R-05-44

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Work description, summary of results and experience

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October 2005

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ISSN 1402-3091
SKB Rapport R-05-44

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Keywords: Repository engineering, Rock excavation, Optimisation, Lessons learned, Reaming, Tunnelling, Raise-boring, Repository.

Preface

This report is an account of the SKB and Posiva joint tests to excavate horizontal deposition drifts for a KBS-3H type of repository. One horizontal drift 15 m in length and one 95 m in length both with diameter 1.85 m were excavated at the Äspö Hard Rock Laboratory during the period October 2004 to February 2005. The results achieved and lessons learned are a basis for evaluation of the feasibility of excavating 300 m long horizontal drifts using horizontal push-reaming under realistic repository conditions.

Erik Lindgren, SKB was the project manager for the overall KBS-3H project. The Äspö Hard Rock Laboratory organisation, in particular Rickard Karlzén at SKB and Hans Wimelius at NCC is acknowledged for the supervision of the field test and the contributions to the final report.

SKB commissioned Entreprenørservice A/S with Trond Øiseth as project manager and John Engesgaar as controller to excavate the drifts using Smart Drilling GmbH as sub-contractor for active steering of the pilot hole. SKB has used independent resources for measurements and surveys, namely Geocon and ATS Lasermätbolaget.

Göran Bäckblom (Conrox) has acted as lead author of this summary report with Erik Lindgren, SKB as co-author. Geological mapping was executed by Roland Jonuks, Sweco VBB in consultation with Björn Magnor, SKB.

The report has been reviewed by SKB, the contractor involved and by independent reviewers, as Jukka-Pekka Salo at Posiva Oy and Jorma Autio at Saanio & Riekkola Oy.

These, as well as all others partners involved in the project are acknowledged for their contributions to this project.

Summary

SKB (Swedish Nuclear Fuel and Waste Management Co) and Posiva Oy in Finland jointly study the possibility to develop a variant of the KBS-3 method for final disposal of spent nuclear fuel. The idea is to make serial deposition of canisters in long horizontal drifts instead of vertical deposition of single canisters in the deposition hole. The studies concerning the horizontal deposition alternative are conducted within the framework of a "KBS-3H project", where certain demonstration activities are implemented. A key issue of the running project is to test the ability to excavate the horizontal deposition drifts. The objectives for this work are as follows:

- To show the feasibility of meeting the geometrical and other requirements;
- To construct two "deposition drifts" needed for the later project stages. One drift is needed to demonstrate that heavy load – a super-container – can be transported into the drift. One drift is needed to demonstrate that a plug (bulkhead) can be constructed by low-pH shotcrete;
- To evaluate the applicability of selected excavation methodologies for realistic repository conditions, and based on the experience in the project define need for technical developments/improvements.

To meet the objectives, two deposition drifts were excavated at the Äspö Hard Rock Laboratory during the period October 2004 to February 2005. One horizontal drift was 15 m in length and one 95 m in length. Both drifts were excavated to the diameter 1.85 m using horizontal push-reaming technology by adapting conventional raise-drilling equipment. The drifts were excavated in good rock conditions where no rock support or grouting was needed for feasible excavation or are needed to operate the drifts.

SKB and Posiva have stringent geometrical requirements for the excavated drifts and the conclusions concerning compliance with the requirements are:

Length: The project met this target. Two drifts were excavated, 15 m and 95 m respectively in accordance with the initial plan.

Diameter: Actually it was not so simple to measure the diameters of the drifts. The few measurements by the tape method show full compliance. Measurements by a dummy super-container in the 95 m drift show that around 90% of the 356 measurements were within the diameter limit 1,840–1,850 mm. Maximum value measured was 1,855 mm and minimum value 1,835 mm. It seems that there is systematic difference between measurements at the rear and at the front of the dummy, so the conclusions concerning these diameter measurements are preliminary.

Inclination: The measurements show that the vertical inclination for the 95 m drift is within the limit 2°±1°. To simplify mucking by flushing, the inclination should be minimum 2°.

Deviation of the pilot hole: For this project it was decided that the end of the pilot hole for the 95 m drift should be within ±22 cm of the theoretical line. The actual measurements show –61 cm deviation in the vertical direction and 11 cm deviation in the horizontal right direction due to the non-functional active steering. The stated requirement was not met, but the pilot hole was straight enough for the dummy of the super-container to be pushed to the end of the drift. The requirement should be restated as deviations horizontally would be worse than deviations vertically.

Steps: A few steps in the drift surface have been recognized in the short 15 m drift and in general the data show steps < 5 mm in accordance with the requirement. However the measurement methods are not good enough to corroborate compliance for all drift surface area.

Roughness: Roughness of the drift surface should be < 5 mm, but the measurement methods are not good enough to corroborate compliance for all drift surface area. In general the surface is smooth. The measurement using profiler shows that the requirements were met for the data collected. The measurements based on evaluation of the gauges at the dummy show very few data points outside the range 5 mm.

Straightness: Waviness or deviation from the centre line should be < ±2.5 mm over a distance of 6,000 mm. No measurement or evaluation methods were tried to examine the requirement; instead the dummy was manufactured to prove that a super-container with the same size would fit into the excavated drift without being stuck. The test verified that a super-container will fit into the drift.

As part of the project scope, measurement technology was partially developed and tested.

Besides the geometrical requirements other requirements were met.

- The method for excavation is feasible and safe with respect to occupational safety and environment.
- The method is also reasonably efficient in spite of that neither the equipment or working procedures are optimised. Maximum daily advance rate during reaming was in the order of 6 m per 12 hour day.

The main conclusion is that horizontal push-reaming can produce 95 m drifts in good rock that likely will meet the requirements for operational and long-term safety. The technology would also be applicable for 300 m long drifts provided that technology is developed and tested to drill straight enough pilot holes. More experience is needed to understand for what rock conditions additional pre-grouting would be necessary before the drift is reamed and for what rock conditions the drift might need temporary support during construction and before emplacement of the super-container.

Several suggestions for additional technical development and improvements have been identified in addition to the developments during the project.

- Active steering for drilling of a 279 mm pilot hole.
- Optimisation of the reaming machine for horizontal push reaming.
- Re-designed muck handling systems for reaming.
- Further development of the geometrical requirements so simple standard measurement technology can be used to show compliance with the geometrical requirements.
- Need for improvements in measuring technology and methodology and securing competent resources for executing and reviewing the measurement activities.
- Improved records of the excavation activities.

Sammanfattning

Svensk Kärnbränslehantering AB (SKB) och Posiva i Finland studerar tillsammans möjligheten att utveckla en variant av KBS-3-metoden för slutförvar av använt kärnbränsle. Tanken är att kunna deponera kapslar i serie i horisontella tunnlar istället för att vertikalt deponera en enskild kapsel i ett deponeringshål. Studierna rörande horisontell deponering sker inom ”KBS-3-projektet”, där vissa demonstrationer genomförs. En huvudfråga i det pågående projektet är att pröva förmågan att tillreda horisontella deponeringsorter. Målen för detta arbete är som följer:

- Att visa förmågan att uppfylla geometriska och andra krav;
- Att tillreda två ”deponeringsorter” som behövs för senare projektsteg;
- Att utvärdera tillämpbarheten av vald tillredningsteknik för en realistisk förvarsmiljö och baserat på erfarenheterna i projektet definiera behoven för teknisk utveckling och tekniska förbättringar.

För att fylla målen, anlades två deponeringsorter vid Äspölaboratoriet under perioden oktober 2004 till februari 2005. En ort var 15 m i längd och en ort 95 m i längd. Båda orterna har diametern 1.85 m och tillreddes med en standardmässig schaktdrivningsmaskin som anpassades för tryckande upprymning av orten. Orterna drevs i bra berg utan behov av bergförstärkning eller tätning under byggande eller drift.

SKB och Posiva har strikta geometriska krav för orterna och slutsatser rörande geometrisk kravuppfyllnad är:

Längd: Projektet nådde målet. Två orter anlades, 15 m och 95 m långa i enlighet med den ursprungliga planen.

Diameter: Det var inte trivialt att mäta orternas diameter. De fåtal mätningar som genomfördes med mätstång visar full kravuppfyllnad. Mätningar i 95 m orten med en tolk som motsvarade super-behållarens geometri visar att cirka 90 % av de 356 mätresultaten är inom kravet 1 840–1 850 mm. Det maximala uppmätta värdet var 1 855 mm och minimivärdet 1 835 mm. Det tycks som om det är en systematisk skillnad mellan mätresultat i tolkens främre och bakre del, så slutsatser rörande dessa mätningar är preliminära.

Lutning: Mätningarna visar att den vertikala lutningen för 95 m orten är i intervallet 2°±1°. För att förenkla utlastning med spolning under tillredning av orten, bör lutningen vara minimum 2°.

Avvikelse i pilothålet: I projektet bestämdes att pilothålets slut för 95 m orten skulle ligga inom ±22 cm av den teoretiska linjen. Mätningarna visar att avvikelsen är –61 cm vertikalt och 11 cm horisontellt, beroende på att tekniken med aktiv styrning inte fungerade. Kravet uppnåddes inte, men hålet var tillräckligt rakt för super-behållarens tolk kunde föras till ortens slut. Kraven bör omformuleras, eftersom avvikelser i horisontell led är sämre än avvikelser vertikalt.

Steg: Några smärre steg påträffades i den korta 15 m orten och i allmänhet är dessa steg mindre än 5 mm i överenskommelse med kraven. Mättekniken är inte tillräckligt bra för att visa kravuppfyllnad för hela mantelytan.

Rakhet: Vågigheten eller avvikelsen från centrumlinjen ska vara < ±2.5 mm over en sträcka av 6 000 mm. Inga mätningar eller utvärderingar prövades för att stämma av kravet. Istället tillverkades en tolk av super-behållaren för att visa att behållaren passar i orten utan att fastna. Försöket visade att en super-behållare kan passa till orten.

Mätteknik utvecklades delvis och prövades i projektet. Förutom geometriska krav, uppfylldes andra krav:

- Metoden för tillredning är genomförbar och säker med hänsyn till arbets- och yttre miljö.
- Metoden är också rimligt effektiv trots att varken utrustning eller arbetsrutiner är optimerade. Maximal framdrift per dag var omkring 6 m per 12 h vid upprymning av orten.

Huvudslutsatsen är att horisontell tryckande upprymning kan tillreda 95 m orter i bra berg som med god sannolikhet uppfyller krav på drift och långsiktig säkerhet. Tekniken är också tillämpbar för 300 m långa orter under förutsättning att teknik för att borra raka pilothål utvecklas och testas. Mer erfarenhet behövs för att förstå för vilka bergförhållanden förinjektering är nödvändig innan orten ryms upp och för vilka bergförhållanden som temporär bergförstärkning behövs under tillredning och före deponering av super-behållaren.

Flera förslag lämnas till teknisk utveckling och förbättring, i tillägg till de utvecklingsinsatser som skett inom projektet.

- Aktiv styrning vid borrning av pilothål 279 mm.
- Optimering av borrhuvud för horisontell tryckande upprymning.
- Ny utformning av kaxhantering vid rymning.
- Vidareutveckling av geometriska krav så att enkel standardmässig mätteknik kan användas för att visa att de geometriska kraven fylls.
- Förbättringar i mätteknik och –metoder och säkring av kompetenta resurser för att gemomföra och granska mätningsaktiviteterna.
- Förbättrade rutiner för uppföljning av berguttag.

Contents

1 Introduction

The plan to construct a geological repository for spent nuclear fuel in Sweden has reached the phase of site investigations at the two candidate sites at Forsmark and Oskarshamn. A general description of the overall programme is found in the latest Research, Development and Demonstration Programme /SKB 2004/. An outline description of the geological repository is conveniently found at SKB's website www.skb.se. Basic engineering of the repository for the KBS-3 method, see Figure 1-1, is developed in parallel with the site investigations with the overall objective that the repository is a safe and effective facility that fully complies with international guidelines and standards, national regulations and the general design requirements for the facility /SKB 2002/. The KBS-3-method is based on the multi-barrier principle and geological emplacement and has been developed by The Swedish Nuclear Fuel and Waste Management Co (SKB) as base for the planning of the final disposal of the spent nuclear fuel.

The principle of the KBS-3-method is that the spent nuclear fuel is encapsulated in a copper canister with a cast-iron insert. The canister is placed in a deep repository constructed in crystalline host bedrock about 500 m below surface. The canister is surrounded by highly compacted bentonite clay and the tunnel system is backfilled with a mixture of crushed rock and bentonite clay, see Figure 1-1. Vertical emplacement has been SKB's reference design for the last 20 years.

The possibility to modify the reference method and make serial emplacement of canisters in long horizontal drifts instead of vertical emplacement of single canisters in the deposition hole is now studied as well, see Figure 1-2 (right); the method is a variant of the KBS-3 method named KBS-3H, where the H is for horizontal emplacement.

The activities concerning the KBS-3H alternative are conducted within the framework of a "KBS-3H project", where certain demonstration activities are in progress.

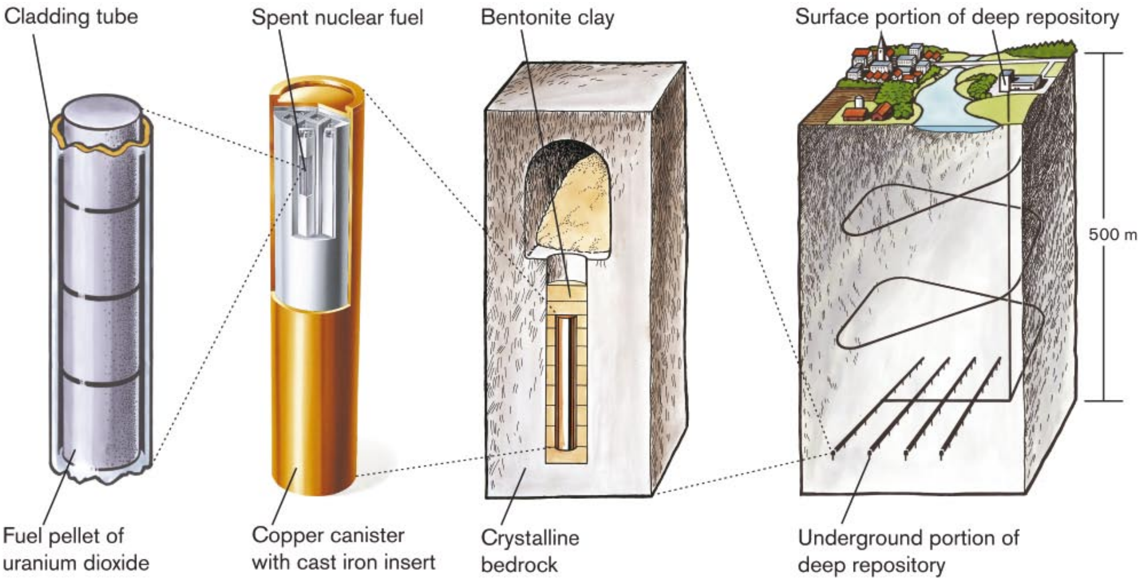

Figure 1-1. *The barriers of the KBS-3 method.*

An important part of the running project is to test the ability to excavate the horizontal deposition drifts. The objectives for this work are as follows:

- To show the feasibility of meeting the geometrical and other requirements;
- To excavate two "deposition drifts" needed for the later project stages. One drift is needed to demonstrate that heavy load – a super-container – can be transported into the drift. One drift is needed to demonstrate that a plug (bulkhead) can be constructed by low-pH shotcrete;
- To evaluate the applicability of selected excavation methodologies for realistic repository conditions, and based on the experience in the project define need for technical developments/improvements.

To meet the objectives, two deposition drifts were excavated at the Äspö Hard Rock Laboratory during the period October 2004 to February 2005. One horizontal drift was 15 m in length and one 95 m in length, both were excavated with the diameter 1.85 m using horizontal push-reaming technology by quite conventional raise-drilling equipment as an alternative to previously tested cluster boring technique. The rationale using this technology to other possible technologies is described in /Bäckblom et al. 2004/.

This report is a summary report of the joint SKB-Posiva KBS-3H excavation project. The KBS-3H design and the KBS-3H project is described in Chapter 2, whereas the geological conditions are contained in Chapter 3. The following chapters detail the plans, equipments and general results obtained. The final chapters intend to evaluate the results for a set of factors, like long term and operational safety, environment, schedules and costs and flexibility as well as evaluating the feasibility and constraints for excavating 300 m long horizontal drifts under realistic repository conditions. It is emphasized that the evaluations are based on the first tests ever using horizontal push-reaming for this specific application and much future fine-tuning of the technology is possible.

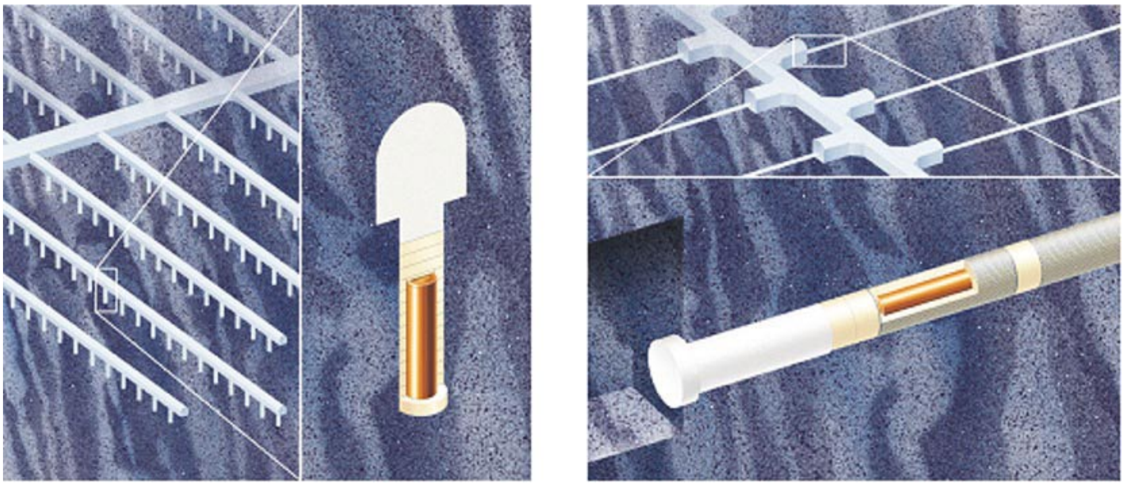

Figure 1-2. *KBS-3V (left) and KBS-3H (right).*

2 The KBS-3H alternative for geological disposal

2.1 The KBS-3H project

As described in the introductory chapter, the KBS-3 reference design is based on vertical emplacement. However for several reasons like cost efficiency and environmental advantages, SKB is also in co-operation with Posiva Oy – the Finnish nuclear waste management organisation in Finland (www.posiva.fi) – studying horizontal emplacement. The budget of the current RTD programme is about 15 million €. The purpose is to develop the KBS-3H alternative to the same level of knowledge as the reference design KBS-3V. The multi-barrier and long term safety principles are the same as for the reference alternative KBS-3V, but construction and deposition would be different for the horizontal emplacement variant.

The main advantage of the KBS-3H alternative is that the method provides a more efficient way of depositing the canisters in the rock as the deposition tunnels of the KBS-3V alternative are not needed. The total volume of rock excavation is therefore decreased by about 50% which leads to a lower environmental impact during the construction of the repository but also to a reduced disturbance on the hydrogeological situation in the rock mass. Furthermore, the reduction in rock excavation leads to a significant cost saving for the excavation and backfilling of the repository.

In the KBS-3H alternative, the deposition tunnels are replaced by horizontal deposition drifts with a circular cross section, see Figure 1-2. The drifts which shall be up to 300 m long are excavated from a niche in the transport tunnel. Up to 40 canisters will be deposited in each drift. The development and demonstration of the KBS-3H alternative is done according to an R&D programme divided into four parts /SKB 2001/:

- Feasibility study, year 2002.
- Basic Design, year 2003.
- Construction and testing at the Äspö Hard Rock Laboratory, year 2004–2006.
- Evaluation, year 2006–2007.

The results of the Basic Design stage are reported in /Thorshager and Lindgren 2004/. This report is a partial documentation of the construction and testing activities performed at the Äspö Hard Rock Laboratory.

2.2 The super-container

Efficient horizontal emplacement requires the canister and the buffer to be assembled into one unit, a so called super-container, which then is pushed into the deposition drift. The super-container consists of a perforated steel cylinder in which the buffer material and one copper canister are assembled, Figure 2-1. A distance block of bentonite is placed between each super-container.

The purpose of the distance block is to seal off each canister position from the other and to prevent transport of water and bentonite along the drift. The distance block also separates one canister from the other in order to get the right temperature of the canister. The length of each super-container is about 6 m and the overall diameter 1,765 mm.

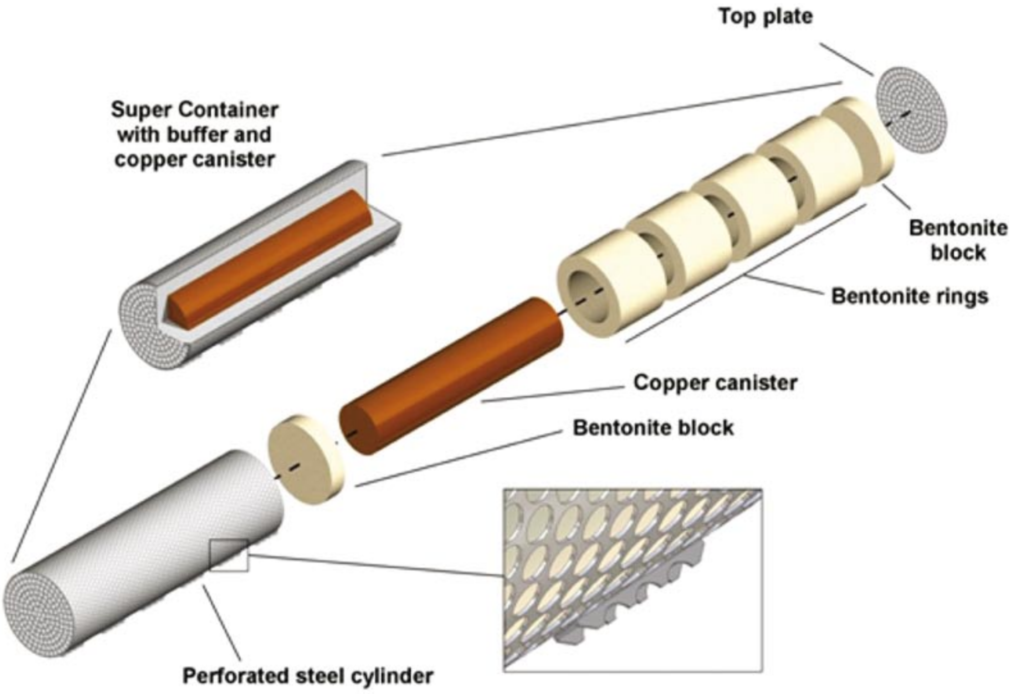

Figure 2-1. *KBS-3H super-container.*

2.3 KBS-3H deposition drifts

The layout for the KBS-3H reference case is similar to the KBS-3V, but the deposition tunnels and deposition holes are replaced by an up to 300 m long deposition drift which is excavated from a niche in the transport tunnel, Figure 2-2. A total of around 45,000 m of deposition drifts are needed with a total volume for deposition drifts being around 120,000 m^3.

The drifts must be excavated with a very high level of accuracy with respect to straightness, tolerances of the diameter and surface smoothness. The requirements are further discussed in the next Chapter 2.4 being related to long term safety as well as to operational aspects.

2.4 Requirements

2.4.1 General requirements

SKB has previously compiled general requirements for the KBS-3 system /SKB 2002/. Most of the requirements are applicable both for the KBS-3V and KBS-3H alternative.

One particular for the KBS-3H alternative is the very stiff requirements on geometry for the deposition drift and these are justified both for reasons of long term safety and reasons of emplaceability.

Figure 2-3 shows a compilation of requirements for this project. All tolerances at this moment are just first inceptions. The tests at Äspö will be used to challenge the requirements and also to fine-tune them based on experience and further analyses so they are sufficient for reasons of long term safety and also are doable to comply with when excavating and emplacing the canister.

Justifications for the geometrical requirements for the repository are compiled in Table 2-1, see also Figure 2-3 (for project requirements). It must be underlined that the requirements are preliminary and will be adjusted in the light of additional studies.

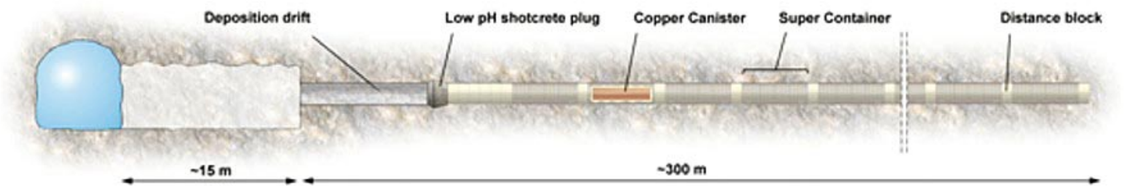

Figure 2-2. *Deposition drift.*

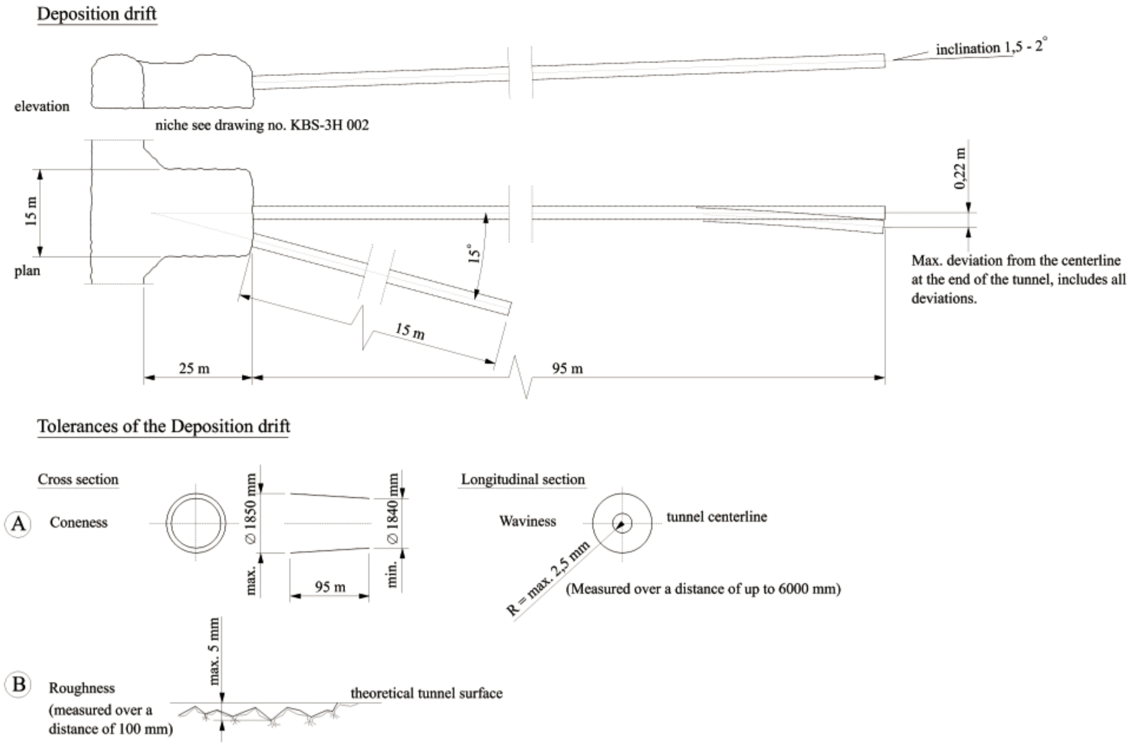

Figure 2-3. *SKB requirements on geometrical tolerance for this field test.*

Table 2-1. Justification for preliminary geometrical tolerances for the repository.

Issue	Requirement	Justification
Length	< 300 m	The repository lay-out shall be similar to KBS-3V. The length is considered to be feasible from constructional and operational view, however a optimization is necessary after the KBS-3H technology has been demonstrated.
Diameter	1,850 mm	The drift diameter is based upon operational aspects as well as thermal heat flow and buffer density aspects.
Inclination	2°±1°	The deposition machine is designed for a positive inclination of 1–3°. A positive inclination is also a prerequisite for water drainage.
Deviation of pilot hole	< 2 m from the nominal position at a distance of 300 m	A minimum distance between the drifts of 36 m has been the input data in thermal dimensioning of the repository lay-out.
Max deviation from the centre line at the end of the tunnel	≤ 220 mm (for the Äspö demonstration)	It has been estimated that a deviation of 2 m at a distance of 300 m corresponds to a deviation of 0.22 m at a distance of 100 m.
Diameter variation	≤10 mm	The void space outside the super-container must be kept within these tolerances to ensure correct buffer density and swelling pressure after saturation.
Steps	≤ 5 mm	Full scale laboratory tests have verified that the emplacement equipment can move properly in the drift for steps up to 5 mm.
Roughness	≤ 5 mm	Full scale laboratory tests have verified that the emplacement equipment function properly for a roughness up to 5 mm.
Straightness (waviness or deviation from the centre line	±2.5 mm over a length of 6,000 mm	The centreline deviation must be kept within small tolerances to prevent the super-container from getting in contact with the rock surface during transport in the drift.

2.4.2 Specific KBS-3H requirements related to the long term safety

One requirement on the buffer material is that the buffer hydraulic conductivity shall be so low that any transport of corrodants and radionuclides solely takes place by diffusion. This is guaranteed by certain minimum saturated buffer density that is 1,995 kg/m^3. The buffer swelling pressure shall not be higher than the canister and host rock can withstand without any damage. This is guaranteed by a certain maximum buffer density that is 2,015 kg/m^3.

Since the unsaturated buffer volume is fixed, the buffer density and swelling pressure is decided by the initial void which is to a large extent depending on the air slot between the super-container and the drift wall. In other words there is a strong benefit to excavate the drift with very stiff tolerances requirements on the drift diameter.

2.4.3 Specific KBS-3H requirements related to the operation phase

Emplacement of the super-container will be carried out by the use of a deposition machine which relies on water cushion for reduction of the friction. The water cushions must have a very smooth surface in order to function properly and therefore a sliding plate constitutes the contact surface of the water cushions. The sliding plate replaces the water-rock contact with water-steel contact. Still it is necessary to reduce the roughness of the rock surface as much as possible.

The super-container is equipped with steel feet. At the occasion when the container is pushed forward the there is gap of about 7 mm between the feet and the rock. The gap of 7 mm must always be there and therefore no steps > 5 mm are permitted in the drift, Figure 2-4.

The deposition machine with the super-container and sliding plate will constitute a long stiff body (about 12 m). To avoid bending of this long body the drift centreline as well must be kept within small tolerances. The free gap between rock surface and super-container is an important design parameter as it affects the design of operation equipment and possible pipe-systems installed in the gap. The width of the free gap at final state depends on the geometrical tolerances (e.g. straightness, diameter variability and surface roughness) of the drift. During operation the canister is lifted and lowered in steps and therefore the free gap during operation becomes clearly smaller (about 20 mm in size) than at final position. The improvement of the surface quality will increase the size of free gap correspondingly and therefore an improvement of 10 mm corresponding to assumed maximum diameter reduction will benefit the operation significantly.

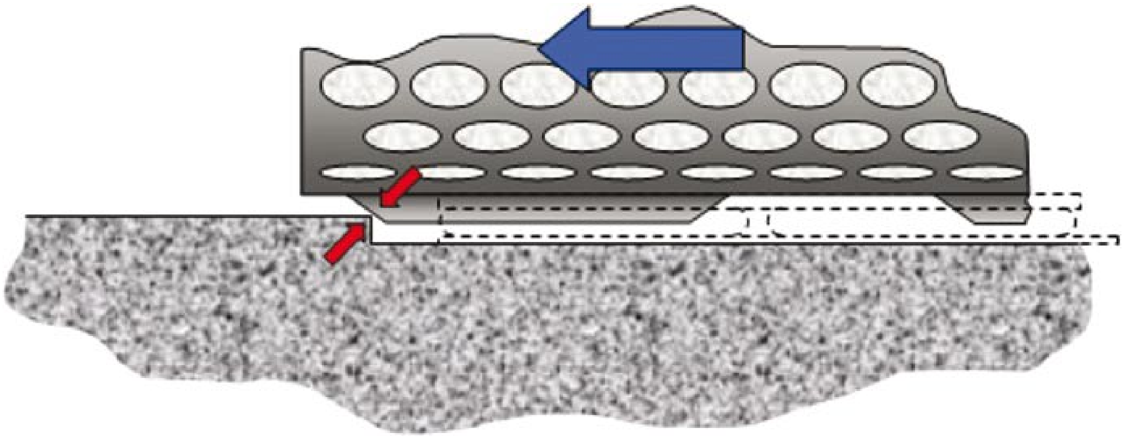

Figure 2-4. *Only very minor steps (< 5 mm) are allowed for feasible emplacement of the super-container.*

3 Description of geological conditions at the excavation site

3.1 Selection of site

Four different potential sites for the test were analysed (see Alternative 1–4), Figure 3-1, with respect to space requirements, installations, bedrock conditions, disturbance of other ongoing experiments, facility operation and information activities. The overall conclusion was that Alternative 3 would be the most favourable location.

The general set up for the field test at a NASA 1623 A is shown in Figure 3-2.

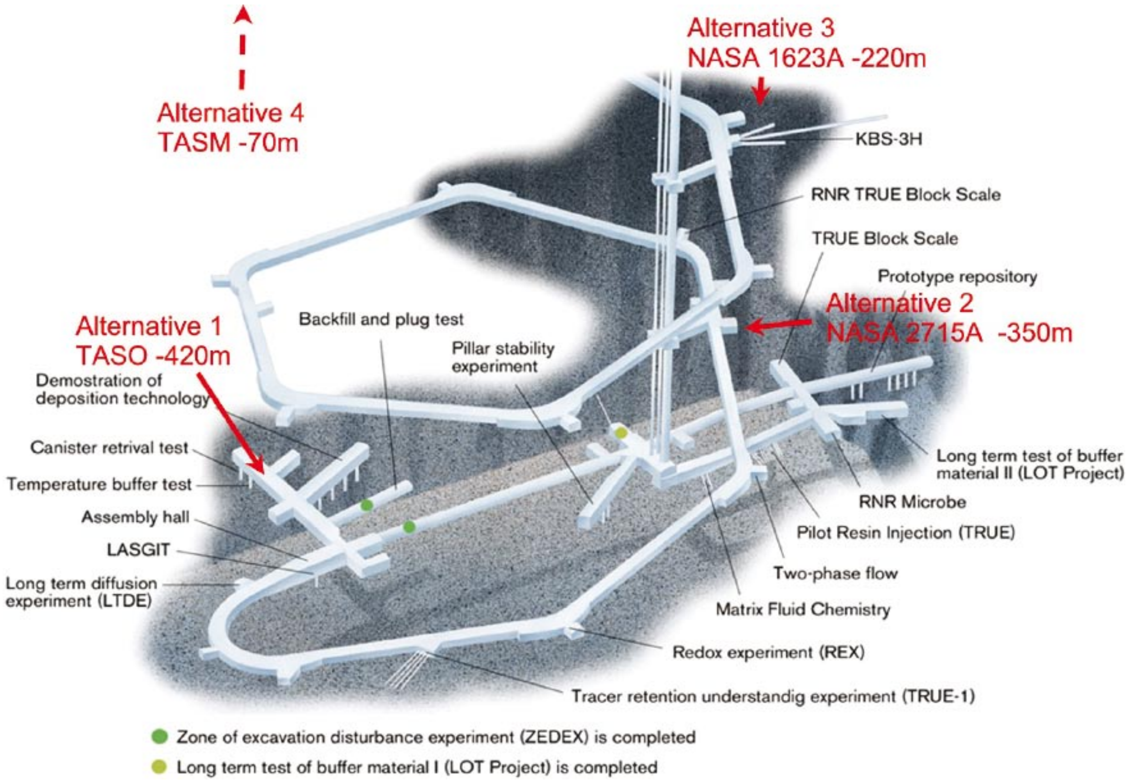

***Figure 3-1.** Alternative 1–4 for siting the KBS-3H test at the Äspö Hard Rock Laboratory.*

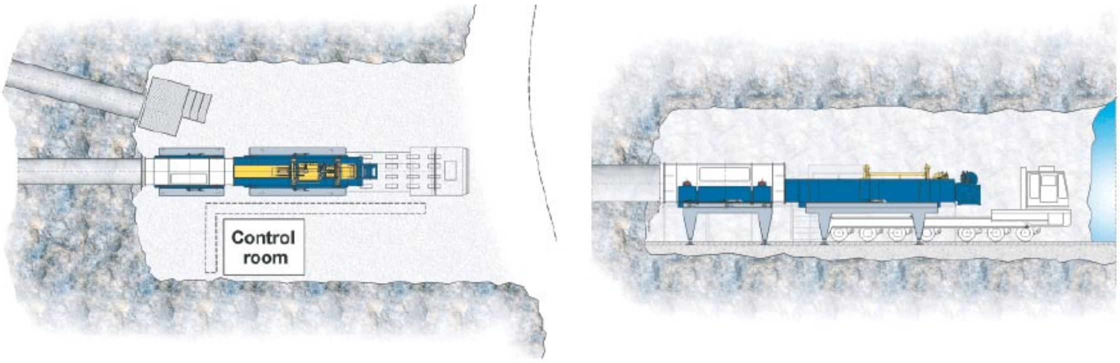

Figure 3-2. Demonstration site at Äspö. The picture shows the equipment for testing emplacement of the super-container.

3.2 General on the Äspö site

Comprehensive site characterisation data at Äspö and the neighbourhood has been collected from surface since 1986 and from underground since 1992. With respect to lithology the dominant rock types are Ävrö granite and Äspö diorite, see Figure 3-3. Geochemical analyses were not a part of the mapping of the excavated drifts. The content of free quartz is in the order of 15–25% for the Äspö diorite and 20–30% for the Ävrö granite.

Rock mechanical parameters were not collected specifically for the KBS-3H niche. Uniaxial strength for the Ävrö granite is in the order of 250 MPa and the Äspö Diorite in the order of 170 MPa. Young´s modulus is in the range of 63–80 GPA for the rock types /Rhén et al. 1997/. The general rock stress data situation is described by /Hakami et al. 2002/.

3.3 Results and information from site investigations prior to the KBS-3H field tests

This section describes some specific data collected in the test area. After the excavation of the demonstration site was completed in year 2003 core drilling in the rock volume was carried out. Three holes were drilled because the project by this time had not decided whether to excavate two or three deposition drifts. The boreholes are KA1616A01 (30 m long, Ø56 mm), KA1619A01 (100 m long, Ø76 mm) and KA1621A01 (30 m long, Ø56 mm) see Figure 3-4. The holes were mapped with respect to lithology, structures and fractures.

An overview of the rock types in the area is shown in Figure 3-5.

Details from the boreholes are shown in Table 3-1. The most common rock type, the granodiorite (Äspö Diorite) is porphyritic, medium to coarse grained. The granodiorite is intruded by several dykes or veins of red, fine grained granites and coarse grained pegmatites showing same sets of orientations: 235/85–90°[1] and 335/60° in the Äspö 96 local coordinate system. The boreholes, especially KA1619A01, also contain some granite (Småland granite) and several small xenoliths of greenstone (meta-basite). A few possible occurrences of hybrid rocks were also observed.

The most prominent discontinuities are shown in Figure 3-6.

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[1] Strike measured clockwise from North/Dip measured from the horizontal plane.

The three boreholes KA1616A01, KA1619A01 and KA1621A01 are relatively poor in natural open fractures. The overall fracture frequency is only 1.2, 1.2 and 0.9 fractures/m, respectively. Two fracture sets were observed: 310/80–90° and 025/80°. The number of fractures along the borehole KA1619A01 is shown in Figure 3-7.

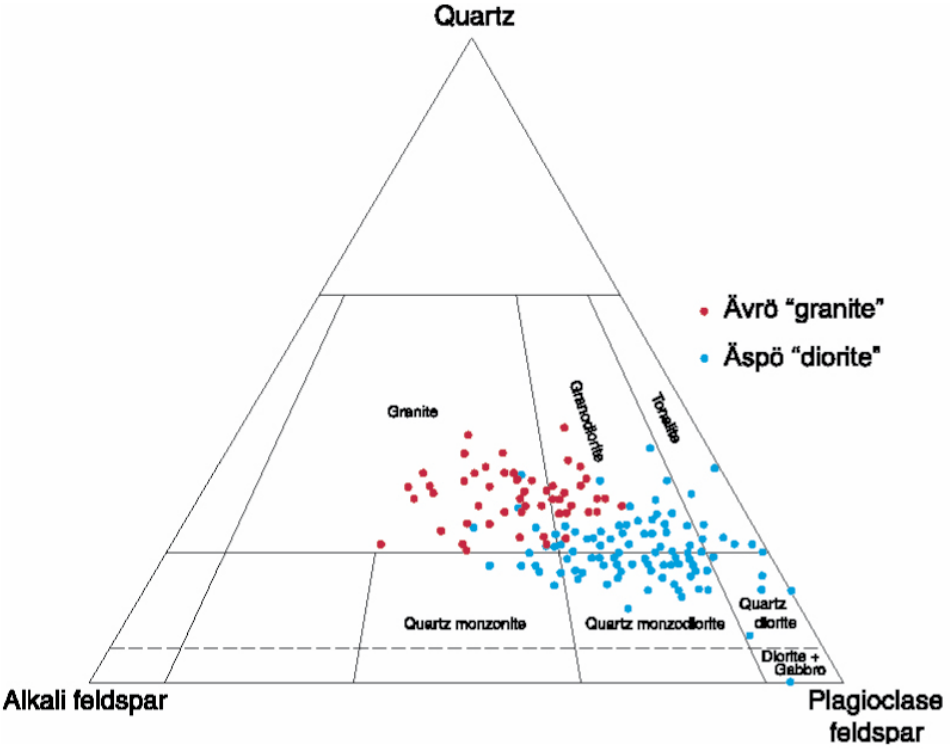

Figure 3-3. *Mineral composition for Ävrö granite and Äspö diorite. /Wikman and Kornfält 1995/.*

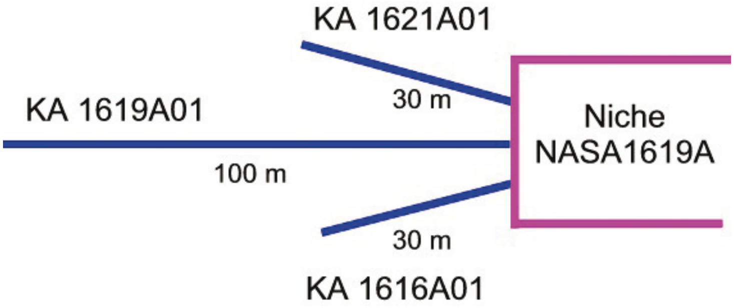

Figure 3-4. *Top view of cored boreholes before excavation.*

Table 3-1. Rock type distribution in the boreholes.

Borehole	Äspö Diorite	Småland granite	Pegmatite	Fine grained granite	Greenstone	Hybrid rock
KA1616A01	93%	< 1%	1.2%	1.9%	3.9%	< 1%
KA1619A01	73.6%	17.5%	1.5%	6.0%	1.4%	< 1%
KA1621A01	90.6%	4.8%	1.4%	2.3%	0.9%	–

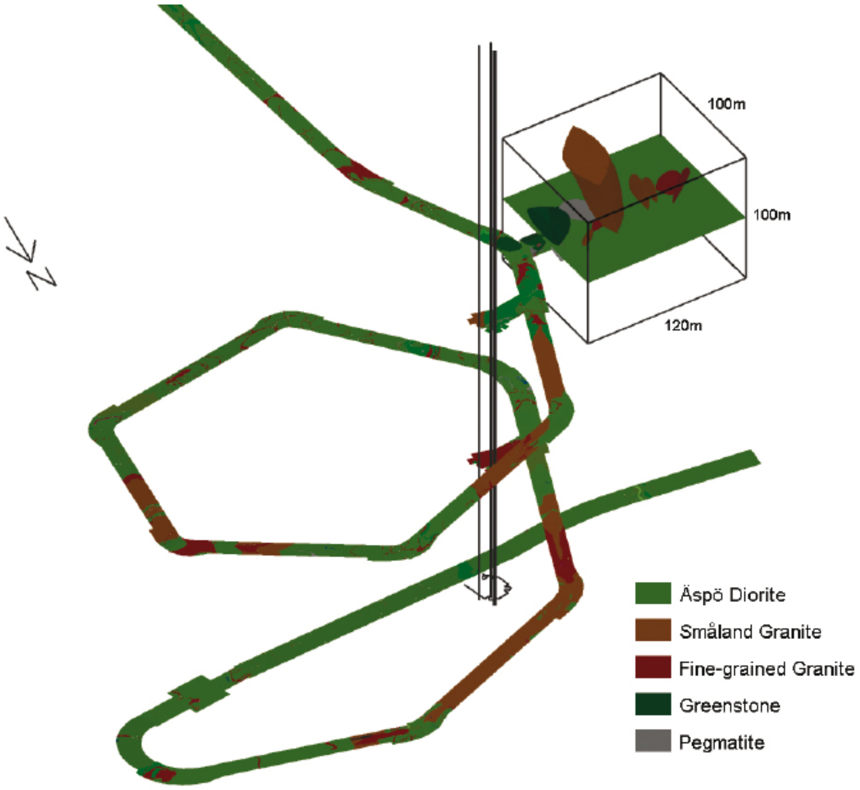

Figure 3-5. *Model of rock types in the field test area.*

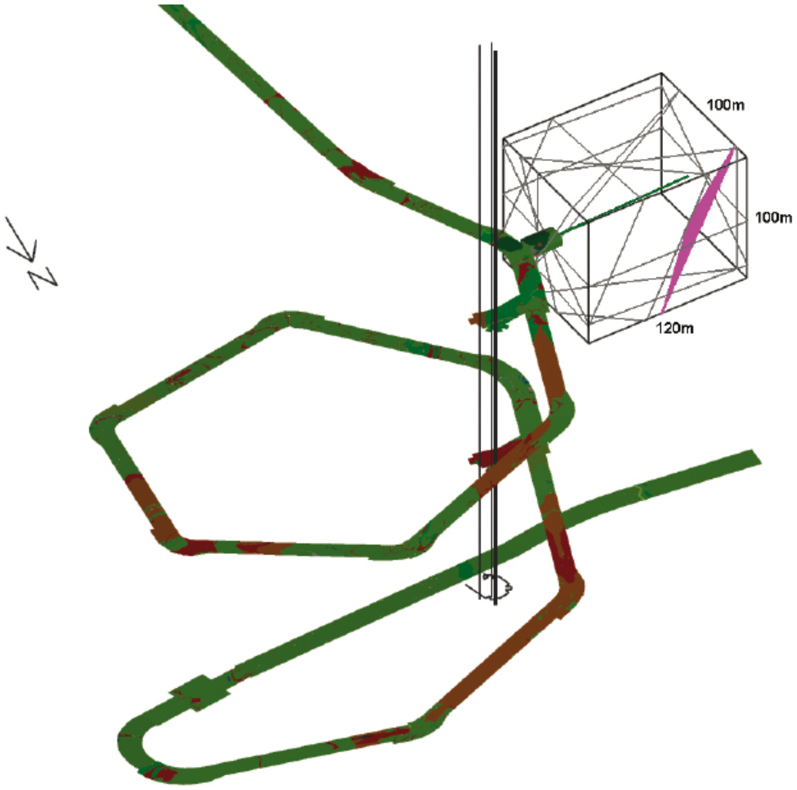

Figure 3-6. *Model of the large fractures in the field test area.*

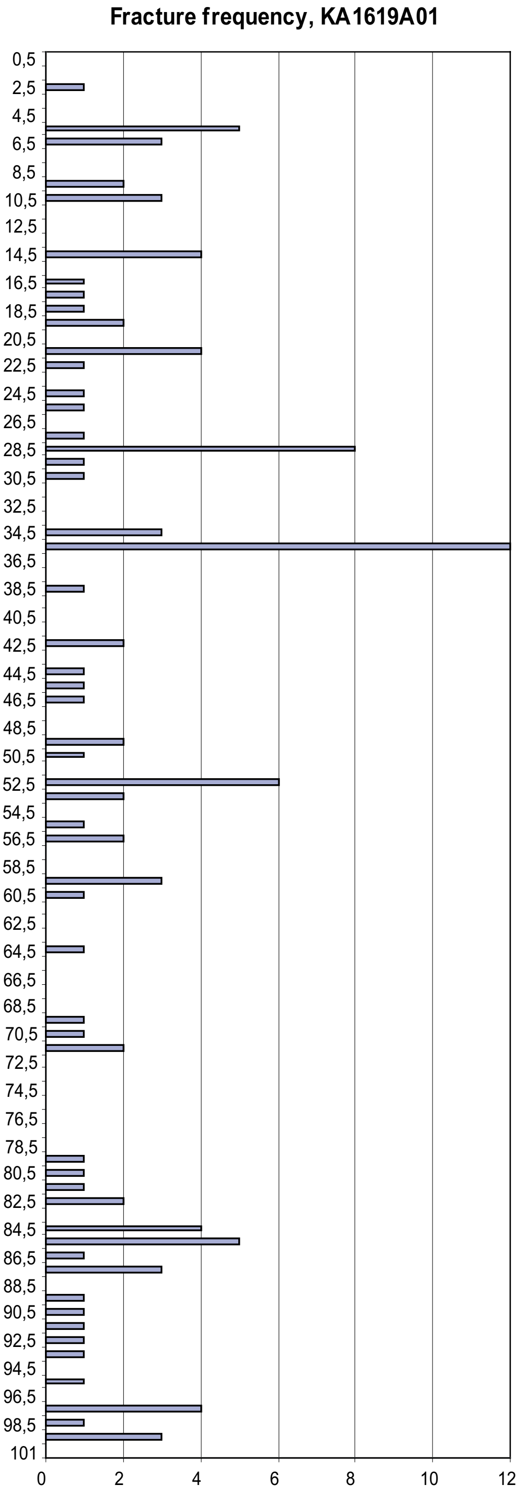

Figure 3-7. *Number of open fractures per m along the borehole KA1619A01.*

3.4 Results after mapping of the two drifts

After excavation, the drifts were mapped during February 2005 (the short 15 m drift) and in March–April 2005 (the long 95 m drift). Focus was on rock types, fracturing, water inflow etc and some results are here extracted to provide the context mainly for evaluation of constructability. Details of geological mapping of the drifts are included in the Appendix 1.

3.4.1 Rock type descriptions

The results of the mapping of the drifts are mainly consistent with the models based on the cored holes. The Äspö diorite contains small elongated fragments of greenstone more or less parallel to the drift direction. The boundaries with the fine-grained granite are quite distinct. Pegmatites also occur as irregular elongated bodies with sharp boundaries to the side rock. Småland granite or Ävrö granite occurs in the 95 m drift as large, irregular but homogenous bodies or as small fragments. One of the large bodies occurs in the left wall between 36 m and 49 m and another between 61 m and 76 m. The latter is strongly faulted by traversing fractures at 62 m, 71 m and 75 m. Between 84 m and 90 m a granitic inclined sheet occurs. The sheet is strongly faulted at 86 m, 88 m and 90 m. A small greenstone-dike crosses the 15 m drift in direction 255/70°. In the long 95 m drift, fine-grained aplitic rocks usually occur as veins or flat veined bodies, often orientated perpendicular to the drift in a steep or medium steep manner. They veins are seldom wider than 1 m but usually continues into the unexposed rock. Examples on rock types are shown in Figure 3-8.

3.4.2 Zones and fracturing

A thin shear zone, slightly mylonitised, with closed fractures filled with epidote, occurs at 7 m into the 15 m drift. The zone is itself sealed. However in the proximity, open water-conducting fractures are present. The shear zone, with a strike/dip 340/60°, seemingly divides the fracture pattern in the drift into two parts. From the drift opening to the shear zone at 7 m, more persistent steep fractures generally occur while the inner parts of the drift generally shows shorter fractures and also a higher number of sub-horizontal fractures. Most fractures are closed or sealed with minerals. Clay filled fractures has not been observed. Clay may however have been washed out during the drilling operation. The most common fracture filling is epidote which often occurs in persistent steep fractures.

The fracturing in the 95 m drift is divided into three groups:

- The first group represents quite steep fractures that traverses the drift perpendicular or in steep angles and continuous outside the cell.
- The second group represents sub-horizontal fractures.
- The third represents short fractures in several directions.

Five fracture zones have been identified in the first group at 29 m, 62 m, 86 m, 88 m and 90 m. The zones are quite similar to each other with close lamella fractures partly filled with epidote or/and calcite. They might also be mylonitized or brecciated in thin zones. Usually some water leakage occurs in the adjacent fractures. Otherwise, the rock mass generally is sparsely fractured; in average five fractures per metre occur but short sections can of course be more or less intensely fractured.

The general fracture pattern changes from section to section in the drift. From the opening to 26 m, fractures from the first group generally occur with 2–3 m distance from each other. From 26 m and to the end of the drift the fractures tend to occur in groups of 3–6 fractures with the groups 3–5 m apart. The distance between the groups however decreases with the distance into the drift. The sub-horizontal fractures are sparse up to 26 m. From there they occur quite frequent in certain sections, for example between 26–52 m and from 68 m to the end of the drift. A fracture frequency diagram is shown in Figure 3-9. Clay filled fractures have not been observed.

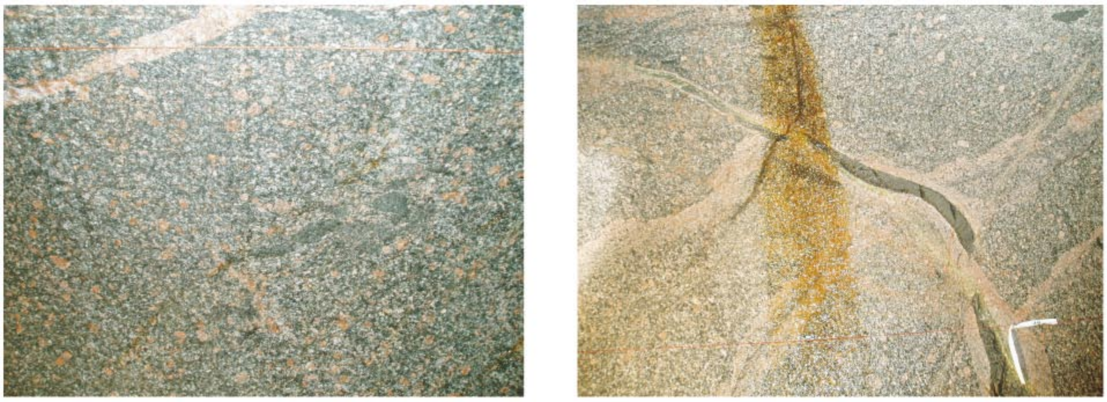

Figure 3-8. Left: Photography of the Äspö Diorite. Right: Greenstone dike cut by aplitic vein in a reopened fracture.

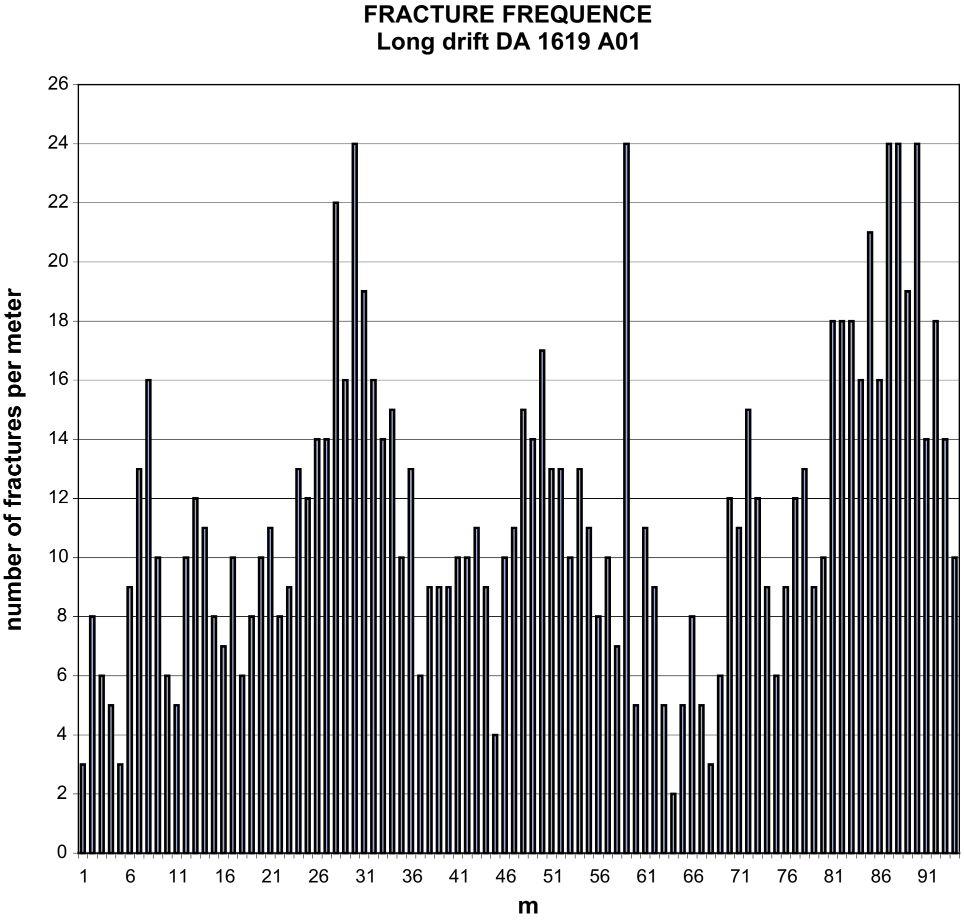

Figure 3-9. Fracture frequency for the 95 m drift.

3.4.3 Water leakage and precipitation

The 15 m drift is dry except for minor leakages. Most seepage water is from the fractures close to the shear zone mentioned above. Water is at this place leaking from distinct spots at an estimated quantity of totally 0.4 L/min. Minor seepage has been observed at a few other spots or along fractures.

The 95 m drift is also quite dry except for a few short sections. Most water seepage is from fractures and fracture zones at 7 m, 37 m and 53 m, where water sprinkles out or intense dripping occurs. Minor seepage has been observed along a number of fractures. The total flow as measured June 4, 2005 was 12 L/min. The typical inflow style is shown in Figure 3-10.

Precipitations of calcite are quite common in minor scale. Calcite growth is most common. However, at 72 m, at the left wall, a quite intense precipitation of calcite occurs from an open fracture. Bacterial growth is also quite common in a small scale where water leakage occurs.

3.4.4 Stability and Rock Mass Rating

No obvious rock stability problems have been observed. Two minor small flakes were observed on the left wall at 43 m and 55 m and due to fractures being parallel to the drift direction; these flakes are drilling induced.

The standard Rock Mass Rating values were calculated, see Figure 3-11 further supporting the model of the drifts being excavated in good bedrock conditions.

Figure 3-10. *Typical seepage pattern in the drift. The inflow is channelled due to the high gradient.*

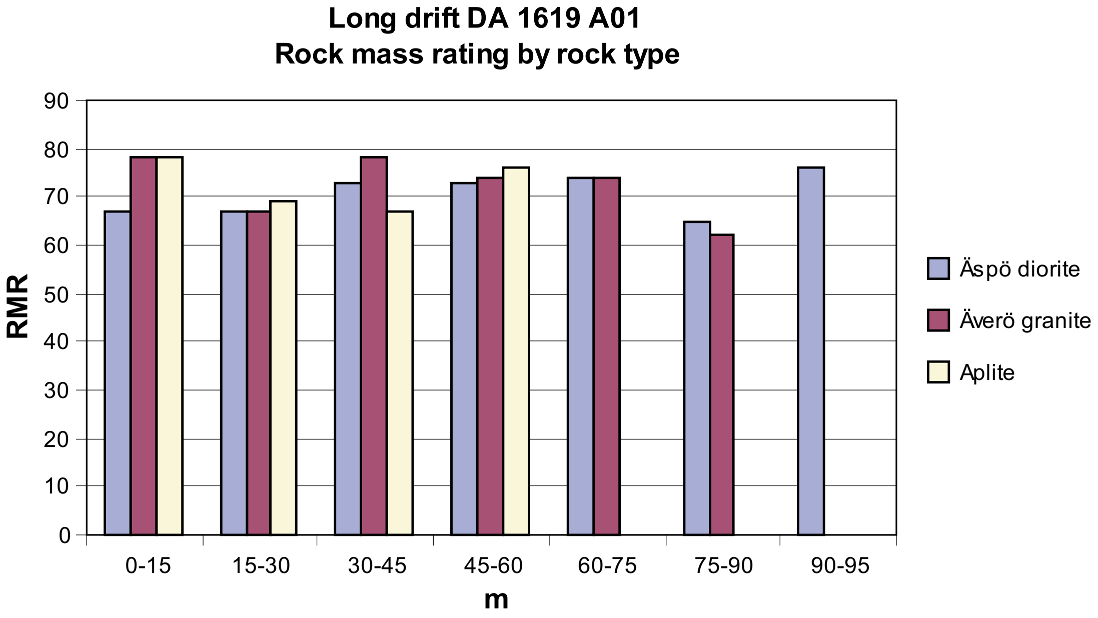

***Figure 3-11.** Mean Rock Mass Rating by 15 m section and rock type in the 95 m drift. RMR is not given for all rock types between 60–95 m because of minor appearance.*

4 The implementation plan

This Chapter provides an overview of the planned implementation plan.

4.1 Introduction

The planned drift length for the future deep repository is planned to be up to 300 m long. According to the SKB and Posiva RD&D Programme, the appropriate length shall later be further analyzed and optimized.

For the particular pilot tests at this stage SKB needed to excavate at least two drifts, one for demonstration of the emplacement process and evaluation of the deposition equipment and one for the construction and testing of a low-pH shotcrete plug. The performance of the chosen excavation method is however evaluated based upon results and experience from both drifts. For economical and practical reasons both drifts extend from the same niche compared to the deep repository layout where each drift will have its own niche.

Two drifts were planned but in order to provide flexibility and enable further technical development the possibility to excavate a third drift was planned for. The general layout of the demonstration site is shown in Figure 3-2.

4.2 Excavation method

SKB has evaluated several methods to excavate horizontal drifts, both by desk-studies as well as by practical field tests. Based on the findings, it was decided to test excavation by horizontal push-reaming, where a pilot hole is excavated, then being reamed to full diameter using quite conventional raise-drilling equipment (see Figure 4-1). As described elsewhere in the report, the geometrical requirements for straightness are very strict. For this reason, SKB decided to use active steering for the pilot hole in the 95 m long drift.

4.3 Drift for test of a low-pH shotcrete plug

The purpose of the first short drift was to provide a drift for construction of the low-pH shotcrete plug, evaluate the results of the reaming of the pilot hole and if necessary improve the technology and equipment before the excavation of the drift to test horizontal emplacement. The minimum length of this drift for the purpose of the low-pH shotcrete plug test was to be 6 m in very good rock conditions. To be sure to find rock conditions which are acceptable for construction and testing of a low-pH shotcrete plug it was decided to excavate about 15 m. Since the deposition equipment will not be used in this drift and the drift is short SKB decided not to use any active steering during the pilot hole drilling. A sketch if the test is shown in Figure 4-2.

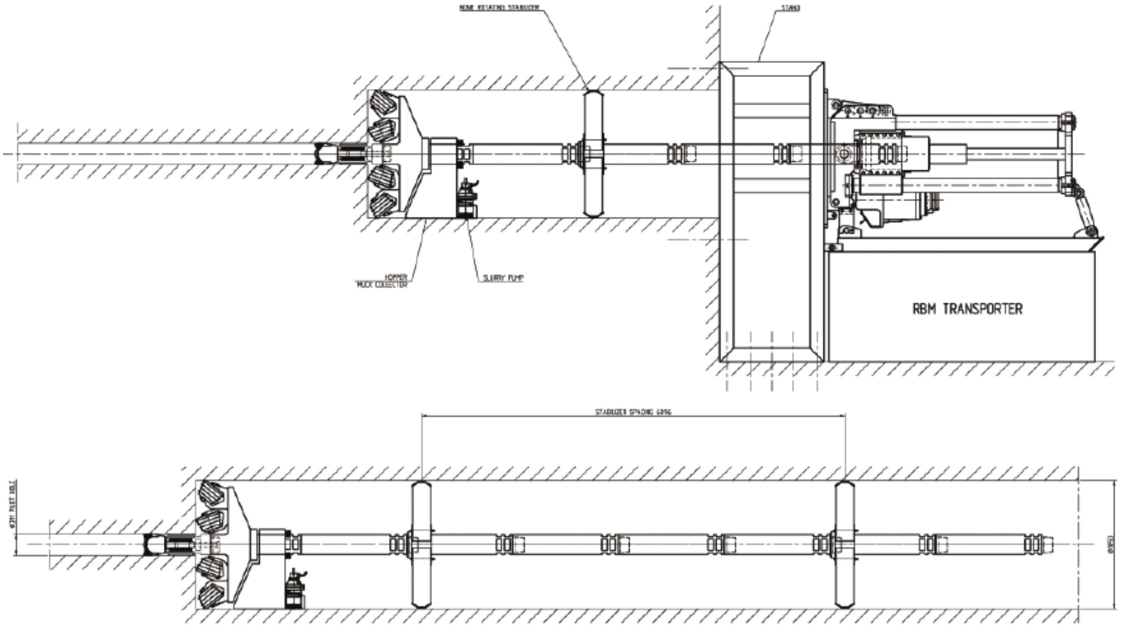

Figure 4-1. *Principle for horizontal push-reaming. After drilling the pilot hole, a reamer head is used to excavate the full diameter of the drift. The drill pipes are supported by stabilisers. /After Bäckblom et al. 2004/.*

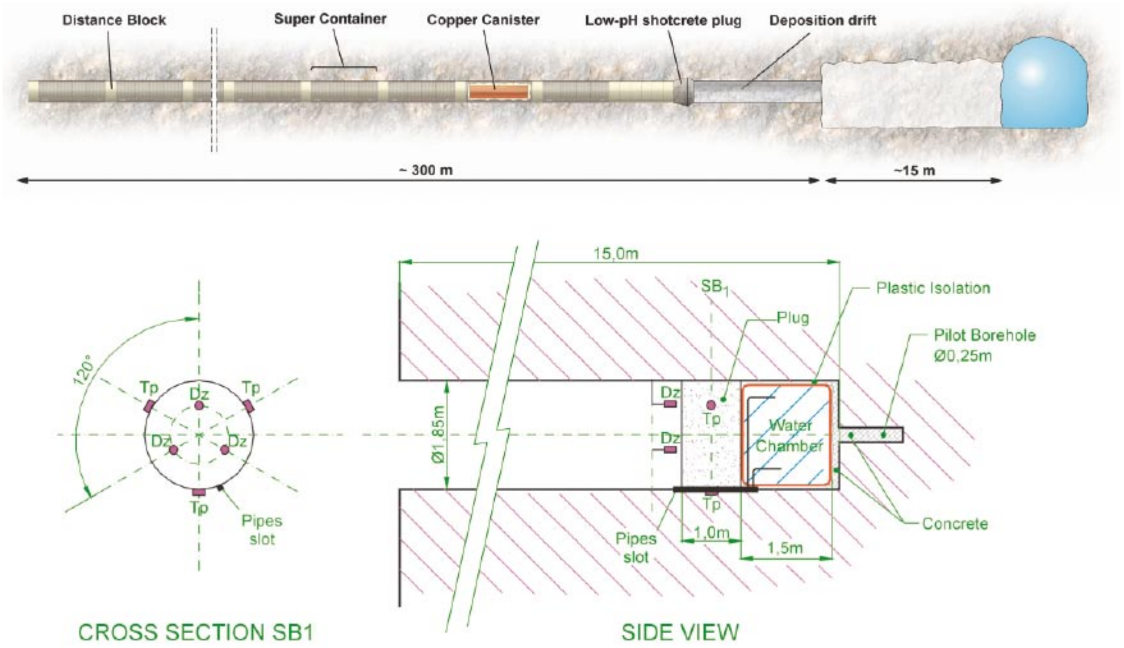

Figure 4-2. *Design of the low-pH plug test to be conducted within the ESDRED-project (see www.esdred.info). A water chamber is pressurized to test the tightness of the cement plug.*

It was also decided that this was the first drift to excavate since SKB then had the opportunity to evaluate and if necessary improve the excavation methodology before excavating the 95 m drift. This second drift, necessary for demonstrating the feasibility of horizontal emplacement necessitate much stiffer requirements.

4.4 Drift for demonstration of the emplacement process

The drift for demonstration of the emplacement process is placed in the middle of the demonstration niche, Figure 3-2. SKB's judgement was that a drift length of about 100 m is fully sufficient for evaluating the performance of the deposition machine although there may be questions related to the excavation and emplacement process that would not be fully answered by a drift which is one third of the planned length for a deposition drift at the repository, see further Table 4-1. Further tests would be needed to verify technology for straightness of the pilot hole and measurement technology. During core drilling before the drift excavation a significant water inflow occurred at about the length 100 m. In order not to jeopardize the deposition equipment tests with high water inflow it was for this particular drift decided to excavate only 95 m and thereby avoid the water ingress.

Since the drift is to be the realistic environment for the Site Acceptance Tests (SAT) of deposition machine all defined quality requirements on a deposition drift were to be complied with. To fulfil the stiff requirements on drift geometry SKB decided to use active steering of the pilot hole.

Table 4-1. Evaluation of what will be gained from excavation of the 100 m drift.

Issue	What can be achieved in the 100 m drift	Additional tests for a 300 m drift
Machine operation	X	–
• Torque thrust	X	–
• Rod handling	X	–
• Mucking in the drift	X	– (if gradient > 2°)
• Automated active steering	X	X
Geometry		
• Straigtness of the pilot hole	X	X
• Roughness	X	–
• Steps	X	–
Muck handling	X	–
Measurement technology	X	X

4.5 Contracting and specifications

SKB in August 2004 signed a turn-key contract with the Norwegian contractor Entreprenørservice A/S based on the Swedish contract standard ABT 94. The contract specifies that two pilot holes and two drifts, 15 m and 95 m are to be excavated at the Äspö Hard Rock Laboratory. It was as well requested that active steering was to be deployed when drilling the 95 m pilot hole, using a Rotary Steerable Drilling System manufactured by Smart Drilling GmbH or similar.

A general idea was to use a contract with fixed prices base on the bill of quantities. The reaming part of the contract was a "true" turn-key where payment is stipulated by fulfilling the functional requirements. However, the pilot hole was treated as a conventional general performance contract based on fixed prices where payment was tied to the work performance rather than the functional performance as no contractor was willing to tender turn-key for the proposed stiff requirements for the pilot hole.

SKB constructed the concrete pad and concrete wall used for the set-up, based on the engineering design of the contractor and later approval by the contractor.

For approval at the final inspection compliance with several requirements were necessary, mainly the geometrical requirements:

- Diameter of the drift to be in between 1,840 mm to 1,850 mm.
- Waviness less than 2.5 mm measured over a distance of 6,000 mm.
- Roughness < 5 mm from the theoretical drift surface when measured over a distance of 100 mm.
- Maximum deviation from the centre line at the end of the 95 m drift less than 1.0 m, including all deviations[2].

The pilot drill holes were to be approved in case boring was in accordance with all the relevant procedures prepared by the contractor before boring is started.

The contractor used sub-contractors to survey the pilot holes of the drift. SKB was to conduct independent surveys and as well contracted the laser scanning of the reamed drift. SKB was also responsible for haulage of the boring debris from the drill niche to the surface.

4.6 Schedule

The initial schedule for the boring is shown in Figure 4-3, also showing the main activities for boring and surveying.

4.7 Overview of data collected

Before, during excavation and after the excavation, several types of data were collected or planned to be collected and these data types are outlined in Table 4-2 and Table 4-3.

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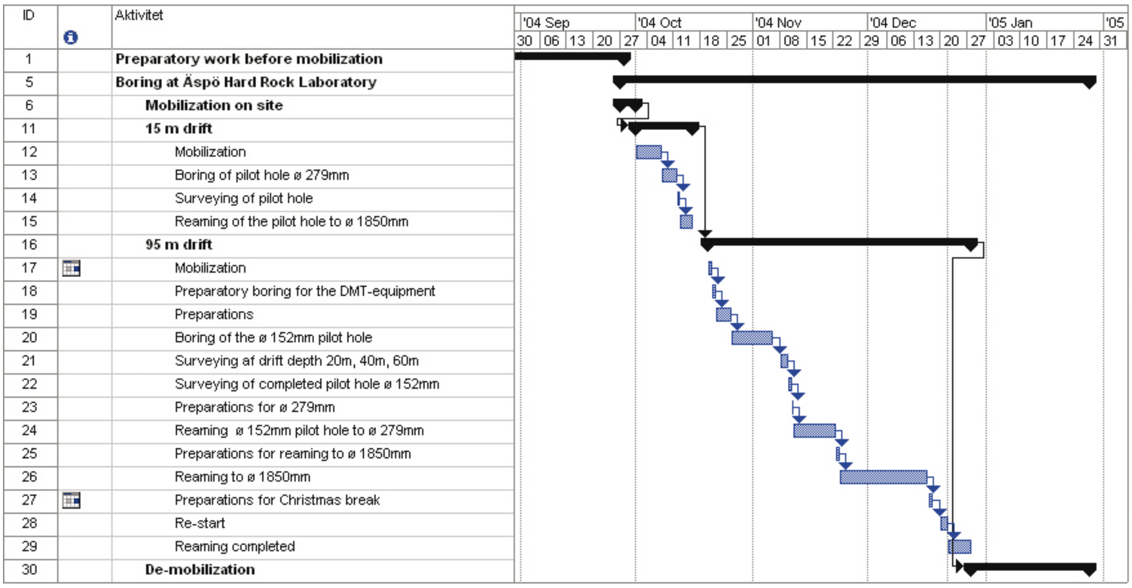
[2] This contractual requirement is slacker than the requirement 0.22 m and rather reflecting terms and conditions for payment.



ID	Aktivitet
1	**Preparatory work before mobilization**
5	**Boring at Äspö Hard Rock Laboratory**
6	**Mobilization on site**
11	**15 m drift**
12	Mobilization
13	Boring of pilot hole ø 279mm
14	Surveying of pilot hole
15	Reaming of the pilot hole to ø 1850mm
16	**95 m drift**
17	Mobilization
18	Preparatory boring for the DMT-equipment
19	Preparations
20	Boring of the ø 152mm pilot hole
21	Surveying af drift depth 20m, 40m, 60m
22	Surveying of completed pilot hole ø 152mm
23	Preparations for ø 279mm
24	Reaming ø 152mm pilot hole to ø 279mm
25	Preparations for reaming to ø 1850mm
26	Reaming to ø 1850mm
27	Preparations for Christmas break
28	Re-start
29	Reaming completed
30	**De-mobilization**

Figure 4-3. *Initial contract schedule.*

Table 4-2. Overview of data collection plan for the 15 m drift.

Datatypes	Geological data	Machine performance	Geometrical data
Before start of pilot hole 279 mm	See Chapter 3	–	Surveying of machine and drill string direction.
During drilling of pilot hole	–	Manual readings of thrust and torque Rev/min Start-stop of drilling Drilled length Average penetration rate	After 0.5 m drilling, direction measurements by Geocon method (SKB). Additional direction measurements after 8 m of drilling.
After drilling of pilot hole	Measurement of water inflow	Wear on drill bits	Surveying with Flexit EMS (Contractor) and surveying by Geocon-method (SKB).
Before reaming	–	–	Diameter of reaming head.
During reaming	–	Manual readings of thrust and torque Rev/min Start-stop of drilling Drilled length Average penetration rate	–
After reaming	Inflow measurements Mapping (see Chapter 3)	Wear on reaming head	Laser scanning for diameter, roughness, steps etc.

Table 4-3. Overview of data collection plan for the 95 m drift.

Datatypes	Geological data	Machine performance	Geometrical data
Before start of pilot hole 152 mm	See Chapter 3		Surveying of machine and drill string direction, boring for 2–3 m. Installation and check of the Rotary Steering System (RSS). Adjustments and control of steering and measuring instruments.
During drilling of pilot hole 152 mm	–	Manual readings of thrust and torque Rev/min Start-stop of drilling Drilled length Average penetration rate	Sampling of directions/10 s for active steering of the pilot hole Measurement by Flexit EMS and Smart Drilling, Survey checks by SKB. Planned measurements at depth of 20 m.
After drilling of pilot hole 152 mm	Inflow measurements	–	Data from Smart Drillings was to be compared with Geocons data using prism.
Before start of pilot hole 279 mm	Due to the DMT instrument failure and and measured deviations a new hole was planned with centre line 0.5 m to the right of cancelled 152 mm hole.	–	Surveying of direction.
During drilling of pilot hole 279 mm	–	Manual readings of thrust and torque Rev/min Start-stop of drilling Drilled length Average penetration rate	Measurements conducted after 15 m, 30 m and 60 m of boring. Thereafter the inclination was measured by water level tubes.
After drilling of pilot hole 279 mm	Inflow measurements		Surveying of direction
Before reaming	–		Diameter of reaming head
During reaming	–	Manual readings of thrust and torque Rev/min Start-stop of drilling Drilled length Average penetration rate	
After reaming	Inflow measurements Mapping (see Chapter 3)		Diameter of reaming head Laser scanning for diameter, roughness, steps etc.

In addition several other data was to be collected like:

- Consumables (water, grease, hydraulic oil, cutter wear, drill pipe wear).
- Energy (power and energy use).
- Health and safety (noise, dust, gases).
- Particle size distribution of muck.
- Operating characteristics of the rig and muck system (capacity, availability, utilization, Mean Time Between Failure, torque, thrust, rotation, penetration etc).

5 Description of equipment and methods

This Chapter provides a general yet fairly detailed description of equipment and methods used. It should be understood that equipment and methods can be quite different for the realistic application at a repository, not the least for the general set-up and for the mucking system. The last section of this Chapter is a detailed account for the 95 m drift.

5.1 General set-up

A niche 15 m wide and 8 m long was excavated at the –220 m level at the Äspö Hard Rock Laboratory. A reinforced concrete pad was constructed on top of the solid rock floor to facilitate move of equipment, prevent dilution by spillage and also to simplify for visitors and the later planned emplacement test work. The drill derrick, muck systems and auxiliary equipment was placed in the niche. The provisional set-up included use of rods to anchor the machine due to the thrust while the bolted steel frame was stiff enough for the torque. The face of the niche was as well concreted to provide a flat surface for the collaring of the drill bit, Figure 5-1. The initial plan to prepare smaller pads was abandoned due to the simplicity to concrete the wall in one step.

The general plan for the intended set-up is also shown in a bird's view, see Figure 5-2.

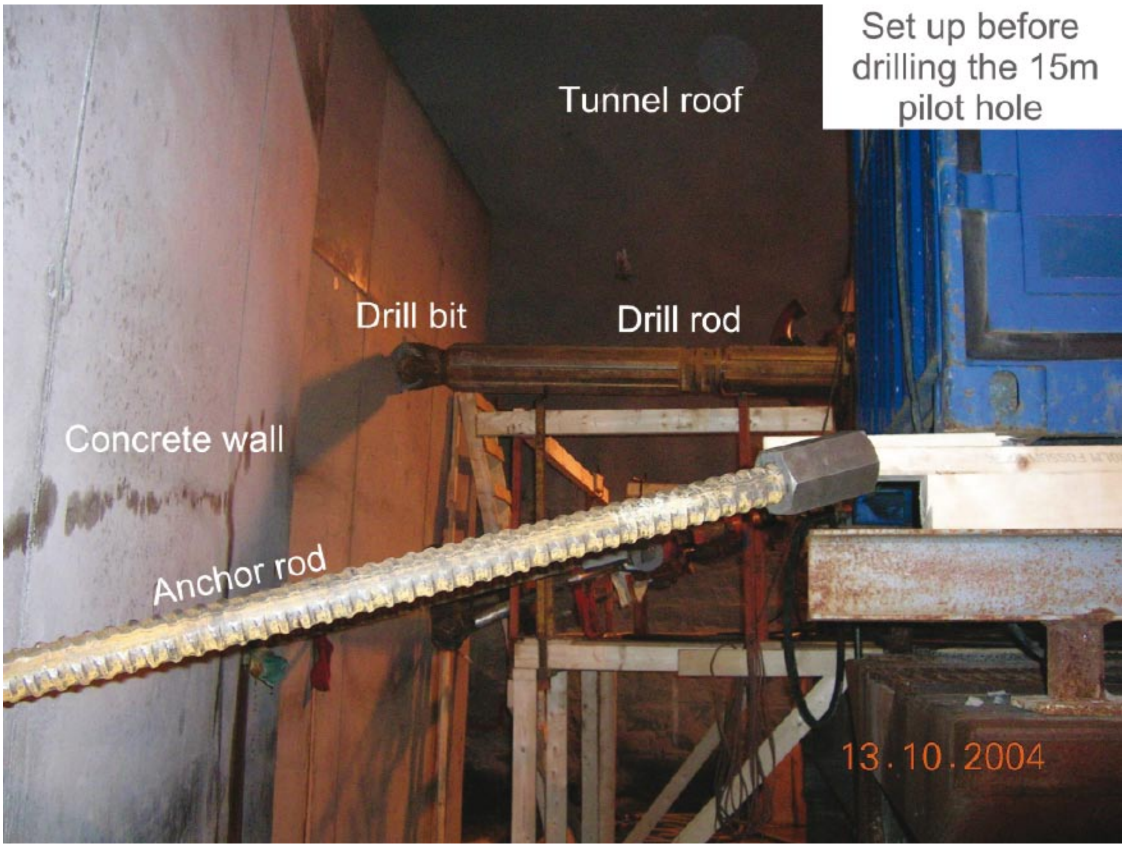


Figure 5-1. Side-view of the set-up at the drift face before drilling the 15 m long pilot hole.

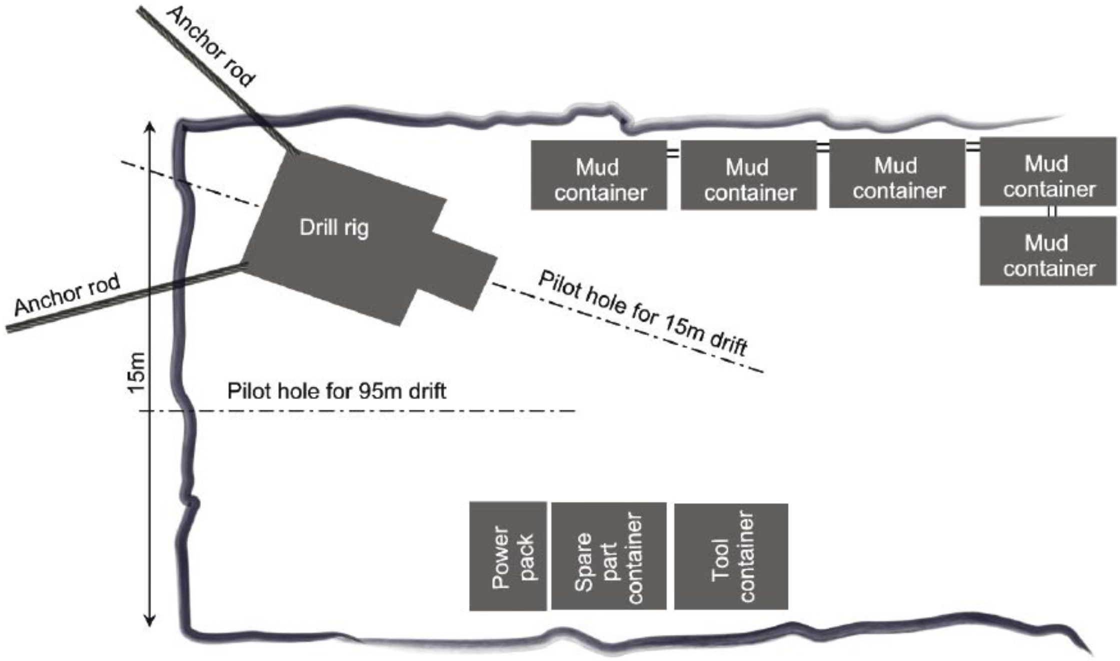


Figure 5-2. Sketch showing the initially planned set-up for the drill rig, mud containers and auxiliary equipment.

5.2 Pilot hole drilling

The straight pilot hole is the requisite to comply with the stiff geometrical requirements on straightness of the hole. Two pilot hole diameters have been used, 152 mm and 279 mm respectively. The smaller diameter is necessary when active steering is used, see Section 5.3 and this smaller pilot hole was bored using a Puntel machine; the larger 279 mm pilot hole was drilled with the raise-boring unit, see Section 5.4.

The Puntel machine used for drilling of the 152 mm pilot hole is a small versatile drill rig normally used for surface drillings, see Figure 5-3 and Figure 5-4. The weight of the machine is around 7 tonnes including the diesel-power pack. Drill pipes are 3 m in length and 114 mm in diameter. Max thrust is 250 kN. Working thrust varies according to hole diameter and rock conditions. Normal thrust for 152 mm drilling is 50–70 kN. Torque is up to 12 kNm. Rotation speed is up to 100 rpm.

The Puntel is a versatile drilling rig that can be used for both Down-The-Hole (DTH) drilling as well as rotary drilling. The machine runs on a diesel power pack, but is hydraulically driven. The machine has four hydraulic feet that enables easy and versatile set up of inclination and breaking in point. The machine is operated by two operators, one to control the panels, the other helping serving auxiliary systems such as the crane and rod handling. Using the control panel, the operators are able to decide the thrust, torque and rotary speed during drilling. The machine is built for rod lengths of 1.5 m or 3 m lengths.

For rotary drilling with 152 mm drill bit, this machine is able to drill up to 5–6 m an hour with a thrust of 70 kN on bit in the rock conditions similar to those at Äspö. However when using the RSS-tool (see also Chapter 5.3), the thrust on bit had to be reduced to 10–25 kN on bit leading to an average penetration rate down to 0.7–0.8 m an hour.

The Puntel and similar drilling rigs are used many places around the world, mainly for DTH drilling of medium to long holes. The typical industrial areas are; holes for water supply and sewer systems, mining, wells, water crossings, etc.

__Figure 5-3.__ Photography of the Puntel 1200. Drilling of the 152 mm pilot hole.

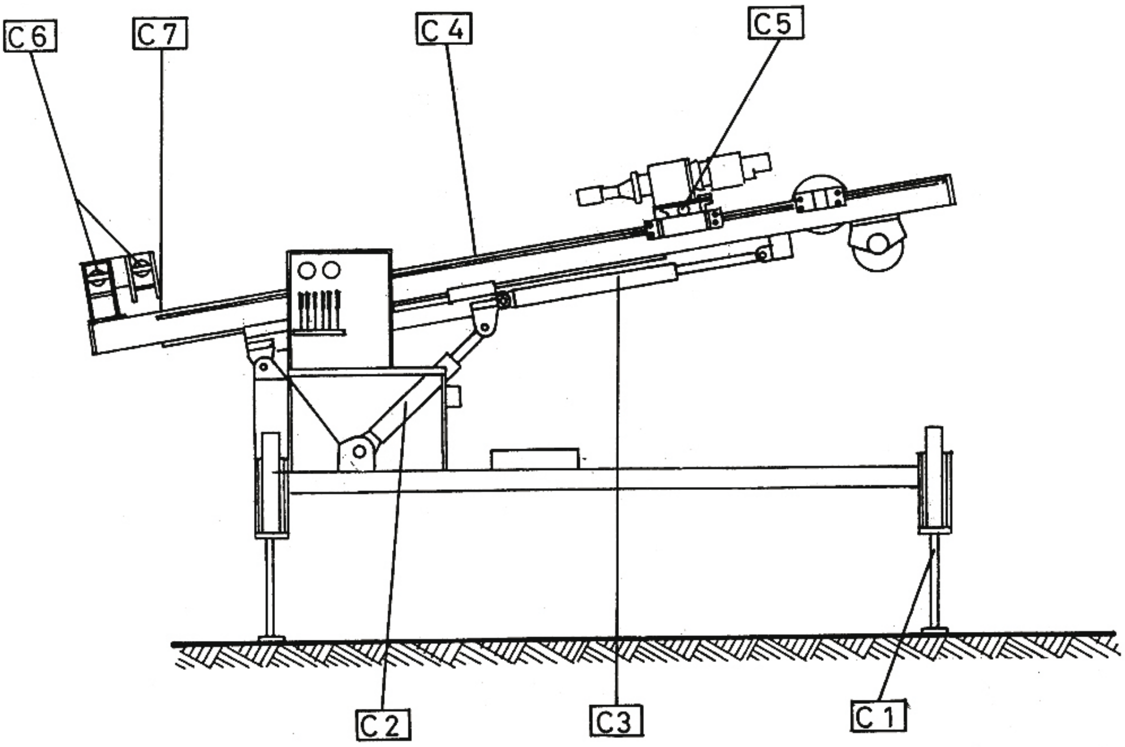


__Figure 5-4.__ Sketch of the Puntel. The machine is around 6.5 m in length, 3.1 m in width and 1.7 m in height.

5.3 Equipment for guiding and steering the pilot hole

As mentioned before, the guidance of the pilot hole is critical. SKB opted for active steering of the pilot hole for rotary crushing drilling. In this case the RSS developed by Smart Drilling GmbH was contracted. The steering principle was based on using hydraulic cylinders directed towards the rock surface. Steering along the predetermined direction requires measurements and transmission of the relevant data to the drilling rig control stand. The measuring data are transmitted wireless every 10th second to a receipt unit at the drilling rig, where data are displayed and visualized. By comparing the planned and the actual deviations detected, a control is initiated to re-orient the external drill pipe. Figure 5-5 shows a detail of the Rotary Steerable System.

Some main data for the system are:

- Operates in 152 mm holes (62").
- Diameter of the Rotary Steerable System is 114 mm (4½").
- Tool length is 1,935 mm with a total weight of 110 kg without the Pulser.
- Rotary speed is 60–120 rpm.
- Weight on bit: 50–70 kN operational, maximum 120 kN.
- Torque: 15 kNm rotary.
- Maximum flow rate of water 1,250 L/min.

Figure 5-5. Detail showing the drill bit and the Rotary Drilling System.

The RSS-tool is a self-steering system. The theoretical line is fed into the system, and the system will adjust deviations automatically during drilling using the internal measuring systems to measure the deviations. To adjust the direction the tool is non-rotating, meaning it does not rotate with the drill rod. The tool has four valves to correct deviations and these valves push according to its own measuring with different force, thereby pressuring the drill bit ahead of the tool to the correct direction. The system is marketed as having two main advantages over most other steering tools:

- Measurements are done while drilling which enables continuous drilling.
- Measurements and corrections of deviations are made frequently (every 10th second) so only small deviations from theoretical line will occur.

The system has been in use for almost a decade, and a similar system for vertical drilling has been used for over 25 years, but its main use has been is soft rock conditions than what is represented at Äspö. As very few industrial references are from hard rock conditions like at Äspö, the sub-contractor offering its services did not want to provide any guaranties for the deviations for the pilot tests.

5.4 Machine for horizontal push-reaming

The purpose of the machine is to exert press and torque to the drill string. The contractor selected to use an Indau machine 120 H, Figure 5-6.

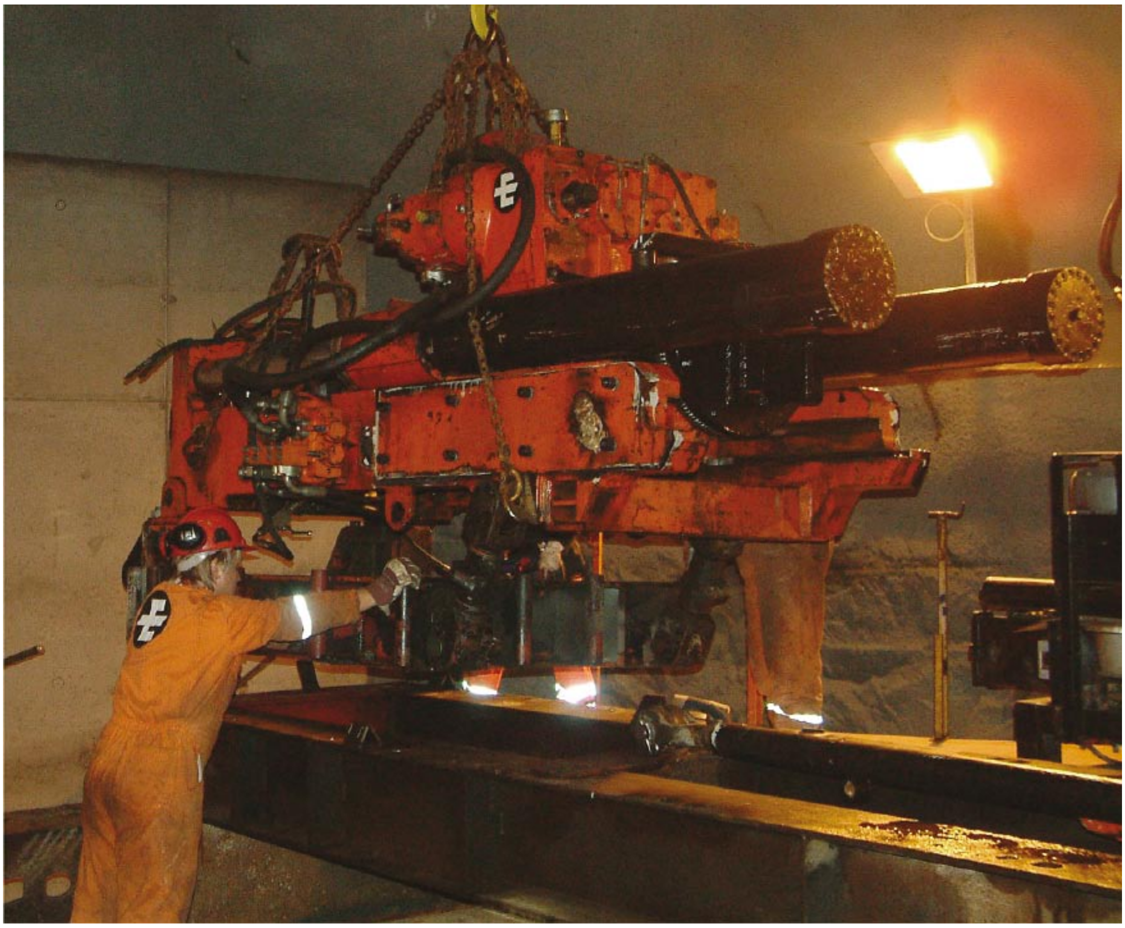


Figure 5-6. *Photography of the Indau main derrick during mobilization.*

The Indau 120 H was modified especially for this project to meet the special and strict demands of the client. For the actual drilling rig the modification consisted of setting up one extra thrust cylinder, increasing max working force with 120 tonnes to 240 tonnes.

The nominal data before modifications were: Weight of main equipment is 12 tonnes. Thrust force is up to 1,255 kN and maximum pull (-reaming) force around 2,400 kN. Rotation speed is 0–45 rpm with continuous torque up to 120 kNm. Penetration rate for pilot hole drilling is between 0–220 mm/min and 0–114 mm/min during reaming. When the machine was used at Äspö HRL, pilot drilling was performed with thrust around 200–250 kN and reaming thrust of up to around 1,650 kN.

The torque of the boring machine is a significant factor. It is expected this machine was torque limited. When the thrust was increased to about 1,400 kN, the cutter head started to jam (Jorma Autio pers.comm.) as the torque was not enough to rotate the cutter head. The maximum torque when cutter head became jammed was measured at site to be about 75 kN, clearly less than the nominal torque 120 kN in the specifications.

The Indau machine is used for rotary drilling. The machine runs on electric power, but is hydraulically driven. The machine is operated by two operators, one to control the panels, the other helping serving auxiliary systems such as the crane and rod handling. Using the control panel, the operators are able to decide the thrust, torque and rotary speed during drilling. The machine is built for rod lengths of 1.5 m lengths.

For rotary drilling with 279 mm drill bit for the pilot hole, this machine is able to drill up to 3 m an hour with a thrust of 200–250 kN on bit, in the rock conditions at Äspö. The penetration is dependant on inclination control and general rock conditions however, so at Äspö the average penetration rate has been around 1.5 m/hour. The rotation speed of cutter head during reaming was about 14 rpm.

For the blind hole reaming the average penetration rate at Äspö has been around 0.5 m/hour during boring (including standard rod handling etc), with a max penetration rate of 1 m/hour and a minimum of 0.23 m/hour.

The Indau R 120 H and similar drilling rigs are used many places around the world, mainly for vertically inclined holes up to 600 m depths, but for standard raise-boring. The typical industrial areas are; drilling for water supply and sewer systems, mining, oil and gas, water inlet tunnels, etc.

5.5 Drill string, pilot bit and and reamer head

The drill string is the mechanical connection between the rock tools and the boring machine. It enables the rotational and thrust forces needed for drilling and reaming to be transmitted from the machine unit to the pilot bit or reamer head. The contractor used threaded drill pipes with diameter 254 mm and length 1,500 mm. The weight of each pipe is around 340 kg. The drill string contains also some special drill pipes with stabilizers. The stabilizers during pilot drilling are of the same diameter as the pilot bit. The function of the stabilizer pipes are twofold – to minimize hole deviation and to ensure the pilot hole diameter when the pilot bit wear down.

The stabilizers are an essential part when trying to drill as straight as possible. To achieve the best possible result, the stabilizers need a diameter very close to the pilot bit diameter. Using stabilizers decreases the natural movements of the pilot bit stiffening the direction of the hole. Using conventional 279 mm pilot hole drilling such that has been done at

Äspö, the horizontal deviations can not be controlled. Good stabilizers, as well as using a correct level of water flushing and rotation will decrease the deviations, but deviations will occur according to rock conditions. With the technique it is however possible, to correct deviations vertically, using thrust, level of water flushing, placement of stabilizers, rotary speed, etc.

For reaming, wing-stabilizers are necessary to avoid lateral buckling as the drill string is in thrust for the case of push-reaming. The wing-stabilizers ensure that the drill string is approximately in the centre of the hole; the wing stabilizers were to be placed with a distance of 6–7 drill rod lengths between each stabilizer. The wing-stabilizers, each with a diameter 1,846 mm were used along the drill string as shown in Figure 5-7.

The pilot bit used for drilling the pilot hole is a standard tricone bit, Figure 5-8.

The reaming of the pilot hole from 152 mm to 279 mm a drill bit with a guidance tool was planned to be used, see Figure 5-9.

The reamer head has ten cutters and two "crusher cutters", where the latter are used to ensure that the larger chips are crushed to facilitate the mucking, Figure 5-10.

Figure 5-11 shows the reamer head in the 15 m drift. Distance between the kerfs (grooves) produced is 1" (25.4 mm). The gauge cutters of the reaming head has tungsten carbide inserts, thereby keeping the diameter for a longer period without replacement. The types of cutters used were Sandvik CMR 41 and CMR 52.

Figure 5-7. *Wing-stabilizer used to centre the drill string and to avoid lateral buckling.*

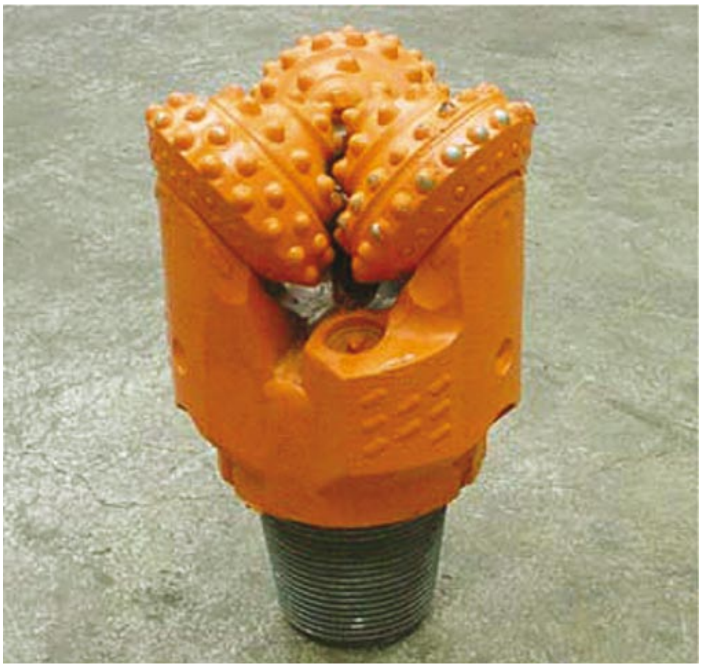


Figure 5-8. *Example on drill bit for rotary crushing. Courtesy Atlas Copco.*

Figure 5-9. *Drill bit planned to be used when the pilot hole is reamed from 152 mm to 279 mm.*

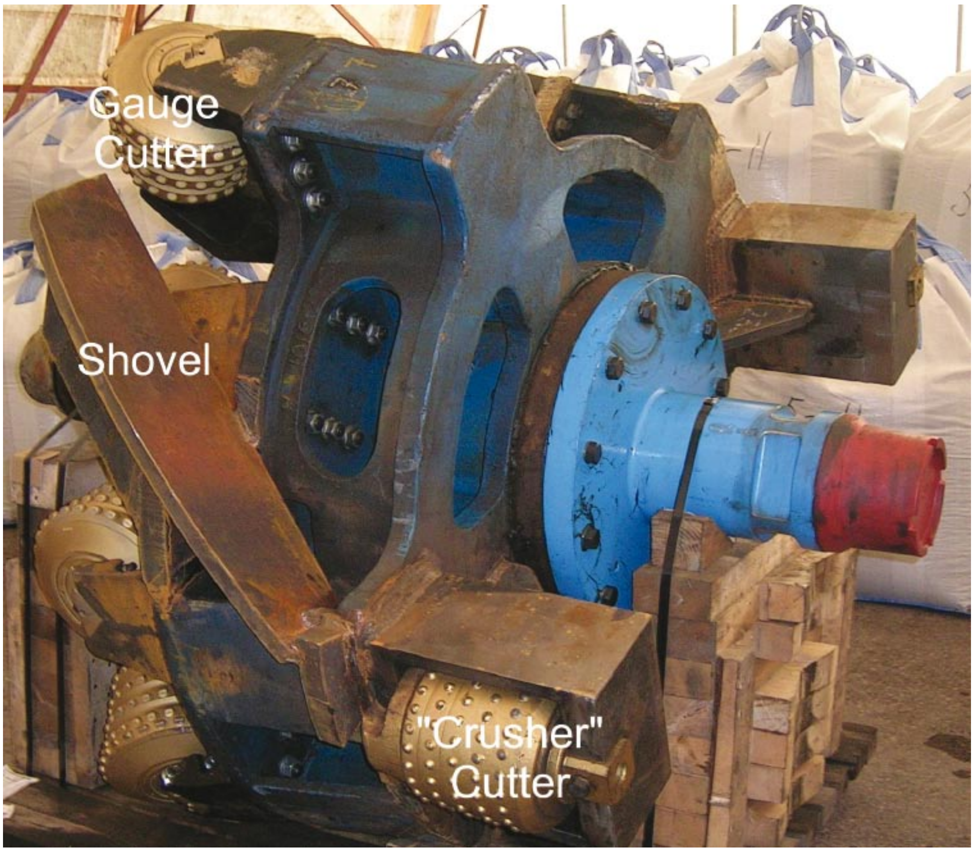


Figure 5-10. *Photography of the reamer head before reaming.*

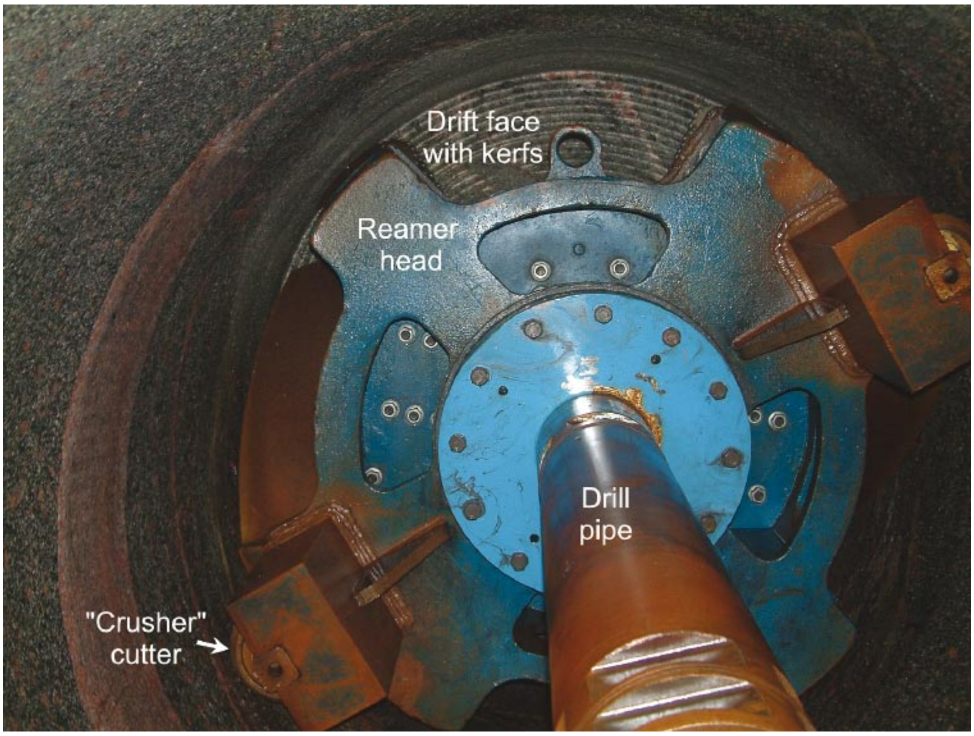


Figure 5-11. *Photography of the reamer when reaming of the 15 m drift commences.*

After reaming the 15 m hole, the reamer head was modified to make the total assembly more stiff: The guidance tool was longer with a smooth surface; no ball bearings were used. Additional four nozzles were added to the reamer head to facilitate flushing of the face, and removing muck and debris, Figure 5-12. A special reaming head stabilizer was specially constructed for the second drift. This stabilizer was placed as close up to the reaming head as possible, and its main mission was to ensure minimal movements from centre line during reaming, thus ensuring a more centric hole, see Figure 5-13. Two layers of ball bearings were used and six spokes added and each spoke was extendable to fit the hole geometry.

The total weight of the reamer head is approximately 5.5 tonnes (including cutters).The typical wear for the rock conditions at Äspö is, that each cutter has a lifetime of around 400 m, whereas the gauge cutters lifetime is reduced to around 200 m. In fact the lifetime is depending on penetration rate, so for low advance rate it might be better to measure cutters lifetime in hours. For the conditions at Äspö, with relatively hard rock, the cutters lifetimes are estimated to 400–600 hours when using recycled salty water for flushing. The reamer being used at Äspö had only four gauge cutters, but for a future project at least six gauge cutters is recommended to allow for even better stability in the drilling process, and less wear on the gauge cutters. The efficiency of flushing system and lacing of outer cutters have also significant impact of the wear.

Figure 5-12. *Modified cutterhead.*

Figure 5-13. *Reamer head stabilizer.*

5.6 Muck systems in the deposition drift

The horizontal push-reaming generates quite substantial volumes of muck (up to around 3 m^3/h) and the rock cuttings need to be removed from the almost horizontal drift using flushing water. Effective mucking was early on considered to be vital for efficient excavation and several options were successively tested and rejected. The maximum flushing required was estimated to be around 2,700 L/min.

Description of mucking system

The first alternative considered and tested, was to prepare a tight seal between the reamer head and a rubber sealing, Figure 5-14. The overpressure generated of the flushing water should be sufficient to flush the muck through the evacuation pipe. Four variants were planned. Design A was drainage of the muck in the pipe, design B was to add additional flushing water in the pipe, design C was design B and a sucking vacuum pump in the evacuation pipe and design D, finally was to put a mud pump between the reamer head and the sealing and put the outlet in the evacuation pipe.

It was thought that around 70% of the flushing water would be re-circulated water and for that purpose five containers were placed in a row, see Figure 5-15.

It was planned that sufficient sedimentation would take place in the five containers where the coarsest muck of course is in the first container. Filled containers were to be replaced by empty containers using a container truck that emptied the filled containers at a surface facility. The first container in the row was to be replaced by a wheel-loader. Formation water was pumped into the last mud container that also hold a water pump for pumping the water into the drill string.

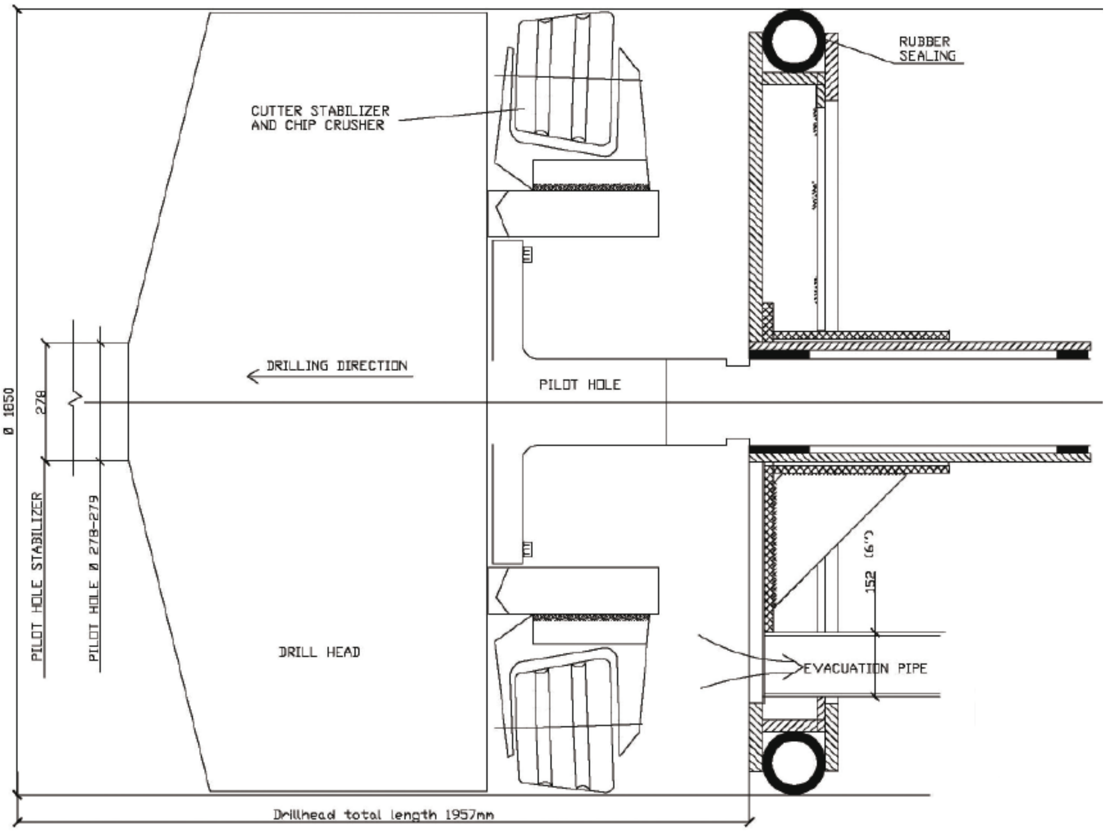


Figure 5-14. *Mucking alternative 1. Courtesy Entreprenørservice A/S.*

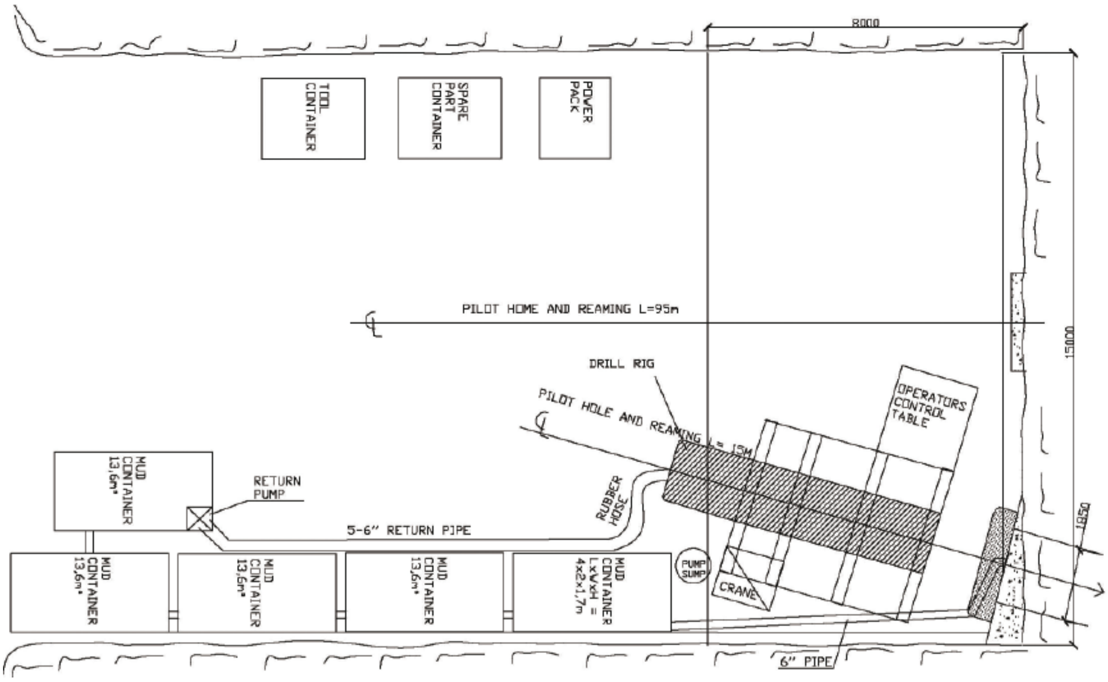


Figure 5-15. *Set up for mucking. Courtesy Entreprenørservice A/S.*

5.7 Auxiliary systems

Recirculation system for water

To be able to recycle/reuse water, five containers were connected in series, enabling sedimentation of muck in the containers, and reusing water in the other end of the system. With such a system the contractor was able to reach nearly 100% reuse of water for flushing.

Pumps for water flushing, muck handling and recirculation

Fresh salt water was taken from the pump sump using a water pump of 6 kW capacity. It delivered up to 1,200 L/min at 3–4 bar pressure. For flushing in the drift and transportation of muck out of the drift, two slurry pumps of 9 kW, with a maximum capacity of 3,000 L/min were in use, one flushing through the drill pipe, the other flushing through a separate flushing pipe that were brought together with the drill pipe inwards in the drift. These two pumps took water from the containers.

Outside the drift, a tray was placed catching up water and muck that were flushed out from the drift opening. In order to transport this to the recycling system two similar pumps were in place in the tray. Because some of the excavated rocks pieces were to coarse, the slurry pumps were having difficulty handling all the muck coming out of the drift, and consequently they were later exchanged for a bigger muck pump after approximately half drilled drift length (40 m). This larger pump enabled more continuously drilling, thus resulting in higher daily advance rates.

Rod/pipe handling system

For the drill pipe changes a hydraulic item crane with grippers, was used to load/unload drill rods into the Indau R 120 H rod handling system.

Power for the works

The Indau 120 has an electrically driven hydraulic power pack system, and the complete power demand for this project was approximately 300 kVA.

5.8 Surveying, measurements

The accurate surveying and measurements are keys to show compliance with the strict geometrical requirements set to ascertain long term safety and emplaceability of the supercontainer. This section shows an overview of the instruments and methods used.

For this project the contractor Entreprenørservice had the responsibility to measure the geometry of the pilot holes and reaming verify for the client SKB that the stipulated requirements according to the contract were met. The client had the opportunity to independently check the measurements carried out by the contractor whenever found necessary. The contractor planned to use a Flexit EMS equipment to verify the direction of the pilot hole alignment for the long drift, a measuring tape to measure the diameter after reaming and visual inspection of other surface parameters like roughness and steps etc.

SKB on the other hand manufactured a special measuring device with a prism in the centre which could be inserted into the 279 mm pilot hole and enable the use of standard theodolite for measuring the position of the hole centre point in all directions at any pilot hole depth, see Figure 5-16.

A simple water scale was used to check the vertical deviations during drilling of the 95 m pilot hole. The vertical direction of the pilot bit can to a certain extent be controlled by the number and position of drill string stabilizers used as "hinges" and the drill string in between the "hinges" acting as "beams". The experienced operator positions the drill string stabilizers to achieve vertical direction and using a simple water pipe leveller for feed-back and this simple and historical method is of course useful. For measurements the drill string is filled with water through a T-valve where the second junction is used for the transparent plastic water pipe. When water is flowing out of the drill string a valve is closed and the valve for the pipe opened. The stand pipe water level is compared with a scale at the wall, where the centre of the scale is at the centre line of the pilot hole at start of drilling. The elevation is compared with a theoretical trend line as a function of drilling depths, see Figure 5-17.

SKB also wanted evaluate laser scanning as a method for mapping rock surfaces and test whether the scanning technology can be used for evaluation of the reamed drifts surface parameters as well as alignment and straightness.

Figure 5-16. *Device used for measuring the straightness of the pilot hole.*

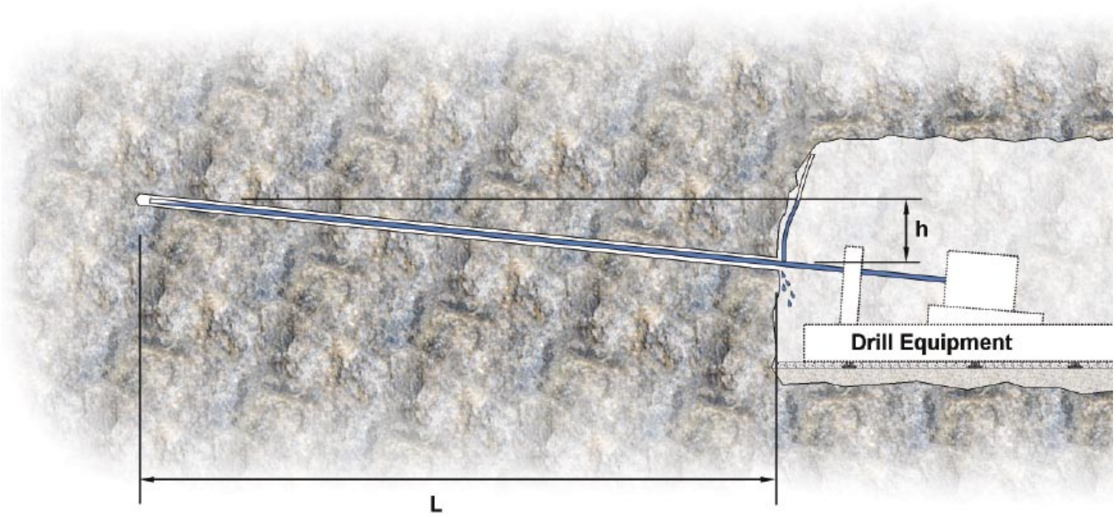


Figure 5-17. *Levelling by water pipe.*

A laser scanning tool iQ800 (see www.iqsun.com) was used to measure the geometry of the reamed drifts, Figure 5-18.

The procedure is to install conventional control prisms in the drift and survey the location of these prisms as well as the position of the iQ800 laser scanner. The surveying was done by using a high-precision total station, a Leica TCA1800. The iQ800 typically features around 28 million 3D-pixels per scan with up to 240,000 3D-measurements per seconds, that is the complete measurement is performed in around 160 s. The accuracy is 3 mm linearity error at 10 m distance. For the 15 m drifts 6 prisms were installed, two at the drift entrance, two at distance 8 m and two at the end of the 15 m drift.

The scanner provides the diameter of the drift and these measurements are also used to back-calculate the centre of the diameter. SKB calculated these every 0.5 m and these centre points were also used to draft a centre line of the drift.

The scanner provides a huge amount of coordinates which in turn can be analysed for a number of different purposes. In this project SKB tried to process the data in order to evaluate the following parameters:

- Variation of section areas (diameters) along the drift.
- Centre line deviation along the drift.

During reaming some diameter measurements were done using a measuring tape, constructed not to being obstructed by the drill string, Figure 5-19.

Roughness measurements were performed at some locations using a profiler, see Figure 5-20.

Experience showed that the present preliminary requirements unfortunately are stated in a way that are difficult verify using the methods used, so SKB also decided to manufacture a super-container dummy with the dimensions 6 m in length and 1,765 mm in width and height, see Figure 5-21, which was used as a complement to check the diameter and straightness of the long drift. The dummy is pulled on small wheels in the drift and ultrasonic instruments measures the distance from the dummy to the rock wall.

Figure 5-21 (left) shows the locations of the ultrasonic gauges: These reside at both ends of the dummy and are named in relation to their position. The group of gauges which are nearest the borehole opening are the rear group gauges, opposite side then becomes the front gauge group. Each gauge is named by an identifier based on the group they belong to and where their placement on the dummy. Identifier count follows the sequence, 1 = left, 2 = right and 3 is the top position. This gives as an example an identifier for the left rear gauge which looks like this G1LR, where G = Gauge, 1 = First gauge in the group, L = Left, R = Rear.

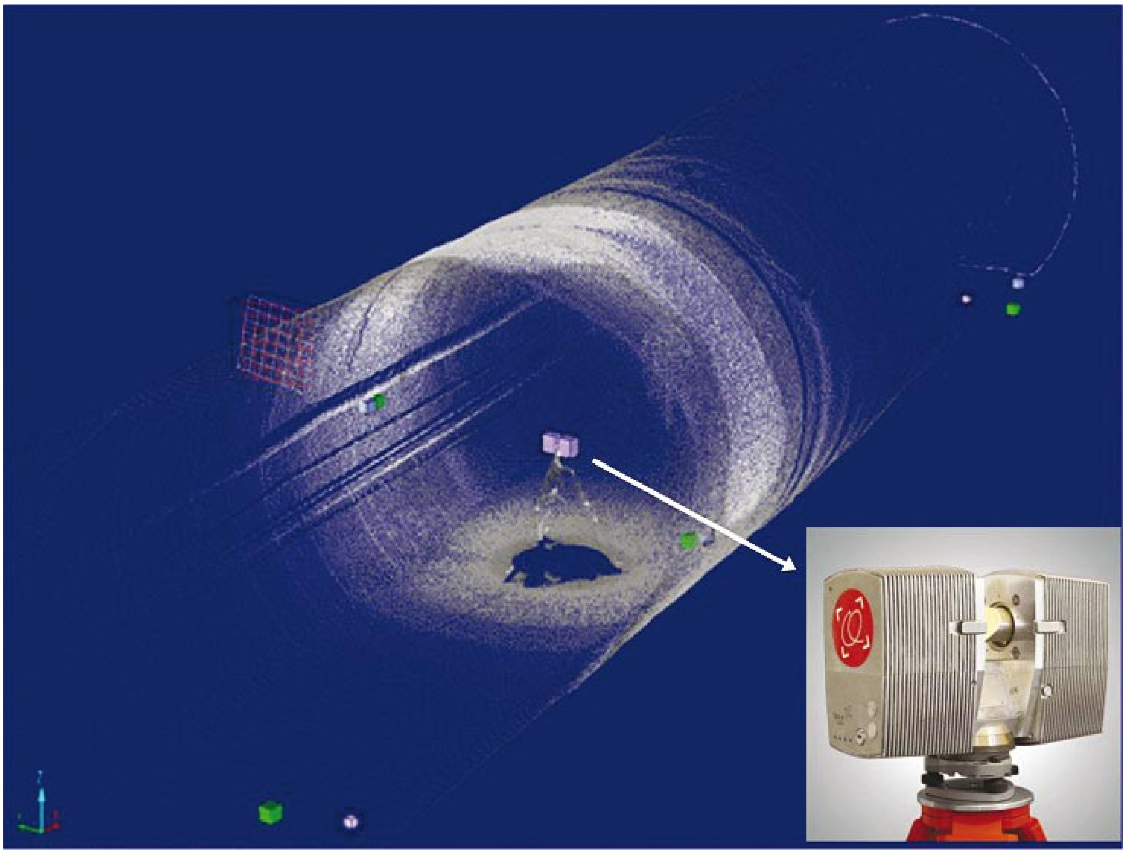


Figure 5-18. *A laser scanner is placed in the drift and used to measure the geometry.*

Figure 5-19. *Measuring tape device for diameter measurements during reaming.*

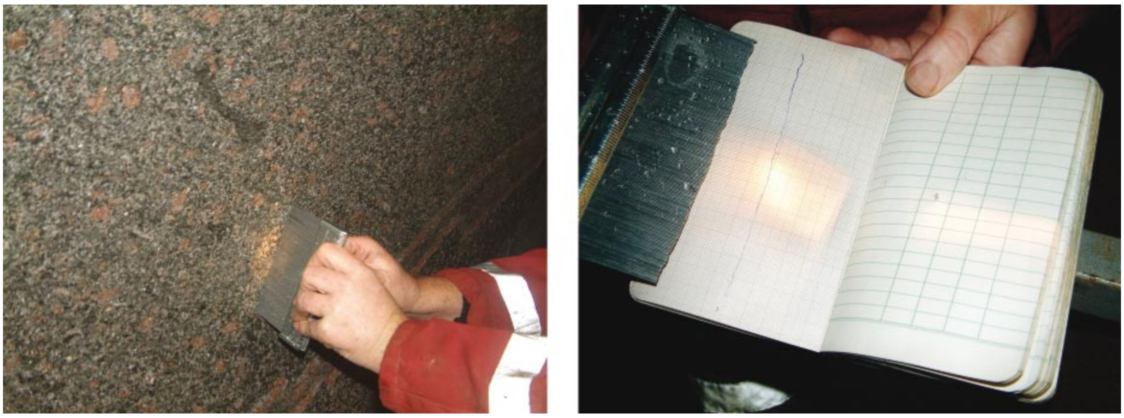


Figure 5-20. *Profiler for roughness measurements.*

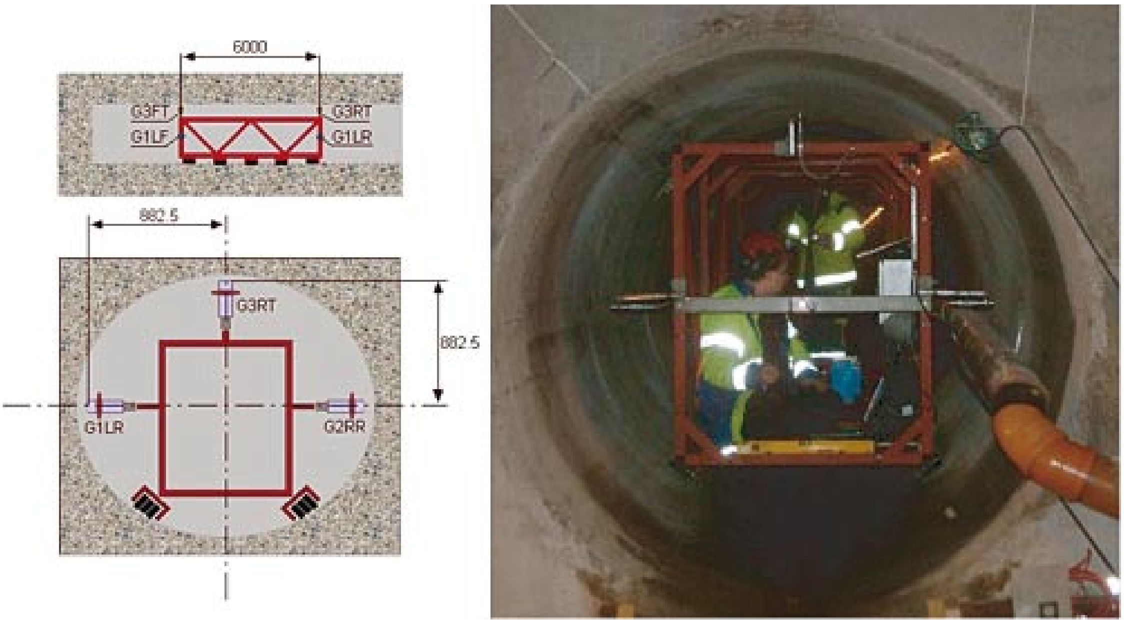


Figure 5-21. *Picture of the dummy (left) and photography of the dummy in the 95 m drift (right).*

The gauge placement is done regarding to the centre of the drift, since the super-container size is Ø1,765 mm, the gauges is placed in the middle of its outer limits. Measurements performed with the dummy then shows the distance between the super-container and borehole wall.

5.9 Boring of the 95 m drift

The planned activities executed for the 95 m drift, Table 5-1, serves as an illustrative example of activities necessary for completion of a horizontal drift.

Table 5-1. Planned activities for boring the 95 m drift.

No	Activity	Comment
1	Description/drawings of rig up area with necessary concrete foundations.	All foundations must be placed on solid, clean rock. Foundation for angular collaring brick must be considered.
2	A special platform for the drilling rigs, enabling the contractor to drill the hole at the prescribed height. Supervision of the construction of concrete pads and concrete wall and marking of drift centre lines and drift centres.	The foundation must be plane. The heigth of the hole is dependent on the equipment to transfer a container from a transport vehicle to the emplacement equipment.
3	Measurement and control of starting point and hole angle for the pilot hole.	Marking of c/c point and 3 m length of directional angle.
4	The lower part of the platform for drilling rig is set up according to centre line, and then bolted through the concrete into the rock underneath. Rigging of drilling machine with equipment is executed. For the 152 mm pilot hole a Puntel 1200 is used. When the rig is adjusted to the starting point of the 152 mm pilot hole, the rig is attached to the platform with bolts.	Centre line and starting point will be controlled with high accuracy, before the bolting takes place.
5	Slow start of pilot hole drilling. Control measurement of inclination and direction after 2.5–3 m drilling from concrete wall surface. Eventually adjustments of the rig.	Flush medium is water only.
6	Installation of the active steering system RSS into the 152 mm pilot hole. Adjustments and control of steering and measuring instruments.	
7	Drilling continues with measurements while drilling (MWD) of the position. The tool is self-steering and gives position with sample frequency of 10 s. After 20 m drilling cross checking will be fulfilled with a Flexit EMS instrument. This procedure will be repeated at 40 m and 60 m of drilling. A drilling log is produced where drill rod length, penetration speed, rotary speed and description of rock conditions are shown. Additionally there will be reports from the RSS system (data log as well as daily reports).	After control measurements at these lengths, SKB makes independent measurements, before drilling continues.
8	When the 152 mm pilot hole is completed and the equipment withdrawn, the hole is measured . After approval of SKB, the 152 mm hole is reamed to 279 mm using a drill bit with a guidance nozzle. For this reaming, the Puntel 1200 is de-mobilized and the Indau 120 mobilized.	Flushing water is fresh water combined with recycled water.
9	After inspection and control of the 279 mm pilot hole, the reaming of the Ø1,850 mm drift is starting.	Flushing is by fresh water combined with recycled water. The flushing volume must be > 3 m^3/min, expected to be recycled at 60–70%. Containers, 3–4 pieces will be used for separating the muck from flushing water.
10	To stabilize the drill string, stabilizers will be attached to the drill string for each 8 m.	
11	When the reaming process is completed, the tunnel/hole will be videotaped and visually inspected.	
12	A project report will be written, including drilling rates, all drilling parameters and description of rock conditions.	Note SKB requirements on the quality plan.

6 General operating experience and main results

This chapter is an account of general experience gained as well as a record of the main data collected. It must again be emphasised that the excavation was carried through with more or less standard equipment and temporary solutions for much of the work. In the real situation we would assume that parts of the equipment are specially designed to improve easiness of operation, robustness and efficiency. However, there are many practical findings and experiences from the test that would be useful to implement for possible future developments.

6.1 Operating experience

6.1.1 Rock conditions and disturbances caused by the rock conditions

The rock conditions have been appropriate for the excavation work and in no way caused excavation problem. Maximum inflow of water measured is in the range of 0.4 L/min for the 15 m drift and 12 L/min for the 95 m drift. The drift was in typically homogenous rock conditions, with generally hard rock, some zones of extremely hard rock, and occurrences of layers of narrow weak zones. The conditions in general are ideal for controlled drilling with generally small natural deviations caused by stratification or inhomogeneous rock.

In one section of the 95 m drift, reaming was through aluminium packers used for sequential grouting in a previous test in the same rock area and these packers caused some pump problems. The general experience is that fragmentation of the reddish granitic rock is better than the greyish Äspö diorite. The straightness of the pilot hole has locally been somewhat affected by a quartz dyke that cuts the drift at an angle.

6.1.2 The set-up

The size of the drill niche was adequate. The height of the cavern should be minimum 3.5 m above the top of the drift and minimum 10 m for the width with the present equipment used in this project. The start of the drift was 3.1 m above the concrete foundation surface, thus a lot higher than the drilling rigs natural starting point. Some special arrangements were prepared that worked out satisfactory but can be simplified for the future. The concrete pad casted on the wall (see Figure 5-1) is not deemed to be necessary at all; it should suffice to arrange a planar surface for the collaring of the pilot boring. SKB should define requirements for the accuracy of collaring.

The thick reinforced concrete foundation is not necessary; the machine can be anchored by rock bolts and the floor levelled with 30 cm un-reinforced concrete just for the practical work conditions.

6.1.3 Muck systems in the deposition drift

The initial plans for mucking did not work out (see Section 5.6), so several alternative designs for mucking by flushing were developed and tested. The experience from alternative 1 was unsatisfactory for several reasons. The first was that the rubber sealing broke down, see Figure 5-14. The second experience was that space was too limited for the pipe from the entrance of the drift to the first mud container, which decreased the flow of muck and severely reduced the advance rate. Thirdly, it was difficult to empty the containers as the muck stuck to the container. It was also difficult to plan and manage the timely arrival of container trucks.

Description of mucking alternative 2 and experience

The idea with a pressurized compartment was abandoned. A 152 mm plastic tube was coupled to the reamer head for flushing the muck out of the drift by drainage. A small container was placed at the entrance of the drift and a mud pump installed in the box to lift the drainage materials to the first mud container. A small excavator was to dig out the muck from the first mud container that was enlarged from 8 m^3 to 20 m^3, Figure 6-1. The muck was to be moved to a truck using the wheel-loader.

The experience was in general good. The flushing and drainage of muck worked properly as well as the use of a small excavator. A negative experience was the wear down of the mud pump, due to coarse muck fraction and the high utilization. During mud pump stops, the small box was filled with material and it was time-consuming to empty the small container at the drift entrance.

Mucking alternative 2 was the main design for the reaming of the 15 m drift.

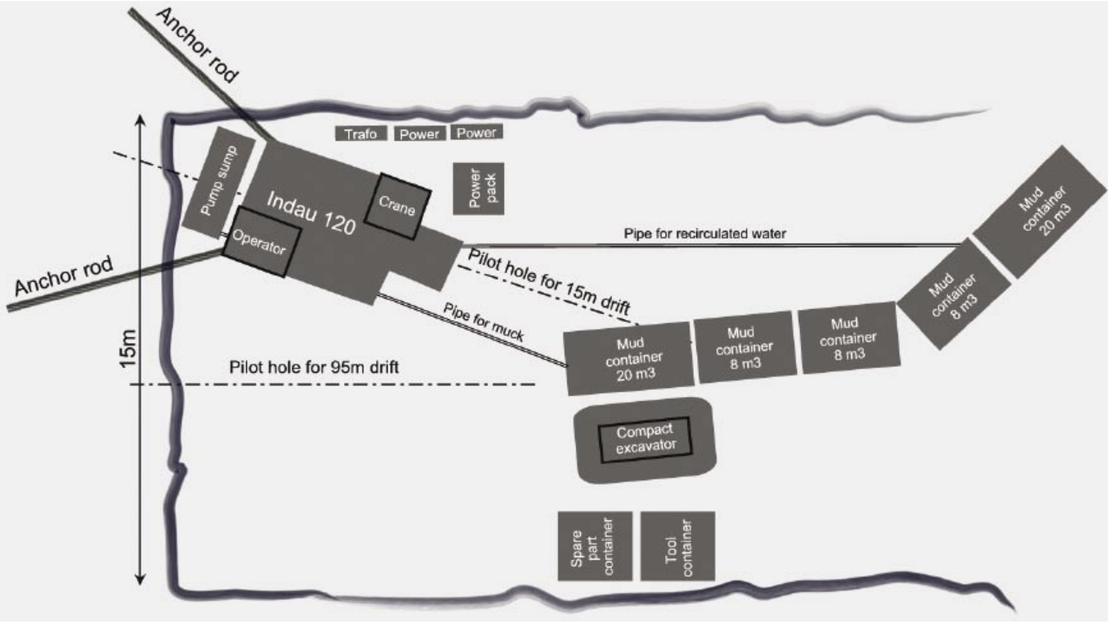


Figure 6-1. *Mucking alternative 2.*

Description of mucking alternative 3 and experience

A third mucking alternative was prepared for the reaming of the 95 m drift, see Figure 6-2. For this alternative the cutter head was also re-designed, so that water was fed by pipes behind the cutter head.

The small container at the drift entrance was replaced by a larger container where two mud pumps were placed. The last sedimentation container was enlarged to 20 m^3 to limit mud flow in the Äspö facility. The flush water for the reaming was by two pumps in container 4 and container 5, where one pump is for the water in the drill string and one for drainage of the muck. The water in the drill string is by a manifold divided to four places at the periphery of the reamer head. One pump was placed in container 3 to feed container 4 with formation water. Some fresh water is fed into the system to replace water loss and to dilute the flush water for drilling. Excess water is drained to the Äspö HRL drainage system. A grizzly was placed over the pump sump to sort out the largest chips and stones. The small excavator was used.

The experience was that the mud pumps in the pump sump frequently failed due to overloading; the grain size distribution was much coarser for the 95 m drift compared to the 15 m drift due to higher advance rate.

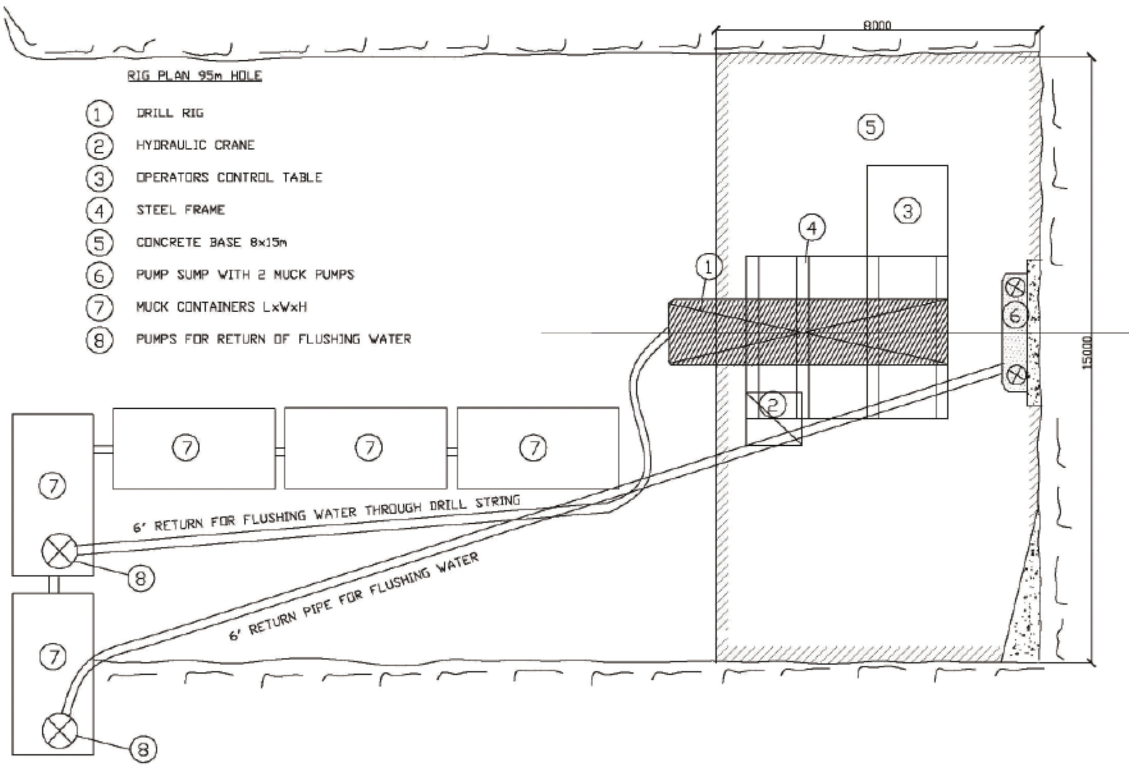


Figure 6-2. *Mucking alternative 3. Courtesy Entreprenørservice A/S.*

Description of mucking alternative 4 and experience

A test was conducted using a mud screw conveyor mounted at the drift entrance. The electrical engine broke down due to overloading.

Description of mucking alternative 5 and experience

The alternative is as alternative 3, but with more efficient mud pumps in the pump sump and this replacement after reaming around 40 m of the 95 m drift very much improved the advance rate.

The final pump equipment was:

- Muck pump sump: Two Tsurumi mud pumps KS 52–120, 9 kW, capacity 3,000 L/min, 3–4 bar;
- Container 4: Tsurumi mud pump KS 52-120, 9 kW, capacity 3,000 L/min, 3–4 bar Tsurumi water pump LH-311 W (installed but not used, not necessary), 11 kW, 800 L/min, 7 bars.
- Container 5: Tsurumi mud pump KS 52-120, 9 kW, capacity 3,000 L/min, 3–4 bar.
- Spare pumps: Two Tsurumi KS 52-120.

For future tests, the mucking system can be much simplified, see Figure 6-3. A hopper should be fitted to the drift. A pipe with at least 300 mm diameter should be fitted to the cone and graded below the machine foundation. The flush water is led into pipe with outlet in a pump pit (at least 10 m long, 3 m deep and 3 m wide) where a pump lift the water into a sedimentation container maybe 20 m^2 in surface area. The pump pit is regularly emptied by a digger.

For repository drift excavation, it would be convenient to fit the derrick and steel frame with tyres so the equipment easily can be towed to nearby drifts to be excavated.

6.1.4 Pilot hole for the 15 m drift

The 279 mm pilot hole was drilled without any guidance of a pre-cored borehole and it is still matter for discussion whether a cored borehole is beneficial. If a cored hole is used it is important that the coring is without kinks as kinks might affect the later pilot hole. To drill a straight pilot hole, the drill bit was followed by three stabilizers before the drill string followed.

6.1.5 Reaming of the 15 m drift

During reaming of the 15 m drift it became apparent that the reamer head had some deficiencies; the guidance pin was too short and with too small diameter, the reamer head was not stiff enough which showed up as vibration and that the reamer head did not follow the pilot hole exactly, which is evident in Figure 6-4.

Most concerns were directed to the mucking, where four mucking alternatives quickly were abandoned, see the previous Section 5.6. It also became evident that the wing-stabilizers were too fit so 20 tonnes of thrust was lost at the reamer head as the wings acted as breaks; the surface Teflon “bearings” between the wing-stabilizers and the drill string were badly heated and damaged.

Compared to the later 95 m reamed drift, surface is quite rough and the drift shows many grooves in a helix shape along the periphery.

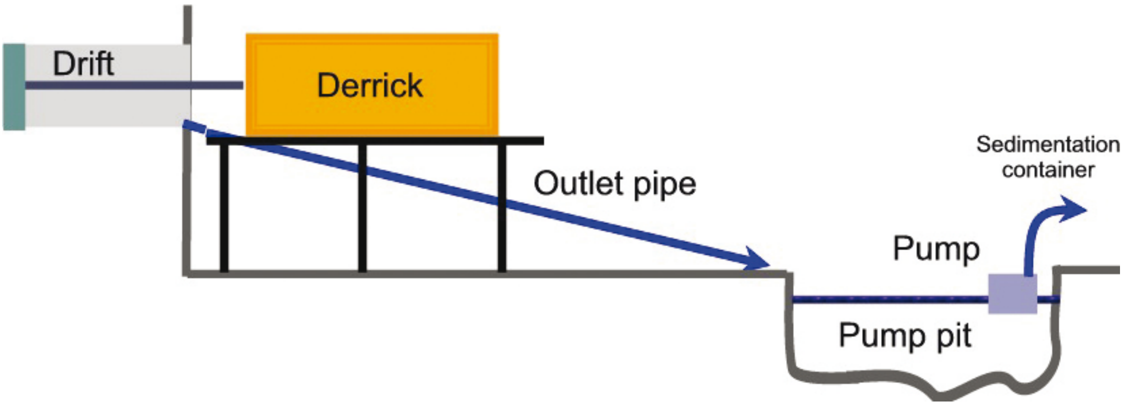


Figure 6-3. *Proposal for a simplified set-up for the muck removal.*

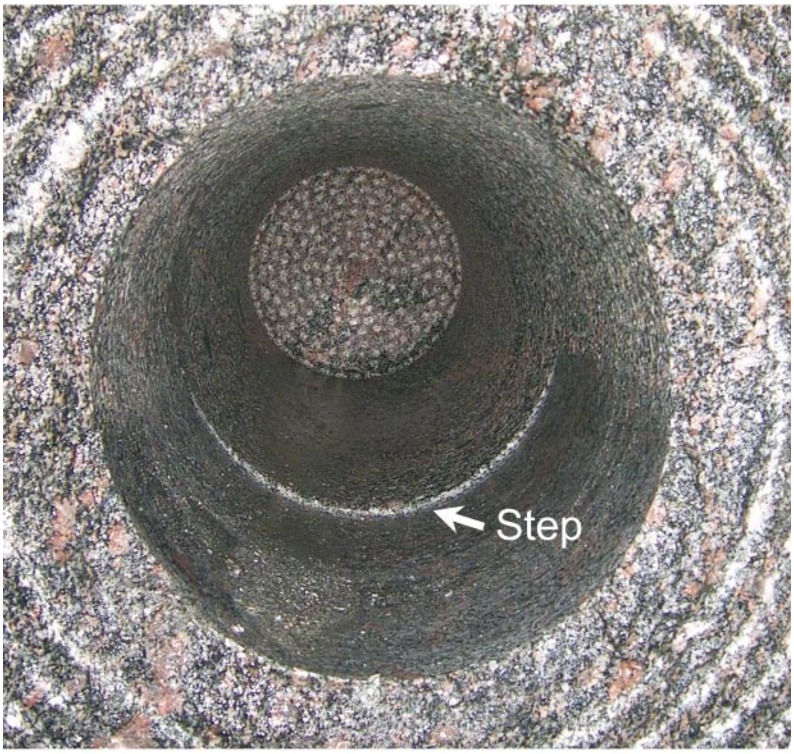


Figure 6-4. *The picture shows the bottom of the 15 m pilot hole after reaming and it is evident that the guidance pin of the reamer head did not follow the pilot hole; the step is in the order of 5 mm.*

6.1.6 Measurements for the 15 m pilot hole and 15 m drift

The contractor used laser and a Flexit EMS equipment to line up and check the straightness of the pilot hole. The contractor had the opinion that the Flexit measurements are uncertain, due to the difference in diameter between the 279 mm pilot hole and the 44 mm diameter instrument where small irregularities at the pilot hole bottom would create measurement errors. Other contractual requirements like "steps" etc were also roughly evaluated by the contractor using straight edge and measuring tape. SKB made their own measurement using theodolite and special device for the pilot hole see Figure 5-16 and laser scanning.

The special device prepared by Geocon and use of a theodolite worked excellent. The prerequisite is of course that the drill pipe is removed and the hole is straight enough so that the prism can be viewed by the theodolite. The diameter was tracked by a scanning laser and the measurements worked properly, but analysis of the data and comparison with other method is tedious and undeveloped. It has been difficult to evaluate the very large number of measuring points collected by the laser scanner and be able to compare it with the quality parameters of the drift. However, laser scanning is a very accurate and quick method if it only comes to defining the position of the drift. The laser scanning could not be used to check the drift surface and compare it to the quality parameters smoothness, waviness and steps. Experience shows that the quality parameters need to be redefined in the light what methods to use to verify the quality.

The measurements of straightness of the pilot hole are shown in Figure 6-5 and Figure 6-6.

The results of the diameter measurements based on the laser scanner measurements are:

An example of roughness measurements including a possible step for the 15 m drift is shown in Figure 6-7.

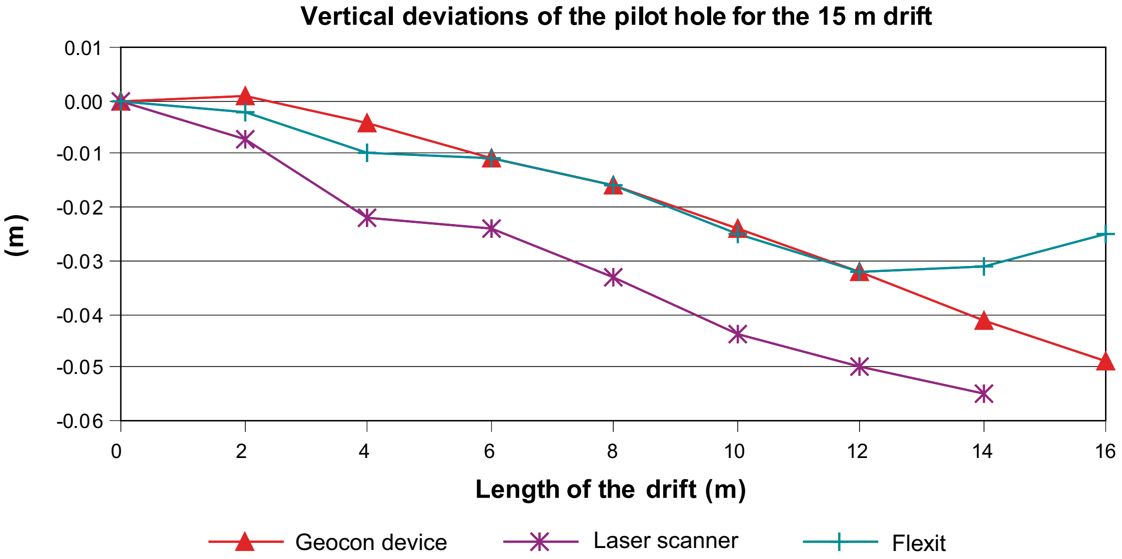


Figure 6-5. *Vertical deviations from the theoretical line for the 15 m pilot hole.+ is upwards. The laser scanner results are calibrated from diameter measurements.*

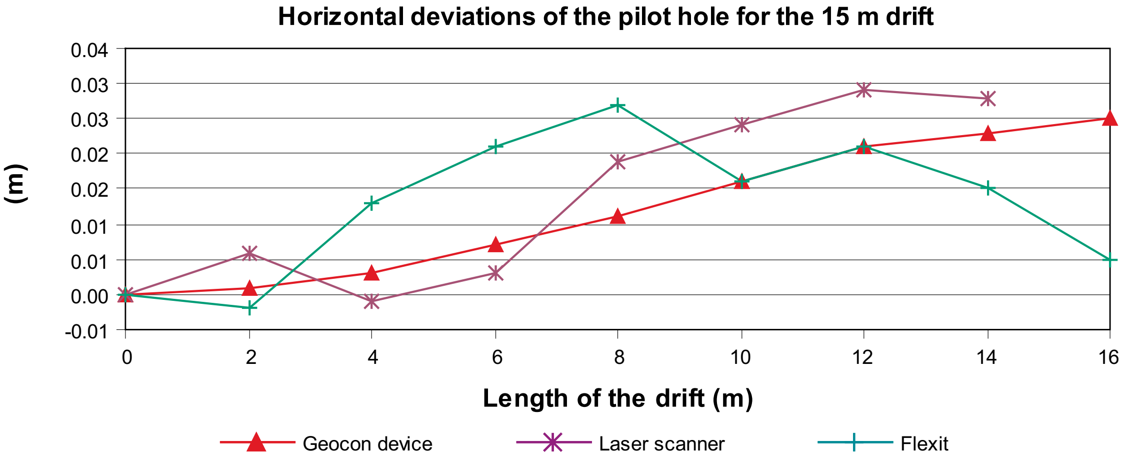


***Figure 6-6.** Horizontal deviations from the theoretical line for the 15 m pilot hole.+ is to the right of the theoretical line. The laser scanner results are calibrated from diameter measurements.*

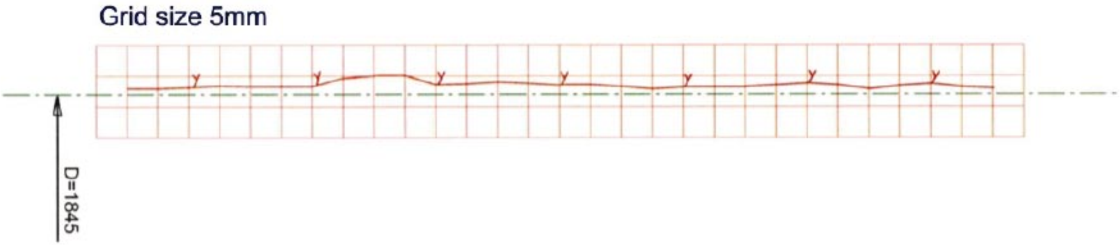


***Figure 6-7.** Example of step[3] in the 15 m drift. Data from section 13 m and 45 degrees clockwise from the top.*

6.1.7 Move of equipment and set-up for the 95 m hole

Movement of the drilling rig was executed by a jack up of the frame, and placement of skids manufactured by SKB beneath the frame for sideways movement. This solution simplified towing the rig over to the position for the 95 m drift and the new set-up was prepared as for the 15 m drift with no unexpected event. The original plan called for the Puntel for the pilot hole to be replaced by the Indau for the reaming. For this case it is essential that both machines have identical alignment.

6.1.8 Pilot holes 152 mm and 279 mm for the 95 m drift

Entrprenørservice drilled a 152 mm (6") hole where the drill string was fitted with the measurement and guidance tool by Smart Drilling GmbH (SD). The tool however failed completely both with respect to deviations as well as to durability. SD was convinced that the pilot hole was straight, however the redundancy measurements using a theodolite commissioned by SKB showed systematic deviation. After 19 m the hole was already 5.3 cm lower than theoretical line, and the deviation showed an increasing decline in inclination compared to theoretical line being 2.15° instead of the target 2.5°.

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[3] Step is not a precise definition; here it is more or less measured as break-out rock outside the drift surface area. No real steps have been found in the drifts.

SD later found the error in their system: The electric data transmission system consumed more electric energy than anticipated which led to friction clutches within the system started to slip whenever more power was required from the generators to transmit data. This problem can probably be solved easily.

The second detriment was that the tool and a spare tool broke down, as no signals at all were received for normal thrust. In fact, most of the drilling was performed by using 10–15 kN thrust instead of the planned 50–70 kN thrust. The result was slow advance and added wear on the pilot bit.

The third nuisance was that SD does not correlate azimuth to drilled length, but to time stamps, meaning it is actually difficult to track and back-calculate the deviation with borehole depth.

While the SD-tool broke down and was not to be replaced for a couple of months, SKB and Entreprenørservice launched a contingency plan to drill the pilot hole without any active steering but aiming at vertical guidance, see Section 5.8. Subsequently the 156 mm pilot hole was abandoned and a new 279 mm hole drilled where the vertical deviations were checked by using the water levelling (see Figure 5-17).

For future work where a 300 m hole might be drilled there is a need to pursue a strategy for drilling the pilot holes. The current plan that failed, aimed first for a 152 mm hole, to be enlarged to 279 mm. Efficient plans should either make use of a straight cored hole for guidance to be enlarged OR that active steering is used directly on diameter 279 mm. Non-rotating stabilizers should be used, 3 stabilizers directly behind the pilot bit and then a stabilizer every 5th pipe (c/c 7.5 m), see Figure 5-13.

6.1.9 Reaming of the 95 m drift

The improved reamer head and stiffened system was much more efficient than previous equipment. The guidance pin in front of the reamer head was increased in length to 95 cm and with larger diameter around 276 mm. A wing-stabilizer was installed just behind the reaming head and then one wing-stabilizer every 5th pipe (c/c 7.5 m).

The design of the reamer head and cutters were however not completely satisfactory; the cutter design is for a 12"¼ hole (311 mm) but an 279 mm pilot hole was used, which meant that the distance between the innermost kerf and the pilot hole was too large, maybe 50 mm instead of 30 mm. This caused creation of large chips that affected the operation of the muck system. The reamer head was designed with four gauge cutters, but six gauge cutters would have been favoured. The design of gauge cutters are also somewhat flawed as the cutter sides facing the periphery is worn down. It is suggested that these cutter faces are designed with a few hard metal ware pads to avoid excessive wear. The cutters placed behind the reamer head was meant to be used for “crushing” in case the rock chips were too large. While the mucking system was completely changed, these “crusher cutter” are of no use at all.

The removal of the debris using a water flow of around 3,000 L/min was sufficient to clean the drift at a 2° grade. The mucking system to remove the debris from the entrance of the drift to the containers did not function properly for the first 40 m of excavation as the capacity of the two slurry pumps were too limited. After change of pumps to a bigger size mud pumps, the overall utilization improved drastically. In addition to change of pumps a grizzly was placed above the pump pit to block large chips from entering the pump pit.

The contractor thinks that 30 m of reaming operating 5 days/week is a reasonable advance based on a fit machine and 12 h excavation work per day. A general observation is that the pilot hole drilling and reaming requires skill that may take a number of years to acquire – it is not only to push one or two buttons!

6.1.10 Measurements for the 95 m pilot hole and 95 m drift

The pilot hole

For more accurate measurements of the pilot hole, the Geocon prism device was used a number of times during the drilling operation. The measurements were interpolated to a line that was compared to the theoretical drift centre line. In case the hole was straight enough, drilling continued. The horizontal and vertical deviations for the 95 m drift pilot hole in Figure 6-8 measured by the Geocon device (vertical and horizontal deviations) and the water-level measurements (vertical deviations).

The vertical deviation from the theoretical line based on the direction of the machine set-up is around –0.6 m and the horizontal around 0.1 m (maximum 0.134 m at 78 m).

The inclination of the borehole should according to the requirements be in the range 2°±1° and this requirement was met for the 95 m drift, see Figure 6-9. The theoretical line for the 95 m drift based on the direction of the machine set-up was 2.09° and the final results show inclination in between 1.86° and 2.43°.

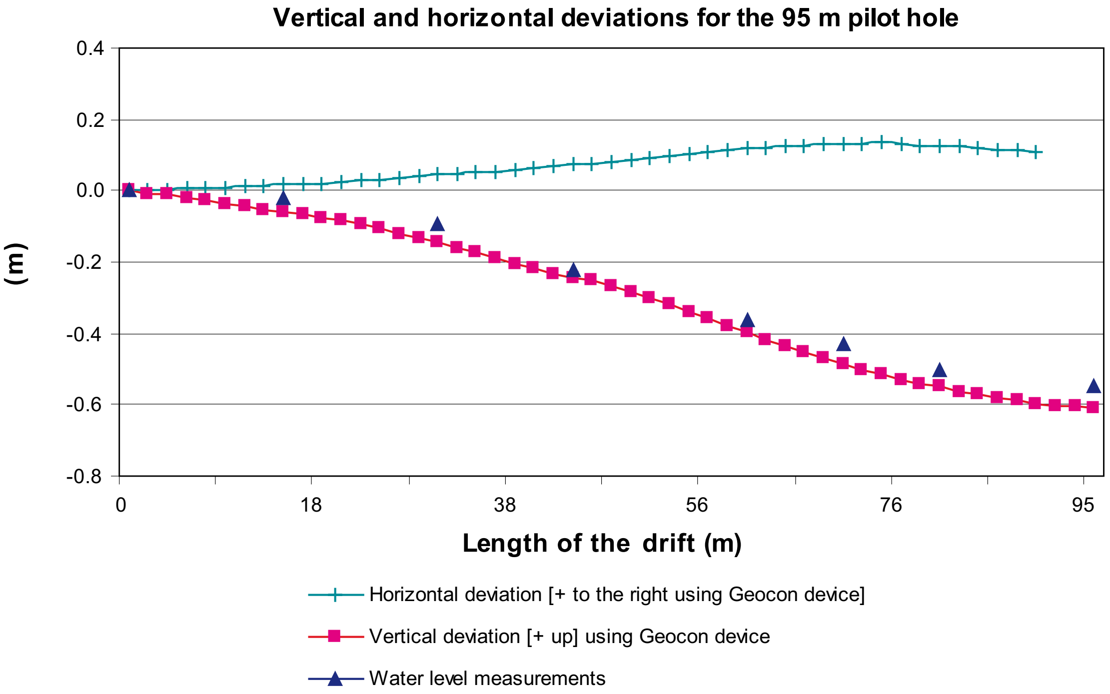


Figure 6-8. *Horizontal and vertical deviations for the 95 m pilot hole Drift 1619 A. Deviations are calculated for a theoretical line based on the actual set-up of the drill rig where the inclination is 3.6% upwards (= 2.1°).*

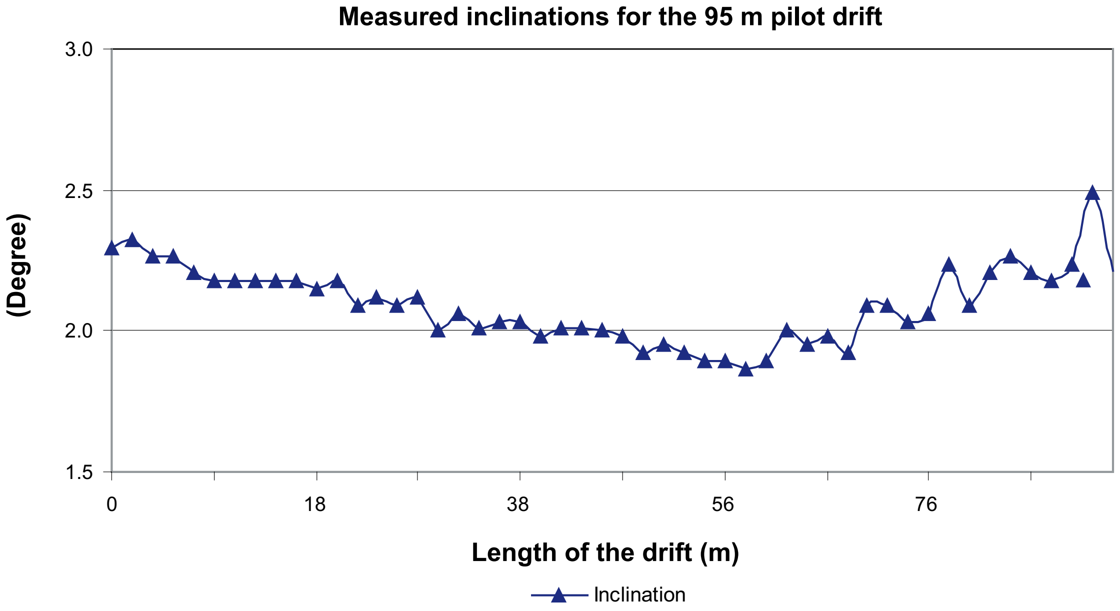


Figure 6-9. *Measured vertical inclination in the 95 m drift.*

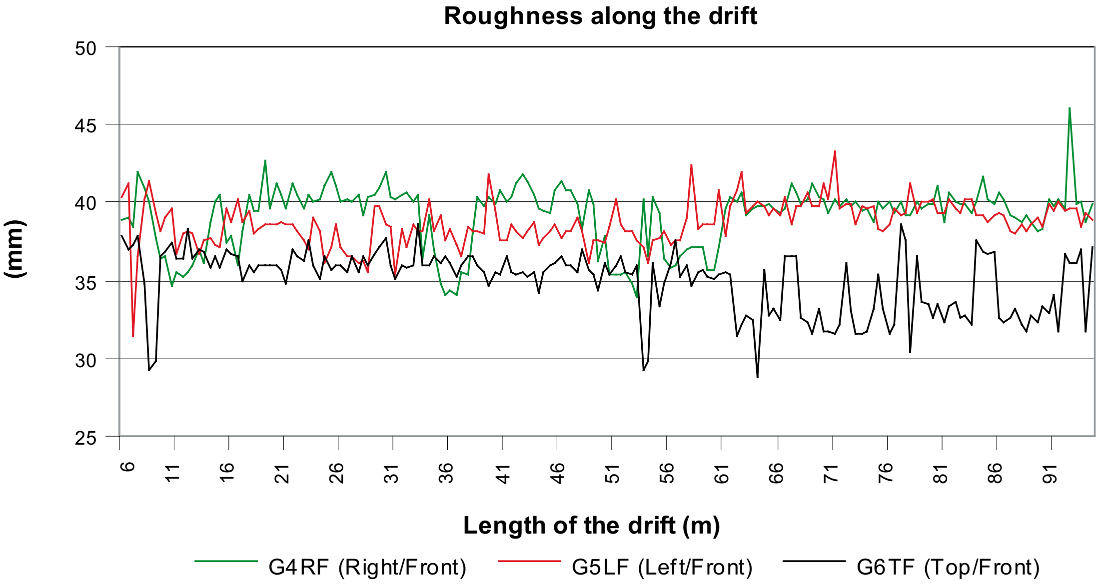
Roughness

The dummy was used to demonstrate that a 6 m long and 1,765 mm device would fit in the drift. The insertion of the dummy into the drift proved that the drift was spacious enough for the dummy. As the dummy also was dressed with gauges, the results can be used to test the roughness along the drift as well as to calculate the mean gap between the dummy and the rock wall, The roughness is interpreted to be < 5 mm for most of the drift, but occasionally the measurements indicate that roughness is at a higher level, up to around 8 mm, see the charts in Figure 6-10.

Roughness was also measured with a profiler (see Figure 5-20) and the measurement results are shown in Figure 6-11. This method is basically manual and from project constraints it is not possible to capture all roughness along the drift with this method. The figure shows some results for the 95 m drift, where roughness was measured along the periphery at 45°, 135°, 225° and 315°; all measurements are within the stipulated requirements.

Diameter variations as measured by the dummy

The measurements are also used to indicate the diameter variations. The gaps for the left and right gauges are summarized for the rear and front gauges respectively, see the charts in Figure 6-12. Now using the requirements stating that diameter should be 1,840–1,850 mm and the dimension of the super-container is 1,765 mm the permissible gap should be around 75–85 mm. Table 6-1 compiles basic statistics and while rear and front gauges do not measure the same spot, we have to accept that there is a spread of results in between the rear and front gauges. Around 11% of the measurements are outside the range 75–85 mm. For the rear gauges all outliers were > 85 mm; for the front gauges one measurement was > 85 mm and 29 measurements < 75 mm. For this reason we assume that the dummy was not the perfect tool for measuring the diameter 1,765 mm.



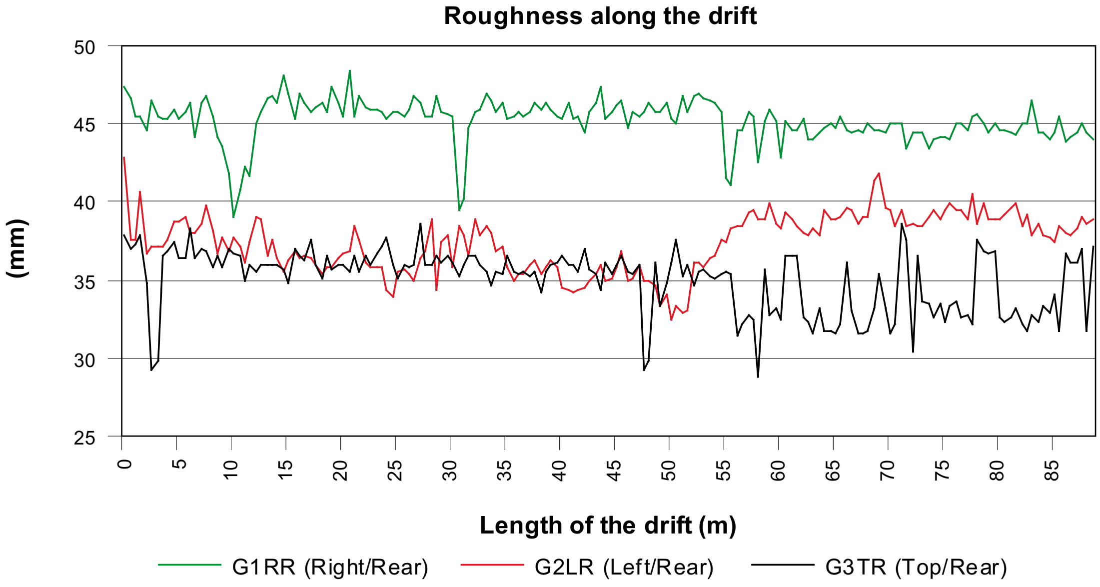


Figure 6-10. *Distance between the gauges and the drift wall. Top: For the three gauges at the rear of the dummy. Bottom: At the three gauges at the front of the dummy.*

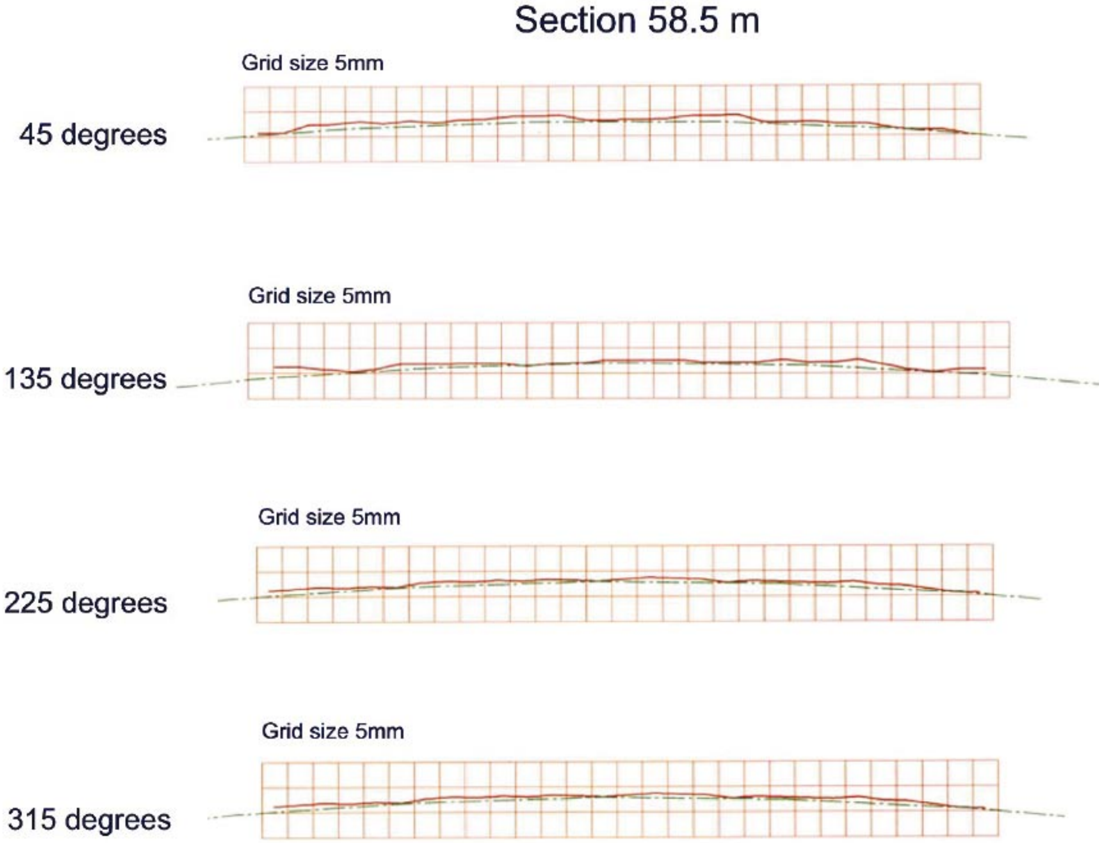


Figure 6-11. *Results of roughness measurements at four positions around the circle periphery. The green circle segment is for radii 1,844 mm. Roughness is in within the requirements for the samples shown.*

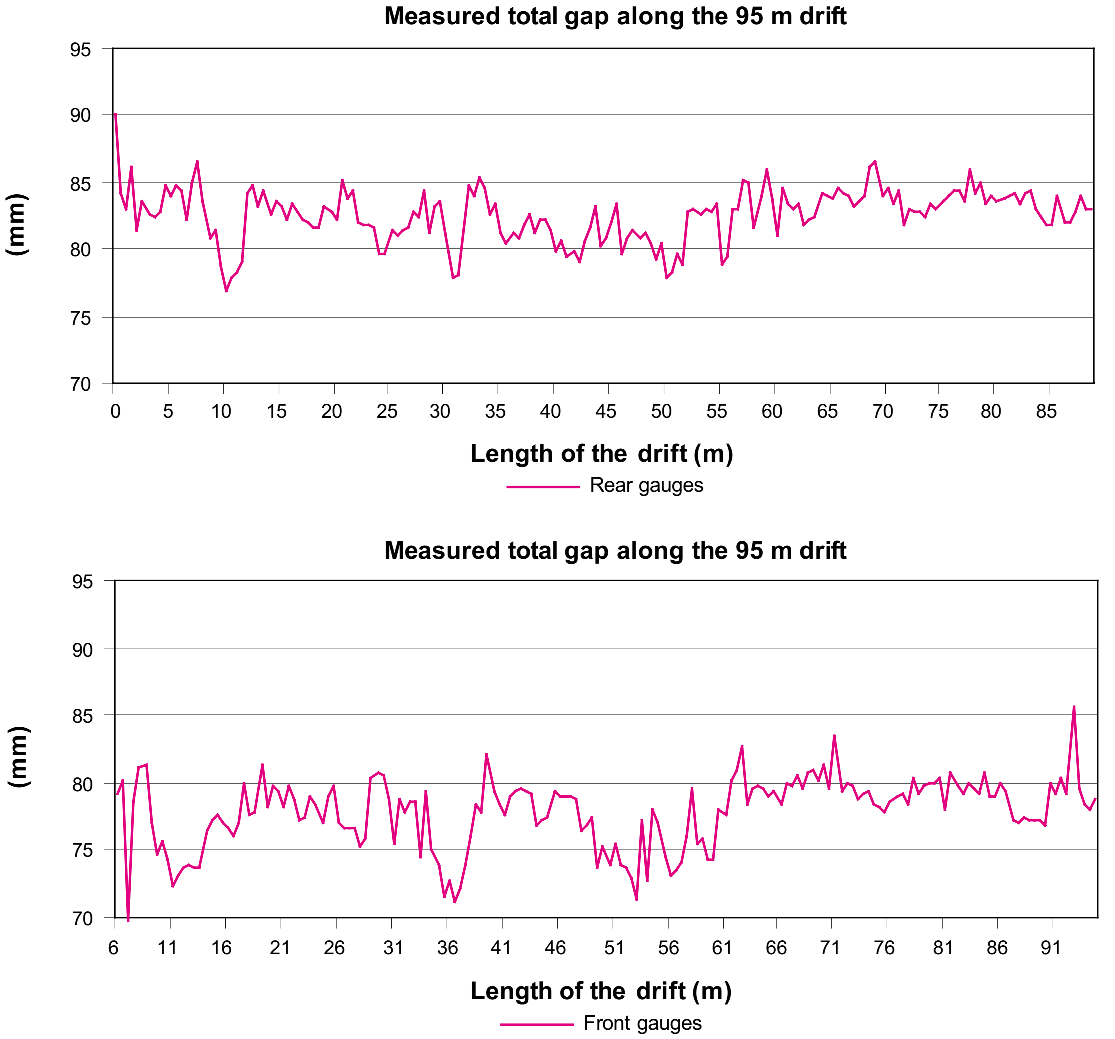


Figure 6-12. *Measured total gap between the drift wall and the gauges. Top: Rear gauges. Front: Front gauges positioned 6 m in front of the rear gauges.*

Table 6-1. Measured data for gaps.

Issue	Rear gauges	Front gauges
Maximum gap measured (mm)	90	86
Mimumum gap measured (mm)	77	70
Average gap	83	78
Standard deviation	2.1	2.7
Number of measurements outside the range 75–85 mm (Average 11%)	10 (6%)	30 (17%)

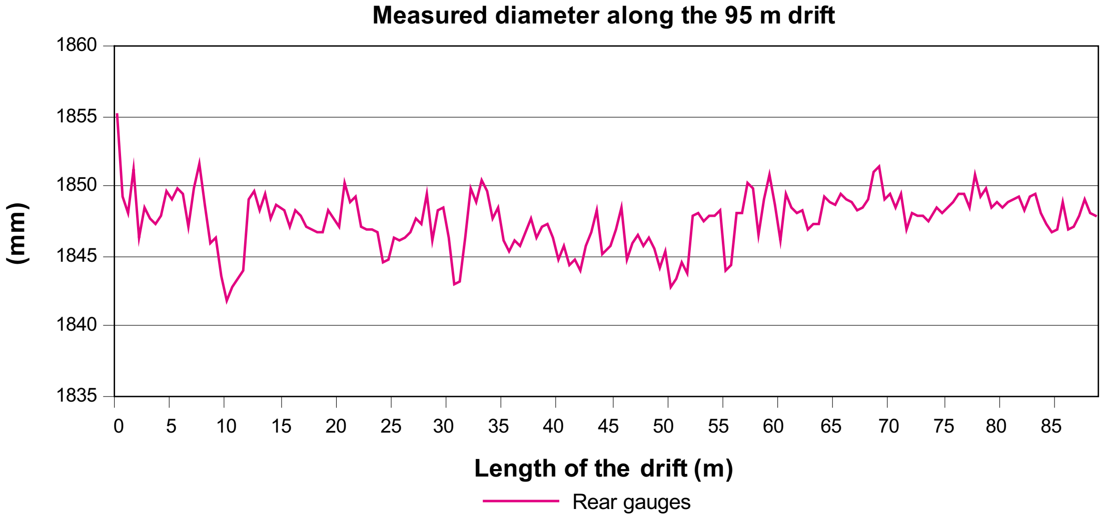
In a similar fashion as for the diameter roughness we evaluate the diameter variations along the 95 m drift, see Figure 6-13. The requirements stipulate diameter 1,840–1,850 mm. Main results are shown in Table 6-2.

Diameter variations using the measuring tape

Diameters were also measured using a measuring tape, see Figure 5-19. As described in Chapter 5.8, a simple measuring tape was used to measure the drift diameter horizontally and vertically. Records are shown in Figure 6-14 and compared to the actual requirements states; using these measurements the requirement is met.

6.1.11 Demobilization

Demobilization is a standard procedure and there are no general experiences to share.



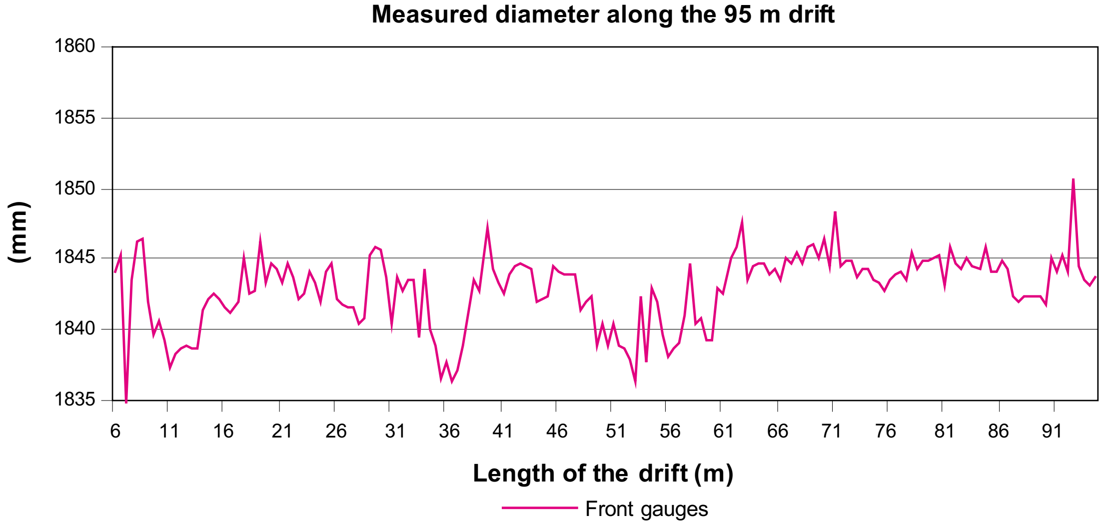


Figure 6-13. Measured diameter by adding measured gaps to the width of the dummy (1,765 mm). Top: Rear gauges. Bottom: Front gauges.

Table 6-2. Measured data for diameter.

Issue	Rear gauges	Front gauges
Maximum diameter measured (mm)	1,855	1,851
Mimumum diameter measured (mm)	1,842	1,835
Average diameter	1,848	1,843
Standard deviation	2.1	2.7
Number of measurements outside the range 1,840–1,850 mm (Average 11%)	10 (6%)	30 (17%)

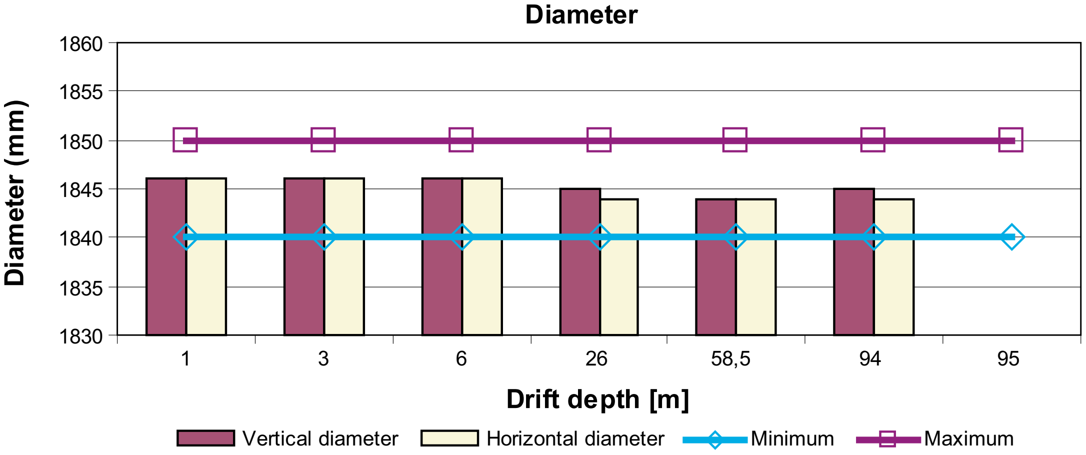


Figure 6-14. Diameter variations as measured by tape and compared to the requirements for maximum and minimum diameter.

6.2 Compilation of operating data

This section provides an overview of data collected during the operation

6.2.1 Advance rate, utilisation and availability

SKB prepared templates for Daily Log, Boring Logs etc and based on these records certain amount of operational characteristics is described for the 15 m and 95 m drift, see Table 6-3. The average penetration during effective drilling is around 0.5 m/h. The low overall system utilization during reaming of the 95 m drift is mainly due to downtime related to the mucking system. Definitions of utilisation and availability are described in Table 6-3.

For the 95 m drift the daily advance rate improved considerably when the mucking started to work better after around 40 m of boring, see Figure 6-15. The typical daily advance increased up to 6 m at the end of the project. At this rate effective penetration was around 0.5–0.6 m/h, extension of rods including extra flushing needed around 15 min per rod change with some 15 min extra time to mount the wing-stabilizers. Downtime was practically zero.

The time-split of activities during utilization is shown in Figure 6-16 and Figure 6-17.

Table 6-3. Compilation of some main characteristic operating data.

Parameter	Pilot hole 15 m	Reaming 15 m	Pilot hole 95 m (no active steering)	Reaming 95 m
Start date boring	Oct 18, 2004	Oct 21, 2004	Nov 6, 2004	Jan 5, 2005
End date boring	Oct 20, 2004	Nov 3, 2004	Dec 15, 2004	Jan 23, 2005
Duration (workdays)	2	10	8	34
Mean penetration during boring (m/h)	2.2	0.26	2.2	0.49
Standard deviation (m/h)	–	–	0.49	0.21
Typical thrust (kN)	200	600–1,100	180–250	1,000–1,600
Typical torque (kNm)	6 (Puntel)	120	60	120
Typical rotation (rev/min)	28	14	28	14
Utilisation[1] (%)	55	67	72	90
System availability[2] (%)	88	97[4]	96	60
System utilisation[3] (%)	45	63	69	54

[1] Utilisation is here defined as time used for boring, rod handling, measurements and maintenance compared to total duration of the shift (%).

[2] Availability is here defined as time used for boring and rod handling less time for maintenance and downtime compared to duration of the shift (%).

[3] Utilisation×Availability.

[4] Procedures for daily log were more detailed at later stages. Downtime not likely properly recorded.

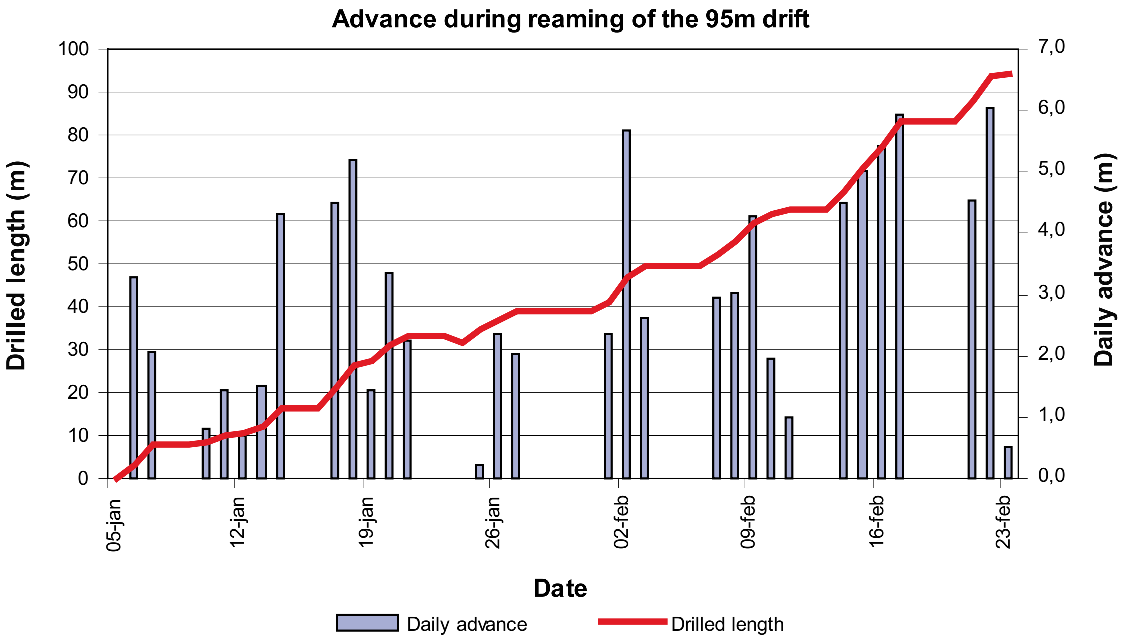


Figure 6-15. Daily advance during drilling of the 95 m drift.

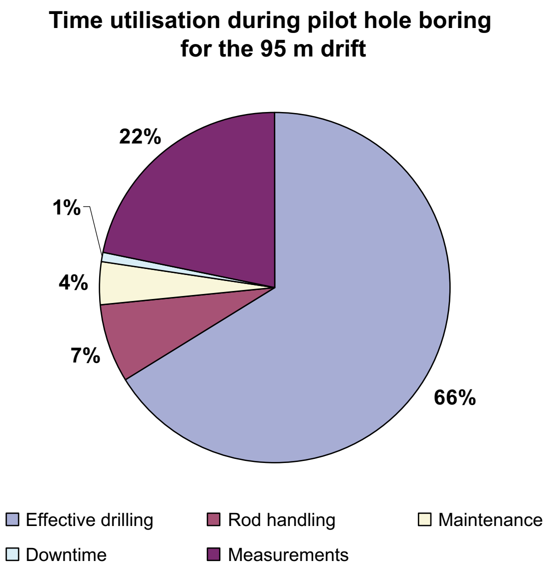


Figure 6-16. *Time utilisation during the pilot hole boring for the 95 m drift.*

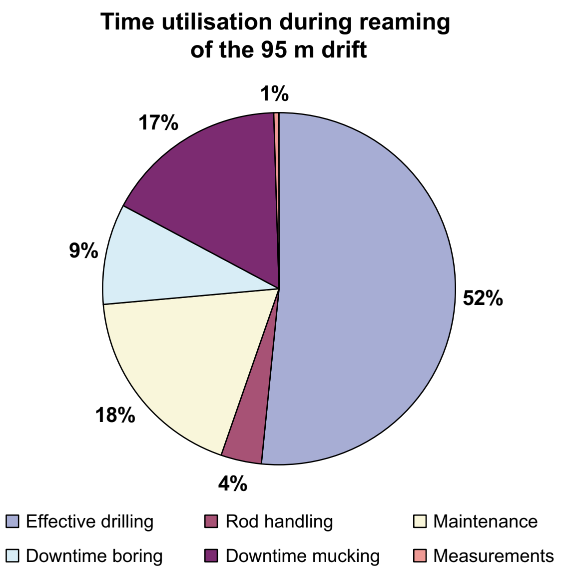


Figure 6-17. *Time utilisation during reaming of the 95 m drift.*

6.2.2 Particle size distribution

Debris from reaming the 95 m drift was collected at section 80 m (February 17, 2005) to analyse the particle size distribution. From the outlet pipe from the drift, around 1 m^3 of water and rock was collected in a box. After drainage, around 100 L of mud was left in the box, the box was overturned and emptied on plywood[4]; three samples one 1 L each were collected for analyses at a concrete station; the data show a considerable amount of fines that is not comparable with the similar exercise in Olkiluoto using similar excavation technique.

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[4] As the samples were not collected by successive sub-division of the volume, starting with the total sample volume, the statistical representativiness of the samples may be questioned and is not shown here. The report by /Bäckblom et al. 2004/ shows some general data from previous records.

6.2.3 Water inflow

The total water inflow measured after the 95 m pilot hole was less than 2 L/min. After reaming 95 m the total inflow was around 10 L/min. Most of the water is seeping through spots, see the photography in Figure 3-10. The water seepage distribution for the individual seepage spots is in the range of 0.3–1.6 L/min.

6.2.4 Environmental issues

Noise measurements were conducted during reaming and showed to be around 75 dB(A) in the cabin and 80–90 dB(A) in the neighbourhood of the derrick measured in the niche. Dust and gases were not recorded, nor the total spillage of oil and grease.

7 Evaluation of the excavation project

This chapter presents evaluations of the excavation project compared to selected factors of importance for the decision process. The reader is referred to /Bäckblom et al. 2003, 2004/ for background to rationales and descriptions.

7.1 Factors of importance for long term safety

7.1.1 Construction and stray materials

For all excavation methods there will be stray materials as steel, hard metal and hydraulic oils. For Drill & Blast we can also assume explosives and detonators.

Using a horizontal push-reaming for drifting would minimize use of construction material in the drift. Spillage of any hydraulic oil could occur, but mainly at the derrick that is outside the drift. The project however lacks clear records of volume of grease and hydraulic oil used. It is here assumed that spillage is in line with previous experience /Bäckblom et al. 2004/ around 0.01 L/m^3. The minute amounts of grease for drill rods and for cutters are thought to be effectively flushed out of the drift due to the mucking method selected.

7.1.2 Excavation damage and excavation disturbed zone

No specific tests have been performed to test the properties of the excavation damaged or excavation disturbed zone, see the report /EC 2005/ for more information on these issues. It is likely that the results are similar to previous results reported for a shaft boring machine used for testing the drilling of deposition holes in granitoid rocks at Äspö and Olkiluoto see for example /Autio and Kirkkomäki 1996, Autio et al. 2003/.

7.1.3 Geometrical considerations for long term super-container function

The gap in between the super-container and the drift wall should be close enough so that the buffer density is preserved above stated design limit in spite of the expansion that will follow when the buffer is in contact with water. The preliminary data from the dummy shows that the average total gap is within the limits stated, but random outliers exist and then often below the low limit 75 mm than outside the high limit 85 mm. The practical test shows that the drift is excavated with small diameter variations and it is suggested that the requirements are revisited to evaluate that the present drift surface is good enough for the purposed of the long-term super-container function.

7.1.4 Water inflow

As shown in examples here, the total water seepage is low; however seepage is through some wet spots with spraying water. Such spots are thought to be an effect of the high gradient and it is a matter for further studies to ascertain that the buffer is not impaired by piping etc during the transient water-uptake in the buffer.

7.2 Factors of importance for operational safety

7.2.1 Incidents for accidents

No incidents or accidents have been reported. The previous conclusion in /Bäckblom et al. 2004/ is still valid that that horizontal reaming of long deposition holes from would be a comparatively safer excavation method compared to TBM and Drill & Blast as the excavation mainly is with less people in the newly excavated drift.

7.2.2 Noise, heat, dust etc

The noise is limited (dBA) especially for the operators that work in a cabin – 75 dB(A) and this noise can be further reduced by additional insulation. The excavation and mucking is performed using flowing water for flushing and mucking thereby reducing any heat or dust.

7.2.3 Geometrical considerations for emplaceability

The use of the dummy proved that the drift would be fit for emplacing the super-container. As stated before, it is necessary to revisit the geometrical requirements and state those in a manner that preferably is easily verified using simple methods.

7.3 Environmental issues

7.3.1 Usefulness of muck for backfill

The present data from this particular project shows a high content of fines that would need some processing before using it as backfill. Another useful application for this material might be for covering waste rock deposits.

7.3.2 Stray materials

The main stray material is spillage of oil that is very limited; most of it would occur at the derrick that can be put on a tray to collect any spillage.

7.4 Schedules and costs

7.4.1 Schedules

The overall plan was to end reaming at the end of 2004 but delays made that the reaming was not finished until late February 2005. The complete schedule includes set-up, drilling the pilot hole, reaming of the drift and demobilization. While the set-up is provisional for this test and while pilot hole drilling is relatively quick we concentrate on the reaming.

The daily advance rate during reaming has by and by increased considerably due to the improvements in the mucking systems. However it not likely that the daily rate for reaming would be higher than around 6 m per day for this equipment; higher thrust and higher availability is needed to increase the mean advance rate to around 1 m/h that is a preliminary design requirement.

The report /Bäckblom et al. 2004/ has been used to compare scheduling. Assuming the lower penetration rate (0.5 m/h) at Äspö instead of 1.15 m/h during actual boring for the case presented in the report by /Bäckblom et al. 2004/, one machine would produce around 700 m of horizontal drifts compared to around 1,000 m per year using a higher advance rate 1.15 m/h everything similar and assuming 72 efficient shift hours per week. One assumption here is that there is special machine for the pilot hole drilling.

7.4.2 Cost analyses

The total cost for the excavation project is in the order of 6.5MSEK (700 k€) where substantial resources were used to adapt a standard raise-boring machine for horizontal excavation. A cost-breakdown is shown in Figure 7-1.

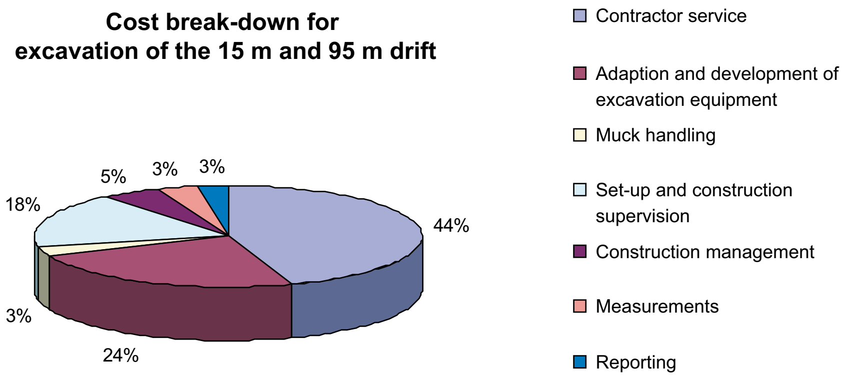

Figure 7-1. *Cost break-down for the excavation project.*

7.5 Flexibility

7.5.1 Adaptation of layout and work procedures to rock conditions

The contractor used Sandvik software evaluation of penetration rates and optimal thrust for the project. Based on these results as well as the contractor's own earlier experience, the equipment was upgraded and modified especially for this project.

Poor rock, weak zones and layered rock will always interfere with the planned drill route. Before starting a project in virgin rock, it therefore is advisable core drill, test water conditions and eventually grout weak zones before excavating the actual deposition drift to minimize possible problems with poor rock conditions. Once the actual drilling of the deposition drift has started rock support would be much more difficult.

7.5.2 Investigations in the rock before, during and after excavation

The excavation project was preceded by core drilling and measurement at the site to ascertain that the rock conditions were good enough for the planned excavation-emplacement and shotcrete plug-projects. No measurements, besides water seepage and measurement of hole geometry was performed in the pilot hole.

After reaming, the drifts were mapped geologically by standard procedures. It is useful to further elaborate objectives and level of mapping details for the purpose of construction, operational safety and long-term safety analyses.

7.5.3 Adverse rock conditions

No adverse rock conditions were encountered. The rock conditions were good for construction point of view; grouting for reducing seepage or rock support was not needed.

7.6 Need for improvements and development work before test of a 300 m long drift

The need for improvements for a longer drift than 95 m should be addressed thoroughly and in detail, before new excavation tests are prepared. We immediately see some modifications as necessary:

- The reamer head need to be redesigned. Important change would be to increase the number of gauge cutters and to use a reamer head that is designed for the diameter of pilot hole selected. Furthermore it is necessary to use wear pads on the gauge cutter faces.
- A more powerful drilling rig would enable higher penetration rates.
- The reaming head stabilizer and the drill string stabilizers need an upgrading to improve toughness and stabilizing effect; non-rotating drill string stabilizers should be considered.
- For optimisation of the system it would be beneficial to create a group with the equipment supplier, the contractor and the client.
- A more effective muck handling and recycling system, where the most important parts will be to remove the dependency of muck pumps outside the hole, and increase the excavating capacity.

The guidance system used by Smart Drilling GmbH) to steer the pilot hole for the 95 m drift failed; a robust guidance system is needed to ensure that a 300 m long hole will be straight enough as the results from the drillings at Äspö showed that the centre line deviated from the stipulated 22 cm vertically (but not horizontally) and this was not in line with the requirements.

It is evident that the geometrical requirements are stated in a way that makes it difficult to show compliance. From geometrical point of view several measures are to be taken:

- The geometrical requirements should be revisited and formulated so that compliance can be shown straightforward.
- Measurement methods and routines should be developed so that measurements are effective; roughness measurements in this project was not complete over the whole surface so it is not possible to judge whether the requirement was met or not, the same applies to measurements of steps; diameter was only measured in a few sections and from the measurements it is not possible to state the this requirement was reached over the full length of the drifts. Measurements of waviness are difficult to evaluate due to few data, expect for the laser scanner measurements that were evaluated every 0.5 m.
- It is suggested for the next project that standard technique (like Maxibor II) is used to measure the straightness of the pilot hole; however it is important that the instrument is centralized.
- The management of records from operation and measurements are not efficient or comprehensive enough and improvements with respect to quality, quantity and processing are necessary.

The 1,765 mm dummy was useful to finally check the emplaceability for the mock-up super-container.

8 Applicability of the excavation project results for repository conditions

8.1 Rock conditions

This test was executed in good rock with no need to stop excavation due to squeezing rock, spalling or major water inflow. We have no experience how the operation will advance for rock conditions requiring temporary support or grouting. However there are several options for excavation in poor rock and some of the options would then be possible to implement for the parts of the deposition tunnel where the rock conditions are poor.

8.2 Schedules

The operating plan for the repository assumes that several, around 10 deposition drifts, should be open. For this reason, keeping the master schedule is just of matter of using a sufficient number of equipments. As discussed previously in /Bäckblom et al. 2004/ it is reasonable to believe that one machine could ream around 1,000 m a year (assuming max penetration 1.15 m/h during boring and total system availability of 63%) providing separate machines are used for the pilot hole drilling. This project does not change this previous estimate.

8.3 Costs

We assume that pilot drilling is done by a separate team. Cost analyses are then compared to the cost analyses in /Bäckblom et al. 2004/. Based on the scheduling experienced (estimated 700 m/year), the capital cost for investment of 20MSEK and 15 year life expectancy is around 700 SEK/m^3. Energy and consumables are around 800 SEK/m^3, direct manpower (one operator, one helper and one hauler) around 800 SEK/m^3 so the direct costs for reaming would be in the range of 2,300 SEK/m^3. This cost does not include costs for set-up, haulage etc.

8.4 Flexibility, risks and opportunities

Flexibility is the ready capability to adapt to new, different, or changing requirements and here we mean that

- a previous decision can be reversed by simple means or a decision can be referred for a certain time,
- there are alternate options available during the decision-making or,
- that new insights and information which emerge during the implementation can be incorporated to develop the most appropriate technical solution.

From these aspects, horizontal push-reaming does not provide much of flexibility during construction besides deciding the final length of the drift and no more flexibility is actually needed; the investigation programme will decide the location of the horizontal drifts and also evaluate any adverse rock conditions that may require adaption of the construction method.

One risk issue that is not solved yet is the lack of technology for locating and steering the pilot hole in hard rocks. It is also deemed that the geometrical requirements and methods to confirm geometrical compliance are not robust enough and this is a risk issue as well.

The main advantage with the horizontal rush-reaming is that it is like a “factory”; the mechanical excavation is more or less continuous with a very constant and high excavation quality as the human factor cannot impact the quality to the extent possible with for example Drill & Blast.

8.5 Overall judgement

The excavation test has proved that horizontal drifts can be excavated by horizontal push-reaming in good rock and up to a length of 95 m. It is also likely that 300 m drifts can be safely constructed and operated assuming good rock conditions. Further tests in a range of rock conditions are necessary to decide the practical limits of constructability. It is also necessary to develop and demonstrate technology for guidance and active steering of the pilot hole over a distance of 300 m. The equipment is not the only important thing for the excavation quality; it is also essential that the equipment is operated by an experienced and skilled operator.

9 Conclusions

An important part of the running project is to test the ability to excavate the horizontal deposition drifts. Three objectives for the work were stated:

- To show the feasibility of meeting the geometrical and other requirements;
- Two "deposition drifts" are needed for the later project stages. One drift is needed to demonstrate that heavy load – a super-container – can be transported into the drift. One drift is needed to demonstrate that a plug (bulkhead) can be constructed by low-pH shotcrete;
- We need to evaluate the applicability of selected excavation methodology for realistic repository conditions, and based on the experience in the project define need for technical developments/improvements.

The conclusions are evaluated against these rationales:

To show the feasibility of meeting the geometrical and other requirements

The geometrical requirements are stated with respect to length, straightness, diameter variations steps etc:

Length: The project met this target. Two drifts were excavated, 15 m and 95 m respectively in accordance with the initial plan.

Diameter: Actually it was not so simple to measure the diameters of the drifts. The few measurements by the tape method show full compliance. Measurements by a dummy super-container in the 95 m drift show that around 90% of the 356 measurements were within the diameter limit 1,840–1,850 mm. Maximum value measured was 1,855 mm and minimum value 1,835 mm. It seems that there is systematic difference between measurements at the rear and at the front of the dummy, so the conclusions concerning these diameter measurements are preliminary.

Inclination: The measurements show that the vertical inclination for the 95 m drift is within the limit 2°±1°. To simplify mucking by flushing, the inclination should be minimum 2°.

Deviation of the pilot hole: For this project it was decided that the end of the pilot hole for the 95 m drift should be within ±22 cm of the theoretical line. The actual measurements show –61 cm deviation in the vertical direction and 11 cm deviation in the horizontal right direction due to the non-functional active steering. The stated requirement was not met, but the pilot hole was straight enough for the dummy of the super-container to be pushed to the end of the drift. The requirement should be restated as deviations horizontally would be worse than deviations vertically.

Steps: A few steps in the drift surface have been recognized in the short 15 m drift and in general the data show steps < 5 mm in accordance with the requirement. However the measurement methods are not good enough to corroborate compliance for all drift surface area.

Roughness: Roughness of the drift surface should be < 5 mm, but the measurement methods are not good enough to corroborate compliance for all drift surface area. In general the surface is smooth. The measurement using profiler shows that the requirements were met for the data collected. The measurements based on evaluation of the gauges at the dummy show very few data points outside the range 5 mm.

Straightness: Waviness or deviation from the centre line should be < ±2.5 mm over a distance of 6,000 mm. No measurement or evaluation methods were tried to examine the requirement; instead the dummy was manufactured to prove that a super-container with the same size would fit into the excavated drift without being stuck. The test verified that a super-container will fit into the drift.

Besides the geometrical requirements other requirements were met.

- The method is feasible and safe with respect to occupational safety and environment.
- The method is also reasonably efficient in spite of that neither the equipment or working procedures are optimised. Maximum daily advance rate during reaming was in the order of 6 m per 12 hour day.

Construction or two drifts, one for the KBS-3H project and one for a shotcrete plug test

This objective was met. The project achieved to excavate two drifts that now will be used for next project phases.

The applicability of selected excavation methodology for realistic repository conditions, and based on the experience in the project define need for technical developments/improvements

The main conclusion is that horizontal push-reaming can produce 95 m drifts in good rock that likely will meet the requirements for operational and long-term safety. The technology would also be applicable for 300 m long drifts provided that technology is developed and tested to drill straight enough pilot holes. More experience is needed to understand for what rock conditions additional pre-grouting would be necessary before the drift is reamed and for what rock conditions the drift might need temporary support during construction and before emplacement of the super-container.

Several suggestions for additional technical development and improvements have been identified in addition to the developments during the project.

- Active steering for drilling of a 279 mm pilot hole.
- Optimisation of the reaming machine for horizontal push reaming.
- Re-designed muck handling systems for reaming.
- Further development of the geometrical requirements so simple standard measurement technology can be used to show compliance with the geometrical requirements.
- Need for improvements in measuring technology and methodology and securing competent resources for executing and reviewing the measurement activities.
- Improved records of the excavation activities.

10 Discussion

The project basically met the stated objectives and we can now reflect on experience what could have been done differently

The implementation strategy was a turn-key delivery of the two drifts where SKB occasionally made redundant measurements. The work was conducted in a very good and co-operative spirit between the contactor and the client. Horizontal push-reaming is not a "push-button" job but requires extensive transfer of years of human experience in case SKB in the future would like to construct the repository under their own construction management.

For the future it is thought to be efficient that SKB take responsibility for the pilot hole – a small rig for the pilot hole – and that a contractor takes turn-key responsibility for the reaming part.

The project has identified substantial possible improvements in set-up, muck handling, machine design, measurement methodology and practical routines and a 2nd test then would be more cost-efficient than this first initial yet successful test.

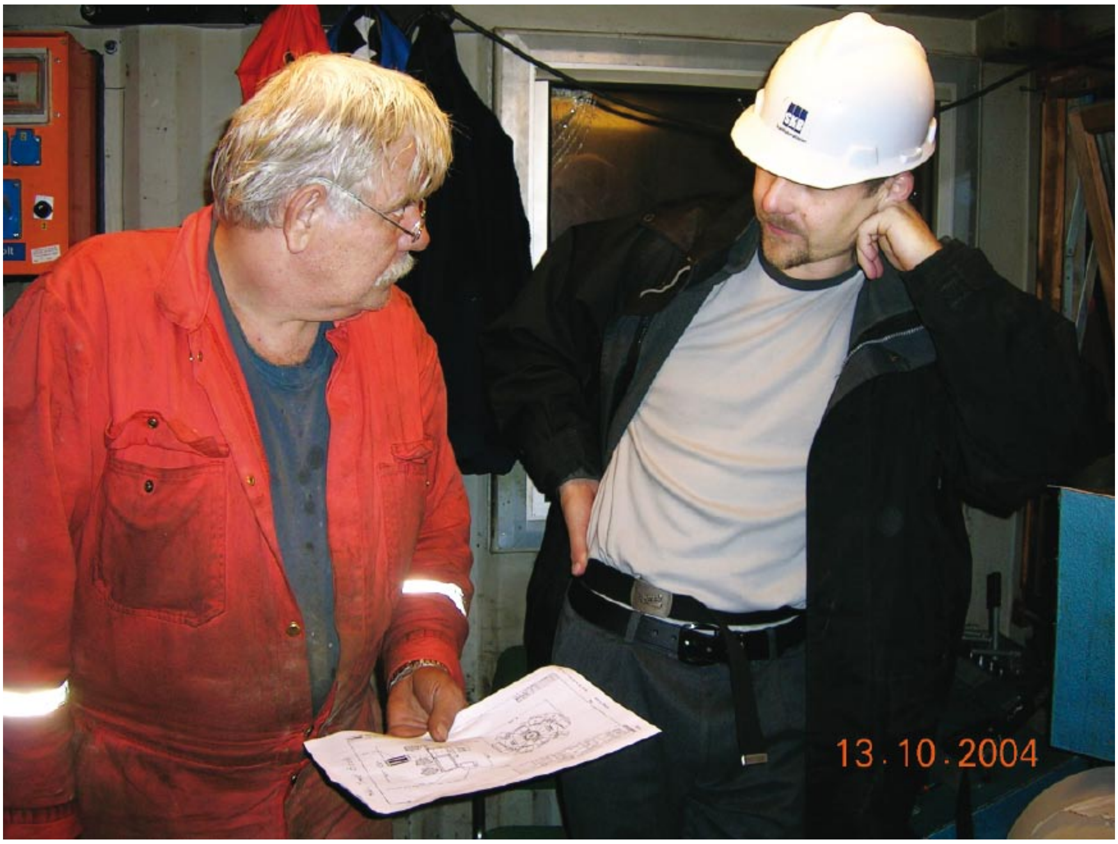

Figure 10-1. *Fruitful discussion between the contractor (left) and the client representative (right) on how to improve the machine stiffness.*

Specific issues are that SKB needs to strengthen the competence and resources available to plan, execute and report the results concerning geometrical measurements to ensure proper requirements, quality of execution and transparency of records. The same applies to the “scientific construction” where the requirements of proper documentation are higher than in standard construction work.

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Appendix 1

Geological mapping of the two horizontal drifts

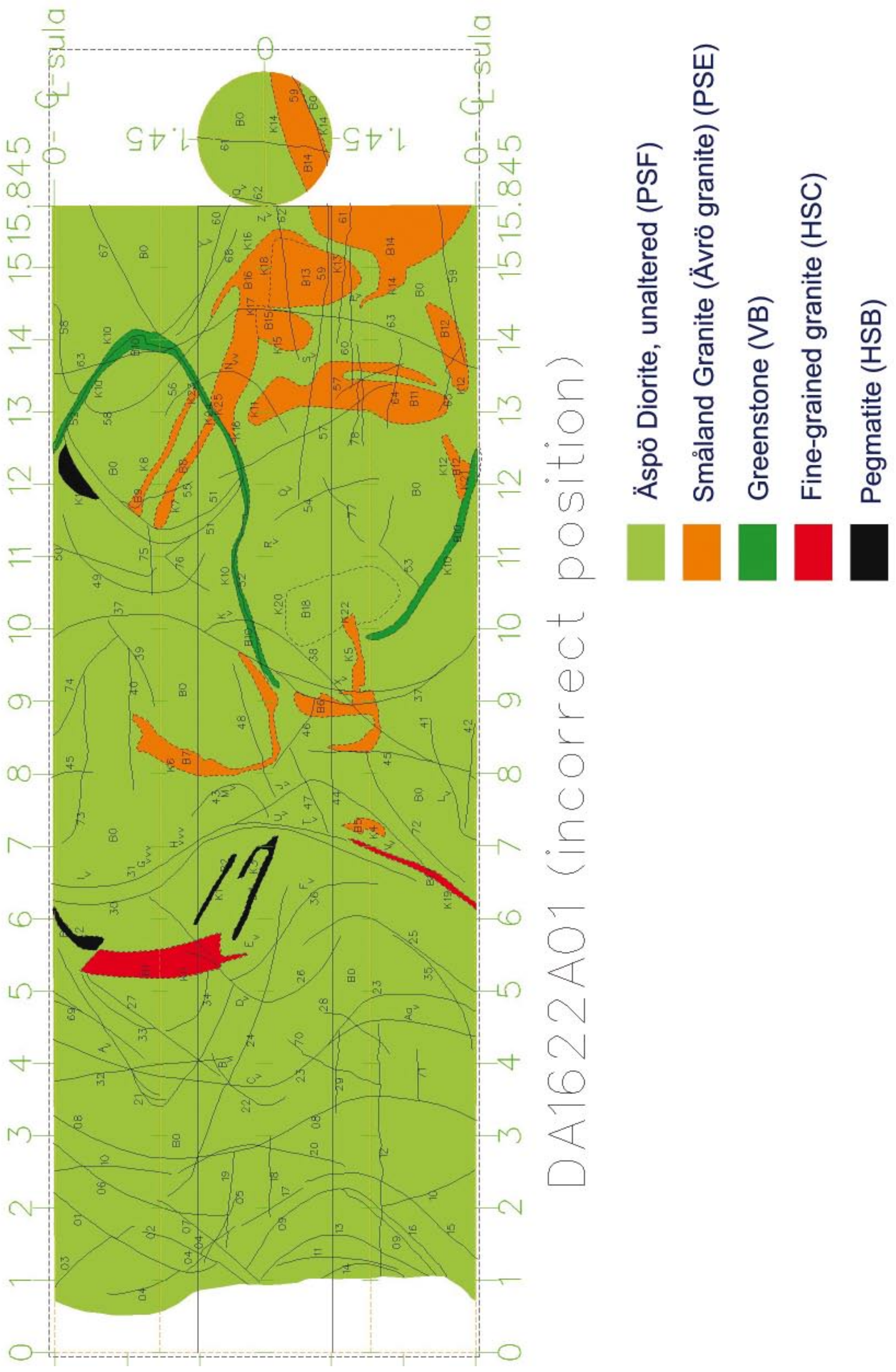

Figure A1-1. Geological map of the 15 m drift.

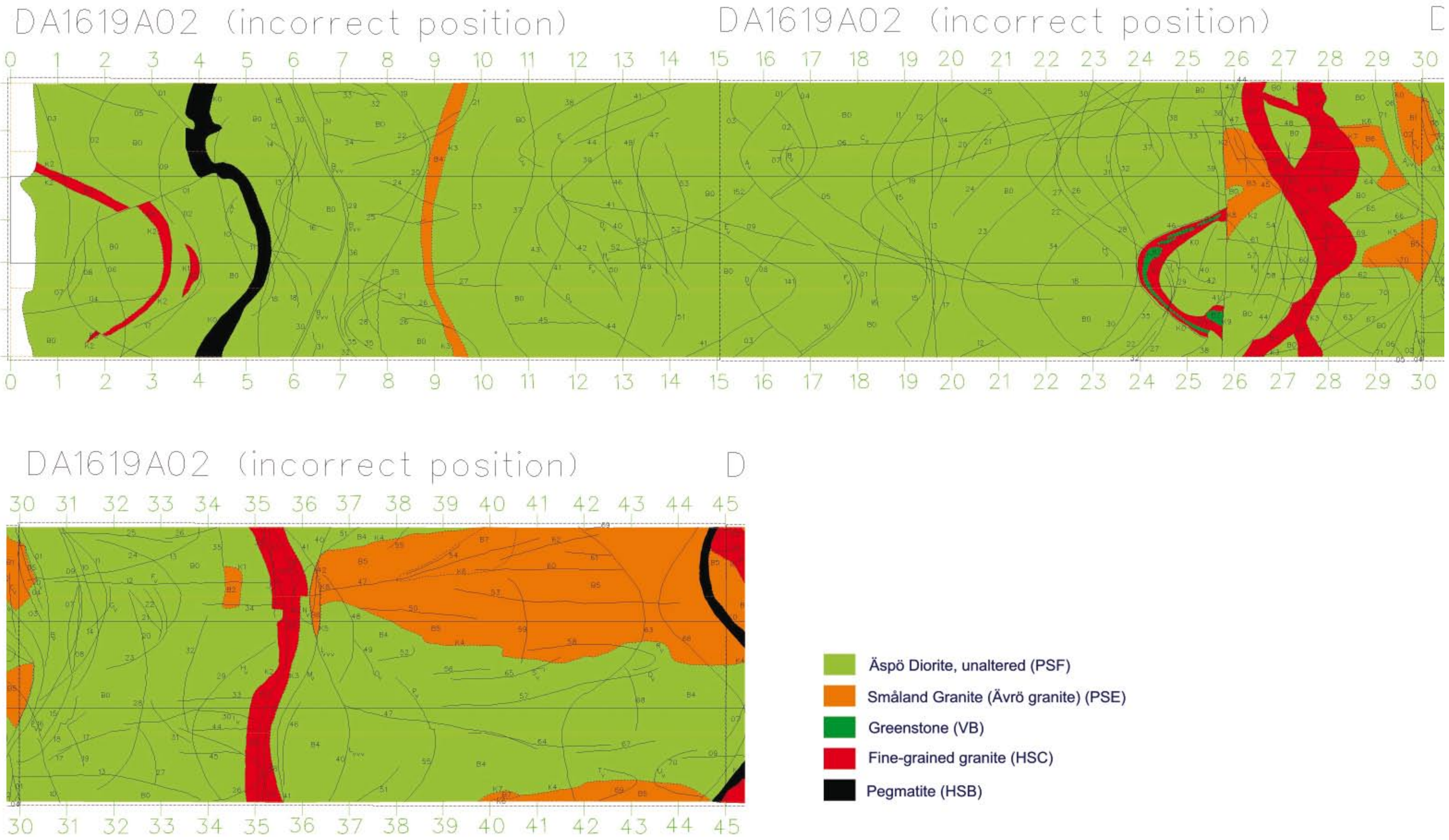

Figure A1-2. *Geological mapping of the 95 m drift 0–45 m.*

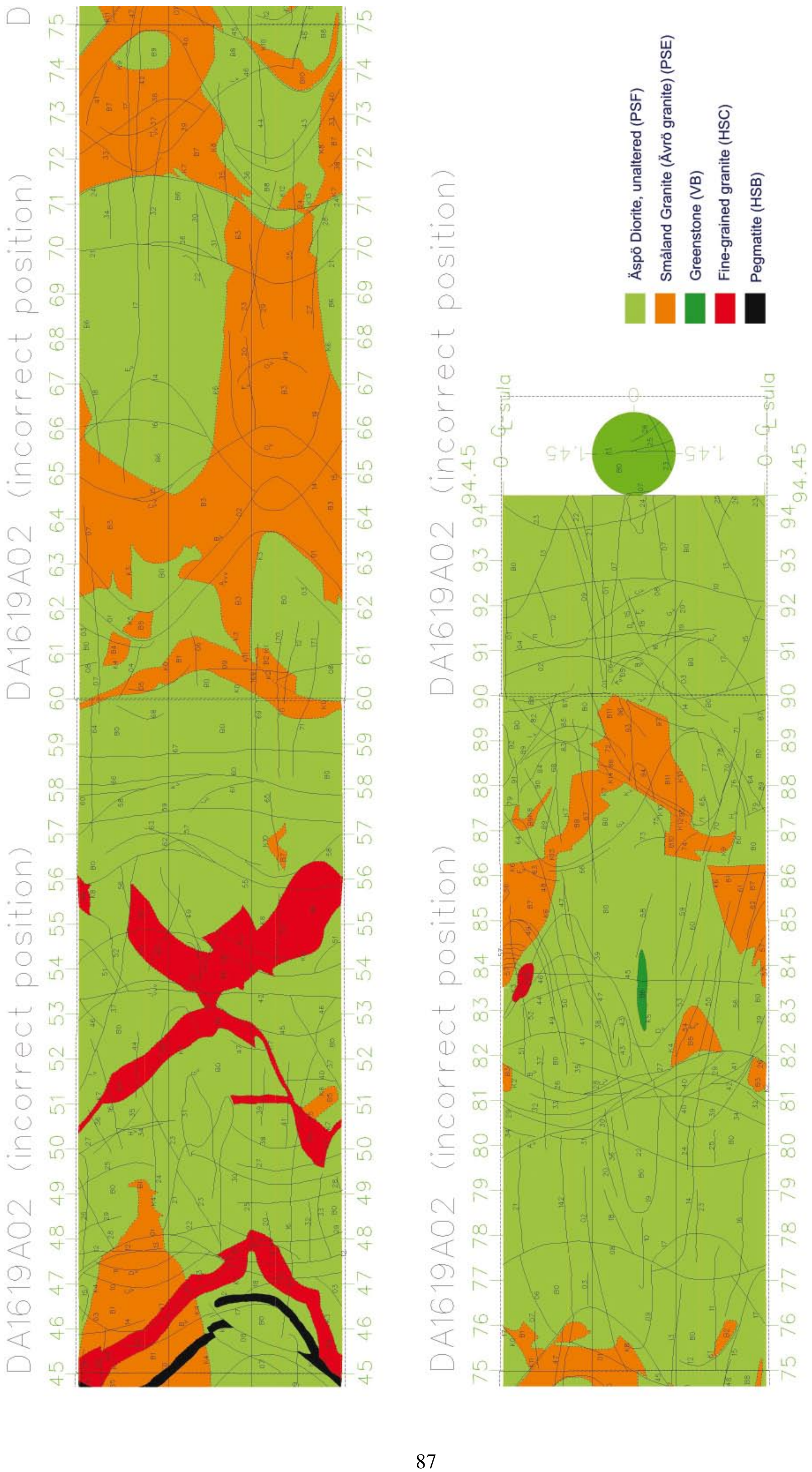

Figure A1-3. *Geological mapping of the 95 m drift 45–90 m.*