head was in the right position the trailer was leveled and bolted to the ground or braced to the tunnel roof using the crown reaction pad, see Figure 3-1.

The boring of the holes was performed in two different types of excavated tunnels, drill and blast and TBM. The Workshop, Demonstration tunnel and Canister Retrieval Test were all tunnels excavated with the drill and blast method with a height of more than 5 meters from floor to roof. The Prototype Repository tunnel was excavated with a tunnel-boring machine with a diameter of 5 meters.

Where large overhead spacing existed (drill and blast tunnels), 16 holes, each with a diameter of 43 mm and three meters deep, were bored adjacent to the main beam of the trailer. In these holes re-enforcement bars were casted and the trailer was rock bolted to the launch pad. Within the 5-meter diameter bored tunnel the trailer was anchored by the crown reaction pad, see Figure 7-5. This pad reacts the thrust of the machine directly to the crown of the tunnel. The crown reaction pad was placed on the head frame. Four thrust cylinders were mounted between the pad and the head frame.

One of the problems was the emplacement of the crown on the head frame without having to move the trailer and boring machine out of the tunnel. The crown has an approximate weight of 900 kilos and it had to be lifted approximately 5.5 meter along the front platform. The problem was solved with a special developed construction that allowed the crown to slide over the platform into position, see Figure 8-1.

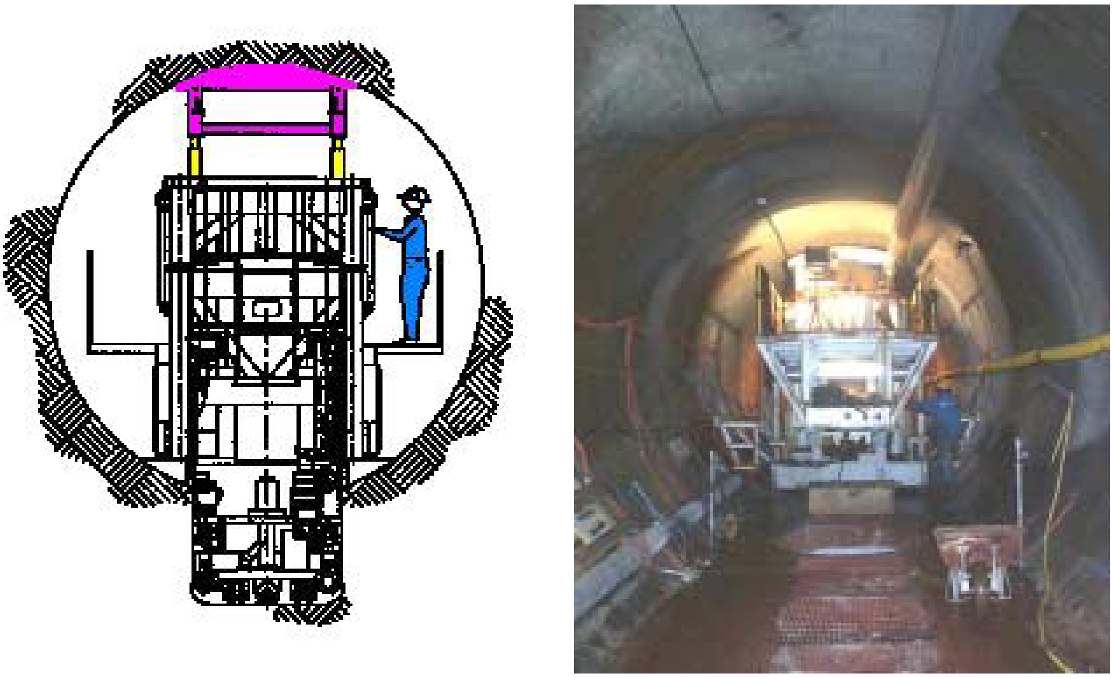


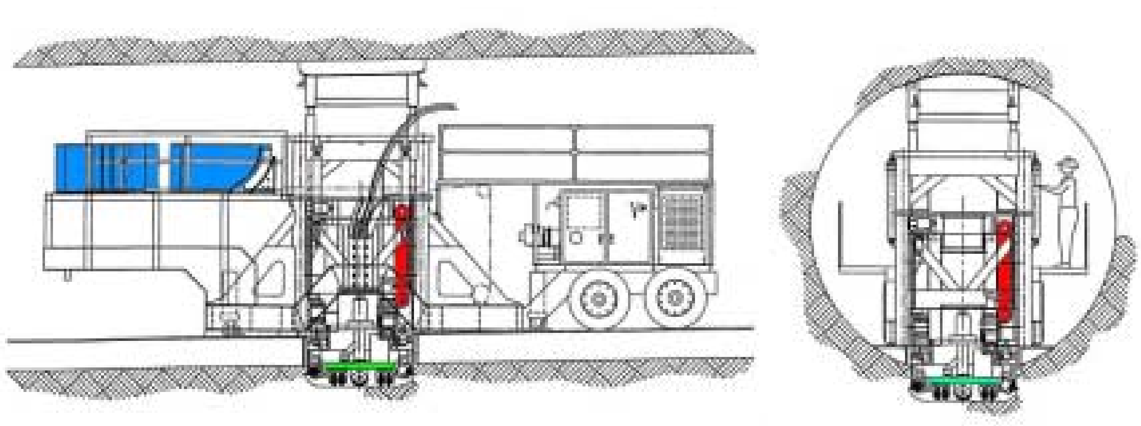
Figure 3-1. The crown reaction pad.

3.2 Boring

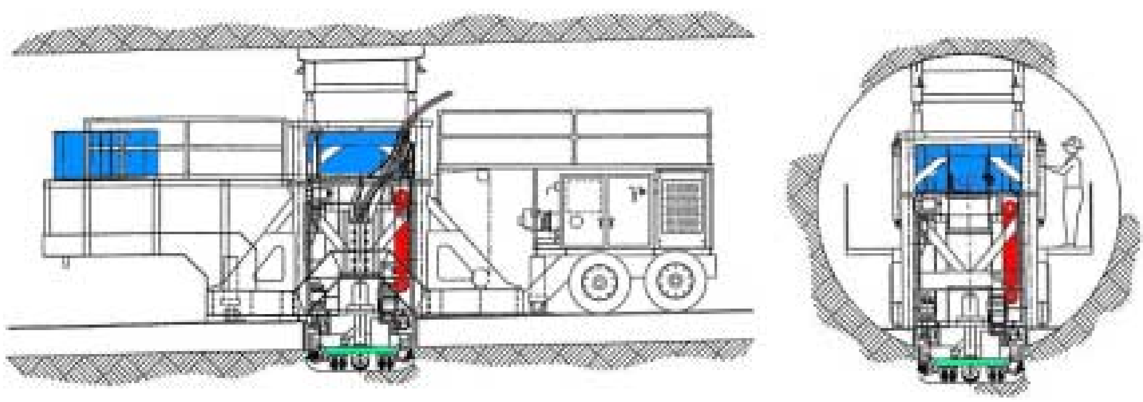
The boring was controlled from the control panel seated on the trailer. The operator could set the boring parameters on his own judgement except for the deposition holes bored in the Canister Retrieval Test. In the Canister Retrieval Test the values of the parameters were set to test the boring performance of the boring machine, see 4.2. The steering of the boring machine was mostly performed with the use of the front stabilizers. A spirit level was placed at the boring machine as a second check method for the control of the straightness of boring and the angel of the bore machine. One of the two operators always controlled the parameters of the stabilizers on the control panel while the other one checked the laser target in the cutter head and the spirit level. Figure 3-2 presents the control panel and the TV monitor to view the laser target in the bore head.

Figure 3-2. The boring was controlled from the control panel seated on the trailer.

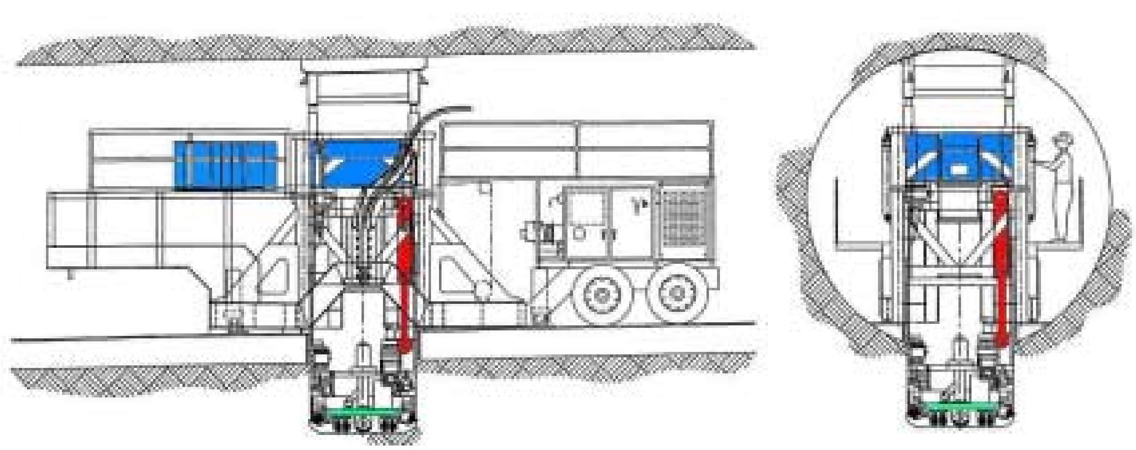
The boring cycle is presented below.



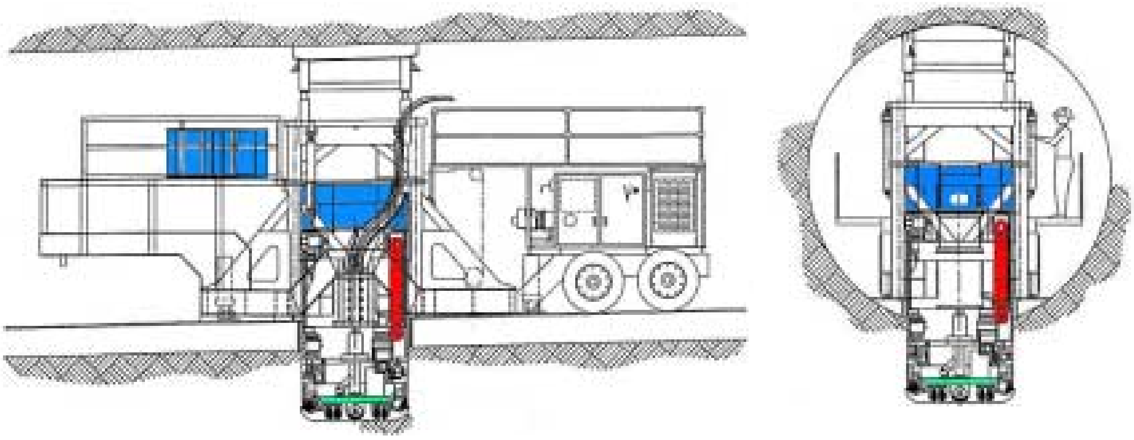
Picture A: Start of a new boring sequence. The starter casing and the second casing is placed on the trailer. The cylinders are fully retracted.



Picture B: The first starter casing has been dragged into position. The casing is then bolted to the SBM and the head frame of the trailer. The lower stabilizers are ungripped and the machine is retracted to steering position.



Picture C: The boring begins and the cylinders are extended fully when one casing is bored. The lower stabilizers are gripped to the shaft wall.



Picture D: The bored chasing is then unbolted from the head frame. The cylinders are fully retracted. A new casing can be dragged into position.

3.3 Change of container for the cuttings

The cuttings were vacuumed and transported from the bottom of the hole through the pipe system to a collecting unit, see Figure 2-7. The unit consisted of two parts, the main container and the vacuum pump. The cuttings were collected in the main container while the finest-grained cuttings were collected in the vacuum pump.

The finest-grained cuttings were transported into the vacuum pump and collected by the main filter. The main filters were cleaned automatically during boring (approximately every tenth minute). The cleaning was carried out buy sudden release of the vacuum. The resultant blasts of air through the filters in a reverse direction rinsed dust out of the filters. The compartment for fine-grained cuttings in the vacuum pump had to be emptied by a bailer after two and a half casing bored, see Figure 3-3.

The container with cuttings was mostly changed after boring of two casings, with exception for the two deposition holes in the Canister Retrieval. When boring the holes in the Canister Retrieval tunnel, tests were done to study the effect of changing boring parameter to the size distribution of the cuttings. Therefore the container was changed after each casing.

When the containers with cuttings had to be changed a truck arrived with an empty container. The pipes were disconnected and the truck loaded the full container and transported it from the boring site to the unloading site outside the tunnel system. The new container was lifted into position on the scale with a wheel-mounted loader, see Figure 3-4.

Figure 3-3. *Fine-grained compartment in the vacuum pump that was emptied by the bailer after two and a half casing bored.*

Figure 3-4. *The new container was lifted into position on the scale with the use of a loader.*

3.4 Handling of casings

There were 10 casings used for the boring of each deposition hole. The casings were stored by the boring machine and were lifted up to the front platform with a loader, see Figure 3-6. The platform could store two casings at the same time.

The first casing was mounted after boring the stroke of 900 mm. The stabilizers were all retracted and the cutter head was left standing in the deposition hole. The eight bolts, connecting the head frame to the boring machine, were released with an electric wrench and removed. A new casing was dragged into position with a hydraulic winch and positioned by hand with an iron bar. Two bolts then centred the new casing to the pushring, and they were then connected with eight bolts, see Figure 2-3 and Figure 3-5. The thrust cylinders then raised the boring machine up to the head frame and two bolts centred the boltholes in the casing and the head frame with each other. The casing was then connected to the head frame with eight bolts. There was also a possibility to use three installed casing steering jacks to help steering the casing string into the right position.

The procedure for installation of a new casing was equal for all casings except for the starter casing where the vacuum tube and cables from the cutter head must be taken into consideration, see section 2.6.

Figure 3-5. *The unscrewing and installation of bolts was done with an electric wrench.*

***Figure 3-6.** Transportation of casings using a loader.*

4 Instrumentation and measurements

4.1 Geometrical criteria

Every hole has been surveyed to control that they fulfilled the geometrical criteria that had been set up. The surveying was done by using a self-adjusting vertical laser at six different positions 60 degrees apart. The laser beam was placed 10–20 cm from the deposition hole wall, see Figure 4-1. The laser's position was surveyed and expressed in Äspö's local coordinate system. The distance between the laser beam and the borehole wall was then measured every 40 cm from the top to the bottom of the hole. The accuracy was +/– 5 mm.

When the measurements were done the coordinates of the borehole wall was calculated at six positions at each level. From these coordinates a mean centre coordinate for each level of the hole was calculated.

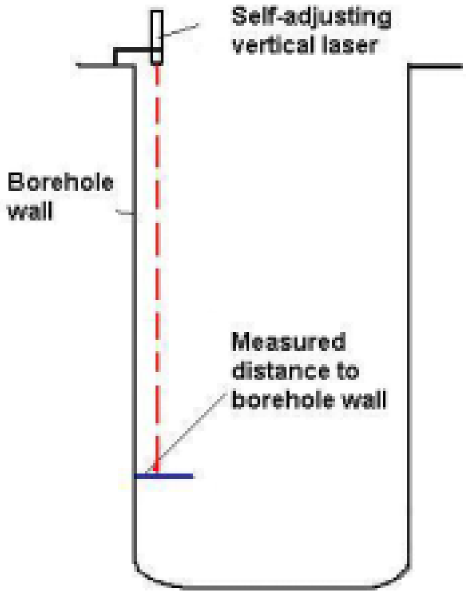


Figure 4-1. *Set up for the control of fulfilling of the geometrical criteria.*

4.2 Boring performance

4.2.1 Data collection during boring

The boring of the deposition holes was carried out to demonstrate the feasibility of the technique used, especially with regard to the quality of the holes and performance of the boring equipment. During boring, a large number of data have been collected for evaluation of the boring performance. The main areas of interest regarding the technical performance were the rate of penetration and the efficiency of the vacuum suction system.

For the data collection InstruNet was used as hardware. InstruNet network supports the digitising of multiple channels at aggregate sample rates of 166kHz, where each channel can be digitised at it's own sample rate.

During boring, data was monitored and analysed in Orchestrator (Measuresoft Technology Ltd). Monitoring of the data during the boring process gave the opportunity to change the boring parameters if judged necessary. After boring of each hole, the collected data was stored on CD-R discs. After the completion of the boring the data has been evaluated and the results are presented in this report.

4.2.2 Measured machine parameters

Absolute time and depth are recorded together with measurements and sampling of:

- Position and rate of rotation of the boring head
- Thrust
- Torque
- Boring and vacuum machine
- Positioning finding pressure indication for stabilizers
- Cutter pressure in the rock wall in borehole DD0086G01 /Zang, 2001/
- Weight of cuttings
- Measurements of pressures in the machines hydraulic system

4.2.3 Sampling equipment

Position and rate of rotation:

Two inductive measuring transducers has been mounted in the gearbox in one of the hydraulic motors that runs the cutter head. One of the transducers transmits 86 pulses and the other one 1 pulse for each cutter head revolution. A pulse initiates when the tooth of a cogwheel in the gearbox passes by the transducers. The measuring transducers transmit a digital signal and were connected to the measurement system. In the measurement system's software there were formulas created to calculate rate of rotation and the position of the cutter head. The sampling rates for these transducers have been 20 Hz to ensure that no pulse could avoid detection. The calculating application for the positioning of the cutter head has been a counter that calculated the number of pulses from the 86 pulse transducer. The 1 pulse measuring transducer has been used to re-zero the counter after one revolution. The 86 pulses correspond to 0–360 degrees. The rate of rotation has been calculated through the numbers of revolutions during a specific time.

Thrust on the cutter head:

Four thrust jacks with a maximum force of 70 tons each created the pressure on the cutter head. A pressure transducer has been mounted in each cylinder. The transducers were from Data Instruments (xpro series with an outlet of 4–20 mA which corresponds to 0–345 bar (0–5000psi, 0–34.5MPa)) in the measurement system. The sampling rate was 20 Hz.

Differential pressure (Torque):

The torque for the hydraulic motors has been measured with two pressure transducers (Data Instruments xpro series). They measured the pressure difference between the inlet and outlet on the hydraulic pump for the driving motor. A formula to calculate the torque using the pressure difference was included in the measurement system. The sampling rate was 20 Hz.

Consumption of energy boring machine:

The energy used by the boring machine has been measured on the electrical feed cable to the hydraulic pump. Outlet from the transducers was 4–20 mA. The sampling rate was 20 Hz.

Consumption of energy vacuum machine:

The energy consumption of the electrical fan in the vacuum container was measured. The outlet from the transducers used for the measurements was 4–20 mA. The sampling rate was 20 Hz.

Level indicators and pressure transducers for stabilizers:

The four front stabilizers and the four stabilizers in the rear had been mounted with stroke indicator sensors. The transducers were from Data Instruments (DC Hydrastar series) and the function was similar to the level indicators for borehole depth but more compact. The four stabilizers in the front have also been mounted with the same type of pressure transducers as in the thrust jacks. If one of the stabilizers indicates maximum stroke and maximum pressure at the same time it was an indication for the operator that the stabilizers has found or made a cavity in the rock. The outlet from these transducers was 4–20 mA corresponding to 0–10 cm in the measurement system. The sampling rate was 20 Hz.

Level indicators for borehole depth:

The borehole depth was sampled with thrust jack stroke indicators. The indicators were linear potentiometers made by Parker Hannifin and mounted in each of the four thrust jack cylinders. The cylinder stroke was 900 mm for the cutter head alone and 800 mm for each casing. The outlet from the measuring transducers was 4–20 mA and corresponds to 0–900 mm in the measurement system. In the measurement system there was a manual counter where the number of casings added should be written. The counter added the total number of casings and stroke to calculate the total boring depth. The sampling rate for these transducers was 20 Hz.

Weight of cuttings:

The cuttings were vacuumed through the suction line to a container.
4 strain gauges from Nobel Elektronik (KIS-1) have been used to measure the total weight of the container and cuttings. The sampling rate was 20 Hz.

Cutter transducers:

Luleå University of Technology has done measurements on two of the cutters. Six strain gauges have been mounted to measure the strain of the shaft for the cutter load. Two gauges have been attached to measure temperature on the shafts. Information has been exchanged through wireless transmission using radio frequency (Telemetry) /Zang 2001/.

4.3 Particle size distribution

With the construction used for the vacuum suction system it was not possible to collect typical samples during boring. Samples have mainly been taken from DD0092G01 but also from borehole DD0086G01. The containers with cuttings was transported from the boring level up to the surface and emptied on the ground. The piles were then marked with borehole- and casing-number. It was important that all the cuttings from the boring of one casing (with the same parameter set-up) were collected in one container. When all the casings had been bored samples were taken from the cutting piles. It was important that it did not rain on the piles in the time span between emptying of the containers and the sampling causing smaller cuttings to be flushed away. No samples were taken from the fine filter compartment where the finest grained particles were collected.

When making the actual sampling the piles where brought to level with a loader to an even height of approximately 30 cm. A shovel was used to collect cuttings and the sampling was made using approximately the same grid for all the levelled piles. Between 24 and 39 kg of cuttings were collected from each pile and placed in a plastic bag in a bucket. From three of the piles duplicate samples were taken to be able to assess the reliability of the sampling method.

The samples were sent to SGU (Swedish Geological Survey) in Linköping and were treated in accordance with SS-EN 45 001. The samples were sieved under flowing water to be able to separate small rock particles from larger chippings. The samples were collected from cuttings created with the boring parameter set-ups listed in Table 6-3. The cutter set-up during boring of DD0092G01 is listed in Appendix 1.

4.4 Shape of cuttings

Samples have been taken from containers containing cuttings from:

- DK0051G01 casing 5, 6 and 7.
- DK0045G01 casing 2, 3, 4, 5 and 6.
- DD0086G01 casing 8 and 9.

No cuttings with a length less than 10 millimetres were included in the statistics. DK0051G01 casing 5, 6 and 7 had a rate of rotation of 9 rpm and the thrust 45 tons. DK0045G01 2 casing 2, 3, 4, 5 and 6 had a rate of rotation of 8.5 rpm and the thrust 40 tons. DD0086G01 casing 8 had a rate of rotation of 9.8 rpm and a thrust of 50 tons. Casing 9 had a rate of rotation of 9.5 rpm and a thrust of 46 tons.

The sampling method was the same as for the sampling for the evaluation of particle size distributions, see 4.3. From the sampled cuttings approximately one litre was taken and the fine-grained material removed. The length, width and thickness of approximately 100 to 170 pieces of cuttings were selected and measured with a caliper.

4.5 Acoustic emission and ultrasonic Monitoring

An ultrasonic array was installed around each deposition hole in the Canister Retrieval tunnel and two of the holes in the Prototype Repository tunnel. Measurements were performed to investigate the response of the rock mass to the excavation. Acoustic emission monitoring has been used to delineate zones of stress related fractures around the deposition hole perimeter. Changes in ultrasonic velocities measured every hour have been used to investigate the response of the rock mass over a broader time and volume than the AE scale and to quantitatively measure the accumulation of fracturing in the damaged zone.

Ultrasonic monitoring started three days before the start boring of each deposition hole, and continued for a number of days after the finish of the boring. Monitoring was performed 24 hours per day except during any time of high frequency noise in the rock volume. During each boring round the acquisition system was switched off. After each casing a two-hour quiet period was observed on the tunnel when no maintenance was allowed on the boring machine. This period was used for AE monitoring. Ultrasonic surveying was conducted hourly to obtain high resolution in the P- and S-wave velocity and amplitude variation along the transmitter receiver ray paths /Pettit et al, 1999/.

4.6 Measurements of cutter forces

A part of the characterization work after the boring was the determination of the crack propagation in the rock wall caused by the boring process. As a first step of this characterization the acting forces on two cutters, one side cutter and one front cutter, have been measured during boring. A second step was to take core samples from the deposition hole wall and the cracks remaining in the rock caused by the mechanical boring were investigated in laboratory. The purpose of the rock sampling in the deposition hole and the subsequent crack discrimination in the laboratory at the division of Rock Engineering at Luleå University were to support the preliminary TBM crack model being developed at the University.

Two cutters, nr 10 and 18A, were prepared for strain gauge wiring, see Figure 2-5. The strain gauges were mounted inside the cutter and the wires brought to the end of the cutter. A small hole and protective cover was provided in each position to rout the wires to the rear side of the cutter head. Luleå University of Technology provided the strain gauge installation. A series of strain gauges were glued at different locations on the cutter axis. A telemetry system for the transmission of signals was used. From the transducers in the cutters there was a cable to the transmitter located on one of the vacuum pipes in the cutter head. The receiver antenna was positioned on the upper part of the boring machine and the receiver instrument at the measurement station, Figure 4-2. Batteries were used as power supply to the transmitter /Zhang, 2001/.

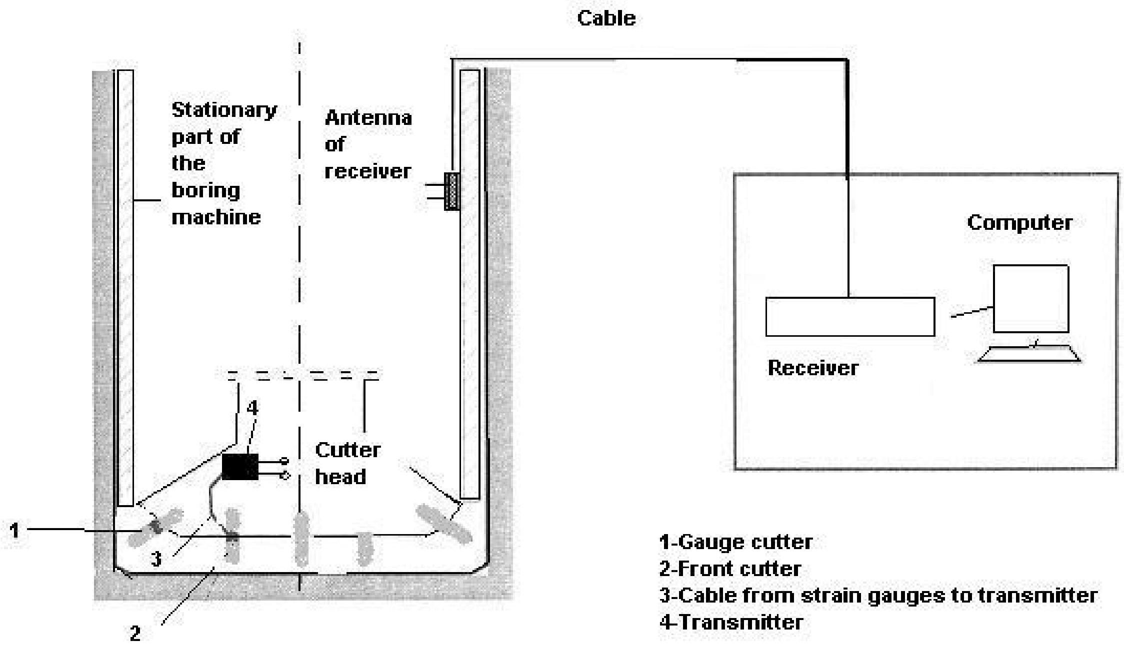


Figure 4-2. *The field-testing system for measurements on cutters.*

5 Experiment procedures and Results

5.1 General

After completion of boring of each deposition hole it was surveyed to make sure that the geometrical criteria were fulfilled. When all the deposition holes had been bored an extensive characterization program was carried out.

Seven of the deposition holes have been chosen for interpreting bore machine data, the two holes in the Canister Retrieval Test and five of the holes in the Prototype Repository tunnel.

During boring of the two holes in the Canister Retrieval Test several test series were carried out where different combinations of thrust and rate of rotation were used. The different combinations had the objective to test the boring-machines performance, e.g. to find the optimum parameter set-up. When boring the second Canister Retrieval Test hole, two instrumented carbide cutters were mounted on the cutter heads 10 and 18A, see section 4.6 and Figure 2-5. These cutters were used to measure the temperature in the cutters bearing and measure normal-, tangential- and side force on single cutters /Zhang, 2001/.

When boring the deposition holes in the Prototype Repository the boring crew could chose the parameter set-up they found most appropriate to make certain that the geometrical criteria were full-filled, see Geometrical criteria 1.5.1.

The configuration of disc and carbide cutters was changed between some of the holes. The configuration for each hole is presented in Appendix 1.

5.2 Canister Retrieval Test

5.2.1 Borehole DD0092G01

The objective of these test series was to see how the penetration rate changed due to the use of different boring parameters. Cuttings from the different boring parameters were also sampled and sieved in order to determine the difference in grain size distribution due to different boring parameters, see 6.2.

From the data achieved during boring representative sections have been chosen for the different parameter set-ups. The objective was to choose continues sections with as long length as possible with a certain parameter set-up. This resulted in that 62% of the logged data was used (approx. 5.3 m per hole). The resulting rate of penetration for the different parameter set-ups is listed in Table 5-1 and in graphical form in Figure 5-1 and Figure 5-2. In Table 5-1 the net penetraton rate in mm/h as well as an extrapolation of the penetration rates to 10 rpm for easier comparison.

Table 5-1. Resulting rate of penetration for different boring parameters in borehole, Canister Retrieval Test DD0092G01.

Section	RPM	Thrust per cylinder [ton]	Section length [mm]	Time [min]	Average rate of penetration [mm/rev]	Rate of penetration at 10 rpm [mm/rev]	Net penetration rate [mm/h]
DD0092G01 1.1	6.3	35	302	59	0.81	1.29	297
DD0092G01 1.2	9	35	462	63	0.81	0.90	485
DD0092G01 1.3	14.7	34	705	39	1.23	0.84	458
DD0092G01 1.4	6.3	40	527	53	1.58	2.51	466
DD0092G01 1.5	9.5	41	720	60	1.26	1.33	720
DD0092G01 1.6	15.4	41	580	32	1.18	0.77	309
DD0092G01 1.7	5.6	46	758	70	1.93	3.45	884
DD0092G01 1.8	9.8	46	614	39	1.61	1.64	399
DD0092G01 1.9	15	46	720	44	1.09	0.73	528

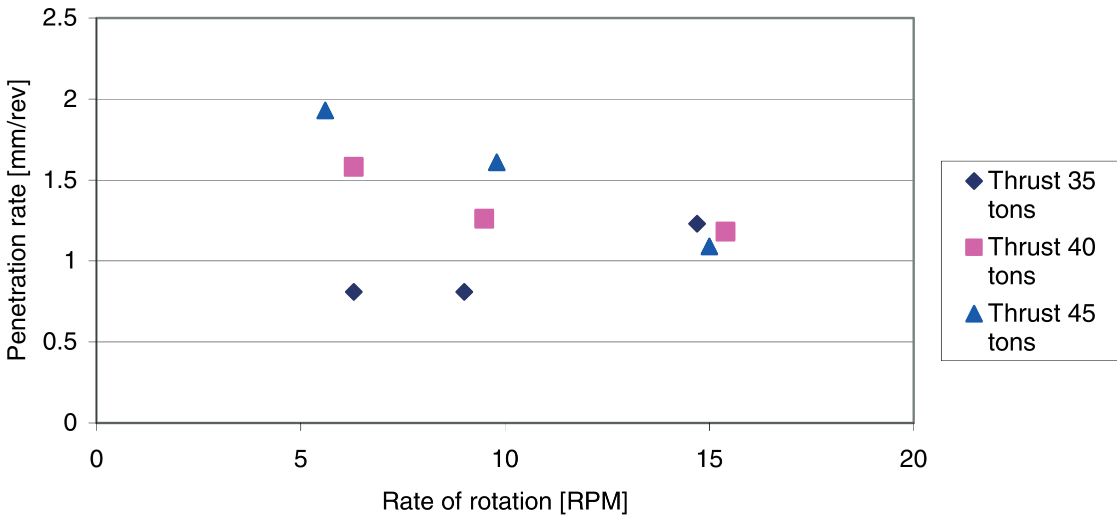


Figure 5-1. Rate of penetration as a function rate of rotation in DD0092G01 (the thrust represents the thrust of one of four cylinders).

The maximum rate of penetration was achieved when the rate of rotation was approximately 5.6 rpm and the thrust per cylinder 45 tons.

From Figure 5-2 it can be seen that the penetration rate is higher as the thrust is increased and from Figure 5-1 it seems that the penetration rate becomes lower as the rate of rotation increases. One reason for this might be that the crushing of rock functions well but the removal of cuttings does not working well at higher rate of rotation.

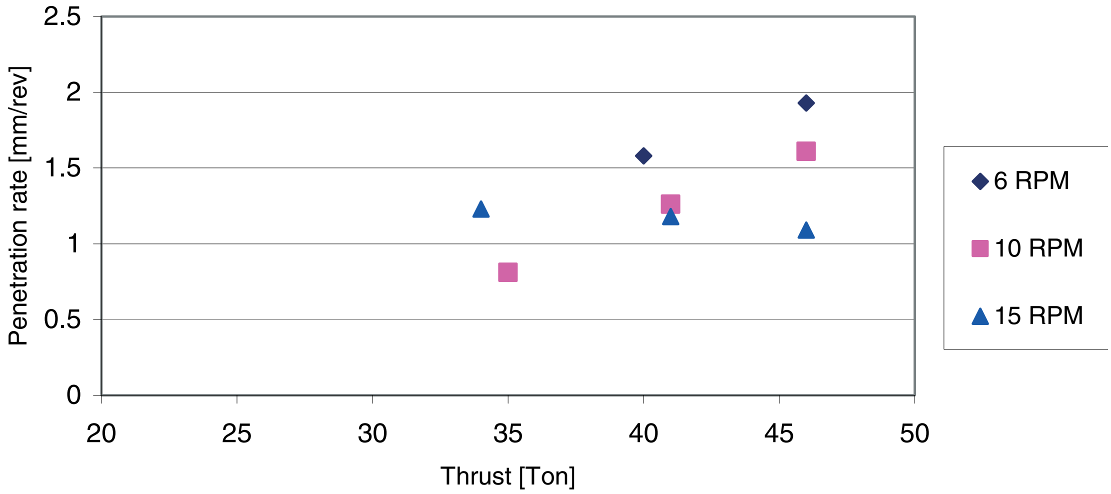


Figure 5-2. *Rate of penetration as a function of thrust in DD0092G01 (the thrust represents the thrust of one of four cylinders).*

During boring of DD0092G01 1.9 (high rate of rotation) the safety release valve to the hydraulic engines opened frequently. This valve opens when the torque required to rotate the cutter-head rate exceeds approximately 120–140 kNm. When this happens the thrust on the cutter head must be released a few moments, which results in a very inequitable boring cycle. The vacuum system is not able to remove all cuttings from the borehole bottom, the resistance on the rolling cutters and the cutter head then becomes too high and the machine opens the hydraulic valve to protect the system.

5.2.2 Borehole DD0086G01

During boring of selected sections in DD0086G01 Luleå University of Technology was collecting data from two different cutters, cutter 10 and cutter 18B of which cutter 18B is the outermost cutter, see section 4.6. The university had prepared carbide cutters for their tests. The disc cutters in these two positions and position 18A (to have the outermost cutters of the same type) were therefore changed to carbide cutters. The change hade to be made despite the knowledge that the button cutters in outermost position causes groves on the borehole wall, see section 2.7.3.

The objective with the test series carried out in this hole was to compare the penetration rate between DD0092G01 and DD0086G01 when the same parameter set-ups were used. The objective was also to let Luleå University collect cutter data from parameter set-ups that they required.

From the data achieved during boring representative sections have been chosen for the different parameter set-ups. The objective was to choose continuous sections with as long length as possible with a certain parameter set-up. The resulting rate of penetration for the different parameter set-ups is listed in Table 5-2. As for hole DD0092G01 the penetration rate becomes higher as the thrust is increased, see Figure 5-4. When the rate of rotation is increased the penetration rate becomes lower, see Figure 5-3.

Table 5-2. Resulting rate of penetration for different boring parameters in borehole DD0086G01.

Section	RPM	Thrust per cylinder [ton]	Section length [mm]	Time [min]	Average rate of penetration [mm/rev]	Rate of penetration at 10 rpm [mm/rev]	Net penetration rate [mm/h]
DD0086G01 2.1	8.5	33	187	46	0.48	0.56	143
DD0086G01 2.2	15.7	40	305	66	0.29	0.18	336
DD0086G01 2.3	15	44	170	9	1.26	0.84	26
DD0086G01 2.4	15.4	40	122	10	0.79	0.51	20
DD0086G01 2.5	9.8	35	726	119	0.62	0.63	1 440
DD0086G01 2.6	9.5	45	743	75	1.04	1.09	929
DD0086G01 2.7	10.1	45	714	72	0.98	0.97	857
DD0086G01 2.8	9.8	50	707	70	1.03	1.05	825
DD0086G01 2.9	9.5	46	170	16	1.12	1.18	45
DD0086G01 2.10	9.5	46	650	57	1.2	1.26	618
DD0086G01 2.11	9.8	40	686	93	0.75	0.77	1 063

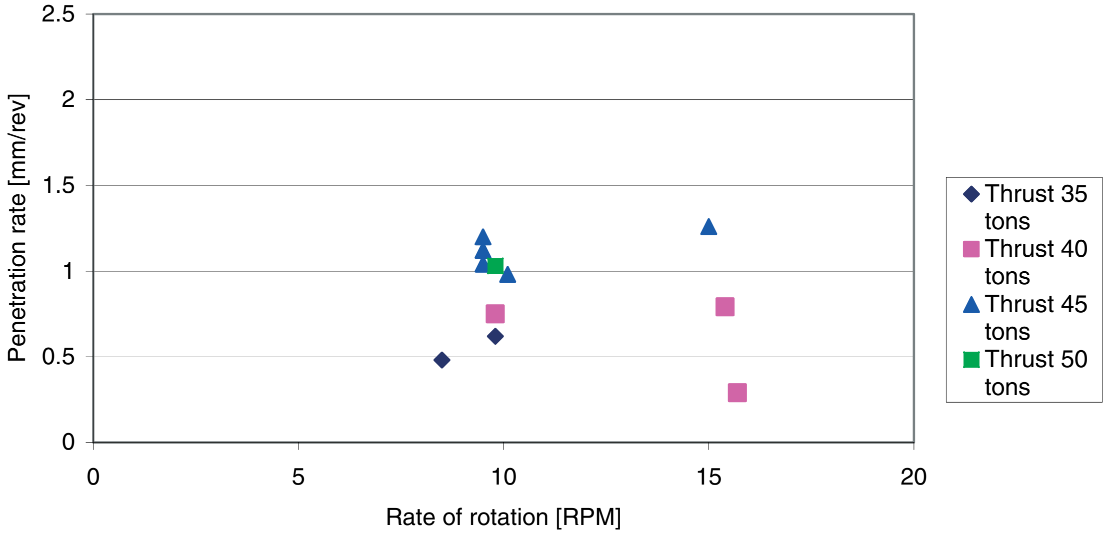


Figure 5-3. Rate of penetration as a function rate of rotation in DD0086G01 (the thrust represents the thrust of one of four cylinders).

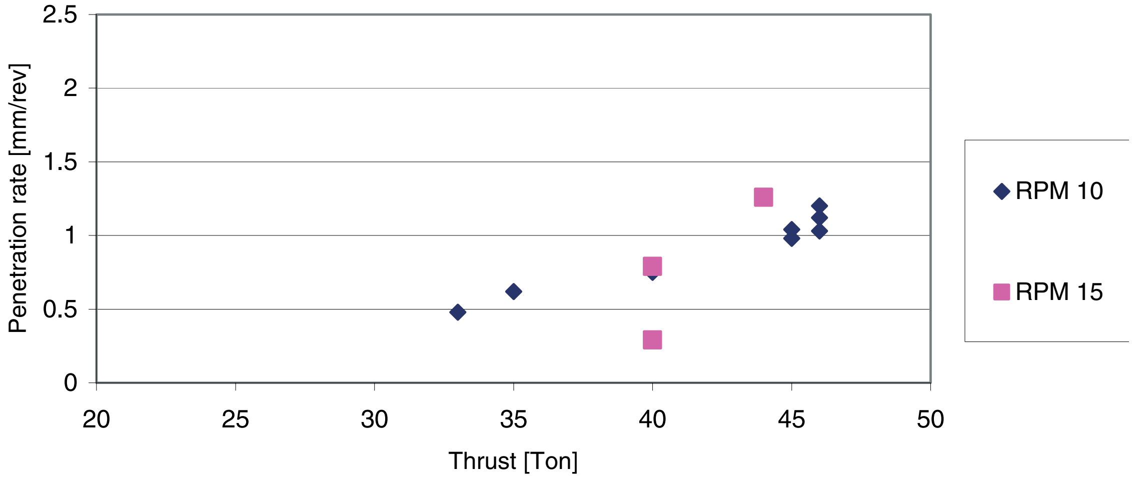


Figure 5-4. Rate of penetration as a function of thrust in DD0086G01 (the thrust represents the thrust of one of four cylinders).

5.2.3 Comparisons between DD0092G01 and DD0086G01

Comparisons between section DD0092G01 casing 1.2, 1.5, 1.8 and DD0086G01 casing 2.1, 2.5–6, 2.8–11 indicates that the penetration rate is higher in borehole DD0092G01. Also comparisons between section DD0092G01 1.6 and DD0086G01 2.2 give the same indication (Table 5-3).

When looking at the rate of penetration in the two holes, Figure 5-4 and Figure 5-2, and also including the rate of penetration in hole DA3587G01, Figure 5-5, the rate of penetration between DD0092G01 and DA3587G01 seems similar. The cutter layout for the two holes differ on four front cutters, Appendix 1. Hole DD0092G01 has disc-cutters in position 10–13 while DA3587G01 has carbide button cutters in these positions. The replacement of four front cutters does not seem to have an effect of the boring performance.

When comparing borehole DD0086G01 with the two boreholes above it is indicated that the changing of the two outermost cutters from disc cutters into carbide button cutters decreases the boring performance. The penetration rate in DD0086G01 is clearly lower than in the other two boreholes. The replacement of the two outermost cutters into button cutters had a clear effect on the boring performance. The button cutters making grooves in the borehole wall and not breaking the rock in the right way probably causes this effect. More thrust is needed to move the cutter head downwards.

There is a very low rate of penetration in section DD0086G01 2.2. One reason for the low penetration rate might be malfunctioning of the boring machine. One of the four hydraulic engines in the boring head broke down during boring of DD0086G01 2.3 and the head was raised up from the hole for reparation. Observations were then made that some of the cutters had been very worn since the start of boring of this hole. The wearing on the cutter wheel from the boring in this hole was much larger than during the boring of all the other holes bored so far. The explanation is probably, as mentioned above, that the button cutters are not breaking the rock efficiently and instead cause grooves.

Table 5-3. Comparison of different sections in DD0086G01 and DD0092G01.

Section	RPM	Thrust per cylinder [ton]	Section length [mm]	Time [min]	Average rate of penetration [mm/rev]	Rate of penetration at 10 rpm [mm/rev]	Net penetration rate [mm/h]
DD0092G01 1.2	9	35	462	63	0.81	0.90	485
DD0086G01 2.1	8.5	33	187	46	0.48	0.56	143
DD0092G01 1.5	9.5	41	720	60	1.26	1.33	720
DD0086G01 2.5	9.8	35	726	119	0.62	0.63	1 440
DD0086G01 2.6	9.5	45	743	75	1.04	1.09	929
DD0092G01 1.8	9.8	46	614	39	1.61	1.64	399
DD0086G01 2.8	9.8	50	707	70	1.03	1.05	825
DD0086G01 2.9	9.5	46	170	16	1.12	1.18	45
DD0086G01 2.10	9.5	46	650	57	1.2	1.26	618
DD0086G01 2.11	9.8	40	686	93	0.75	0.77	1 063
DD0092G01 1.6	15.4	41	580	32	1.18	0.77	309
DD0086G01 2.4	15.4	40	122	10	0.79	0.51	20

5.3 Prototype Repository, observations from logged data

When studying the bore machine data from the boring in the Prototype Repository five deposition holes have been taken in consideration. The sixth hole has been neglected because of malfunction of the transducer that was measuring the rate of rotation.

During boring of the deposition holes the boring crew quite frequently changed the thrust and rate of rotation. Sections in the logged data have been selected with small to none variations in the thrust and rate of rotation parameters. Each section containing an almost constant parameter set-up for a boring length of approximately 10 cm was selected. These criteria resulted in that 59–76% of the boring length was selected from the different holes. On average 67% of the logged data was used (approximately 5.5 m per hole).

The first 3–5 cm of each chosen section in the boreholes were ignored. The disturbed zone from the boring of the previous casing could this way not effect the compared data. A table of the studied sections is included in Appendix 2.

The penetration rate during boring was studied with respect to:

- Rate of rotation
- Geology
- Depth in borehole
- Use of stabilizers

5.3.1 Penetration rate with respect to rate of rotation

Data from the selected parameters was first visualized by drawing of diagrams with the rate of penetration as a function of thrust for each studied borehole. The objective was to see if small changes in the rate of rotation gave different rates of penetration.

When studying the small differences in rate of rotation for each hole in Figure 5-5 to Figure 5-9 the penetration rate is unaffected. The difference in the rate of rotation is too small to see any differences in penetration rate.

The penetration rate in five of the holes in the Prototype tunnel is compiled in Figure 5-10. The first hole bored was DA3587G01 and the last borehole DA3551G01. It can be seen that the penetration rate decreases as the boring progresses in the tunnel. Worn cutters and rubber sleeves can have caused the decrease of penetration rate. The cutters and sleeves were not always changed into new ones as they were worn, during boring of these holes, since it was known that the boring of the experimental deposition holes at Äspö was almost finished.

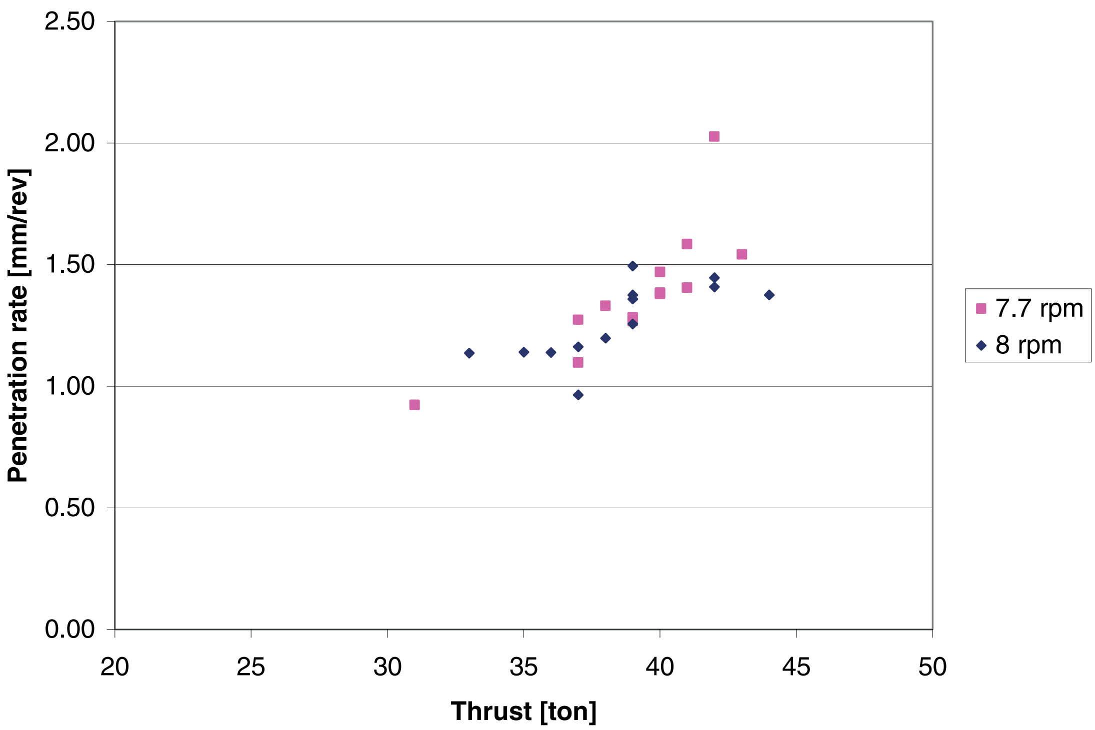


Figure 5-5. *Penetration rate in borehole DA3587G01 (the thrust represents the thrust of one of four cylinders).*

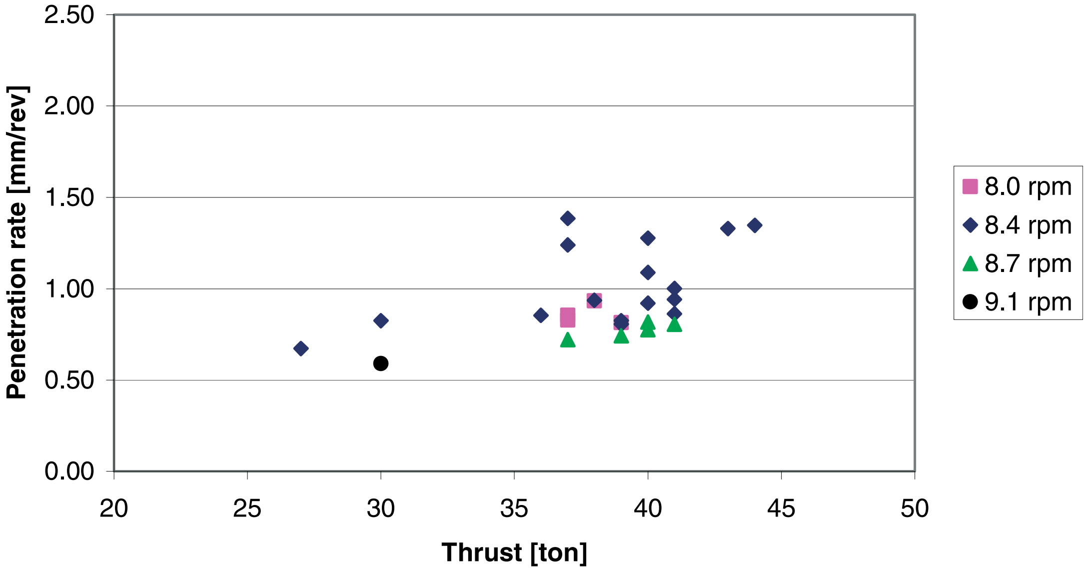


Figure 5-6. Penetration rate in borehole DA3581G01 (the thrust represents the thrust of one of four cylinders).

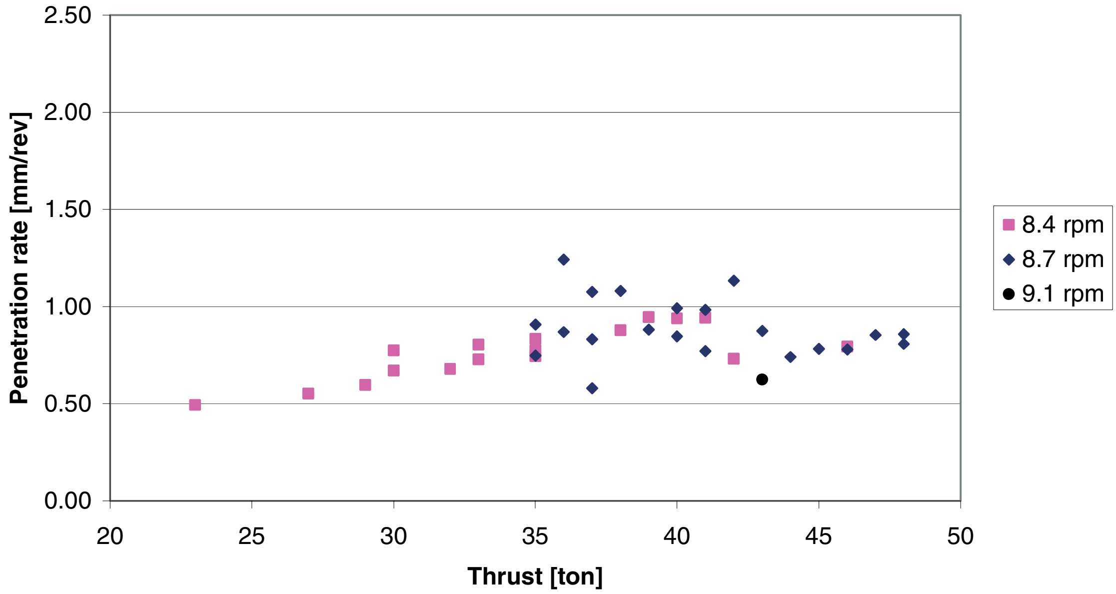


Figure 5-7. Penetration rate in borehole DA3575G01 (the thrust represents the thrust of one of four cylinders).

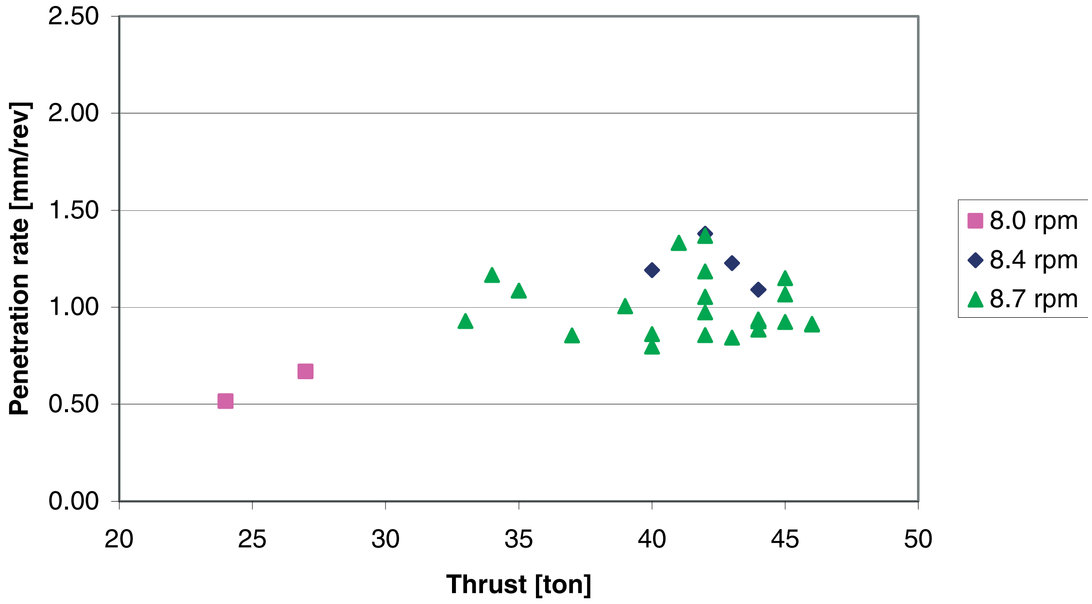


Figure 5-8. Penetration rate in borehole DA3569G01 (the thrust represents the thrust of one of four cylinders).

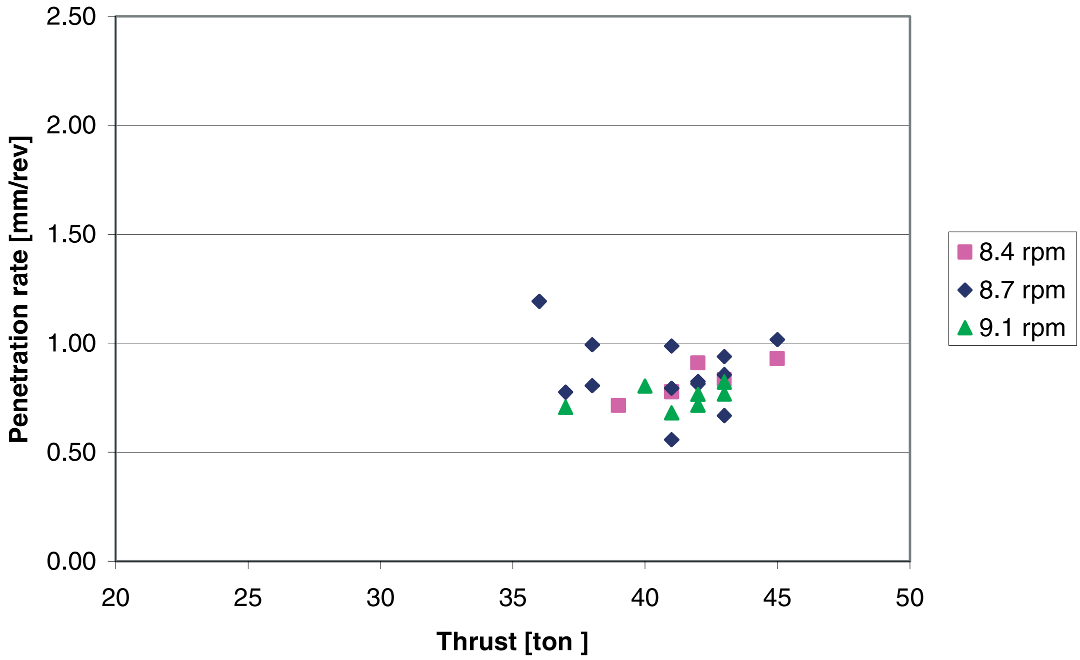


Figure 5-9. Penetration rate in borehole DA3551G01 (the thrust represents the thrust of one of four cylinders).

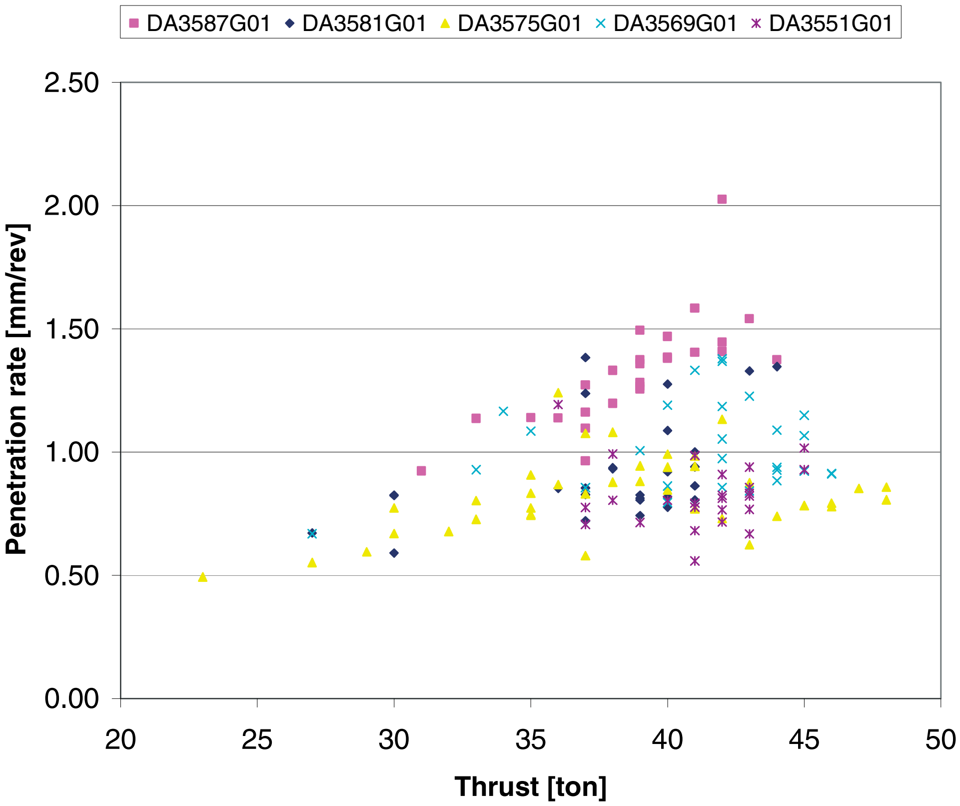


Figure 5-10. *Penetration rate in 5 holes in the Prototype Repository (the thrust represents the thrust of one of four cylinders).*

5.3.2 Rate of penetration versus actual boring depth

The rate of penetration was plotted against the actual boring depth. With exception of deposition hole DA3575G01 there is a trend towards a lower rate of penetration in the second half of the holes, see Figure 5-11 and Appendix 3.

The probable reason is that the vacuum suction system cleans the borehole more efficiently at an upper level than deeper down in the borehole.

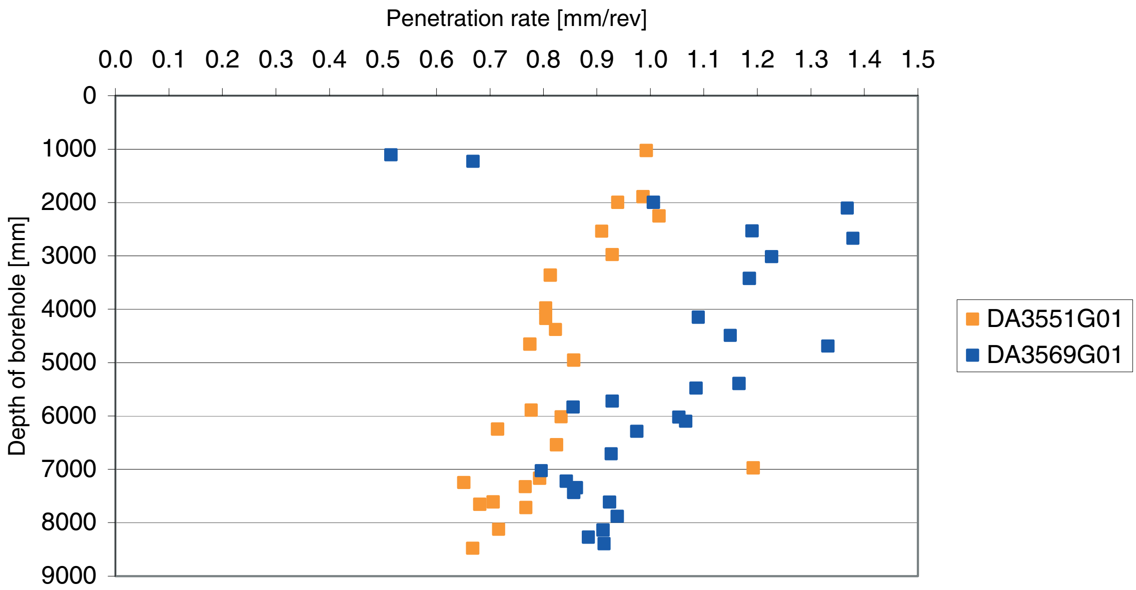


Figure 5-11. Penetration rate versus depth of borehole in DA3551G01 and DA3569G01.

5.3.3 Geology

The advance rate for the studied sections was first compared with the charts drawn by the geologist during the detailed geological mapping. The objective was to study if more fractured zones or zones with a majority of the fractures oriented vertical or horizontal influenced the advance rate.

The advance rate was then compared with colour photographs taken of the deposition hole walls with the objective to see if the advance rate was influenced by variations in the geology spotted on the geologist's chart or the photographs.

No relations between the advance rate and the fracturing or variation in geology were found and the conclusion is that this part of the bedrock, from a boring point of view, is very homogenous with a rather evenly distributed fracture network. The fracture mapping and the water inflow locations of the deposition holes in the Prototype Repository is presented in Appendix 6.

5.3.4 Effect of stabilizers on penetration rate

When comparing different sections with the same thrust and the same rate of rotation to the advance rate the results are inconsistent. It is not unusual to find a 30% difference in the advance rate when using the same parameter set-up in different parts of one deposition hole. It was noticed when boring that the change of the thrust on the stabilizers might have had an effect on the advance rate. When pressing the stabilizers against the rock wall a frictional force is created which reduces the thrust on the cutters. During boring, normally 2–3 of the 4 stabilizers were used for the steering. The thrust on the stabilizers was individually changed approximately 15–20 times every hour. The magnitude of each thrust change was though small and in the range of 0.05–0.15 tons. The maximum thrust on each stabilizer is about 20 tons, but a thrust higher than 15 tons was rarely used. Normally, the average thrust on three stabilizers was 7 tons each. If a friction coefficient at 0.7 is assumed the thrust on the cutter-head is reduced by 14.7 tons or 0.8 tons per cutter. The holes in the Prototype Repository were studied with the objective to try to find a possible relationship between the boring performance and the use of the stabilizers.

If the advance rate in different sections in the last three meters bored in deposition hole DA3587G01 and DA3581G01 is compared it is obvious that the values of deposition hole DA3587G01 are more scattered. A comparison of the thrust from the stabilizers on the rock wall in the same part of the hole was made. That indicated that the stabilizers in DA3587G01 were more frequently changed and the thrust on the stabilizers was also higher than in DA3581G01.

To further investigate the role of the stabilizers to the rate of penetration a few sections in each of the five deposition holes were selected. The selection was made with the criterion that the rate of penetration should differ at least 20% between two points of observation located close to each other. The compared sections are listed in Table 5-4.

Table 5-4. Compared sections with at least 20% difference in rate of penetration. Section start and stop are measured from the roadbed.

Deposition hole	Thrust per cylinder [ton]	Rate of rotation [rpm]	Penetration rate [mm/rev]	Section start [mm]	Section stop [mm]
DA3587G01 #1	42	7.7	2.03	3464	3542
	37	8.0	0.96	3604	3712
DA3587G01 #2	41	7.7	1.58	3978	4100
	39	7.7	1.28	3775	3854
DA3587G01 #3	39	8.0	1.38	6698	6753
	37	8.0	1.16	6819	6977
DA3581G01	40	8.4	0.97	4942	5122
	37	8.4	1.24	5260	5312
DA3575G01	36	8.7	1.24	4317	4371
	35	8.7	0.75	4821	4886
DA3569G01	37	8.7	1.17	5392	5463
	34	8.7	0.86	5834	5901
DA3551G01	41	8.7	1.19	6977	7060
	36	8.7	0.79	7168	7237

DA3587G01

The differences in penetration rate in both sections #1 and #2 depend on rather large changes in the thrust to the stabilizers. A higher rate of penetration is achieved when less thrust on the stabilizers are used. There are though no indications in section #3 that the difference in rate of penetration depends on the stabilizers.

DA3581G01

In this section the higher rate of penetration coincides with higher thrust on the stabilizers.

DA3575G01

The section with a penetration rate of 1.24 mm/rev seems to have lower thrust on the stabilizers. The difference in thrust on the stabilizers between the two compared sections is though very small.

DA3569G01

The combined thrust on the stabilizers in these sections is rather equal. The section with higher penetration rate might even have a bit higher thrust on the stabilizers than the slower section.

DA3551G01

The difference in combined thrust on the stabilizers in these two sections is very small and the difference in penetration rate does not seem to depend on it.

After studying these sections it does not seem like that the use of the stabilizers can explain the occasional large variations in rate of penetration in the deposition holes. The comparison is summarized in Table 5-5.

Table 5-5. Stabilizers effect on penetration rate.

Deposition hole	Rate of penetration	Thrust on stabilizers
DA3587G01 #1	High	Low
DA3587G01 #2	High	Low
DA3587G01 #3	No indication	
DA3581G01	High	High
DA3575G01	High	Low
DA3569G01	High	High
DA3551G01	No indication	

5.4 Conclusions

It can be seen that the net penetration rate increases as the thrust and the rate of rotation is increased. The penetration rate per rotation is though decreased when the rate of rotation is increased. One reason for this might be that the crushing of rock functions well but the removal of cuttings does not work well at higher rate of rotation. When the vacuum system is not being able to remove all cuttings from the borehole bottom the resistance from the rolling cutters and the cutter head becomes too high and the machine opens the hydraulic valve to protect the system. It is possible that the penetration rate could be increased if a boring machine that produces higher torque is used.

It can also be seen when boring DD0086G01 that the changing of the two outermost cutters from disc cutters to button cutters had a clear effect on the penetration rate. The explanation is probably that the button cutters are not breaking the rock the right way and instead cause grooves. The wearing on the cutter wheel from boring this borehole was much larger than during boring of all holes bored so far. An example of the wearing of the cutters is presented in Figure 5-12. The insufficient breaking of the rock creates ridges of intact rock on which the cutter matrix is worn upon. Finally the matrix around the buttons becomes too thin and the buttons fall off. To prevent this the future design of a deposition hole boring machine needs to be more thought through.

When comparing the rate of penetration for sections with small variances in the rate of rotation in the Prototype tunnel no correlation could be found. The reason for this is probably that variations in the rate of rotation have been too small to result in variations in the rate of penetration.

There is a trend towards a lower rate of penetration in the second half of the holes. The probable reason is that the vacuum suction system cleans the borehole more efficiently at an upper level than deeper down in the borehole. A cutter head designed to produce cuttings with a smaller particle size could increase the vacuum system's performance in the lower part of the deposition holes.

No connections between the rate of penetration and changes in the geology and use of stabilizers were found.

While boring the holes in the Prototype Repository there was water leaking into the holes from the tunnel. There was no control of the amount of leakage into the holes. It was though noted that it did not have a clear effect on the performance.

Figure 5-12. *Wear of button cutter.*

6 Results from geometrical and particle size measurements

6.1 Geometrical measurements

A compilation of the results from the surveying of the deposition holes is presented in Table 6-1 and Table 6-2. Offset X and offset Y is the distance between the true centre point in the beginning of the hole and the theoretical one. Deviation X and deviation Y is the deviation of the centre point in the deposition hole bottom compared to the true centre point in the beginning of the hole. X corresponds to North and Y corresponds to East.

In deposition hole DK0051G01 the largest difference between the vertical projection of the actual starting point and the centre point in the bottom of the hole is found and calculated to 13 mm. The criterion for this projection was set to 25 mm. On average the difference between the start and end points is 5 mm.

The maximum horizontal displacement of the centre point at certain depths for the different holes is presented in Table 6-2 as bending. Bending is the largest distance between the centre point, at any depth, and a line going through the true start and end centre point of the hole. Bending depth is the distance from the tunnel floor to the point where the largest bending distance was measured. The table also presents the average diameter of the holes. The radius was measured in 6 points 60 degrees apart at 23 different levels.

Diameter average is the mean diameter of the deposition hole calculated from measurements at 23 different levels.

The criterion for the maximum bending was set to 16 mm. This value was exceeded in deposition holes DA3147G01 and DK0051G01 that were the first deposition holes bored. The average bending for all the thirteen deposition holes is 8 mm.

The offset, deviation and bending terms are explained graphically in Figure 6-1.

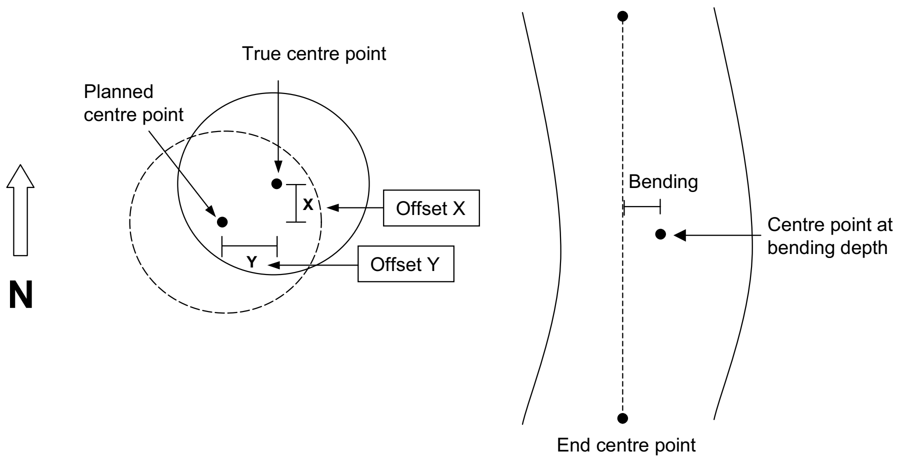


***Figure 6-1.** Explanation of the offset, deviation and bending terms.*

Table 6-1. Compilation of results from surveying of the deposition holes showing the difference between the vertical projection of the actual starting point and the centre point.

Deposition hole ID	Offset X [mm]	Offset Y [mm]	Deviation X [mm]	Deviation Y [mm]
DA3147G01	6	–4	4	7
DK0051G01	5	4	12	5
DK0045G01	2	–10	4	–6
DK0031G01	3	–12	3	5
DK0025G01	2	6	–1	–2
DD0092G01	2	–9	3	–5
DD0086G01	16	0	0	1
DA3587G01	2	–6	–5	–2
DA3581G01	11	2	–6	5
DA3575G01	–1	–6	0	1
DA3569G01	–4	–5	0	4
DA3551G01	4	–5	0	4
DA3545G01	9	–8	–1	1

Table 6-2. Compilation of results from surveying of the deposition holes presenting the maximum horizontal displacement of the centre point for the different holes. The table also presents the average diameter of the holes.

Deposition hole ID	Bending [mm]	Bending depth [mm]	Diameter average [mm]
DA3147G01	24	4000	1757
DK0051G01	19	5200	1763
DK0045G01	3	5600, 6000, 6400, 7200, 7600	1758
DK0031G01	7	4400, 5200	1770
DK0025G01	4	6000	1756
DD0092G01	6	6800	1762
DD0086G01	6	5200	1757
DA3587G01	6	3200	1760
DA3581G01	5	2800	1760
DA3575G01	5	1600, 2400, 7200	1761
DA3569G01	4	3600, 4400, 7600	1761
DA3551G01	6	3200	1762
DA3545G01	8	5600	1760

6.2 Particle size distribution

Cuttings from mainly the boring of deposition hole DD0092G01 but also from deposition hole DD0086G01 were collected for sieving analysis. The boring parameter set up during boring DD0092G01 is presented in Table 6-3. A complete set of diagrams for the three main groups including its sub groups is included in Appendix 5.

The resulting curves from the sieving analysis have been arranged in three different main groups. The main groups are divided into sub groups in which the comparisons have been made. The main groups and their sub groups are:

1. Same thrust
   - 5 rpm
   - 10 rpm
   - 15 rpm
2. Same rate of rotation
   - 35 tons
   - 40 tons
   - 45 tons
3. Same rate of penetration
   - 1.20–1.21 mm/rev
   - 1.99 and 2.17 mm/rev

The difference in the sieving results is very small. Most of the graphs presented in this section are ones that gave some kind of relationship between the boring performance and the particle size. A complete set of graphs from the sieving is presented in Appendix 5.

Table 6-3. Boring parameter set-up during boring of deposition hole DD0092G01.

Section [depth in mm]	Rate of rotation [rpm]	Thrust per cylinder [ton]	Rate of penetration [mm/rev]
900–1700	5	35	1.02
1700–2500	10	35	0.73
2500–3300	15	35	1.21
3300–4100	5	40	1.99
4100–4900	10	40	1.20
4900–5700	15	40	1.21
5700–6500	5	45	2.17
6500–7300	10	45	1.56
7300–8100	15	45	1.09

When comparing results from the sections where the rate of rotation was 15 rpm there is a very small difference between the sections where the thrust was 35 and 40 tons respectively. Where the thrust was raised to 45 tons the accumulated weight up to 8 mm is 5–10 percent higher, Figure 6-2.

When comparing the sieving results at constant rotation speed and at constant thrust the difference is small. Even if a cross comparison is made, the difference is still small.

There is though an indication of difference in sieving result when comparing the results from the constant rotation group, Figure 6-3 and Figure 6-4. The group with the lowest rate of penetration curves have roughly the same particle size distribution. The particle size in the group with penetration rates between 1.99 and 2.17 mm/rev has an approximately 5–10% smaller share of cuttings with a grain size smaller than 8 mm compared to the lower penetration rate sieving curves.

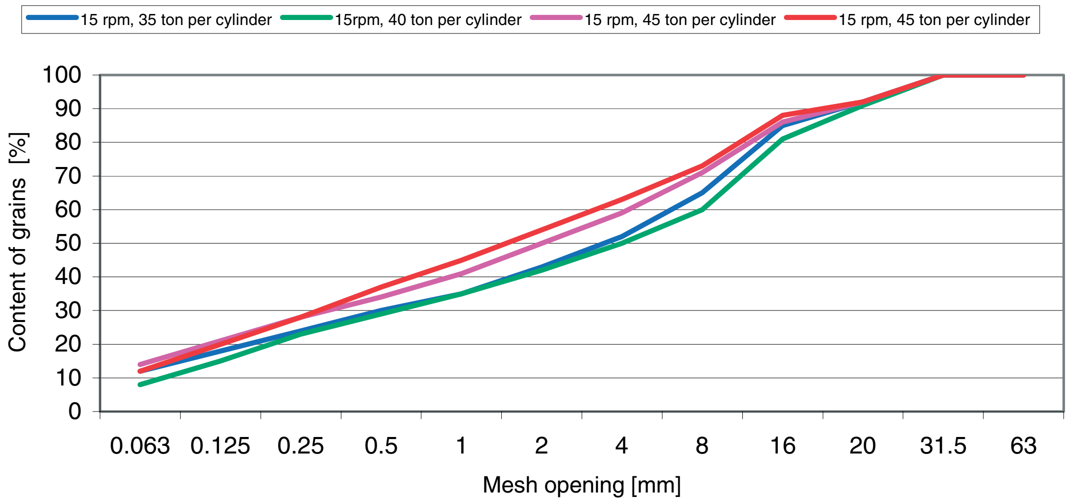


Figure 6-2. *Sieving analysis from sections where the rate of rotation was 15 rpm, DD0092G01.*

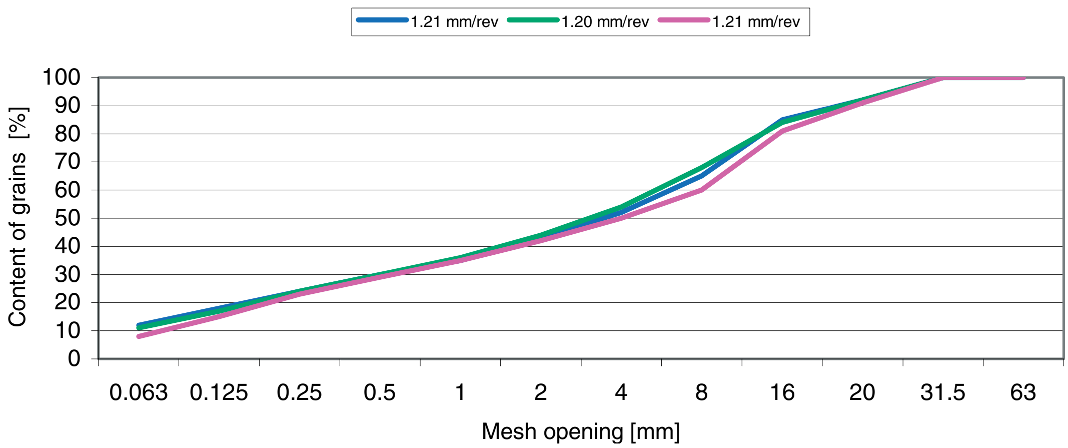


Figure 6-3. *Sieving analysis from sections where the rate of penetration was 1.20–1.21 mm/rev, DD0092G01.*

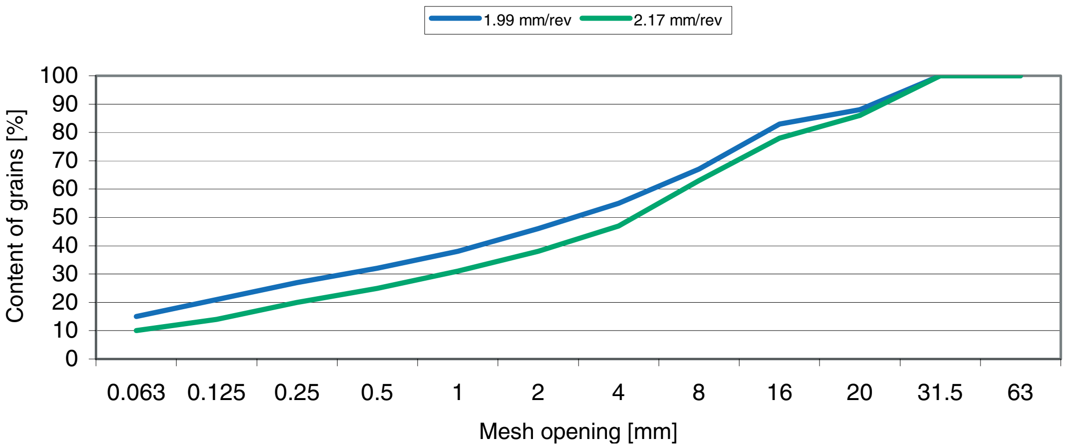


Figure 6-4. *Sieving analysis from sections where the rate of penetration was 1.99 and 2.17 mm/rev, DD0092G01.*

It was mentioned before that the difference in the sieving results is very small. Figure 6-5 presents a graph with all the sieving curves from borehole DD0092G01 for the reader's own comparison.

The average d_{50} value for all samples is 2.8 mm (50% of the cumulative weight is less than 2.8 mm). However the d_{50} value for the sub-groups with the highest penetration rate is approximately 4 mm and for the other 2 groups approximately 2 mm.

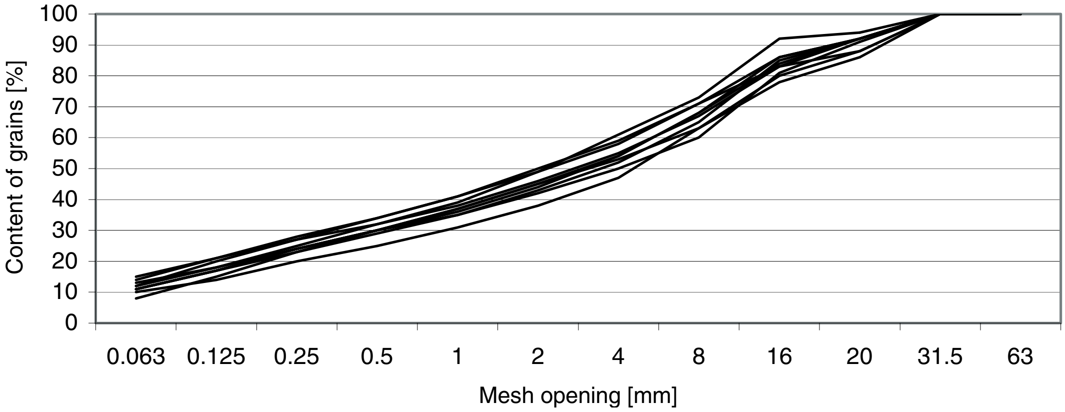


Figure 6-5. *Sieving analysis from all 10 casings boring DD0092G01.*

6.3 Shape of cuttings

The size of cuttings is quite irregular when comparing the four different samples. The difference is probably due to both the performance of the boring machine and the sampling technique. The cutter head set-up was changed after completion of DK0051G01. Yet another cutter-head set-up was used in DD0086G01. A table of the precise type and position of different cutter types is included in Appendix 1. Three of the samples roughly have the same size of cuttings but the results from DK0045G01 indicate larger particle size. The larger particle size likely depends on the cutter head configuration.

When the particles were measured the ratio between length and thickness (elongation) and width and thickness (flakiness) was calculated. Average values from the particle size measurements for the four samples are listed in Table 6-4.

Table 6-4. Average values from particle size measurements.

Sample	Length [mm]	Width [mm]	Thickness [mm]	Elongation (length/width)	Flakiness (width/thickness)
DK0051G01	20.5	15.2	6.1	3.52	2.62
DK0045G01	29.4	20.9	8.0	3.78	2.73
DD0092G01 #8	22.6	16.9	6.0	3.84	2.89
DD0086G01 #9	22.9	17.5	6.8	3.50	2.68

7 Work time analysis

7.1 General

A work time analysis on the boring of the 13 deposition holes at Äspö HRL during 1998–1999 was made. The analysis was based on daily reports from the contractors and from time investigation made by SKB personnel on the site during boring of all the thirteen deposition holes.

The boring cycle has been divided into 11 different activities, as follows:

A	Transport
B	Set up
C	Preparations for boring
D	Boring
E	Repair & Maintenance of boring machine
F	Repair & Maintenance of vacuum system
G	Repair & Maintenance of other equipment
H	Change of container for the cuttings
I	Measurements during and after boring (Measurements on cutters and Acoustic Emission)
J	Miscellaneous
K	Handling of casings

7.2 Organization

Drillcon Raise AB performed the boring. The work time was scheduled to be twelve-hour shift, six days a week with two operators and one supervisor. The twelve-hour shift initiated that three men worked at a rolling schedule, two weeks of work and one week off.

At the beginning, before the machine was working properly, the Robbinson Company also had one person on site helping out installing the cutter head and solving problems before starting up. Because of the delays, caused by late deliverance and other installing problems with the machine at the beginning, the working hours mostly varied from day to day and week to week. Working time was also influenced by other activities in the tunnel system.

SKB had one to two engineers collecting data from the boring process during boring. SKB also supplied personnel for installation of transducers, emptying containers and moving equipment.

All the time units presented are calendar time. Two workers were always working together. Hence the calendar time has to be multiplied by two to get the total man hours.

7.3 Time spent on different activities

7.3.1 Transportation

The time for transportation was measured from the time that all the casings were dismantled until the excavation started at the next hole. This time also includes transportation of tools, equipment for the vacuum system and containers for the measurement system.

The transportation of the trailer with the boring machine was performed with a loader. The distance had a big impact on the time used for transportation. The transportation time from one boring site to another lasted longer because of the transportation of the extra equipment for the measurement system and the vacuum suction system. When moving between deposition holes in the same tunnel the transportation time was less. The time for transportation was longest for the three deposition holes DK0051G01 (15h), DD0092G01 (29h) and DA3587G01 (36h), see Figure 7-1. In all these cases the machine, vacuum equipment and containers were transported from one tunnel to another. When moving the trailer with the boring machine to the Prototype Repository tunnel, it had to be transported between two levels, from the 420-meter level down to the 450-meter level. This caused the long transportation time of 36 hours. The transport was partly performed by a specialized company for heavy transportation and lifting. The transportation time for the equipment between two holes was on average six hours. The actual transport time for the trailer with the boring machine itself was approximately 1 hour.

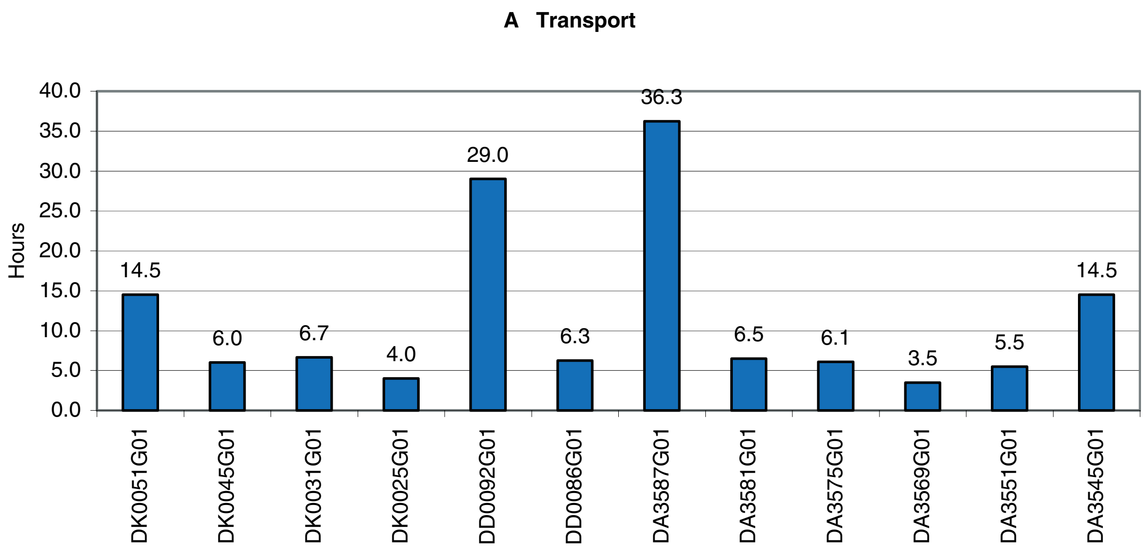


***Figure** 7-1. Time used for transportation. Calendar hours.*

7.3.2 Set-up

Set up of equipment includes:

- Survey and positioning of machine
- Installation of power supply
- Boring of holes for rock bolting and grouting of re-enforcement bars or mounting the crown reaction pad.

Most of the set up time for deposition hole DK0051G01 in the Demonstration tunnel (53 hours) was spent on positioning the machine over the deposition hole including preliminaries for the laser position and bolting the machine to the floor.

A vertical laser was mounted in the roof of the tunnel and a laser target positioned in the cutter head. The laser target was monitored through a camera mounted inside the cutter head. The arrangement was made to improve the steering and the related straightness of the deposition hole. Problems when bolting the machine to the floor also delayed the start of boring. The hardening of the grouted cement did not work properly. Time spent for "set up" also included setting up the pipeline for the transportation of cuttings.

When boring deposition hole DA3587G01 in the Prototype Repository tunnel the vacuum unit had to be stationed outside the tunnel to leave room for transportation of the casings in and out the tunnel. This caused much time for mounting the pipeline system in the 96-meter tunnel, see Figure 7-3.

Figure 7-2. *Crown reaction pad in the Prototype Repository Tunnel.*

Figure 7-3. Mounting of pipeline in the Prototype Repository tunnel.

7.3.3 Boring preparations

Boring preparations includes time in the morning, where for example the mounting of the camera inside the boring head is included. The installation and preparation for the measurement systems affected the time for preparation in the Canister Retrieval Test holes DD0092G01 and DD0086G01 and in the Prototype Repository hole DA3569G01.

7.3.4 Boring

This activity includes the actual boring time for each deposition hole. Figure 7-7 presents the time spent for the actual boring of each hole. Actual boring time: time used only for boring. All time for maintenance and handling of casings is excluded.

The average boring time was approximately 19 hours. The deposition holes in the Workshop hall, Demonstration tunnel and in the Canister Retrieval Test tunnel had all a concrete floor between 400–800 mm thick. In the Prototype Repository tunnel the deposition holes could be bored directly through rock and no time was spent for penetrating concrete. The actual time required for boring one large hole was approximately 2.5 h/m except for three holes: DK0031G01, DK0025G01 and DK0092G01, see section "Demonstration tunnel" below. A compilation of the time required for boring the different deposition holes is presented in Table 7-1. The actual time required for boring one large hole in Finland was in the range of 2.4–2.8 h/m /Autio et al, 1996/.

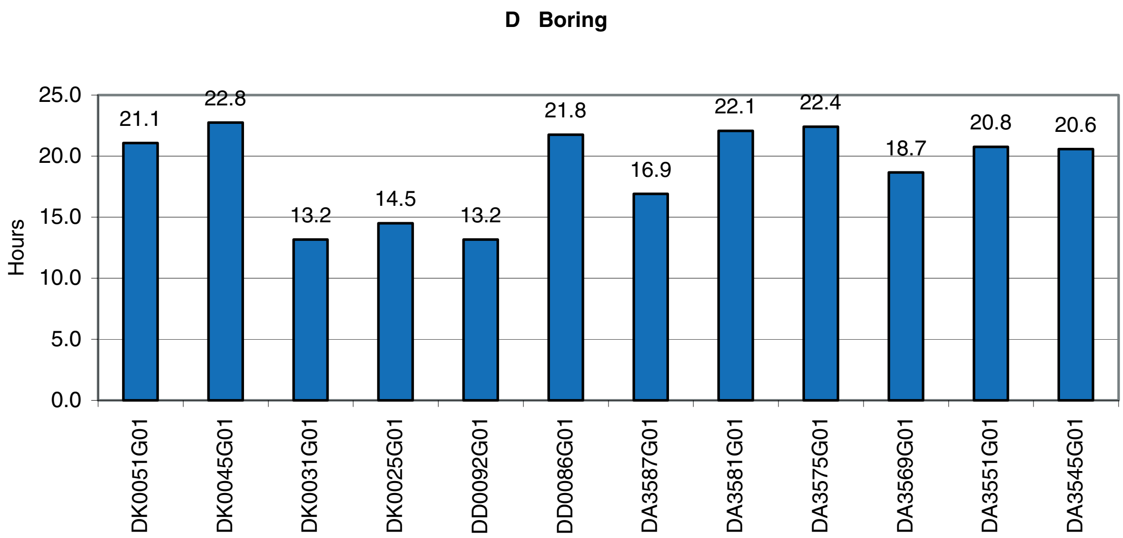


Figure 7-4. Calendar time invested for the actual boring of each hole.

Table 7-1. Calendar hours per meter.

Deposition hole	Boring hours	Hours / meter
DK0051G01	21.1	2.4
DK0045G01	22.8	2.6
DK0031G01	13.2	1.5
DK0025G01	14.5	1.7
DD0092G01	13.2	1.5
DD0086G01	21.8	2.5
DA3587G01	16.9	2.1
DA3581G01	22.1	2.7
DA3575G01	22.4	2.7
DA3569G01	18.7	2.3
DA3551G01	20.8	2.6
DA3545G01	20.6	2.5

Demonstration tunnel

The boring of two of the deposition holes in the Demonstration tunnel lasted only 13 hours each. Before the start of the boring of the second hole in the demonstration tunnel four of the disc cutters were changed to new carbide button cutters (Appendix 1). The cutter head was also equipped with new rubber sleeves.

Canister Retrieval test tunnel

In the two deposition holes in the Canister Retrieval test SKB carried out tests in order to establish the effect of changes in the operating parameters on the performance of the boring equipment and the quality of the resulting hole. The time spent for the boring activity varies a great deal between the two holes. DD0092G01 took 13 hours and DD0086G01 took 22 hours. In DD0092G01 the machine was equipped with 13 disc cutters and boring parameters were changed after each casing, see 5.2 Canister Retrieval Test. The test pushed the machine quite hard and increased the wearing and tearing of the machine and the cutters. When boring casing #3 in DD0086G01 one of the gearboxes broke down. It was then discovered that some of the cutters had had substantial wearing during boring of these three casings. Test with different operating parameters was supposed to be carried out in DD0086G01 but because of the break down of the gearbox and the wearing of the cutters the test was cancelled. The operator instead operated the boring machine on his own judgement. Six of the cutters had to be changed after completion of DD0086G01 before the boring could commence in the Prototype Repository.

Prototype Repository tunnel

In the Prototype Repository tunnel the boring time for each deposition hole varies between 17–23 hours. No major changes were made to the cutter head that could affect the boring rate.

7.3.5 Reparation and maintenance of boring machine

This activity includes all maintenance of the cutter head including the change of cutters. Most of the time spent for reparation of the boring machine was during installation of the boring machine in the Workshop before start boring of the first deposition hole, see section 2.7.

Boring of the first deposition hole in the Workshop hall lasted 48 days. After improvement of the vacuum system and changing of vacuum suction machines the reparation and maintenance of the boring machine summed up to a total of 223 hours.

The time invested for reparation and maintenance of the boring machine was short for most of the deposition holes. Change of cutters was often the reason for accumulation of time on this activity. For two of the deposition holes, DD0086G01 (96h) and DA3587G01 (39h), the reparation of the boring machine was time consuming.

When boring the third casing in DD0086G01, one of four gearboxes for the rotation broke down and had to be changed. Before taking out and changing the gearbox dismantling of the casings, the vacuum system in the cutter head, hydraulic tubes and the hydraulic motor had to be done. The new gearbox had to be delivered from USA.

The time spent for maintenance in DA3587G01 mainly reefers to the changing of six cutters and changing of the vacuum systems' rubber sleeves on the cutter head (28h).

7.3.6 Reparation and maintenance of vacuum system

The repair and maintenance of the vacuum system was one of the activities that was most time consuming, a total number of 129 hours. Over all, the vacuum system was the critical part of the boring.

The first vacuum equipment used at DA3147G01 was not powerful enough to effectively remove the cuttings. A new vacuum unit was therefore brought in before boring of deposition hole DK0051G01 in the Demonstration tunnel. In the beginning problems occured with the driving belts. They were sliding and the heat generated at some times caused them to break and long stops for reparations had to be made. There were also problems with cuttings getting clogged in the nozzles and in the transportation tubes.

When boring the deposition holes in the Canister Retrieval tunnel the cuttings wore a hole in the swivel connection in the cutter head. The swivel was replaced with a new one when the broken down gearbox was changed.

The rubber sleeves on the cutter head also had to be changed after boring deposition hole DK0051G01 in the Demonstration tunnel and after the two holes in the Canister Retrieval tunnel, see section 2.7.2.

Most of the problems with the vacuum system in the Prototype Repository tunnel appeared when boring deposition hole DA3551G01 and DA3545G01. The problem was not the long transportation line but the vacuum suction itself. Before boring hole DA3551G01 the emergency shutdown broke down and had to be replaced before the start of boring.

When boring borehole DA3545G01 the door to the large cutting section on the vacuum machine got stuck and could not be opened and cleaned. The cleaning of the small section had therefore to be done more often.

Figure 7-5. *Wear of vacuum hose.*

7.3.7 Reparation and maintenance of other equipment

The disturbance of the boring cycle caused by reparation on other equipment than the boring head and the vacuum suction line can mostly be related to improvement of the working cycle. Two major improvements were made during the boring of the thirteen deposition holes. The first was the installation of a vertical laser in the roof and a target in the cutter head for the controlling of the straightness of the boring head during boring. The change was made before the start of boring of the first hole in the Demonstration tunnel. The laser system also includes a mounting of a camera inside the boring head and a monitor by the controlling board. The other major improvement was the beam construction helping out to install the roof of the trailer in the Prototype Repository tunnel.

A four hour cleaning period of the inside of the cutter head was made before installing the measurement box for measuring of acting forces on two cutters.

7.3.8 Change of container for cuttings

The absolute time for the changing of containers for the cuttings was difficult to estimate at the beginning of the bore period. This was due to the difficulties in estimating the boring time for each casing. For the majority of the holes the containers were filled with cuttings from boring of 2.5 casings before they were emptied. DD0092G01 is excluded from this procedure. The containers containing cuttings for borehole DD0092G01 were changed after boring of each casing since they all had a different parameter set up. This was made in order to be able to take samples of the cuttings from each casing. The samples were later sieved to determine the particle size distributions, see section 4.3. The activity needed two men besides the truck and the loader because of the precise positioning of the container on the scale.

In the Demonstration tunnel cuttings were collected from every second casing. In the Canister Retrieval Test cuttings were collected from each casing due to the change in boring parameters. When boring the deposition holes in the Prototype Repository tunnel the activity change of containers was mostly performed at the same time as the loading of new casings to the boring machine and the time for changing the containers was hence reduced.

7.3.9 Measurements during and after boring

The Acoustic Emission Monitoring was the only measurements that interrupted the boring cycle. The measurements were performed in both of the holes in the Canister Retrieval tunnel and the two last holes in the Prototype Repository tunnel, see section 4.5. The breaks in the boring cycle caused by measurements were totally 173 calendar hours.

7.3.10 Miscellaneous

Miscellaneous includes for example cleaning up after each day's work, waiting time and breaks for visitors. The 32 hours miscellaneous for the Canister Retrieval Test hole number one includes 20 hours of cleaning up after boring in the Demonstration tunnel.

7.3.11 Handling of casings

This activity, handling of casings, includes installation of casings when boring and removing all casings afterwards. The handling of casing was time consuming for the first deposition holes, while the unscrewing and installation of bolts was done with a wrench. The time for the bolting was decreased by using an electrical wrench instead of the manual.

Handling of casings is the one activity that could be improved and clearly reduce the total time for completion of one borehole. The time used for handling of casings for each hole is presented in Figure 7-6.

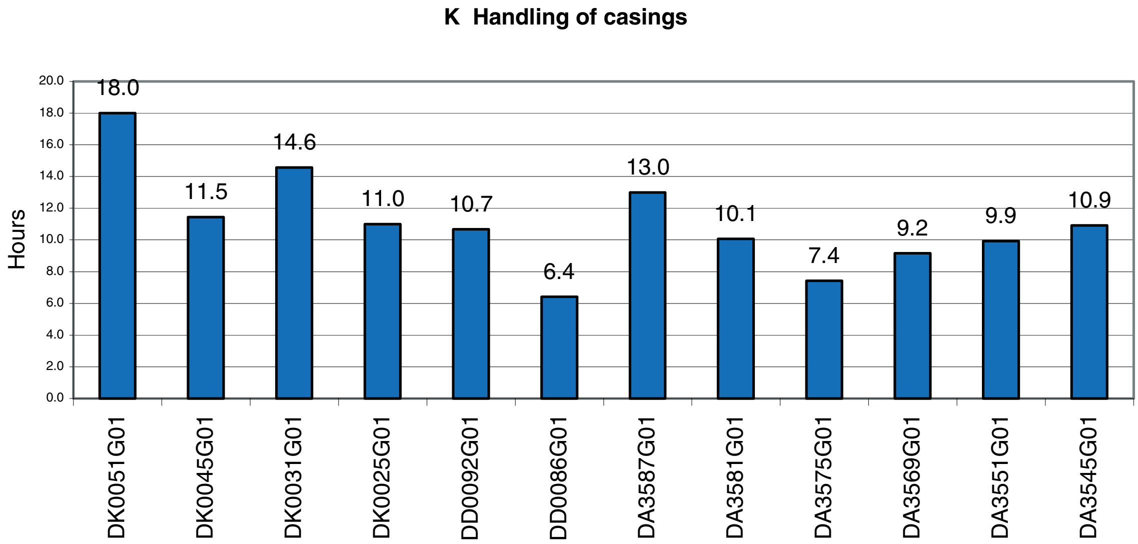


Figure 7-6. *Calendar time used for handling of casings.*

7.4 Analysis of results

The boring of the first deposition hole started at the 24th of November 1998 and the last hole in the Prototype Repository tunnel was completed 21st of September 1999. The boring of the thirteen deposition holes lasted 141 working days. The total working time for all holes was 1,430 hours excluding breaks and lunch.

The following work time analysis is related to the 12 deposition holes bored after the first one in the workshop if not stated otherwise. The presentation of the first deposition hole is made separate because of the long time invested for rebuilding the vacuum system and other supplementary work that had to be completed before the boring machine was working properly, see 7.4.5 "Reparation and maintenance of boring machine".

After the rebuilding of the vacuum system and installation of disc cutters on the outer positions on the cutter head the machine was transported into the Demonstration tunnel.

The boring of the four holes in the Demonstration tunnel lasted 38 working days. Boring of the two deposition holes in the Canister Retrieval tunnel lasted for 39 days and the 6 holes in the Prototype Repository tunnel lasted for 58 days. The time used for each hole is presented in Figure 7-7.

The total time spent for the 11 different activities for completion of all the deposition holes, except the first one in the Workshop hall are presented in Table 7-2 and Figure 7-8. A detailed presentation on time spent for each hole bored is presented in Appendix 4.

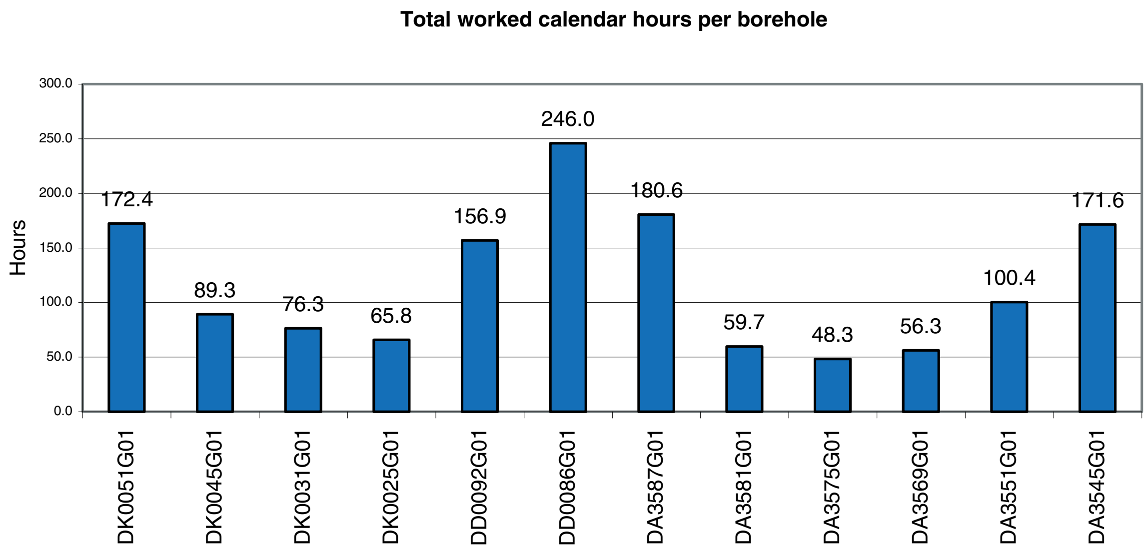


Figure 7-7. The calendar time used for completion of each hole.

The boring and the mounting of new casings have a total time-share of 25 percent. For normal TBM boring this figure is between 45 and 50 percent /Sundin, 1998/. In this case the boreholes are approximately 9 meters deep and more time is therefore spent on transporting the boring machine from one deposition hole to another compared to continuous boring of one long TBM tunnel.

The work time analysis has also been compared to the analysis made for the boring at Olkiluoto in Finland. The activities in the two different boring projects are not always the same and the work time has been split into different activities. The name for the different activities at Olkiluoto may not agree exactly with the activity names used for the boring in Äspö HRL /Autio et al, 1996/.

When comparing the TBM boring at Äspö HRL with Olkiluoto at Posiva Oy in Finland, the percentages for the actual boring is 19% at Äspö to compare with boring of large hole 9% and boring of pilot holes 4% at Olkiluoto, see Table 7-3. The most time consuming activity at Äspö was repair and maintenance, totally 34%, while the preparation for boring at Olkiluoto had a high rate of 23% (Äspö 13%). Miscellaneous and sampling times have been excluded.

Table 7-2. Total and proportional time spent on different activities for 12 of the deposition holes.

Activity	12 holes (the first hole in the workshop not included) Calendar hours	Percent
A Transport	138.8	10%
B Set up	231.4	16%
C Preparations for boring	18.2	1%
D Boring	227.8	16%
E R&M of boring machine	221.8	16%
F R&M of vacuum system	129.1	9%
G R&M of other equipment	47.0	3%
H Change of container for the cuttings	18.8	1%
I Measurements during and after boring	172.3	12%
J Miscellaneous	84.4	6%
K Handling of casings	132.6	9%
TOTAL	**1422.1**	**99%**

Table 7-3. Comparing the TBM boring at Äspö HRL and at Olkiluoto at Posiva Oy in Finland.

Olkiluoto	Percent of total time	Äspö HRL	Percent of total time
Transfer of equipment	24%	Transport, set up	26%
Boring of large holes, Boring of pilot holes	13%	Boring	19%
Emptying of the tank for crushed rock	3%	Change of containers for the cuttings	2%
Preparation for boring	23%	Preparation for boring, Handling of casings	13%
Repair and maintenance	24%	R&M	34%

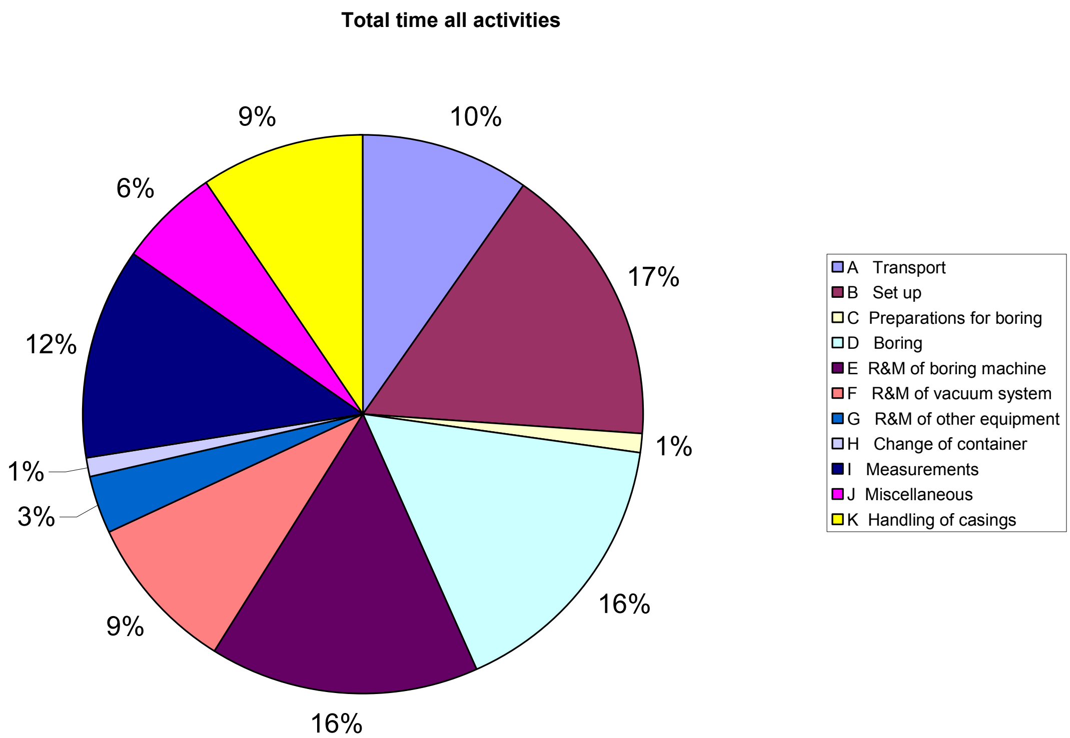


Figure 7-8. Pie-graph of time spent for the eleven different activities.

7.4.1 Deposition hole number one, DA3147G01

The boring equipment arrived at Äspö Hard Rock Laboratory the 22 nd of October 1998. The cutter head had to be mounted on the trailer before transportation to the first boring site, the workshop. Robbins had an own crewmember at the boring site during the set up, installations and preparations for boring the first hole. The trailer with the boring machine was positioned and ready to start boring the 11th of November.

Due to problems when electrifying the boring machine and malfunctioning transducers the boring start of DA3147G01 was delayed with 20 days. Because of continuous problems with a non-working vacuum suction system, see section 2.7 "Test of boring" and 7.4.6 "Reparation and maintenance of vacuum system", the boring of the first deposition hole lasted 48 days.

Figure 7-9. *Installation contractor wireman in the bore head.*

8 Experiences from boring

This chapter will discuss the experiences of Drillcon Raise AB boring crew and their recommendations to improve the boring cycle.

8.1 Positioning of boring machine over deposition hole

To reduce the time for making the last millimetre positioning of the trailer with the SBM it could be equipped with eight horizontal hydraulic jacks, two on each long side and two on each short side. The jacks on the long side can be attached to the tunnel wall and be used to move the machine perpendicular to the tunnel. If the tunnel floor is prepared with equipment for attachment of the jacks on the short side of the bore machine they can be used for moving the machine along the tunnel axis. It is assessed that using this method might reduce the time for positioning of the machine from 3–5 hours to 1 hour.

8.2 Attachment of trailer with SBM at boring site

The reaction force from the thrust cylinders was handled in two different ways depending on which kind of tunnel the machine was operating in.

When operating in a drill and blast tunnel the trailer with the SBM was rock bolted to the tunnel floor. One time consuming operation before the machine could be bolted to the rock was that the gangways had to be removed in order to put the reinforcement bars in the drilled holes. The gangways were heavy and bolted to the trailer. To reduce the time for this operation the gangways should be made of aluminium or another light material. They should also be attached to the boring machine with hinges. It would then be easy to lift them up and attach them to the machine.

Three different types of chemical grouting were then tested to grout the rock bolts that anchored the boring machine to the ground. Only one of the chemical grouting types was working satisfactory but it needed the same time to harden as concrete. Concrete was therefore used when boring the rest of the deposition holes in the Demonstration tunnel and for the Canister Retrieval Test.

When operating in the TBM tunnel the crown reaction pad was used to transfer the forces from the thrust cylinders to the tunnel root. The original thought was that the reaction pad should be lifted with a wheel loader onto the head frame. This manoeuvre was though quite risky for the operators and instead a frame was created on which the reaction pad could be slid into position, see Figure 8-1. The frame construction was very simple and it could be modified with roller bearings to decrease the frictional force acting when sliding the reaction pad in place.

Figure 8-1. *Simple frame for sliding of crown reaction pad in place.*

8.3 Handling of casings

The most problematic casing was the starter casing, the one to be installed after boring of the first stroke. This casing is different from the others since the package with the vacuum and hydraulic hoses is led from the inside of the bore head to the outside of this casing. Approximately one hour has to be invested in this casing compared to approximately 20 minutes for each of the other casings. There are no obvious improvements to be made with the current design of the casings. It might though be an idea to think through the concept with how the casings shall be bolted to each other and the use of the four dowel pins.

The casings were supposed to be retrieved with help of the stabilizers according to the manufacturer's idea. After completion of the borehole the thrust cylinders should be retracted and the stabilizers pushed into the rock with maximum thrust. The tenth casing was then to be removed. The thrust cylinders should then be used to push up the drill string to make it possible to remove the ninth casing. This plan of action did not work because the stabilizers were not able to maintain the bore head in position. The friction between them and the rock was too small, which caused the boring head to slide down. Instead of using the tenth casing to bolt the others in and retrieve them one by one with the retrieval jacks, eight 1 m long bolts were used, see Figure 8-2.

Figure 8-2. *Retrieval of casings.*

8.4 Boring

The hoses for vacuum and hydraulic oil started to slide down the drill string by their own weight after boring a few meters. This caused problems with the vacuum hose since it was folded. The flowing cuttings in the hose then very heavily wore the sharp bend created by the fold. It was also a risk that the hoses could get in contact with moving parts in the cutter head. Hanging the hose package in a chain connected to a tackle solved the problem. The operators though had to keep an eye on the chain and prolong it during the excavation of the hole. The risk of tearing the hose package apart if the chain is not prolonged can be avoided if a spring-loaded hose reel is mounted on the bore machine.

It is important to note that a rate of rotation over approximately 12 rpm causes the boring rig to vibrate heavily. The vibrations are likely to cause exhaustive damage on the boring rig and the main hydraulic system as well as the machinery in the boring head. The gains of higher rate of penetration therefore have to be compared with the higher costs for maintenance.

The reasons for the vibrations have not been studied. It is though unlikely to depend on the wear of the cutters since the vibrations started at the same rpm during boring of all the holes. It is possible that the vibrations were caused by a resonance phenomenon.

8.5 Steering during boring

The cutter head was steered exclusively with the front stabilizers. The steering of the machine was not seen as a problem during boring. It was noted that it was more difficult to steer the machine with higher thrust and rate of rotation. More thrust had then to be put on the stabilizers.

8.6 Vacuum system

When boring approximately 70% of the vacuum machine's capacity was used. The pressure in the system was then 50 kPa. If the capacity of the machine was increased the wear of the hoses and tubes increased. On average 0.65 m of 150 mm diameter pipe and 0.17 m of 200 mm diameter pipe vacuum hose was consumed per bored meter deposition hole. For the four holes in the demonstration tunnel and the six holes in the prototype tunnel approximately 130 m of 200 mm steel pipe was consumed which is equal to 1.5 m pipe per bored deposition hole meter.

The wear on the nozzles, piping in the boring head and the swivel was considerably low. Only the swivel had to be replaced once.

The silt size of the cuttings passed straight through the first container and was filtered in the vacuum machine itself. A compartment under the filters had to be cleaned with another vacuum system on a truck. This procedure had to be repeated 3 to 4 times per deposition hole. This cleaning took 15–30 minutes. The major compartment in the vacuum machine (before the filters) was filled up after boring of 2 deposition holes. Cleaning of this compartment took 3–4 hours.

8.7 Working environment

The ventilation and lighting around the bore machine and the vacuum system has been satisfactory. The boring though creates very high noise levels. It is therefore appropriate to build a steering cabin on the boring machine.

Figure 8-3. *Wear of pipe going into the vacuum pickup system.*

9 Conclusions and discussions

The boring of the thirteen deposition holes at Äspö HRL was a quite successful operation. After correction of some initial problems all of the criteria set up for the boring were fulfilled. The initial problems were rather frustrating but not unexpected, as initial problems are a natural part of the start up process when a completely new type of machine is commissioned.

The criterion for the boring time was that it should take no more than 40 hours from the first rock contact with the cutters until the hole was completed and the drill-string removed. This criterion was fulfilled with an approximately 10-h margin. The boring time including change of casings was approximately 20 h and the handling of casings took approximately 10 h.

The geometrical criteria set up for the boring were also fulfilled with a fair margin.

When the cutter head and vacuum system were rebuilt there were only a few technical problems with the boring. The cutter head was equipped with 3, 4, 7 or 10 disc cutters (Appendix 1). For possible future projects it should be tested to dress more of the cutter-head with discs, which probably would increase the rate of penetration as it could be seen when boring DD0086G01. The change of the two outermost cutters from disc cutters to button cutters clearly reduced the penetration rate. It is difficult to make a fair comparison of the disc and button cutters since the design of the cutter head is unfavourable for the button cutters used.

The vacuum system worked well but could be improved regarding the effectiveness at higher rate of rotation. It could be seen that the net penetration increases as the thrust and the rate of rotation are increased. The penetration rate per rotation is though decreased when the rate of rotation is increased. One reason for this might be that the crushing of rock function well but the removal of cuttings does not work well at a higher rate of rotation.

There is a trend towards a lower rate of penetration in the second half of the holes. No connections between the rate of penetration and changes in the geology were found.

The probable reason for a lower rate of penetration in the lower parts of the holes is that the vacuum suction system cleans the borehole more efficiently at an upper level than deeper down in the borehole.

Bolting the bore machine to the tunnel floor in the drill and blast tunnels was rather labour intensive and time consuming. The technique should be reviewed if more boring should be performed in drill and blast tunnels. The use of a crown-reaction pad in the TBM-tunnel worked well.

The changing of containers, the cleaning of the compartment for the finest-grained cuttings and the set up of the boring machine were very time consuming activities. Especially these activities should be improved to reduce the time of the boring cycle.

The average total time for boring one deposition hole during this project was 118 hours. If the time used for acoustic emission measurements is excluded from the total time the average for the holes is 105 hours. It has earlier been stated from SKB that one canister per day shall be deposited in the future repository during regular operation. If the boring of the deposition holes begins five years before the deposition starts approximately 220 deposition holes have to be bored each year during 20 years. If single shifts are used and a working year is 1,800 hours 16 different boring machines have to be used simultaneously. If the average time for boring is reduced to 30 hours, which is the fastest time of completion of one hole, it will still take approximately 4 different boring machines working simultaneously to be able to complete the task. In this perspective efforts made in making the boring cycle more effective and hence reducing the time for completion of each hole are needed. The utilization degree of the boring equipment could be increased significantly by planning the maintenance work beforehand and carrying out as much of the repair and maintenance work as possible during transport and set-up.

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Appendix 1

Position of cutters

NO	DA3147G01	DA3153G01	DK0051G01	DK0045G01	DK0031G01	DK0025G01	DD0092G01	DD0086G01	DA3587G01	DA3581G01	DA3575G01	DA3569G01	DA3551G01	DA3545G01
1	C	C	C	C	C	C	C	C	C	C	C	C	C	C
2	C	C	C	C	C	C	C	C	C	C	C	C	C	C
3	C	C	C	C	C	C	C	C	C	C	C	C	C	C
4	C	C	C	C	C	C	C	C	C	C	C	C	C	C
5	C	C	C	C	C	C	C	C	C	C	C	C	C	C
6	C	C	C	C	C	C	C	C	C	C	C	C	C	C
7	C	C	C	C	C	C	C	C	C	C	C	C	C	C
8	C	C	C	C	C	C	C	C	C	C	C	C	C	C
9	C	C	C	C	C	C	C	C	C	C	C	C	C	C
10	C	D	D	D	D	D	D	C	C	C	C	C	C	C
11	C	D	D	D	D	D	D	D	C	C	C	C	C	C
12	C	D	D	D	D	D	D	D	C	C	C	C	C	C
13	C	D	D	D	D	D	D	D	C	C	C	C	C	C
14	C	D	D	C	C	C	C	C	C	C	C	C	C	C
15	C	D	D	C	C	C	C	C	C	C	C	C	C	C
16	C	D	D	C	C	C	C	C	C	C	C	C	C	C
17A	C	C	C	C	C	C	C	C	C	C	C	C	C	C
17B	C	C	D	D	D	D	D	D	D	D	D	D	D	D
18A	C	C	D	D	D	D	D	C	D	D	D	D	D	D
18B	C	C	D	D	D	D	D	C	D	D	D	D	D	D

C= Carbide cutters

D= Disc cutters

Appendix 2

A table of the studied sections in Prototype Tunnel

RPM	Thrust per cylinder [ton]	From depth [mm]	To depth [mm]	Time [min]	Rate of penetration [mm/rev]	Deposition hole ID
7.7	31	934	1439	71	0.92	DA3587
7.7	37	3322	3371	5	1.27	DA3587
7.7	37	8716	8885	20	1.10	DA3587
7.7	38	3710	3751	4	1.33	DA3587
7.3	39	1798	2276	49	1.34	DA3587
7.7	39	3775	3854	8	1.28	DA3587
7.7	40	7575	7735	15	1.39	DA3587
7.7	40	8124	8305	16	1.47	DA3587
7.7	40	8375	8545	16	1.38	DA3587
7.7	41	3978	4100	10	1.58	DA3587
7.7	41	7375	7494	11	1.40	DA3587
7.7	42	3464	3542	5	2.03	DA3587
7.7	43	7782	8055	23	1.54	DA3587

RPM	Thrust per cylinder [ton]	From depth [mm]	To depth [mm]	Time [min]	Rate of penetration [mm/rev]	Deposition hole ID
8	33	7170	7270	11	1.14	DA3587
8	35	6999	7154	17	1.14	DA3587
8	36	6167	6249	9	1.14	DA3587
8	37	3604	3712	14	0.96	DA3587
8	37	6819	6977	17	1.16	DA3587
8	38	6267	6497	24	1.20	DA3587
8	39	2298	2499	20	1.26	DA3587
8	39	4520	4770	23	1.36	DA3587
8	39	5346	5621	23	1.49	DA3587
8	39	6698	6753	5	1.38	DA3587
8	42	4246	4489	21	1.45	DA3587
8	42	5904	6118	19	1.41	DA3587
8	44	4975	5129	14	1.38	DA3587
8	37	5946	6191	37	0.83	DA3581
8	37	6508	6590	12	0.85	DA3581
8	38	5820	5917	13	0.93	DA3581
8	39	6214	6494	43	0.81	DA3581
8	24	1110	1213	25	0.52	DA3569
8	27	1230	1690	86	0.67	DA3569

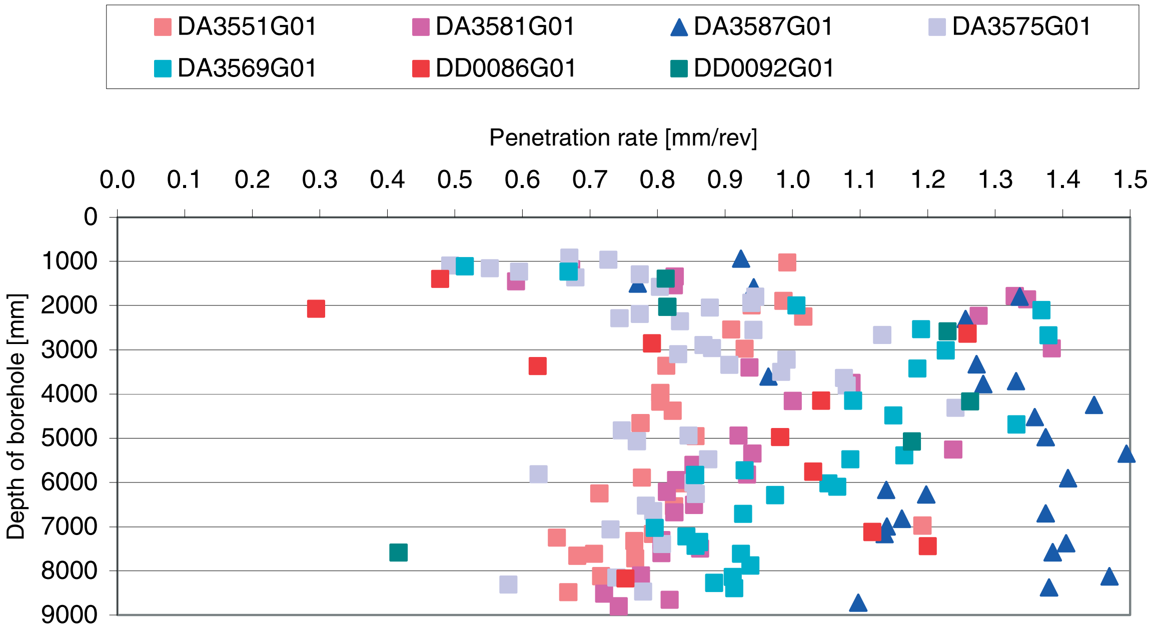
RPM	Thrust per cylinder [ton]	From depth [mm]	To depth [mm]	Time [min]	Rate of penetration [mm/rev]	Deposition hole ID
8.4	27	1174	1270	17	0.67	DA3581
8.4	30	1347	1451	15	0.83	DA3581
8.4	36	5605	5691	12	0.85	DA3581
8.4	37	2970	3063	8	1.38	DA3581
8.4	37	5260	5312	5	1.24	DA3581
8.4	38	3402	3701	38	0.94	DA3581
8.4	39	6678	7288	88	0.83	DA3581
8.4	39	7307	7456	22	0.81	DA3581
8.4	40	2234	2952	67	1.28	DA3581
8.4	40	3751	4089	37	1.09	DA3581
8.4	40	4942	5112	22	0.92	DA3581
8.4	41	4156	4887	87	1.00	DA3581
8.4	41	5344	5589	31	0.94	DA3581
8.4	41	7497	7584	12	0.86	DA3581
8.4	43	1784	1851	6	1.33	DA3581
8.4	44	1855	2104	22	1.35	DA3581
8.4	23	1091	1149	14	0.49	DA3575
8.4	27	1159	1210	11	0.55	DA3575
8.4	29	1231	1286	11	0.60	DA3575
8.4	30	915	960	8	0.67	DA3575
8.4	30	1298	1350	8	0.77	DA3575
8.4	32	1368	1539	30	0.68	DA3575
8.4	33	970	1025	9	0.73	DA3575
8.4	33	1582	1690	16	0.80	DA3575
8.4	35	2192	2257	10	0.77	DA3575
8.4	35	2285	2335	8	0.74	DA3575
8.4	35	2357	2490	19	0.83	DA3575
8.4	38	2046	2105	8	0.88	DA3575
8.4	39	1800	1927	16	0.94	DA3575
8.4	40	1941	2012	9	0.94	DA3575
8.4	41	2555	2650	12	0.94	DA3575
8.4	42	7069	7290	36	0.73	DA3575
8.4	46	6650	6850	30	0.79	DA3575
8.4	40	2532	2652	12	1.19	DA3569
8.4	42	2672	2950	24	1.38	DA3569
8.4	43	3017	3285	26	1.23	DA3569
8.4	44	4153	4391	26	1.09	DA3569
8.4	39	6248	6326	13	0.71	DA3551
8.4	41	5893	6004	17	0.78	DA3551
8.4	42	2540	2960	55	0.91	DA3551
8.4	43	6021	6084	9	0.83	DA3551
8.4	45	2974	3255	36	0.93	DA3551

RPM	Thrust per cylinder [ton]	From depth [mm]	To depth [mm]	Time [min]	Rate of penetration [mm/rev]	Deposition hole ID
8.7	37	8522	8660	22	0.72	DA3581
8.7	39	8806	8890	13	0.74	DA3581
8.7	40	8110	8488	56	0.78	DA3581
8.7	40	8660	8781	17	0.82	DA3581
8.7	41	7606	8083	68	0.81	DA3581
8.7	35	3345	3416	9	0.91	DA3575
8.7	35	4821	4886	10	0.75	DA3575
8.7	36	2896	2964	9	0.87	DA3575
8.7	36	4317	4371	5	1.24	DA3575
8.7	37	3102	3196	13	0.83	DA3575
8.7	37	3639	3742	11	1.08	DA3575
8.7	37	8312	8428	23	0.58	DA3575
8.7	38	3810	3904	10	1.08	DA3575
8.7	39	2966	3081	15	0.88	DA3575
8.7	40	3221	3290	8	0.99	DA3575
8.7	40	4944	5025	11	0.85	DA3575
8.7	41	3503	3580	9	0.98	DA3575
8.7	41	5067	5375	46	0.77	DA3575
8.7	42	2667	2736	7	1.13	DA3575
8.7	43	5481	5580	13	0.88	DA3575
8.7	44	8151	8299	23	0.74	DA3575
8.7	45	6529	6638	16	0.78	DA3575
8.7	46	8469	8889	62	0.78	DA3575
8.7	47	6008	6201	26	0.85	DA3575
8.7	48	6263	6442	24	0.86	DA3575
8.7	48	7393	8088	99	0.81	DA3575
8.7	33	5724	5821	12	0.93	DA3569
8.7	34	5392	5463	7	1.17	DA3569
8.7	35	5481	5566	9	1.09	DA3569
8.7	37	5834	5901	9	0.86	DA3569
8.7	39	2000	2070	8	1.01	DA3569
8.7	40	7025	7212	27	0.80	DA3569
8.7	40	7348	7423	10	0.86	DA3569
8.7	41	4692	4889	17	1.33	DA3569
8.7	42	2106	2487	32	1.37	DA3569
8.7	42	3423	4083	64	1.19	DA3569
8.7	42	6022	6077	6	1.05	DA3569
8.7	42	6290	6485	23	0.97	DA3569
8.7	42	7440	7604	22	0.86	DA3569
8.7	43	7223	7289	9	0.84	DA3569
8.7	44	6712	6962	31	0.93	DA3569
8.7	44	7882	8086	25	0.94	DA3569

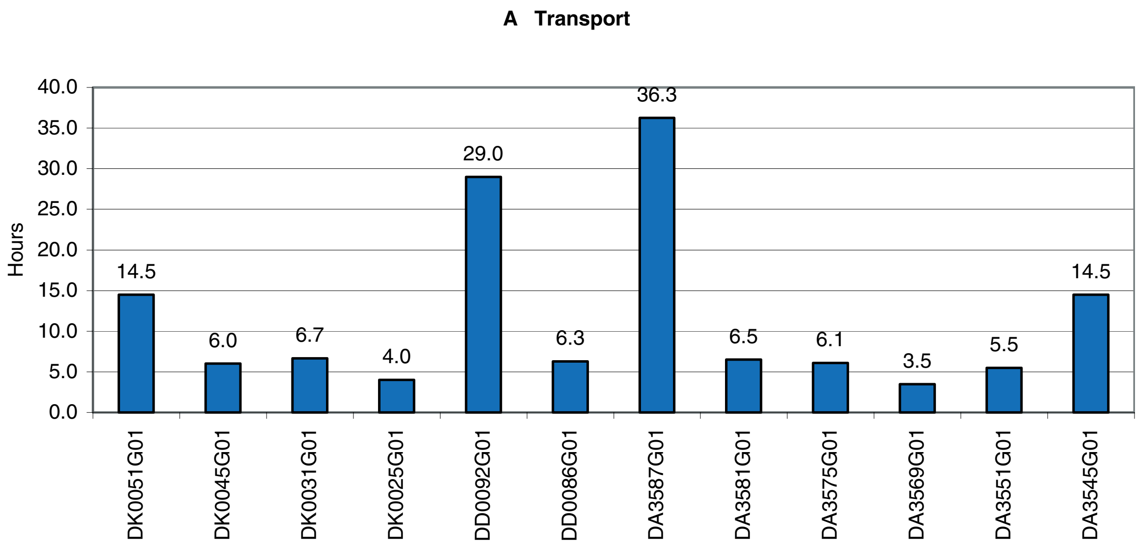
RPM	Thrust per cylinder [ton]	From depth [mm]	To depth [mm]	Time [min]	Rate of penetration [mm/rev]	Deposition hole ID
8.7	44	8272	8372	13	0.88	DA3569
8.7	45	4490	4560	7	1.15	DA3569
8.7	45	6102	6269	18	1.07	DA3569
8.7	45	7618	7843	28	0.92	DA3569
8.7	46	8141	8260	15	0.91	DA3569
8.7	46	8394	8887	62	0.91	DA3569
8.7	36	6977	7060	8	1.19	DA3551
8.7	37	4657	4893	35	0.78	DA3551
8.7	38	1026	1691	77	0.99	DA3551
8.7	38	3977	4082	15	0.80	DA3551
8.7	41	1895	1998	12	0.99	DA3551
8.7	41	7168	7237	10	0.79	DA3551
8.7	41	7251	7285	7	0.56	DA3551
8.7	42	3362	3928	80	0.81	DA3551
8.7	42	6544	6788	34	0.82	DA3551
8.7	43	1998	2235	29	0.94	DA3551
8.7	43	4957	5583	84	0.86	DA3551
8.7	43	8480	8887	70	0.67	DA3551
8.7	45	2252	2420	19	1.02	DA3551

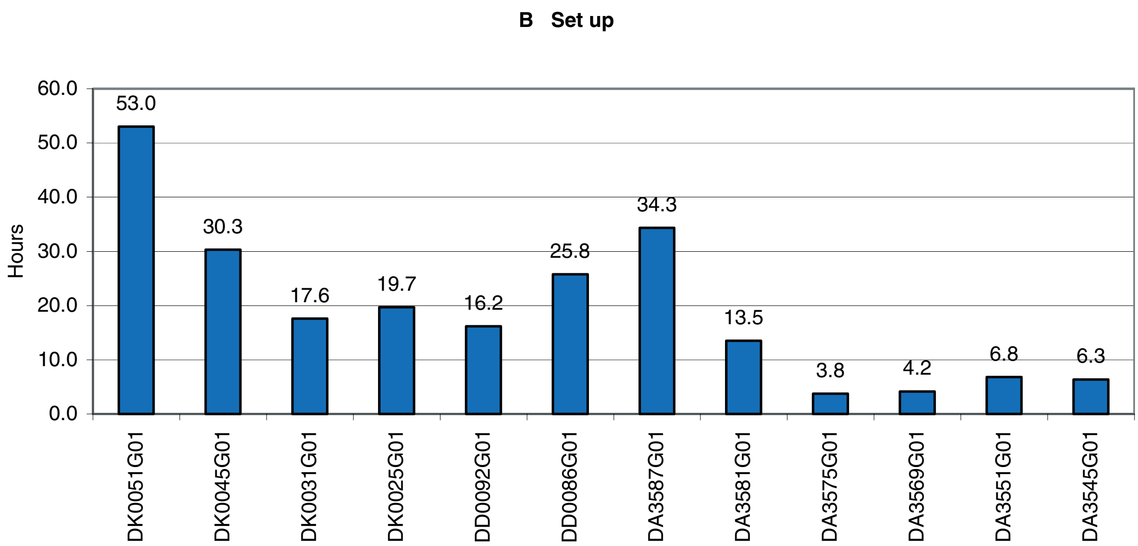
RPM	Thrust per cylinder [ton]	From depth [mm]	To depth [mm]	Time [min]	Rate of penetration [mm/rev]	Deposition hole ID
9.1	30	1452	1495	8	0.59	DA3581
9.1	30	1545	1695	20	0.82	DA3581
9.1	43	5813	5938	22	0.62	DA3575
9.1	37	7613	7658	7	0.71	DA3551
9.1	40	4178	4339	22	0.80	DA3551
9.1	41	7658	7720	10	0.68	DA3551
9.1	42	7326	7570	35	0.77	DA3551
9.1	42	8124	8287	25	0.72	DA3551
9.1	43	4379	4641	35	0.82	DA3551
9.1	43	7720	8090	53	0.77	DA3551

Penetration rate versus depth of borehole in five of the deposition holes in the Prototype tunnel and the two holes in the Canister Retrieval Test tunnel

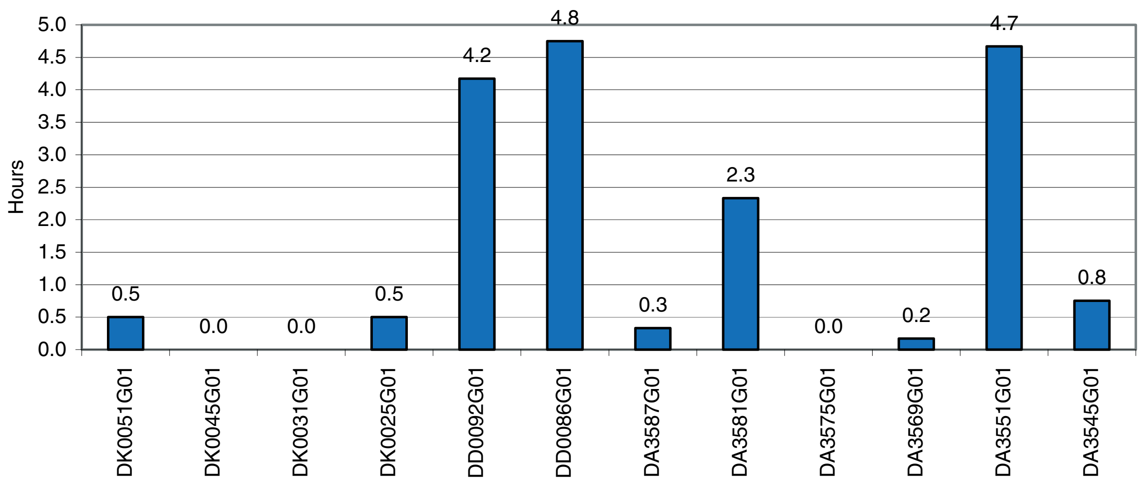


Time spent for each hole bored

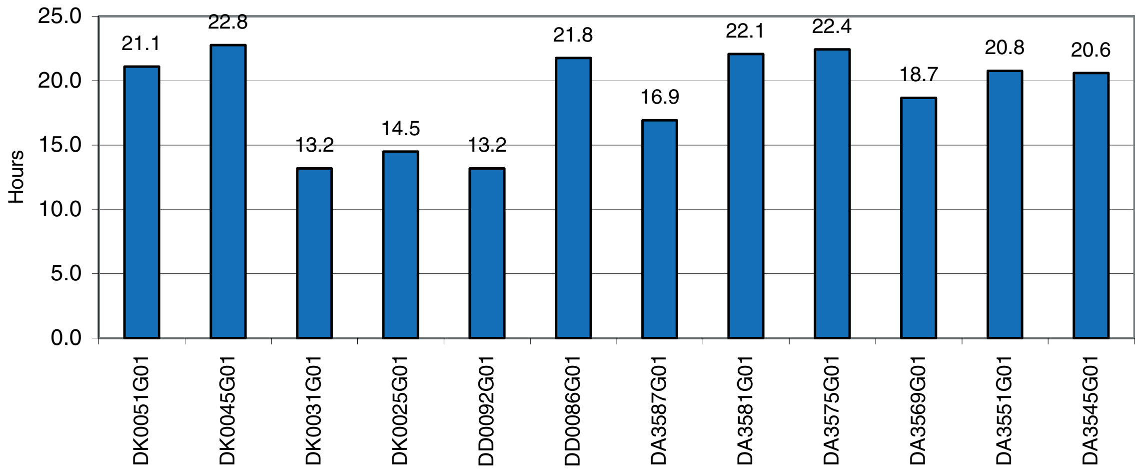




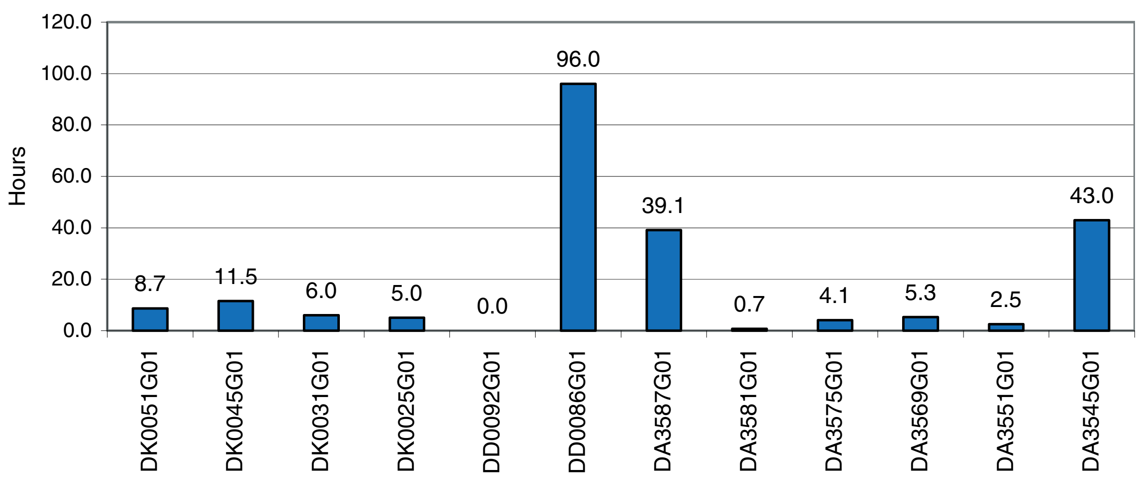
C Preparations for boring

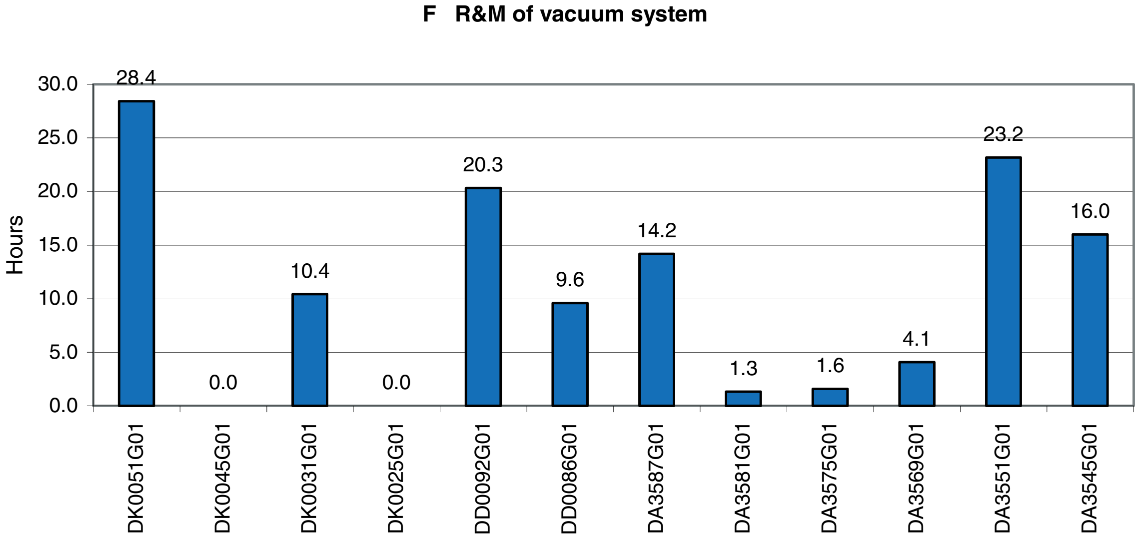


D Boring



E R&M of boring machine





F R&M of vacuum system
Hours
30.0
25.0
20.0
15.0
10.0
5.0
0.0
28.4
0.0
10.4
0.0
20.3
9.6
14.2
1.3
1.6
4.1
23.2
16.0
DK0051G01
DK0045G01
DK0031G01
DK0025G01
DD0092G01
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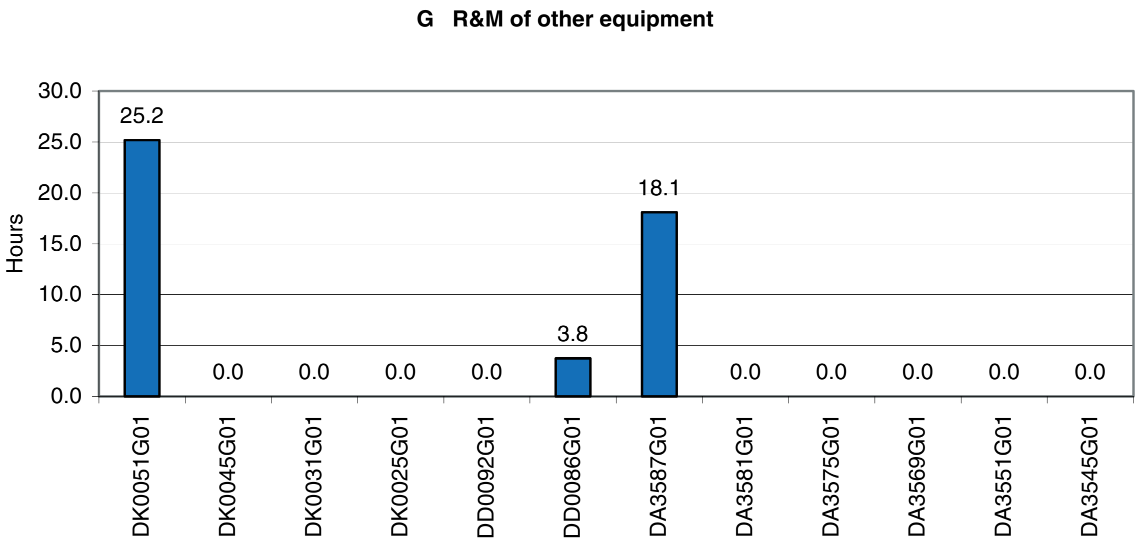
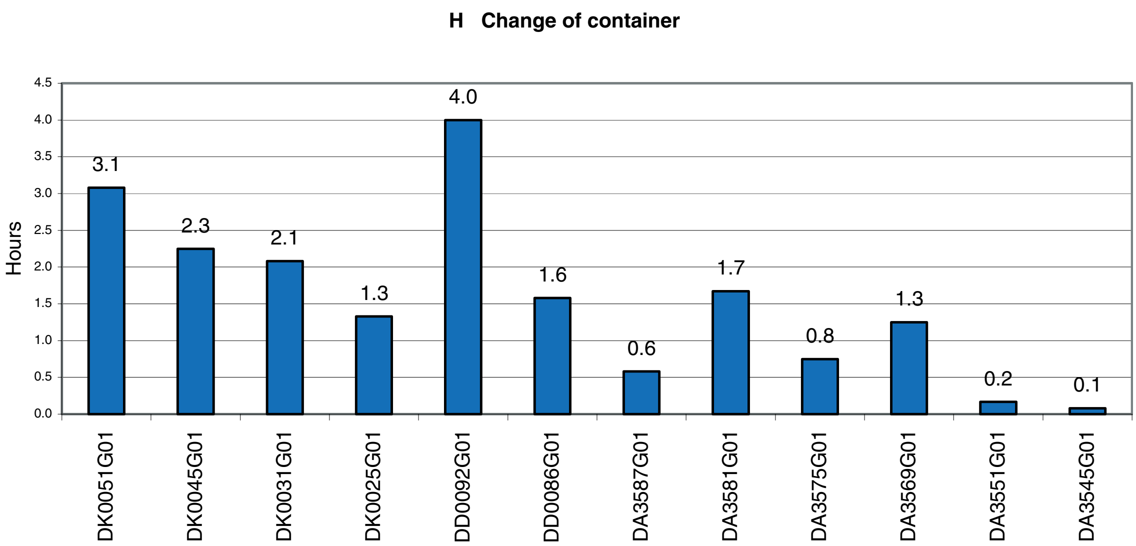
DA3551G01
DA3545G01

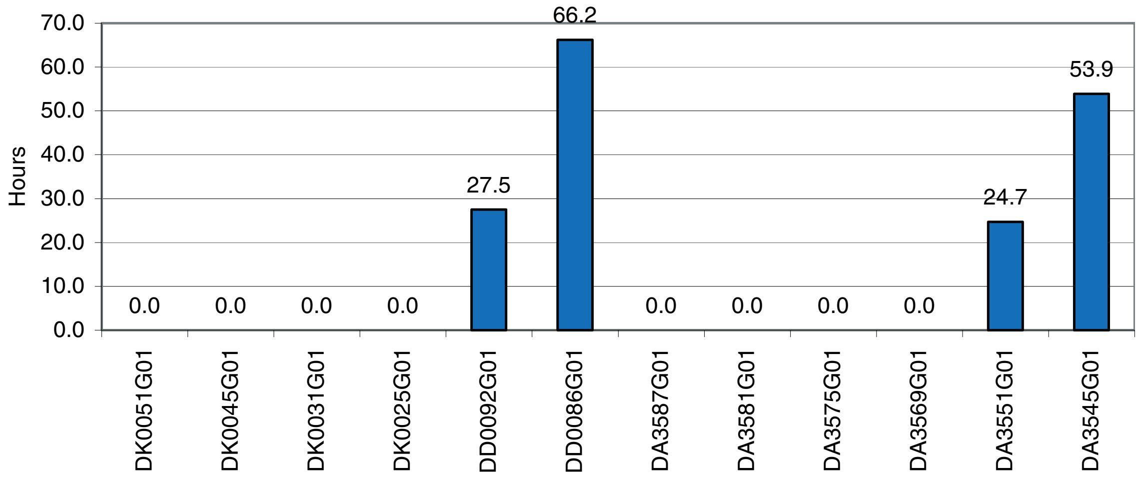


G R&M of other equipment
Hours
30.0
25.0
20.0
15.0
10.0
5.0
0.0
25.2
0.0
0.0
0.0
0.0
3.8
18.1
0.0
0.0
0.0
0.0
0.0
DK0051G01
DK0045G01
DK0031G01
DK0025G01
DD0092G01
DD0086G01
DA3587G01
DA3581G01
DA3575G01
DA3569G01
DA3551G01
DA3545G01

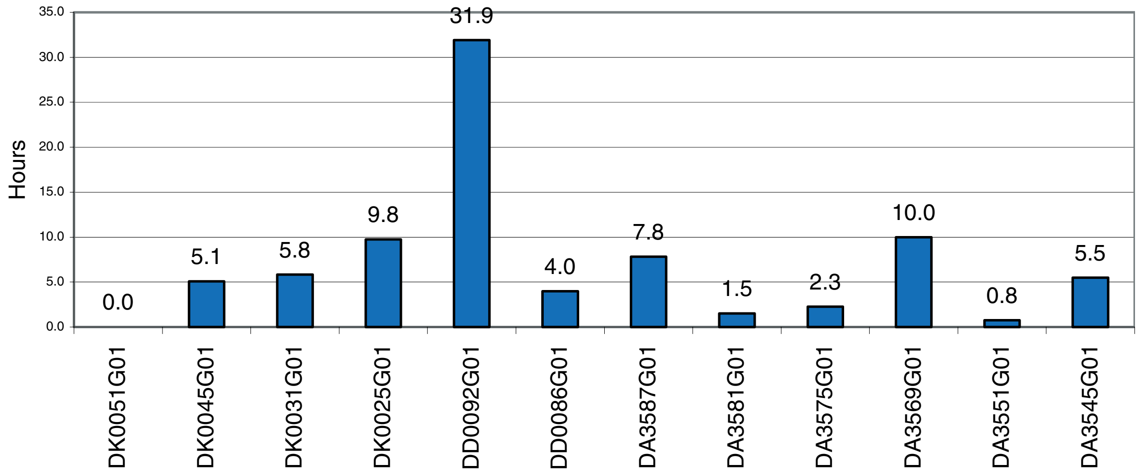


H Change of container
Hours
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
3.1
2.3
2.1
1.3
4.0
1.6
0.6
1.7
0.8
1.3
0.2
0.1
DK0051G01
DK0045G01
DK0031G01
DK0025G01
DD0092G01
DD0086G01
DA3587G01
DA3581G01
DA3575G01
DA3569G01
DA3551G01
DA3545G01

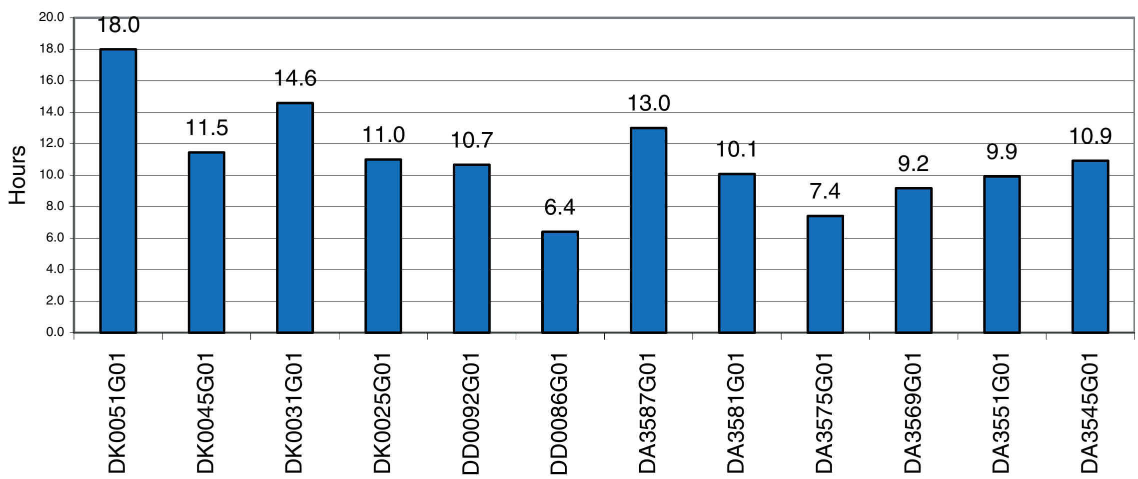
I Measurements

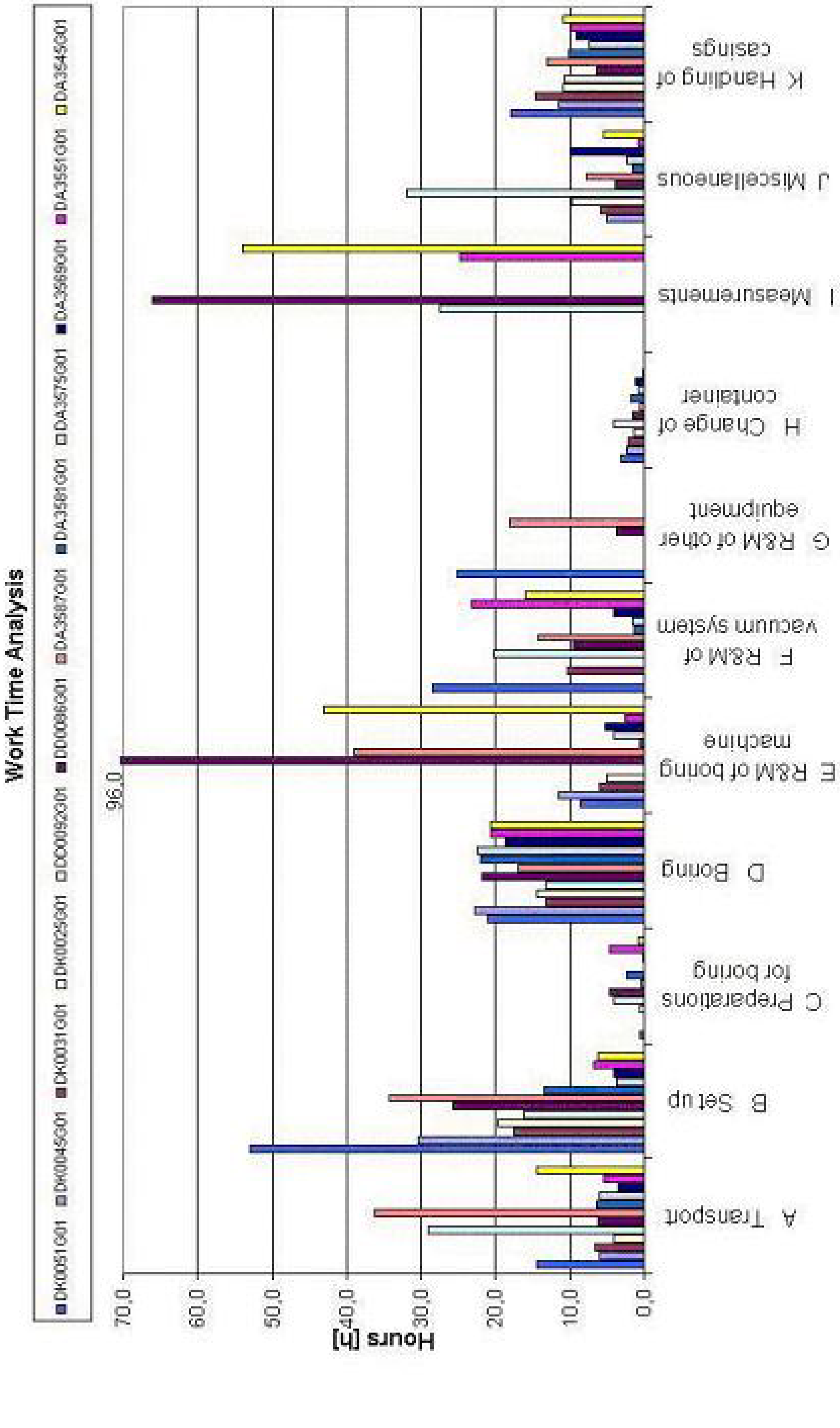


J Miscellaneous



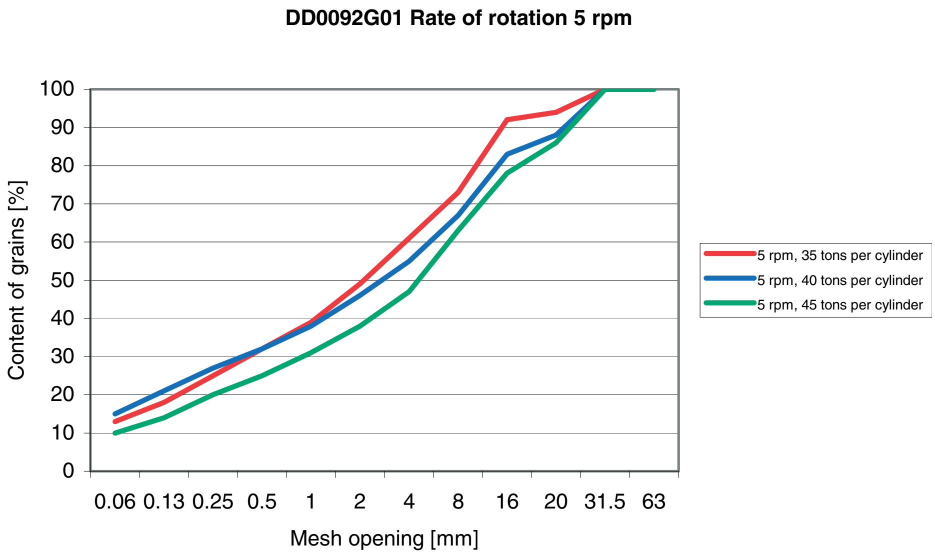
K Handling of casings

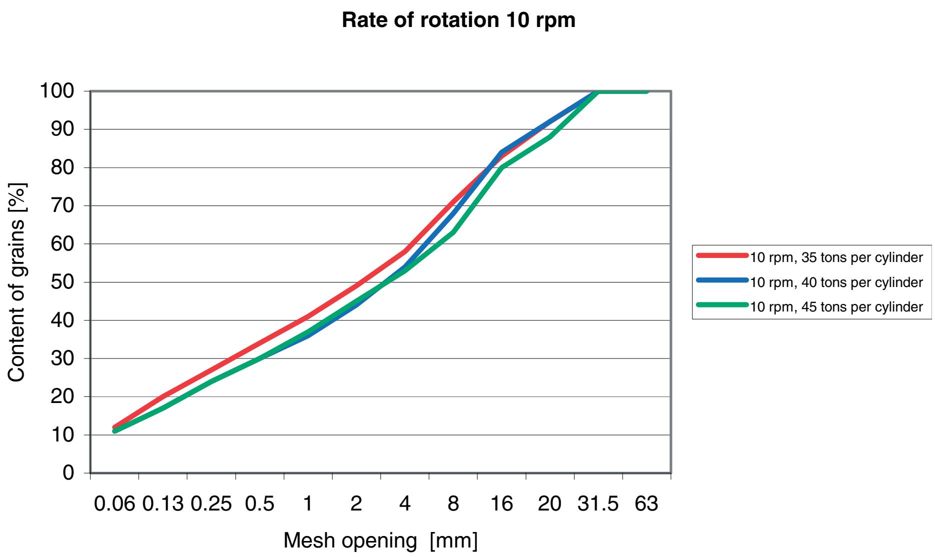




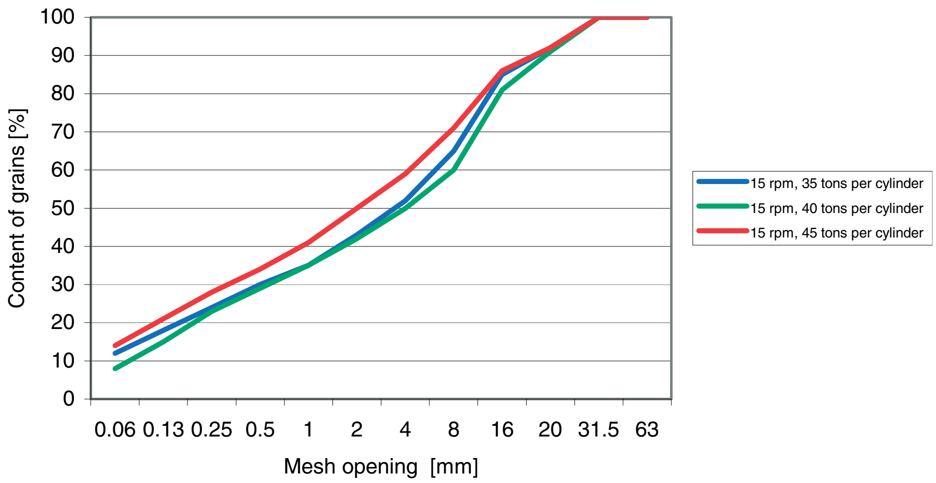
Work Time Analysis
DK0051G01
DK0045G01
DK0031G01
DK0025G01
DD0092G01
DD0086G01
DA3587G01
DA3581G01
DA3575G01
DA3569G01
DA3551G01
DA3545G01
Hours [h]
70,0
60,0
50,0
40,0
30,0
20,0
10,0
0,0
96,0
A Transport
B Set up
C Preparations for boring
D Boring
E R&M of boring machine
F R&M of vacuum system
G R&M of other equipment
H Change of container
I Measurements
J Miscellaneous
K Handling of casings

Diagrams from sieving analyses of cuttings

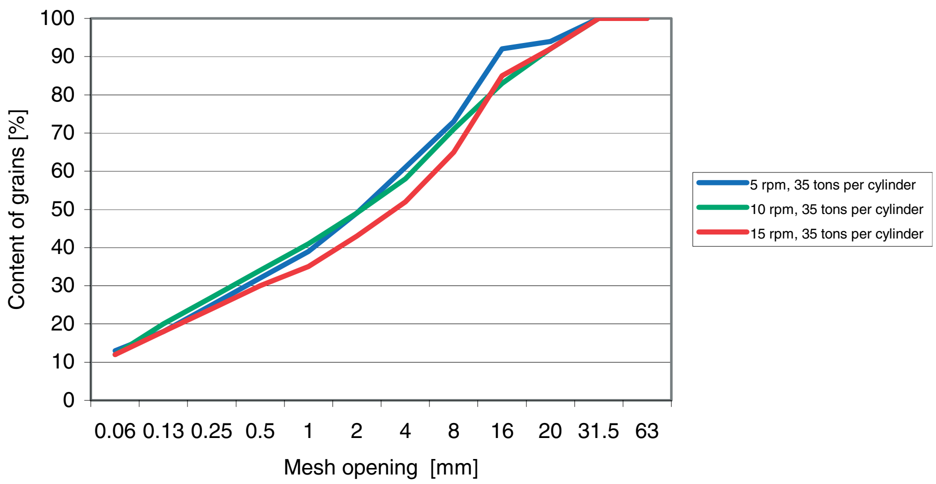




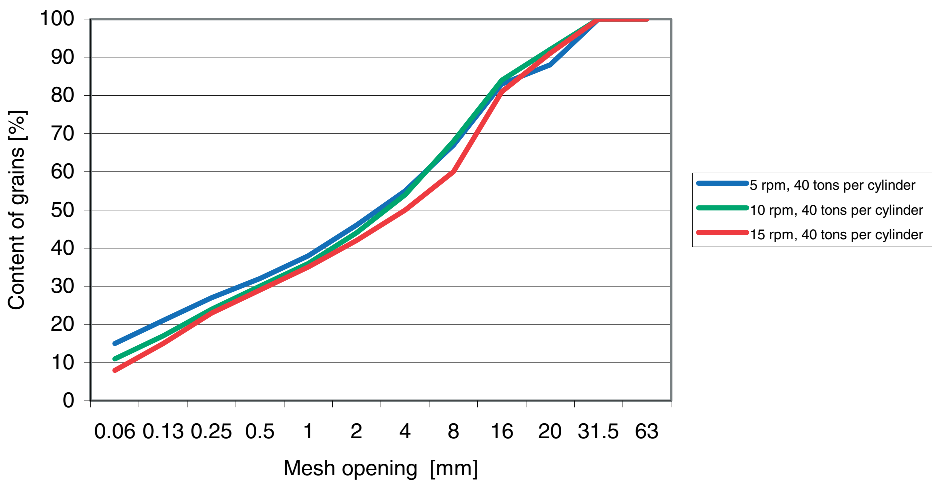
Rate of rotation 15 rpm

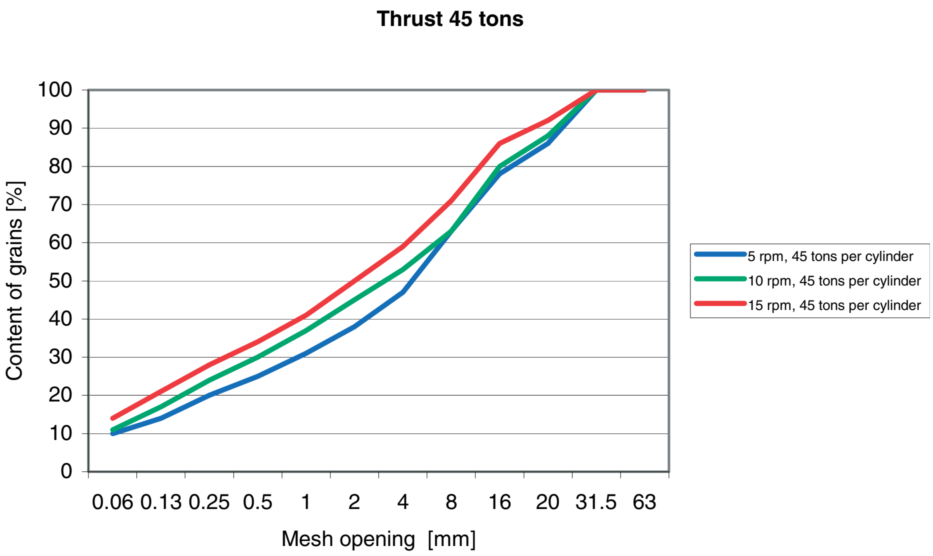


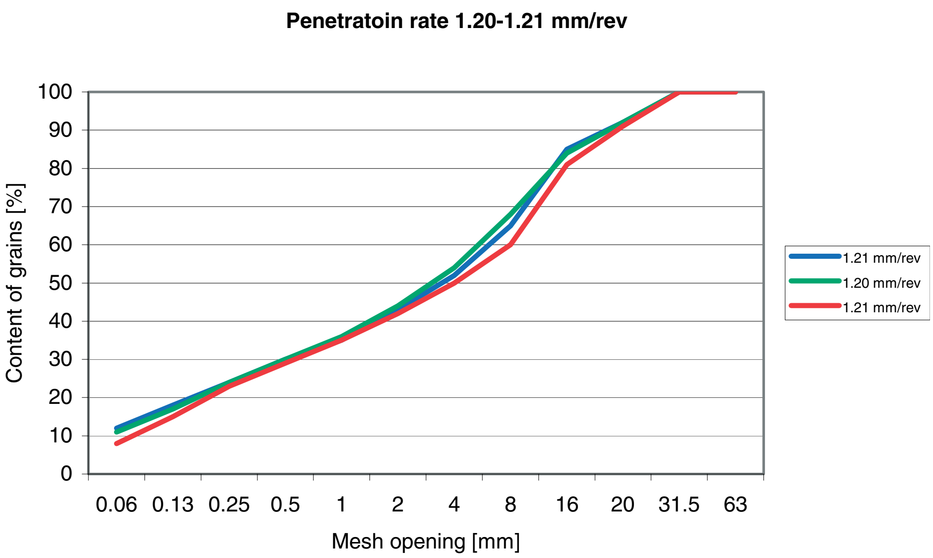
Thrust 35 tons

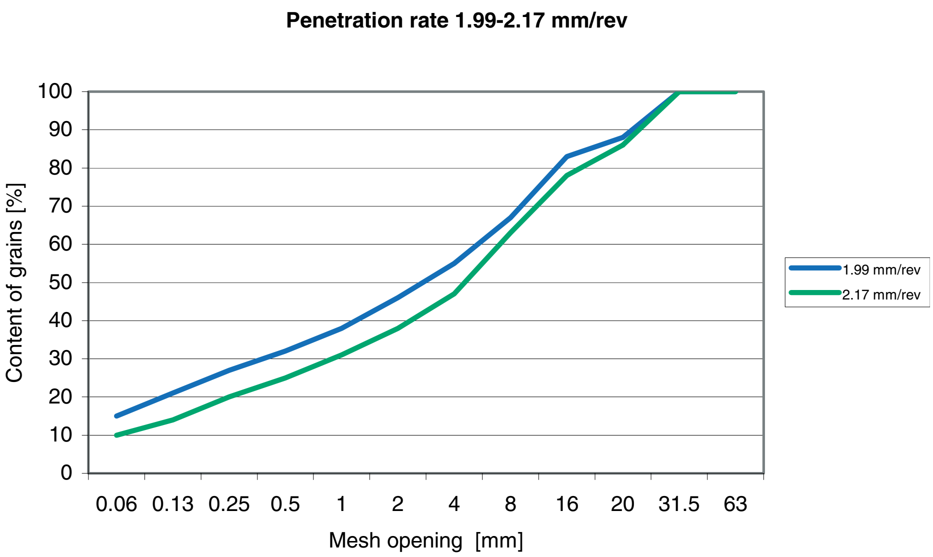


Thrust 40 tons

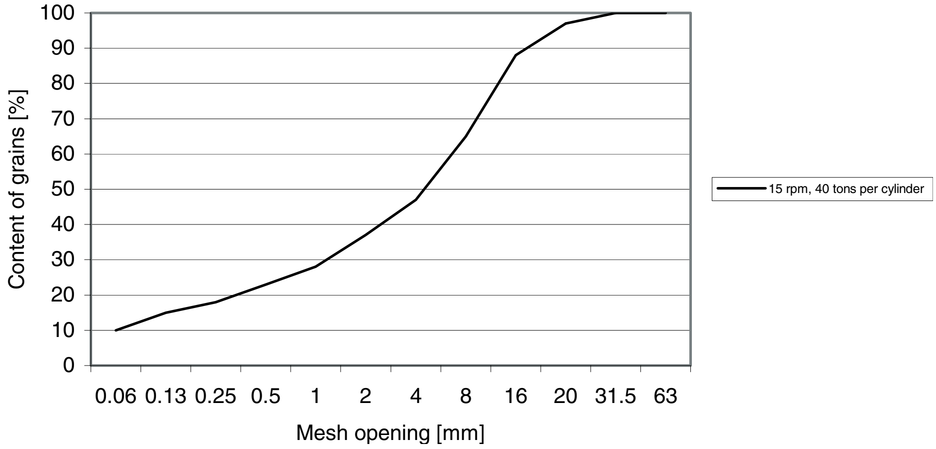



Thrust 45 tons
100
90
80
70
60
50
40
30
20
10
0
Content of grains [%]
0.06 0.13 0.25 0.5 1 2 4 8 16 20 31.5 63
Mesh opening [mm]
5 rpm, 45 tons per cylinder
10 rpm, 45 tons per cylinder
15 rpm, 45 tons per cylinder

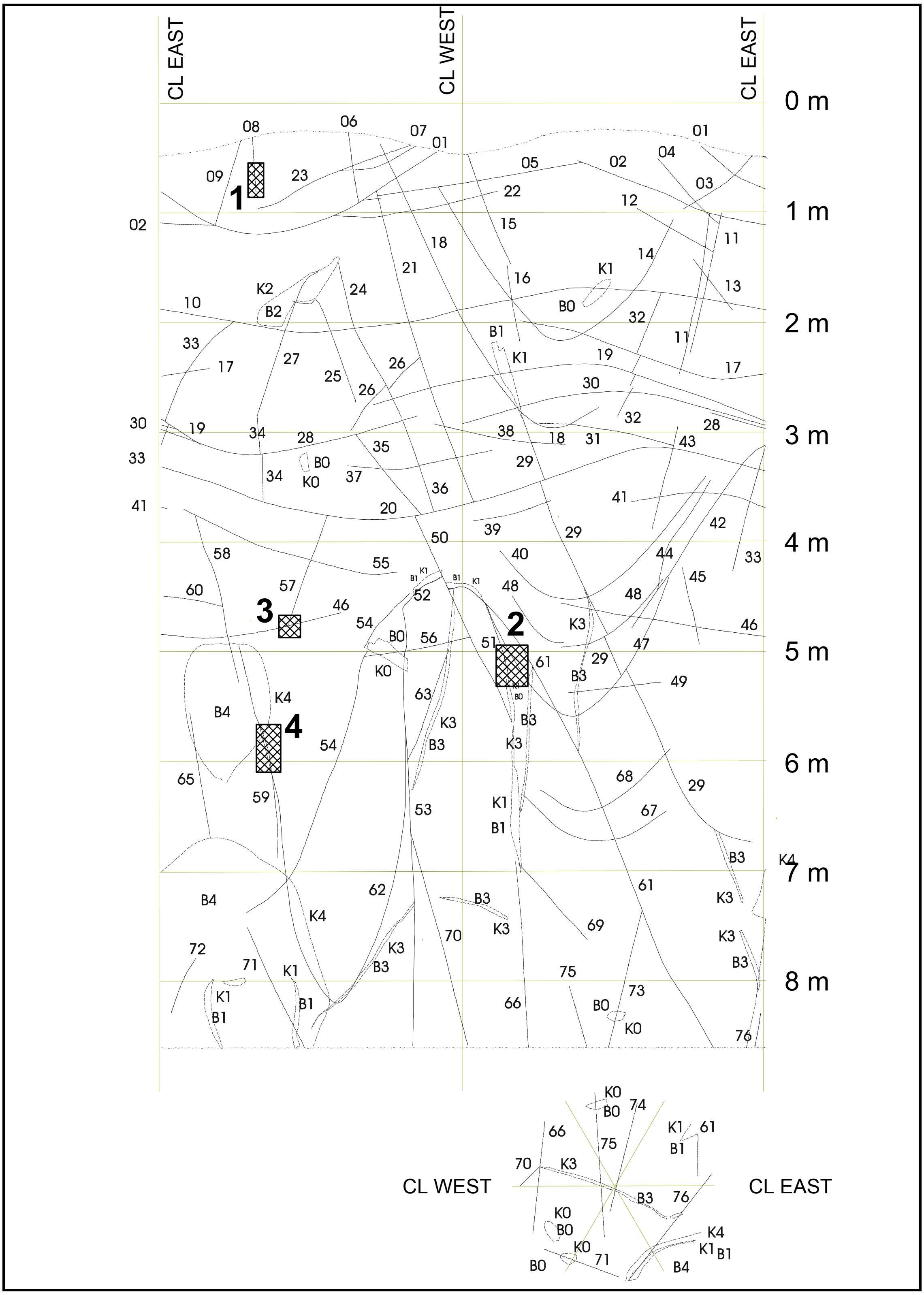

Penetratoin rate 1.20-1.21 mm/rev
100
90
80
70
60
50
40
30
20
10
0
Content of grains [%]
0.06 0.13 0.25 0.5 1 2 4 8 16 20 31.5 63
Mesh opening [mm]
1.21 mm/rev
1.20 mm/rev
1.21 mm/rev


Penetration rate 1.99-2.17 mm/rev
100
90
80
70
60
50
40
30
20
10
0
Content of grains [%]
0.06 0.13 0.25 0.5 1 2 4 8 16 20 31.5 63
Mesh opening [mm]
1.99 mm/rev
2.17 mm/rev

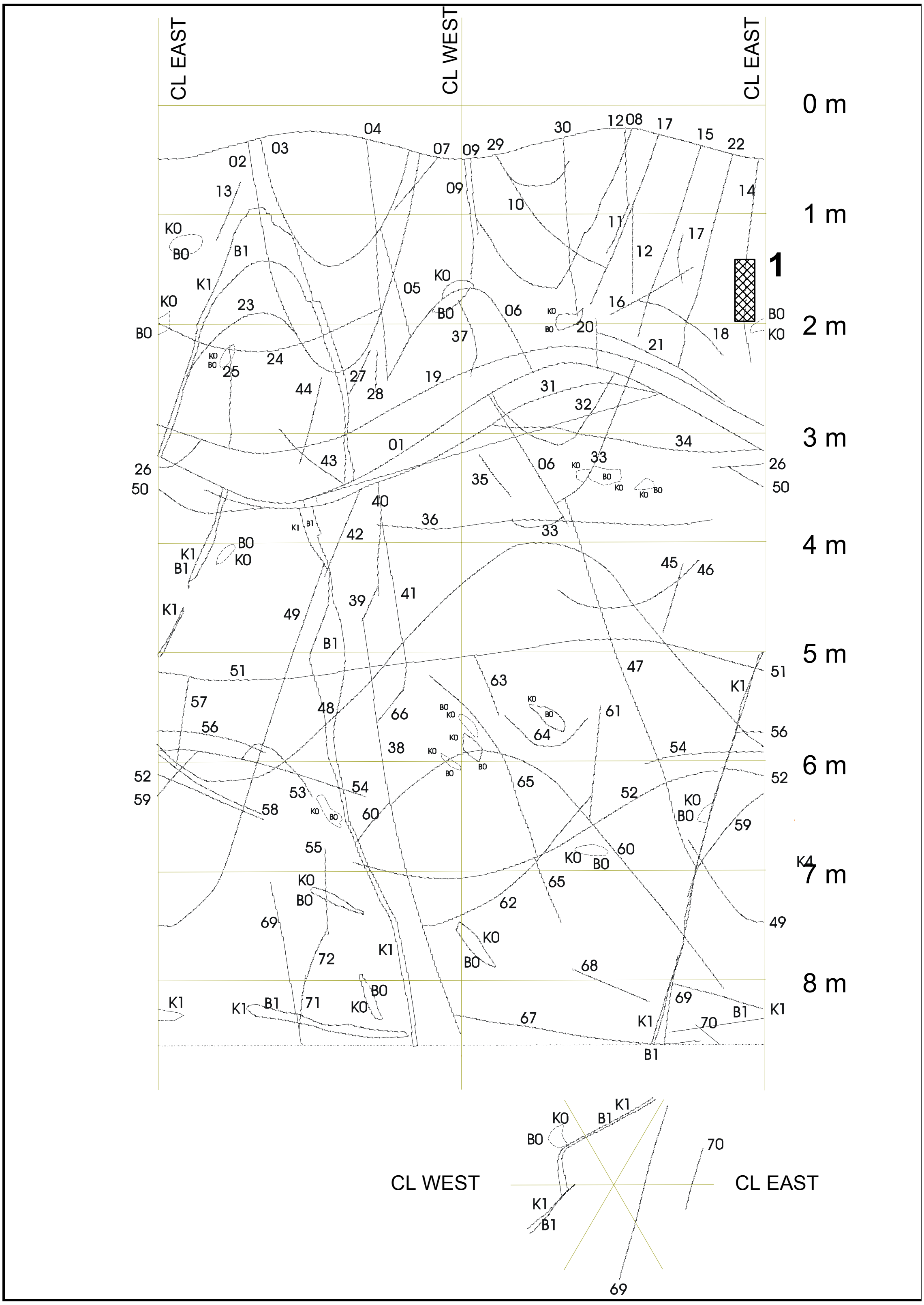
DD0086G01



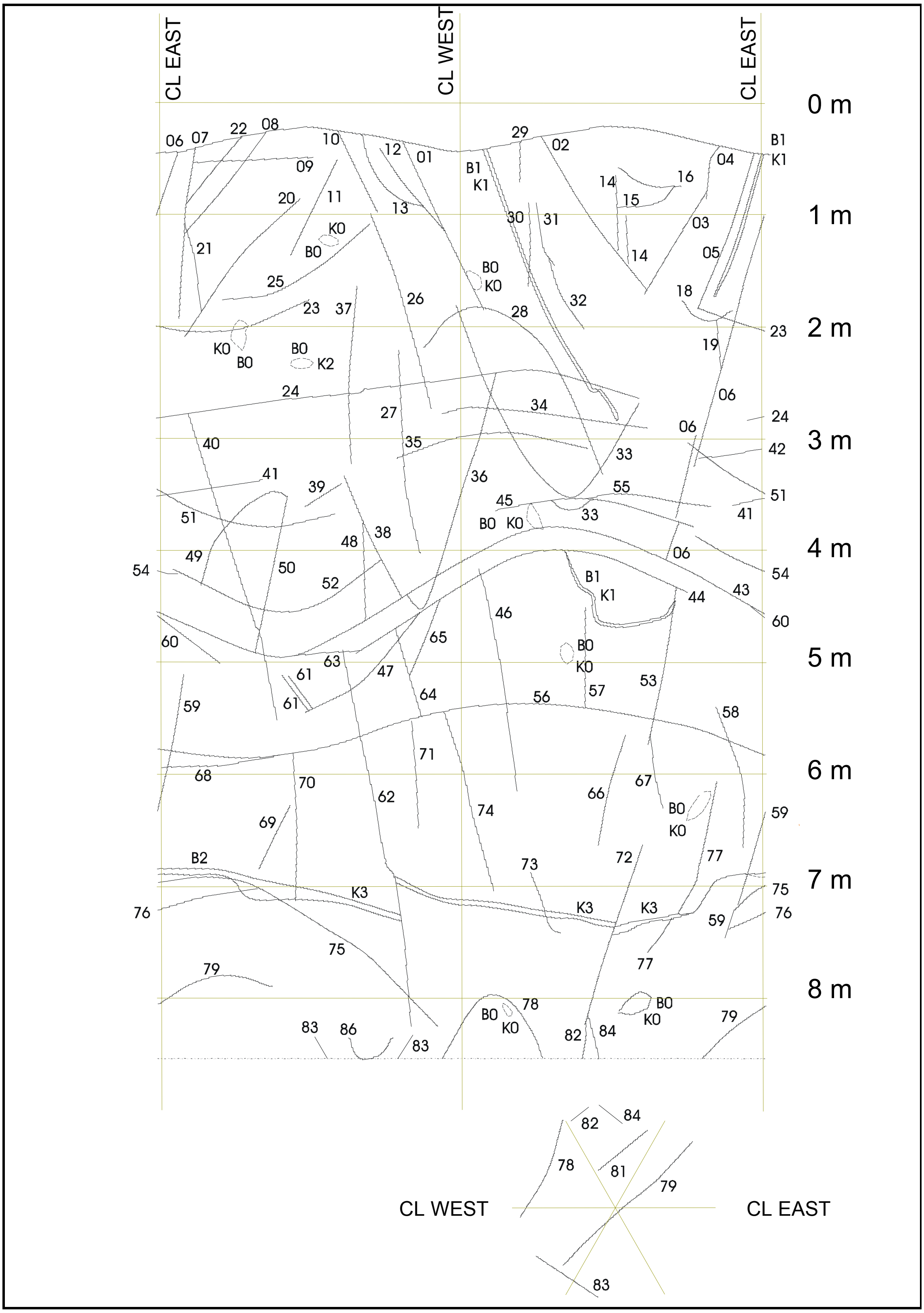
100
90
80
70
60
50
40
30
20
10
0
Content of grains [%]
0.06 0.13 0.25 0.5 1 2 4 8 16 20 31.5 63
Mesh opening [mm]
15 rpm, 40 tons per cylinder



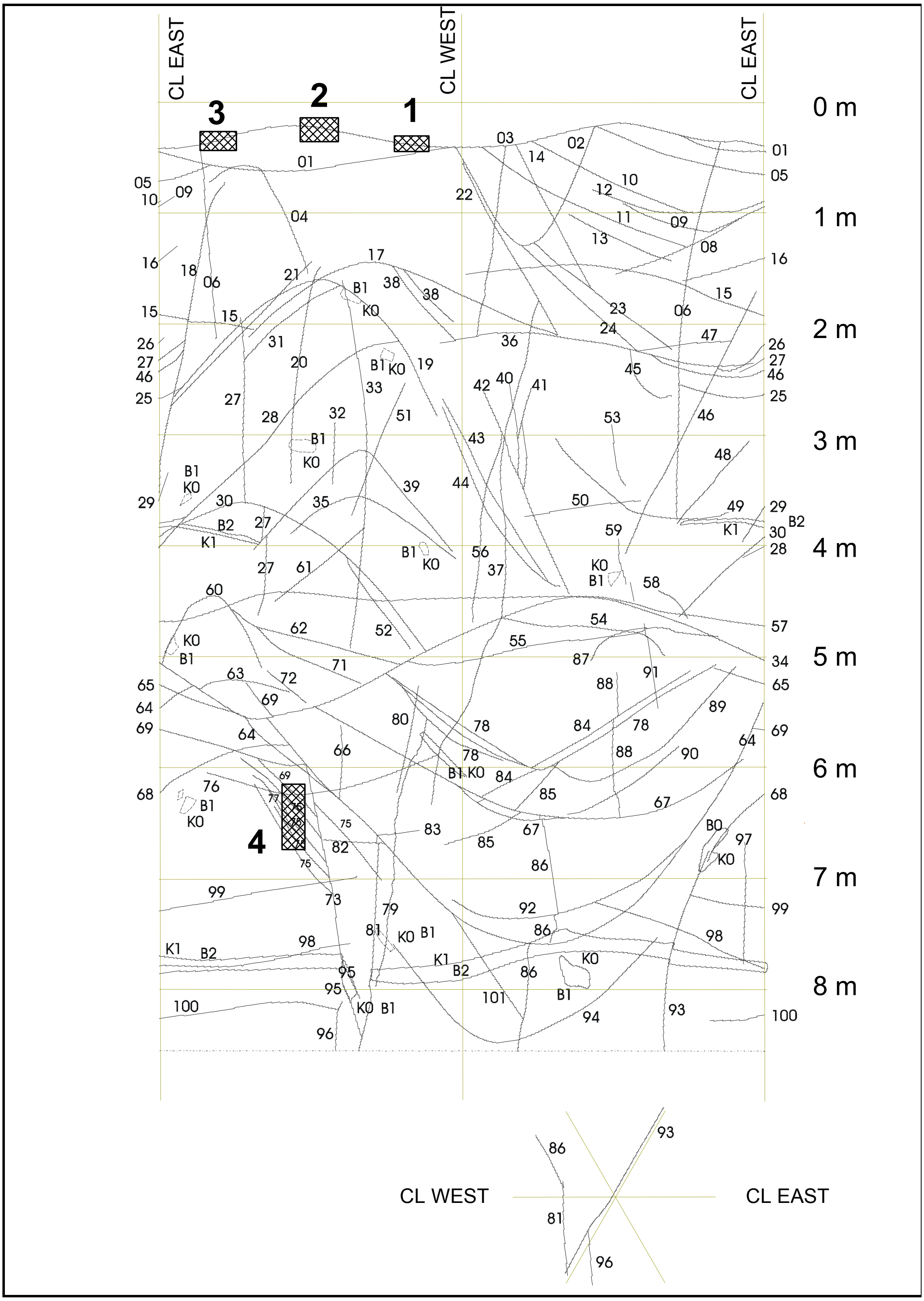
Deposition hole mapping in DA3587G01. Water bearing features are marked with shaded areas.



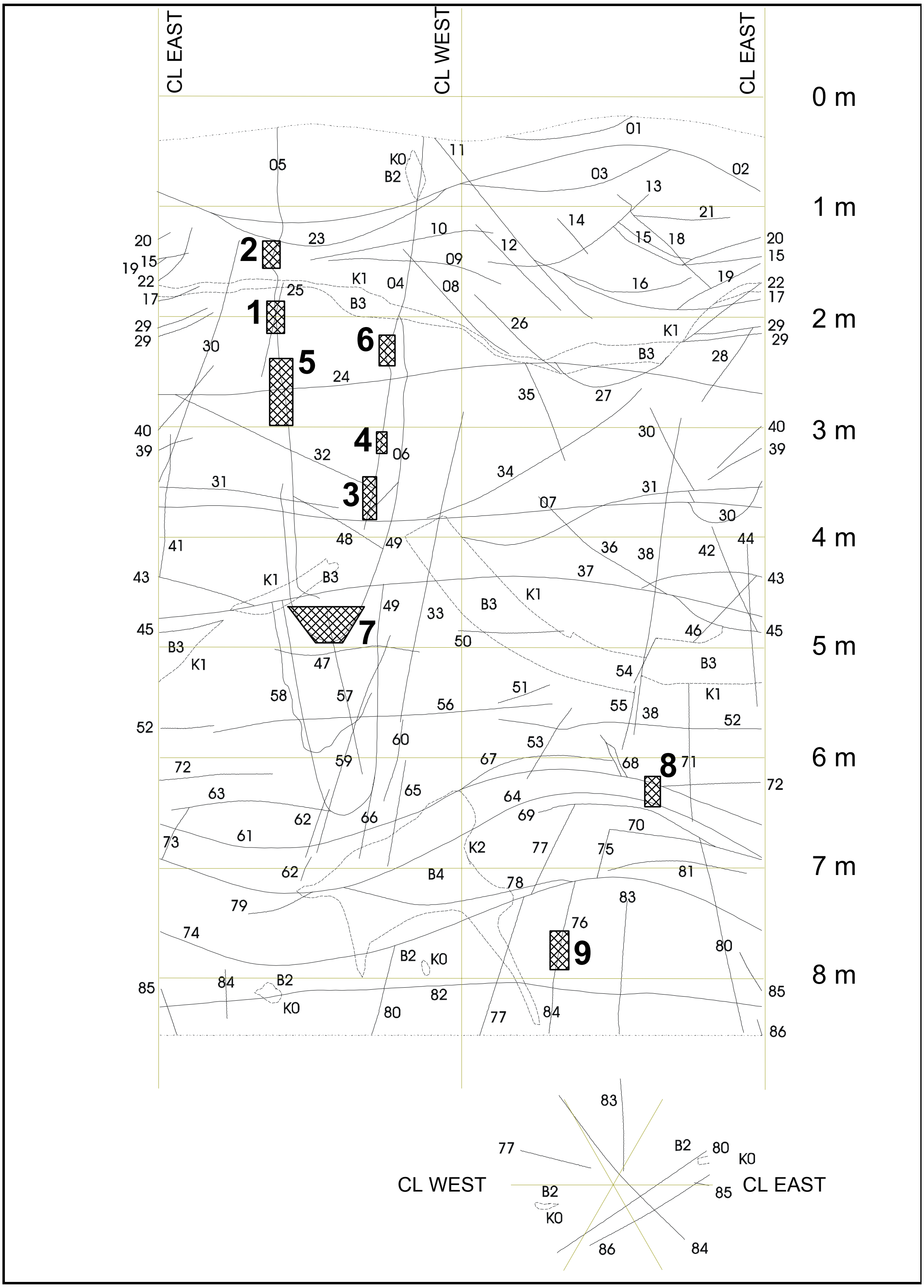
Deposition hole mapping in DA3581G01. Water bearing features are marked with shaded areas.



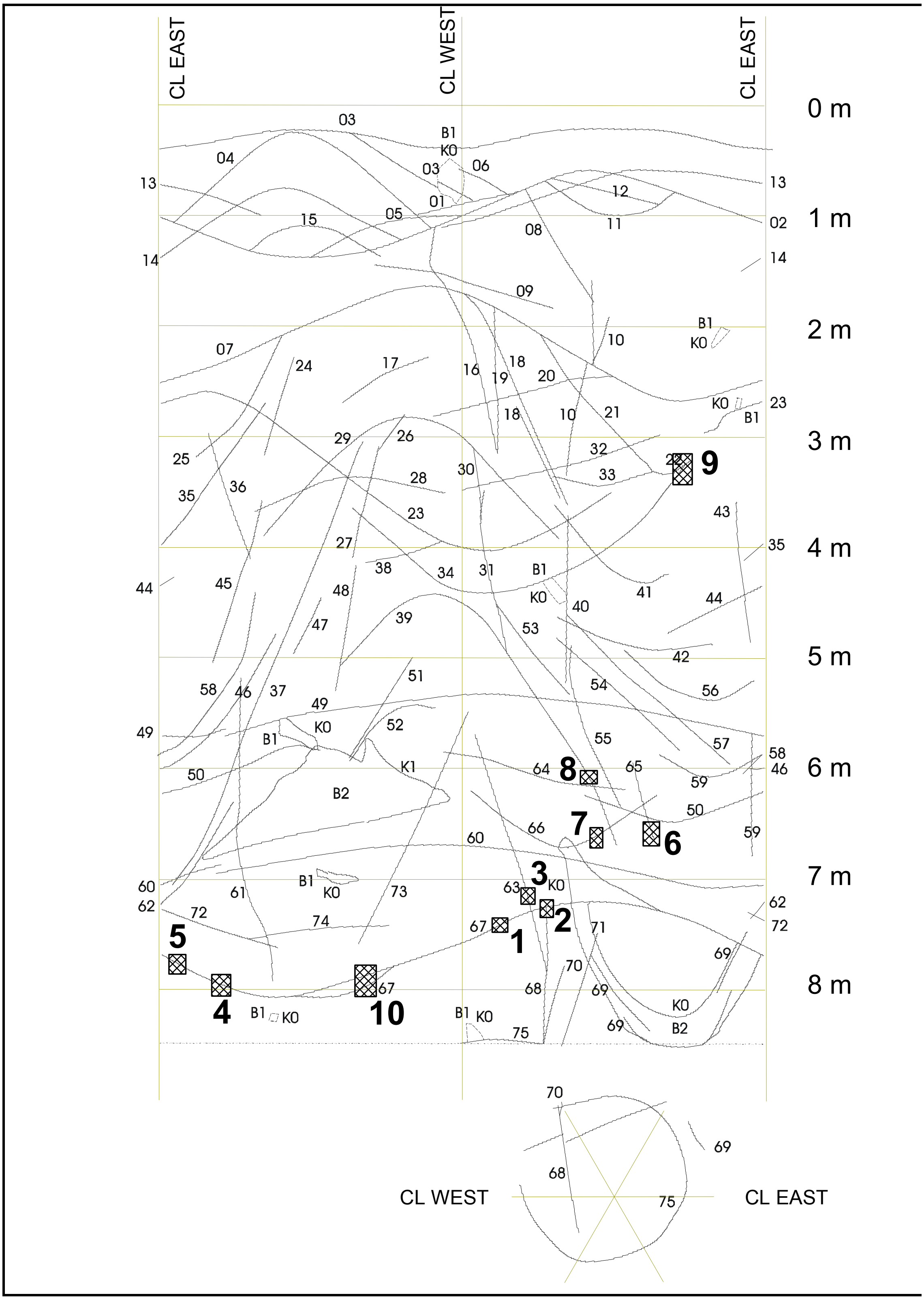
Deposition hole mapping in DA3575G01. No water bearing features were observed.



Deposition hole mapping in DA3569G01. Water bearing features are marked with shaded areas.



Deposition hole mapping in DA3551G01. Water bearing features are marked with shaded areas.



Deposition hole mapping in DA3551G01. Water bearing features are marked with shaded areas.