Technical Report

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Techniques for freeing deposited canisters

Final report

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Summary

Four different techniques for removal of the bentonite buffer around a deposited canister have been identified, studied and evaluated: *mechanical, hydrodynamical, thermal,* and *electrical* techniques. Different techniques to determine the position of the canister in the buffer have also been studied: *mechanical, electromagnetic, thermal* and *acoustic* techniques.

The *mechanical techniques* studied are *full-face boring, milling* and *core-drilling*. It is expected that the bentonite can be machined relatively easily. However, the tools will have to be resistant with regard to abrasion even at elevated temperatures. It is assessed that cooling by means of flushing water over the outer surfaces of the tools is not feasible in view of the tendency of bentonite to form a gel. If water is to be used as a coolant nonetheless, the cooling will have to be carried out using a closed system.

The mechanical techniques are characterized by the potential of damaging the canister, a high degree of complexity, and high requirements of energy/power input. The generated byproduct is solid and cannot be removed by means of flushing. Removal is assessed to be simplest in conjunction with full-face boring and most difficult when coredrilling is applied. Full-face boring can, however, be used only when the gable of the canister is to be freed while the other mechanical techniques can be used for freeing the gable surface as well as the mantle surface.

The *hydrodynamical techniques* comprise *high-pressure hydrodynamic techniques,* where pressures above and below 100 bar, and *low pressure hydrodynamical techniques* (< 10 bar) are separated. At pressures above 100 bar, a water jet with a diameter of approximately a millimetre cuts through the material. If desired, sand can be added to the jet. At pressures below 100 bar the jet has a diameter of one or a few centimetres. The low-pressure hydrodynamic technique is based on a combination of hydrodynamical effects and chemical modification of the bentonite. In this case, the force and extent of the jet is small in comparison but is nevertheless essential to the process. It serves the purpose of removing material, which has previously been in contact with the liquid and thereby modified chemically. The liquid contains a few percent of salt, which is essential for the efficiency of the process. The flushing is important not only because it removes the modified bentonite but also because it frees previously unaffected bentonite and thereby makes it accessible to chemical modification.

All of the hydrodynamical techniques are applicable for freeing the end surface as well as the mantle surface. The degree of complexity and the requirement on energy/power decrease with a decrease in pressure. A significant potential for damaging the canister is considered to exist only in the case of the highest pressures. Slurry is generated in all of the processes. However, the slurry generated in the low-pressure hydrodynamic method is more concentrated (i.e. has a high dry solid content) and more homogeneous than the others, and can therefore easily be pumped. It is also assessed that this method has the necessary conditions for an integrated process, in which the suspended solids can be continuously separated from the liquid. However, no investigations related to this issue are included in the present report.

The assessment of *thermal techniques* is based on theoretical calculations as well as experiments performed on water-saturated bentonite. The calculations include heat conduction together with changes in temperature and the associated changes in volume and pressure. The assessments are based on the assumption that any possible discontinuities (separations) appear in the interface between the canister and the bentonite and not within the bentonite itself. The following cases have been studied:

- Only the heat provided by the spent fuel in the canister is included together with the cooling provided by the surrounding rock.
- Heat is added to the bentonite buffer so that its temperature is increased by 50°C.
- The bentonite buffer is cooled so that its temperature is decreased by 50°C.
- The canister is cooled so that its temperature is decreased by 50°C.

Thermal methods are applicable only in conjunction with the freeing of the mantle surface of the canister. They are complex to apply and require a high energy/power input. No byproduct is generated, however. The studies conducted show that the canister can be freed only when cooling is applied, and in these cases, there is a potential for damaging the canister.

The *electrical techniques* studied comprise *direct current* and *high frequency alternating current*. The application of direct current was observed to have an insignificant effect on the bentonite but gave rise to a significant evolution of oxyhydrogen gas (oxygen and hydrogen which form a highly explosive mixture). No significant advantages could be identified regarding the high frequency alternating current technique. Little information was found, however, regarding the interaction between high frequency alternating current and bentonite. It could nonetheless be assessed that the technique would be associated with a high degree of complexity as well as a high demand for energy/power.

None of the methods studied for determing the position of the canister (i.e. mechanical, electromagnetic, thermal and acoustic methods) could be assessed to have any significant potential for an accurate determination of the position of the canister in an opened deposition hole. Acoustic methods as well as electromagnetic methods might, however, be used for approximate determinations or perhaps accurate determinations during ongoing freeing operations in cases where the distance to the canister is small. The conclusion is that the choice of methods for freeing should be focussed on methods which do not require any detailed determination of the position of the canister.

A number of generic criteria were identified and used in the subsequent categorization of the different techniques for freeing:

- Is the technique applicable for the removal of the bentonite from the entire deposition hole?
- Is the equipment or process complex or complicated?
- Are the demands for energy or power high?
- Is any byproduct or waste generated?
- Does the byproduct or waste require any treatment, which is demanding or complex?

- Is there any inherent risk of damaging the canister?
- Is the technique sensitive to the position of the canister?
- Does the exact position have to be known?

After the evaluation the techniques were divided into three groups:

- Techniques which have a *high potential* for development of a system for freeing of the canister.
- Techniques which have a *low potential* for development of a system for freeing of the canister.
- Techniques which are *not recommended* for further investigation.

Only one technique was identified in the high potential category, namely the low-pressure hydrodynamic technique. Four techniques were identified to have a low potential (cooling of the buffer, cooling of the canister, water jet technique and application of direct current). The other seven techniques included are not recommended for further studies.

The flexibility and robustness with regard to disposal alternative – vertical or horizontal – was considered in a second step. The result of this analysis is that the potential for the low pressure hydrodynamic technique is equally high for vertical disposal as compared to horizontal, while analyses of the other techniques did not give rise to any basis for upgrading to the category of high potential.

Since the comparison had to be based on a simple and generic set of criteria, a further analysis was made in order to determine whether or not the low pressure hydrodynamic method is robust enough in order to remain in the high potential category even when some other relevant issues are considered. This was found to be the case.

Sammanfattning

Fyra olika tekniker för att avlägsna bentonitbufferten kring en deponerad kapsel har identifierats, studerats och utvärderats: *mekaniska, hydrodynamiska, termiska* och *elektriska* tekniker. Olika tekniker för bestämning av kapselns position i bufferten har också studerats, nämligen *mekaniska, elektromagnetiska, termiska* och *akustiska* tekniker.

De *mekaniska teknikerna* avser *fullortsborrning, fräsning* och *kärnborrning*. Bentoniten förväntas kunna bearbetas relativt lätt men de mekaniska teknikerna kräver verktyg med hög beständighet mot såväl nötning som förhöjd temperatur. Kylning genom spolning på verktygens utsida bedöms inte kunna tillämpas på grund av bentonitens tendens att bilda gel, varför eventuell kylning med vatten måste ske i slutna system.

De *mekaniska teknikerna* karakteriseras av risk för kapselskada, en hög grad av komplexitet och höga krav på energi/effekt. Biprodukten är fast och kan inte bortföras med hjälp av spolning. Bortforsling bedöms vara enklast vid fullortsborrning och svårast vid kärnborrning. Fullortsborrning kan emellertid endast utnyttjas för att frilägga kapselns ändyta medan de övriga mekaniska teknikerna kan användas för att frilägga såväl ändyta som mantelyta.

De *hydrodynamiska teknikerna* avser dels de *högtryckshydrodynamiska*, där man skiljer mellan spoltryck över respektive under 100 bar, dels den *lågtryckshydrodynamiska* (<10 bar). Vid tryck över 100 bar skär en tunn vattenstråle med en diameter på någon millimeter genom materialet. Eventuellt tillsätts sand i strålen. Vid tryck under 100 bar spolas i stället med en kraftig stråle med en diameter på någon centimeter.

Den lågtryckshydrodynamiska tekniken avser i själva verket en kombination av hydrodynamiska effekter och kemisk påverkan på bentonitmaterialet. I detta fall har strålen såväl ringa kraft som omfattning men är ändå av väsentlig betydelse för processen genom att den för bort material som varit i kontakt med och påverkats kemiskt av spolvätskan. Denna innehåller några procent salt, vilket också är av väsentlig betydelse för processens effektivitet. Spolningen syftar inte enbart till att föra bort kemiskt modifierad bentonit utan även till att frilägga tidigare opåverkad bentonityta så att spolvätskan kan verka kemiskt på denna.

Alla de hydrodynamiska teknikerna kan tillämpas för att frilägga såväl ändyta som mantelyta. Graden av komplexitet samt kravet på energi/effekt avtar med avtagande tryck. Risk för kapselskada bedöms föreligga endast i samband med de högsta trycken. Alla processerna genererar slam, men det som erhålls vid tillämpning av den lågtryckshydrodynamiska metoden är dels mera koncentrerat (d v s har en hög torrhalt), dels mera homogent och pumpbart. För den senare metoden bedöms även förutsättningar föreligga för en integrerad process där klarlösning och fast (våt) fas separeras kontinuerligt, vilket dock ej redovisas närmare i denna rapport.

Bedömningarna av *termiska tekniker* baserar sig på såväl teoretiska beräkningar som experiment vilka avsett vattenmättad bentonit. Beräkningarna omfattar värmeledning samt volymsförändringar till följd av ändrad temperatur och med denna sammanhäng-

ande förändringar i volym och tryck. Bedömningarna baserar sig på antagandet att eventuella spalter uppstår mellan kapsel och bentonit och inte inuti bentoniten och avser följande fyra typfall:

- Endast den uppvärmning som sker till följd av det radioaktiva sönderfallet i bränslet samt den kylning som erhålls genom närvaron av det omgivande berget.
- Extern *tillförsel av värme till bentonitbufferten* så att temperaturen höjs med 50ºC.
- Extern *kylning av bentonitbufferten* så att temperaturen sänks med 50ºC.
- Extern *kylning av kapseln* så att dess temperatur sänks med 50ºC.

Termiska metoder är tillämpbara endast för friläggning av kapselns mantelyta. De är komplicerade och kräver också hög energi/effekt. Ingen biprodukt genereras emellertid. Friläggning av kapseln sker endast i samband med kylning och i dessa fall föreligger även viss risk för kapselskada.

De *elektriska tekniker* som studerats avser *likström* och *högfrekvent växelström*. Applicering av likström visade sig ha en ringa inverkan på bentoniten men gav upphov till en besvärande hög avgivning av knallgas (syre + väte i explosiv blandning). Beträffande högfrekvent växelström kunde inga särskilda fördelar med denna metod identifieras, samtidigt som kunskapen kring hur bentonit påverkas framstod som ringa. Det gick emellertid att fastställa att tekniken skulle vara mycket komplex och innebära ett högt behov av energi/effekt.

Ingen av de studerade detekteringsmetoderna (dvs mekaniska, elektromagnetiska, termiska och akustiska) förefaller ha förutsättningar för att detaljerat bestämma kapselns läge i ett oöppnat deponeringshål. Akustiska metoder samt elektromagnetiska metoder förefaller kunna användas för ungefärliga bestämningar, eller möjligen noggranna bestämningar, under pågående friläggningsoperation under förutsättning av att man befinner sig i närheten av kapseln. Slutsatsen är därför att valet av friläggningsteknik bör fokuseras mot sådana tekniker som inte kräver någon närmare bestämning av kapselns position.

Följande generella kriterier identifierades och användes därefter i en kategorisering av de olika teknikerna för friläggning:

- Kan tekniken användas för att avlägsna bentonit i hela deponeringshålet?
- Är utrustningen eller processen komplicerad?
- Är behovet av energi/effekt stort?
- Bildas någon biprodukt eller avfall?
- Kräver biprodukten eller avfallet någon komplicerad behandling?
- Finns det någon risk för att kapseln skadas?
- Är tekniken känslig för kapselns position?

Efter utvärderingen delades de olika teknikerna in i tre grupper:

- Tekniker med en *hög potentia*l för utveckling av ett system för friläggning av kapseln.
- Tekniker med en *låg potential* för utveckling av ett system för friläggning av kapseln.
- Tekniker som *ej rekommenderas* för fortsatt utvecklingsarbete.

Endast en teknik tillordnades kategorin med hög potential, nämligen den lågtrycks-hydrodynamiska tekniken. Fyra tekniker bedömdes ha låg potential för utveckling, nämligen kylning av bufferten, kylning av kapseln, vattenjet och applicering av likström. De övriga sju teknikerna rekommenderas inte för fortsatta studier.

I ett andra steg av analysen undersöktes flexibilitet och stabilitet med avseende på deponeringssätt, dvs vertikal eller horisontell deponering. Resultatet blev att potentialen för den lågtryckshydrodynamiska tekniken är densamma för vertikal inplacering som för horisontell. En analys av vertikal inplacering för övriga alternativ ledde inte till identifiering av någon grund för uppgradering till kategorin med hög potential.

Eftersom jämförelserna ovan utförts utgående från en enkel men generell uppsättning kriterier utfördes även en kompletterande analys med syfte att utröna huruvida den högtryckshydrodynamiska tekniken är tillräckligt robust för att kvarstå i kategorin med hög potential även när vissa andra relevanta kriterier beaktas. Detta befanns vara fallet.

Contents

1 The Swedish system for management of spent nuclear fuel

The Swedish Nuclear Fuel and Waste Management Company (SKB) plans to build a repository for the spent nuclear fuel generated in the Swedish nuclear programme. The reference outline /1, 2/ of the repository, called KBS-3, is shown in Figure 1-1. The repository is situated in crystalline bedrock at a depth of about 500 metres. The exact location will depend on the conditions at the site selected. At this depth, deposition holes are bored through the floors of the deposition tunnels. Canisters containing the spent nuclear fuel are emplaced in these holes. The canisters consist of an outer shell made of copper which provides corrosion resistance, and a cast iron insert to provide mechanical strength. The canisters are surrounded with blocks made of highly compacted bentonite clay. When contacted with water, the bentonite clay will swell, fill the space between the canisters and the rock completely, and exert a certain pressure onto the canister as well an onto the rock walls in the deposition hole.

In this way, the canisters will be essentially cut off from any flow of water which might occur around a deposition hole. Any transport of species in the groundwater to the canister surface will have to take place by diffusion through the bentonite.

In addition to the reference design described above, SKB also has studied alternative designs /3, 4/, most of which are closely related to the reference design. For instance, the reference canister can be deposited in a vertical as well as in a horizontal orientation.

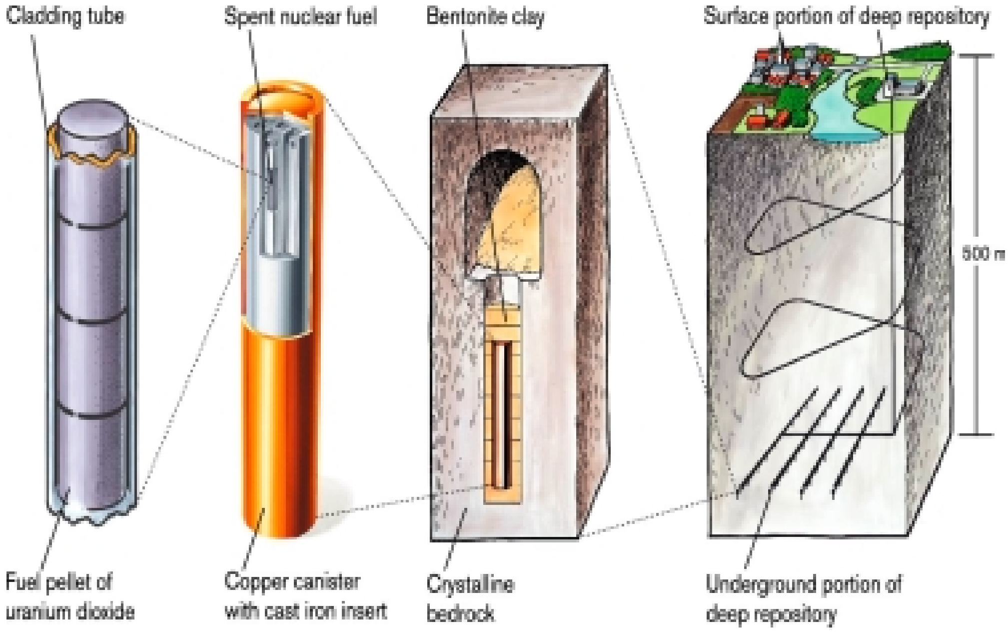

***Figure 1-1.** SKB:s reference outline of the repository, KBS-3. The spent fuel is encapsulated and deposited in crystalline bedrock at a depth of about about 500 metres.*

The deep repository is built in two stages /1, 2/. Approximately 400 canisters will be deposited in the first stage. After this initial stage, the experience gained will be evaluated.

If the result of the evaluation is that continued deposition is suitable and acceptable the entire repository will be built, and the activities will continue until all waste has been deposited.

If, on the other hand, the evaluation leads to a decision to terminate deposition after the initial operation, the option is open to retrieve the deposited canisters and place them in an interim storage.

2 Retrieval

2.1 Prerequisites

The option to retrieve the canisters deposited in the first stage implies that retrieval should constitute a part of SKB’s comprehensive disposal scheme. Equipment, processes and competence for retrieval should exist in the same manner as for the disposal operations. Furthermore, retrieval should be an integral part of a repository system for quality assurance reasons.

In a disposal system, each deposited canister must fulfil certain requirements, most of which result from safety considerations. It can be foreseen that in order for such requirements to be fulfilled, a comprehensive quality assurance scheme will be implemented, and that part of such a scheme will concern the operation of the final repository.

One important consideration in such a scheme is at what point in time, and under what circumstances, the decision shall be made as to whether or not a disposal of a certain canister is acceptable. It is anticipated that a quality assurance and a quality control scheme will be designed in such a manner that retrieval will be a rare event, if it will occur at all.

The disposal process is governed largely by the requirements on safety after and before closure of the repository. The retrieval process is governed by prerequisites of several origins: requirements on safety, technology and economy of the process itself as well as the deposition process.

2.2 The retrieval process

Three different cases of retrieval might be distinguished.

Disposal situation	**State of the bentonite**
The disposal *has not* been carried out to completion	The bentonite *has not* absorbed water and become swollen
The disposal *has* been completed	The bentonite *has not* absorbed water and become swollen
Any	The bentonite *has* absorbed water and become swollen

In cases where the bentonite had not absorbed water and become swollen, the removal of the canister from the hole might – at least in some cases – be carried out by using equipment, which is the same or similar to that used for the disposal of the canister.

If, on the other hand, the bentonite has been in contact with water –groundwater or added water – swelling has taken place and the associated swelling pressure has developed. Thus, the canister may be held in a firm grip in the deposition hole and considerable force may be needed if it were to be retracted.

In preliminary studies, carried out in the introductory stages of the present work, it was found through calculations that for an expected swelling pressure of about 5 MPa, the pulling force required might be between 800 and 1 500 tonnes. This would lead to tensile forces in the canister wall close to $\sigma_{p0,2}$[1]. Additional challenges or difficulties include achieving the pulling force needed and to transfer this force to the canister.

Thus, the interpretation was made that it is likely – or at least plausible – that the canister would be impared if a retrieval were to be attempted by simply applying force, without previous freeing of the canister. The reason is, that in such a case, stresses would develop which would be high in relation to the mechanical properties of the canister.

It was therefore concluded that before the canister can be retracted from the deposition hole, the swelling pressure must be reduced. It was also concluded that such a reduction can be achieved by freeing the canister. Furthermore, this step was identified as the most critical step in any retrieval process.

The main steps in a full retrieval process are as follows:

1. Determination of the position of the canister in the deposition hole.
2. Removal of the bentonite near the front gable of the canister.

3a. Freeing of the front gable of the canister.

3b. Docking of equipment to the front gable of the canister (horizontal disposal).

4a. Freeing of the mantle surfaces of the canister, i.e. elimination or substantial reduction of the swelling pressure exerted by the bentonite onto the mantle surface of the canister.

4b. Transfer of the canister to the mouth of the deposition hole.

5. Transfer of the canister to a transport vehicle.

Another important conclusion made at an early stage in the present work is that the actual position of the canister in the deposition hole, together with the ability to determine this position, may be crucial for the applicability of a technique for freeing the canister. As will be described subsequently, some techniques are less sensitive to the exact position, while detailed information may be needed for other techniques. Considerable emphasis must therefore be put on finding a reliable and precise technique for locating the canister and determine its position.

It was described in Chapter 1 that the reference alternative of SKB is vertical disposal.

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[1] According to MNC handbook no. 8, $\sigma_{p0,2}$ = 40–120 MPa, and the tensile strength for sheet metal of quality SS 5011-02 at 100°C is 72 MPa. [$\sigma_{p0,2}$ denotes the permanent set stress (offset yield strength), i.e. the stress for which the remaining strain after removal of load is 0,2%.]

It is highly desirable that the retrieval process is simple and readily adaptable to various alternatives in the detailed design of the repository system. Thus, the retrieval process selected should preferably be adaptable also to e.g. horizontal disposal.

It has been assessed, however, that it is desirable that the reference technique be specified – at least in general terms – when detailed studies are to be made regarding the removal of the canister.

2.3 SKB's programme on retrieval

Some early SKB work regarding the prerequisites and potentials for retrieval of the deposited canisters have been reported previously /5/.

The main work on SKB:s system for retrieval comprises the following four parts or stages:

- studies of different conceivably applicable techniques, comparisons between these techniques, and the selection of (a) reference technique(s),
- process development,
- full-scale demonstration of the reference technique in the Äspö Hard Rock Laboratory,
- development of the process and equipment for retrieval in conjunction with actual final disposal.

3 Purpose, scope and execution of the work

3.1 Purpose

The purpose of the preparation of the present report is to document the work and the results of the first stage of the SKB programme on retrieval (section 2.3).

The main purpose of the underlying work is to provide a basis for SKB in the selection of one or more reference systems for retrieval. The basis relates primarily to the freeing of the canister, since this has been identified as the critical step in any retrieval process. Thus, the main work is to compile and develop a knowledge base and to structure and analyse this material with regard to what constitutes a reference technique. It is also the purpose of the underlying work to provide a basis for the development of a process for retrieval. Another purpose is to identify the relevant criteria (see Chapter 2) and to perform a systematic comparison in which these criteria are used.

3.2 Scope

The scope of the present work is as follows:

A Identification and investigation of different techniques for freeing the canister: *mechanical, hydrodynamical, thermal* and *electrical* techniques. (Chapter 4).

B Identification and investigation of different techniques for determining the position of the canister in the buffer: *mechanical, electromagnetic, thermal* and *acoustic* techniques. (Chapter 5).

C Identification of generic criteria for a systematic comparison of the different techniques for freeing the canister. (Chapter 6).

D Utilisation of these criteria in an actual comparison. (Chapter 6).

E Identification of non-generic criteria and the utilisation of these criteria in a comparison between some of the most favourable alternatives. (Chapter 7).

F Investigation of the robustness of the result of the comparison with regard to some non-generic criteria including flexibility with regard to disposal alternative. (Chapter 7).

G Analysis and conclusions. (Chapter 8).

H Reporting.

The detailed studies of the techniques for freeing the canister can be limited to only one of the disposal alternatives (vertical or horizontal). Subsequently, the techniques can be revisited from the perspective of the other alternative. These latter studies can be less comprehensive and focus on the significant differences.

This conclusion led to the decision that the comparison against generic criteria should be carried out under the assumption of horizontal disposal and that the implications of vertical disposal should be analysed subsequently.

4 Freeing

During the introductory stages of the development work, different techniques or types of interactions were identified, which were assessed to have a potential for reducing or eliminating the swelling pressure of the bentonite. These types of interactions are as follows:

- Machining.
- Hydrodynamic effects, including combinations of hydrodynamical and chemical effects.
- Thermal interactions.
- Electrical effects, including electrochemical effects.

The different techniques considered and investigated are listed in Table 4-1 together with information about in which section they discussed in the present report.

Table 4-1. The different techniques considered and investigated together with information about in which section they are dealt with in the present report. The external specialists participating in the project together with their affiliations are also presented.

Main technique	Sub-technique	Section
Mechanical	Full-face boring	4.1.1
	Milling	4.1.2
	Core drilling	4.1.3
Hydrodynamic	High pressure (<100 bar)	4.2.1
	High pressure (>100 bar)	4.2.1
	Low pressure / chemical	4.2.2
Thermal	Heating	4.3.1
	Cooling	4.3.2
Electrical	Direct current	4.4.1
	High frequency alternating current	4.4.2

4.1 Mechanical techniques

The mechanical techniques comprise three sub-techniques:

- Full-face boring.
- Milling.
- Core drilling.

All three techniques are well established and are standard technologies in geotechnology on soil as well as on rock. These applications deviate, however, somewhat from those in the present case since the tribologic properties of the bentonite are different as well as the geometries involved (including the geometry of the canister).

It is also necessary to consider the choice of disposal alternative. The majority of the analyses conducted assumes horizontal disposal of the canister. This is also the prerequisite for the analyses in this section. The implications of vertical emplacement are described in Chapter 7, where also between horizontal and vertical disposal are compared.

The conclusion of the assessments made is that all three of the mechanical techniques can be used for the present purposes. The assessments are based on three significant properties:

- Data for the operation of the equipment.
- Design of the tool.
- Properties of operation.

In the studies performed, no records have been found regarding machining of bentonite. Therefore, the assessments made are based on analogies with other materials which may resemble bentonite tribologically, and for which data and experience are available.

No specific ranking between the different mechanical methods is possible, since the uncertainties are too large. Some general circumstances can be identified, however:

- All three (sub-)techniques require that the relative position of the tool and the canister should be monitored continuously. This is necessary in order for ensure that the canister is not damaged during the operation.
- Different mechanical techniques may be disqualified or be very difficult to apply as a consequence of the very limited space available in the deposition tunnel. The space actually available as well as the need for space depends on the alternative selected for the disposal, see Chapter 7.
- These three techniques differ regarding the use to which they might be put in the present context. The differences depend on the combination of the geometric conditions in the deposition hole and the different properties of the different tools of the techniques.

A summary of the assessed differences and similarities is given in Table 4-2.

Table 4-2. Relative assessed differences and similarities between the three mechanical techniques full-face boring, milling and core drilling with respect to tool design, operational data, operation considerations.

Main consideration	Sub-consideration	Full-face boring	Milling	Core drilling
Tool design	Prototype exists?	No	yes	conceptual
	Can be realized using conventional methods and means	Yes	yes	yes
	Replaceable wearing parts?	Yes	yes	yes
Operational data				
(“100%” refers to data for full-face boring)	Torque	100%	20%	20%
	Power	100%	20–100%	20%
	Feed force	100%	50%	50%
Operation	Wear of the wearing parts	Uneven	even	even
	Need for cooling	No	yes	no
	Need for accessory medium for removal of machined material	No	yes	yes
	Need for accessory systems for operation	No	yes	yes

4.1.1 Full-face boring

The conceptual outline of a tool for full-face boring is presented in Figure 4-1.

The following operational data are recommended for the two main movements of the full-face boring:

Rotation:	5~10	revolutions per minute.
Feed:	0.5~2	millimetres per revolution.

The time required for drilling one metre is expected to amount to between 50 and 400 minutes. The heat evolution and the heat balance is assessed to be such that there is no need for forced cooling. The heat generated during the drilling of one meter into the hole is assessed to amount to between 25 000 and 150 00 kJ. A possible weight of a tool is about 500 kg which means that the heat capacity may be on the order of 24 000 if the temperature difference is on the order of 100°C. For the same temperature difference, 100 kg bentonite corresponds to about 16 000 kJ. The material in the tool withstands temperatures up to about 400–500°C.

The following aspects are particularly significant and should be carefully considered when the design of the tool is to be selected:

- Optimum angles for chip formation and breaking vary with the diameter of the tool.
- The cutting angle should be as large as possible and should exceed 70º.
- The design of the cutting edge should include some kind of intermittence in order for the chip breaking properties to be improved.

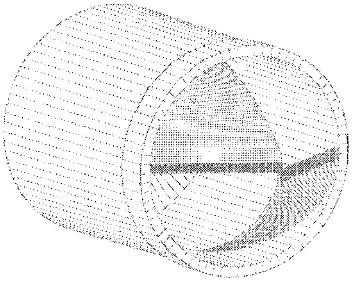

Figure 4-1. *The conceptual outline of a tool for full-face boring for the present purpose.*

Machined material should collect in the interior of the tool. Boring using a certain tool can therefore continue until the inner volume of the tool is filled, after which the tool will have to be emptied. The time between such stops is proportional to the length of the tool. This length, in turn, depends on certain other prerequisites relating to the functioning of the tool as well as on the space available.

Two tools can be alternated so that one is used for boring while the other one is being emptied.

4.1.2 Milling

The conceptual outline of a tool for milling is presented in Figure 4-2.

The milling operation comprises two main movements and a secondary movement:

Main movements:
- rotation
- scanning

Secondary movement:
- feed

The following operational data are recommended for the different movements of the milling:

Rotation:	150~200	revolutions per minute.
Scanning:	2~5	millimetres per tooth.
Feed:	10~15	millimetres per cycle.

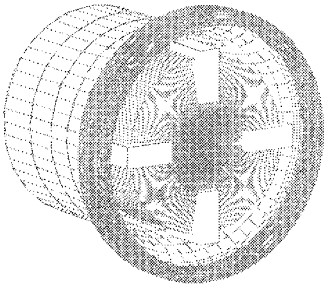

Figure 4-2. *The conceptual outline of a tool for milling for the present purpose. The tool is supplied with a protective casing.*

The time required for drilling one metre is expected to amount to between 100 and 400 minutes.

The heat evolution and the heat balance is assessed to be such that there is no need for forced cooling. This assessment is based in part on comparisons between the thermal conditions for full-face boring and milling. This comparison amounts to the following:

- The heat generation may be expected to be about 25–50 times larger for milling as compared to full-face boring.
- The volume of the tool is 3–4 times less than for full-face boring.
- The cooling surface is about 3–3 times less than for full-face boring.

A smaller volume implies a lower heat capacity and less ability to absorb heat.

The requirements on the geometry of the milling operation (cutting angle etc) are less demanding since the cutting edge is considerably shorter. The angles defining the geometries of the tool as well as of the actual cutting may be about the same as in the case of full-face boring.

Cleansing of the fines formed in the milling process should be carried out under dry conditions since the addition of water can be expected to lead to gel formation. It can be foreseen that the milled material will form lumps and a viscous liquid, which will inhibit further removal and thereby also further machining.

Moreover, milling is normally designed as dry machining and, for this reason, flushing with water is probably also unsuitable from a purely tribological point of view. Potentially suitable methods for the removal of milled material include mechanical methods as well as a combined application of vacuum and compressed air.

As mentioned above, the issue of removal of the milled material is closely connected to that of cooling. Removal of milled material by means of compressed air also involves the removal of heat. Experience might show, however, that such cooling could be insufficient. If this turns out to be the case, additional cooling can be achieved by applying cooling water. Such cooling will, however, have to be carried out in such a manner that the water does not come into contact with the bentonite.

4.1.3 Core drilling

The conceptual outline of a tool for core drilling is presented in Figure 4-3.

The milling operation comprises two main movements for which the following data are recommended:

Rotation:	5~10	revolutions per minute
Feed:	0.5~2	millimetres per revolution

The time required for drilling one metre is expected to amount to between 50 and 100 minutes.

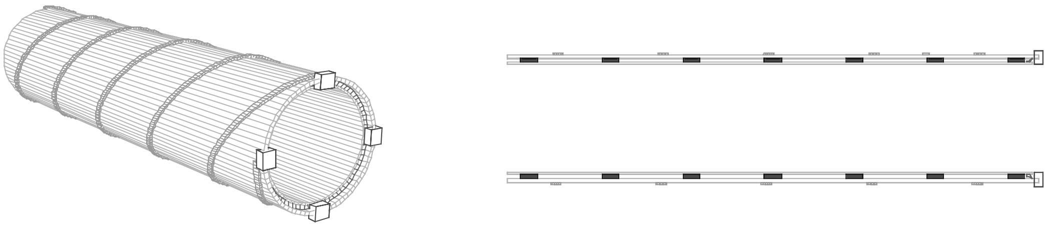

Figure 4-3. *The conceptual outline of a tool for core drilling for the present purpose.*

The heat evolution and the heat balance are assessed to be comparable to that of full-face boring. Nevertheless, it is assessed that forced cooling might be needed due to certain differences in the respective designs.

The requirements on the geometry of the cutting are lower in the case of core-drilling compared to full-face boring since the cutting edges are shorter. The differences in the rate of cutting are also considerably lower. The reason for this is that the rate of cutting increases as the distance from the axis of rotation increases. The angles of cutting may be about the same as in the case of full-face boring.

Cleansing of the area of cutting should be carried out under dry conditions. Under such conditions, chips which break at short intervals are formed.

The addition of liquid, particularly the addition of water, is expected to give rise to a viscous liquid, which prevents the removal of milled material, and thereby also inhibits further machining. A great need for flushing can be foreseen in conjunction with the removal of the machined material. Even so, adequate removal might be achieved in practice.

Therefore, the same removal techniques are recommended as for milling, i.e. removal by mechanical means or by a combination of applying vacuum and compressed air. It is emphasized that tests on a suitable scale are needed in this case since the removal of machined material may be more difficult in the case of core-drilling as compared to milling.

Removal by air flow will give rise to a cooling effect similar to that described above (section 4.1.2) for milling. Experience might show that such cooling would be insufficient. If this turns out to be the case, additional cooling can be achieved by applying cooling water. Such cooling will, however, have to be carried out in such a manner that the water does not come in contact with the bentonite.

4.2 Hydrodynamic techniques

Hydrodynamic techniques comprise techniques whereby the canister is freed by the action of water in motion. The speed of the water is closely related to the pressure difference which gives rise to its acceleration.

Since the action of the water varies with its speed, this technique can be divided into two groups, one of which comprises a further division into two sub-groups:

- High pressure hydrodynamic techniques;
  - pressures lower than 100 bar
  - pressures higher than 100 bar
- Low pressure hydrodynamic techniques.

Removal of bentonite by means of hydrodynamic techniques is in general different from the application of a mehanical technique, since a hydrodynamic technique may influence the bentonite in two principally different ways:

- Physical and mechanical influence originating from the strains in the bentonite near its surface caused by the water in motion. The strains would cause the bentonite to disintegrate.

- Chemical and physical influence caused by water entering the pores of the bentonite. The mechanical properties of bentonite are modified in this process, which also includes chemical changes.

It is well known that the disintegration of bentonite into a slurry can be achieved by allowing it to come into contact with pure water. The only constraints are that the volume of water should be sufficient and that the bentonite should be free to expand.

Under such conditions, the bentonite will eventually convert into a dispersion with a low dry content and a low viscosity. The rate of uptake of water is very low, since the uptake of water takes place through diffusion. It has therefore been assessed that just contact with water has a very low potential to become an industrial process with a reasonable productivity.

However, the opposite is conceivable. Material might be removed from bentonite by means of high pressure water jets without any prior softening of the structure of the bentonite caused by the contact with water.

This is the basis for the division above of the hydrodynamic techniques into high pressure techniques and low pressure techniques. In the former, the removal of matter is caused – at least for the most part – by external mechanical influences. In the latter, a surface layer of the bentonite first undergoes internal conversion – uptake of water and the concomitant softening of the material – and then becomes removed by the external mechanical action of water. In view of this dual influencing, the low pressure hydrodynamic technique can also be denoted the hydrodynamical and chemical technique. Pressures below 10 bars are sufficient for the low-pressure technique. A commonly used application of the high pressure hydrodynamic technique, pressure less than 100 bar, is shown in Figure 4-4.

The general scheme of the high pressure hydrodynamic technique, pressure higher than 100 bars, is shown in Figure 4-5.

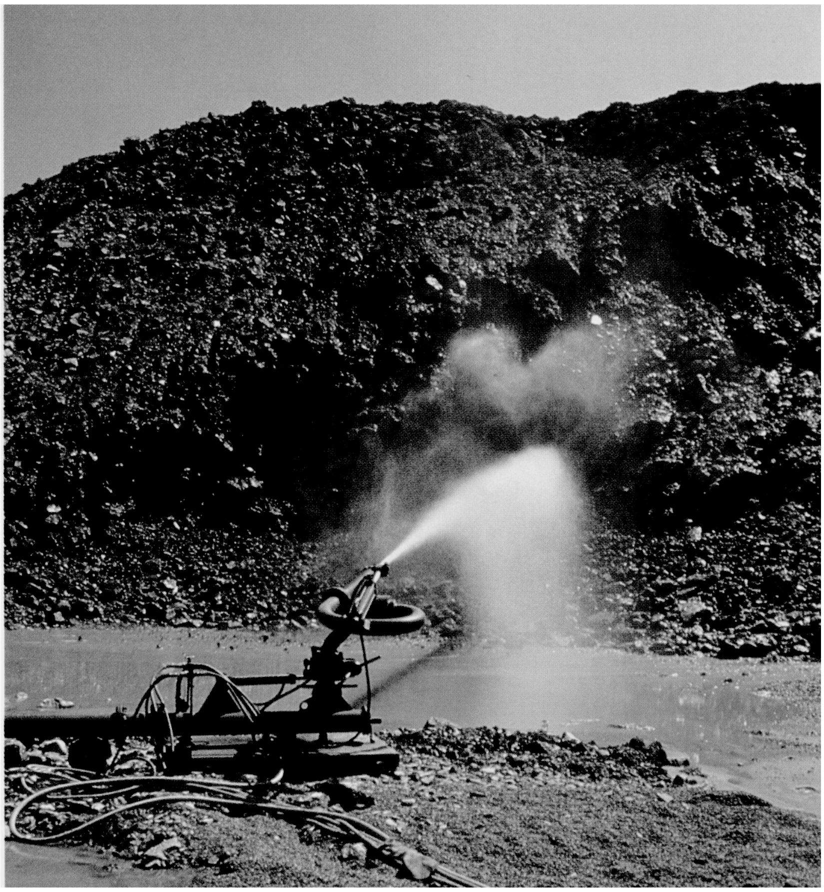

Figure 4-4. *A commonly used application of the high pressure hydrodynamic technique, pressure less than 100 bar.*

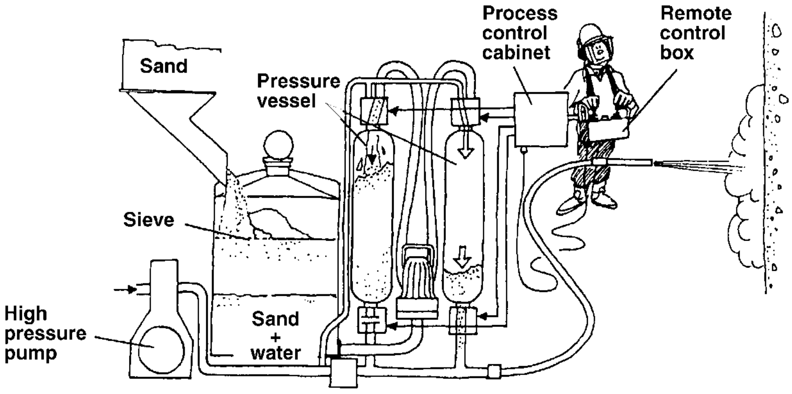

Figure 4-5. *The general scheme of the high pressure hydrodynamic technique, pressure higher than 100 bars.*

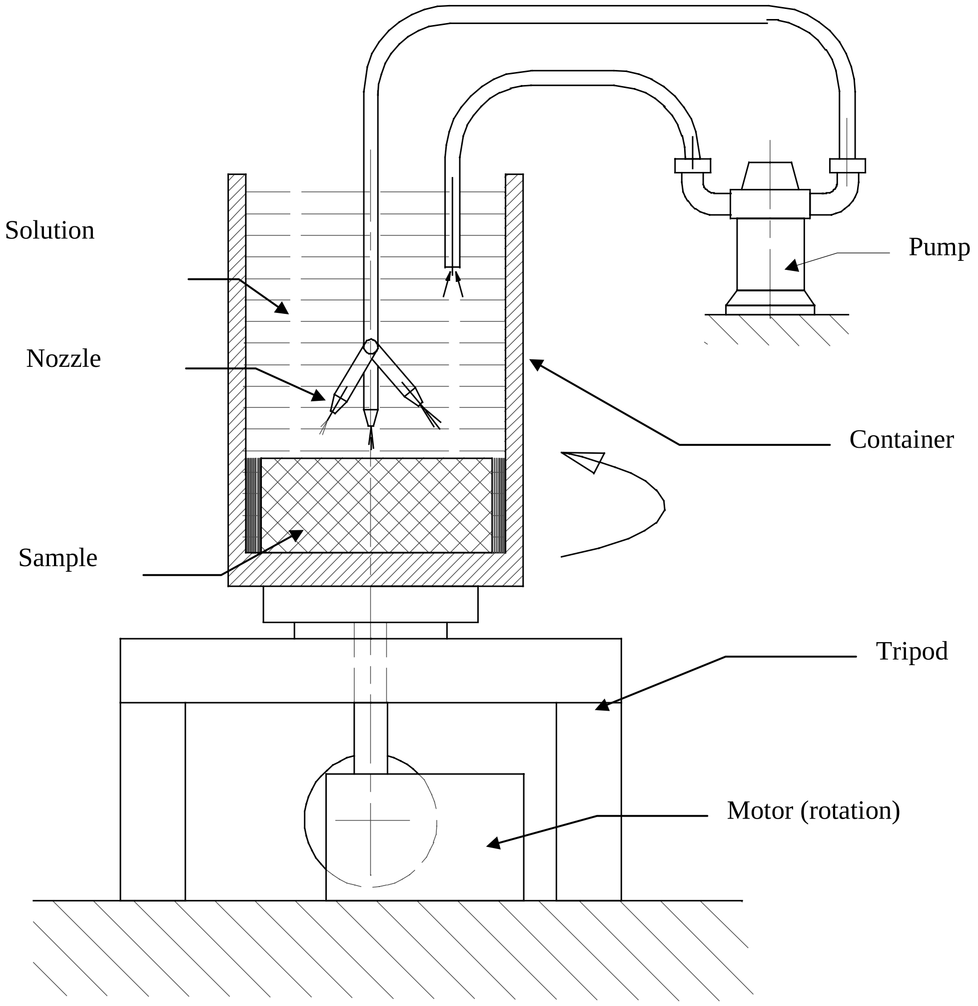

Figure 4-6. *Principle of operation of the low pressure hydrodynamic technique. Test arrangement at ÅF-Industriteknik AB.*

The principle of operation of the low pressure hydrodynamic technique is apparent from Figure 4-6, which shows a test arrangement.

Laboratory-scale tests have been performed for the high pressure hydrodynamic technique, pressure above 100 bar, and for the low pressure hydrodynamic technique.

The work on the high pressure hydrodynamic technique has been carried out using commercially available equipment for cutting.

The efficiency of this technique was such that the incentive for testing the high pressure hydrodynamic technique, pressure below 100 bar, was assessed to be relatively low. Moreover, although this technique is generally used in the excavation of clays, it is, to the knowledge of the authors, not used for the mining of bentonite. On the contrary, such mining is carried out using mechanical techniques, and excavation activities may be discontinued if weather conditions make the material very wet.

Furthermore, the technique (high pressure hydrodynamic technique, pressure below 100 bar) is not readily applicable to simple small-scale tests.

The work on the low pressure hydrodynamic technique is quite extensive and includes the following:

- Pilot-scale tests.
- Tests during which the composition and concentration of the addition of salt (to the flush water) has been varied.
- Tests revealing the influence of the degree of water saturation of the bentonite.
- Tests revealing the influence of the composition of the saturation water.
- Investigations regarding the principles of interaction.

Although the knowledge base is very different in size for the three hydrodynamic techniques, it has been assessed that all three techniques have a good potential to be feasible for the present purpose.

Comparisons may be made between the three hydrodynamical techniques based on general features of the techniques and on the following three main essential aspects.

- Operational data.
- Complexity of the technique.
- Complexity of the system.

Opposite to the mechanical techniques, which are principally different, there are no strict borders between the hydrodynamical methods. The division presented above is a partly idealized one relevant for bentonite. Other materials with other properties would interact differently with water jets and water and, consequently, the choices of equipment and process would also be different.

A system for freeing a canister by means of a hydrodynamical technique should also include a sub-system for the management of the generated sludge. Such a sub-system may comprise the following: diminution of lumps, transfer of sludge, and dewatering. A complete process for freeing a canister using a hydrodynamic technique thus comprises two main parts: generation of sludge and management of sludge.

The hydrodynamic techniques are compared with the other techniques investigated in Chapter 6. Some general features may, however, be mentioned already at this point:

- The differences between the three hydrodynamic techniques, with respect to the content of the deposition hole, are assessed to be insignificant.
- The hydrodynamic techniques are less sensitive than the other techniques to deviations or uncertainties regarding the position of the canister in the deposition hole. Certain differences exist between the different hydrodynamic techniques, as discussed in Chapter 6.
- The space available in the deposition tunnel is of less significance in the case of a hydrodynamic technique as compared to the case of a mechanical technique. It has been mentioned above that the space available also depends on the alternative selected for disposal, see Chapter 7.

A summary of the assessed differences and similarities is given in Table 4-3.

Table 4-3. Relative assessed differences and similarities between the hydrodynamic techniques in the different pressure regions with respect to operational data, complexity of the technique and complexity of the system.

Main consideration	Sub-consideration	Low pressure hydrodynamic technique	High pressure hydro-dynamic technique	
			< 100 bar	≥ 100 bar
Operational data				
The values relate to those for the low pressure hydrodynamic technique which are taken to be unity	Power	1	20	50
	Rate / efficiency	1	0,025	0,025
	Volume of liquid	1	3–4	2–3
Complexity of the technique				
The values reflect a qualitative assessment primarily based on the central elements of each technique. A higher value indicates a higher degree of complexity		1	2	3
Complexity of the system				
The values reflect a qualitative assessment based on the system structure of each technique. A higher value indicates a higher degree of complexity		1	2	3

4.2.1 High pressure hydrodynamic techniques

Pressures lower than 100 bar

An examples of high pressure hydrodynamic technique is provided in Figure 4-4.

This technique has wide applications and is also referred to as slurry technique. The way of functioning can be characterized as “cutting by flushing” and is practised through three types of influences:

- Local removal of affected material (undercut).
- Sliding (demolition).
- Flushing.

The technique is also characterized by the following features:

- It is applicable primarily for materials which readily convert into suspensions and materials prone to erosion.
- The medium usually used for flushing is water.
- High flows of the medium are needed (≈ 4 cubic metres per minute).
- Large volumes of sludge are generated (≈ 200 cubic metres per deposition hole).
- Under optimal conditions, the time for removal of a volume of material equal to that of bentonite in a deposition hole would be around one hour. In the case of bentonite, this time is assessed to be much longer.

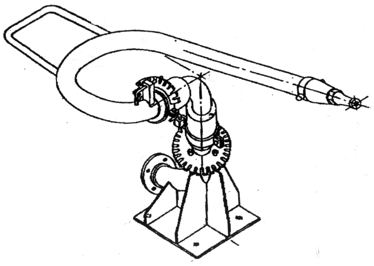

Figure 4-7. *The high pressure hydrodynamic technique, pressure less than 100 bar. A possible realisation of the monitor part.*

The management of sludge is treated in section 4.2.3.

A possible realisation of the monitor part of a conceivable system is shown in Figure 4-7.

Pressures higher than 100 bar

In this technique, very high pressures (≥ 100 bar) are used so that the water jet hits the target at a very high speed. The high speed implies that the local stresses on the object, from which material is to be removed, also become high. This technique is therefore applicable even to hard and strong materials. Occasionally abrasive sand (a hard material with sharp edges) is added. This greatly improves the efficiency on many materials.

When the method is applied to porous materials (with or without water in the pores), having a high mechanical strength, pressure is being built up in the cavities. This causes pieces of the material to release. The mode of operation may thus include both hewing and cutting.

Operational parameters, which may be varied, include composition of the cutting liquid (with or without addition of sand), diameter and shape of the jet, and pressure. The method is very flexible and can be applied on a great variety of materials with widely different properties, e.g. polymer foam, thermoplastic polymers, concrete, marble glass, steel and titanium.

The high pressure hydrodynamic technique, pressures above 100 bar, is characterized by the following properties:

- It is applicable to a wide range of solid materials.
- The cutting medium is water or oil with or without addition of sand.
- The flow of medium can vary between a few cubic metres per minute and a couple of litres per minute.
- The volume of sludge generated can vary depending on how the method is applied. In this case, provided that the diminuted bentonite is flushed away by the medium used, the volume of sludge is assessed to be about the same as for the high pressure hydrodynamic technique for pressures lower than 100 bar. The volume amounts to about 200 cubic metres per deposition hole. It is possible, however, that the volume of sludge may be smaller if mechanical means are applied to remove the loosened bentonite.

- The rate of removal depends on how the method is applied. The time for removal is assessed to vary from an hour and upwards. In addition, time needs to be added for the removal of sludge from the deposition hole area.

The management of the sludge generated is described in section 4.2.3.

A possible realisation of the high pressure hydrodynamic technique, pressures higher than 100 bar, for the present purpose includes a high pressure lance which can be swept over the bentonite surface with sufficient flexibility and precision.

4.2.2 Low pressure hydrodynamic technique

A qualitative description of the differences between the low and high pressure hydrodynamic techniques is given in Chapter 6. The low pressure hydrodynamic technique can also be referred to as the “hydrodynamical / chemical technique”.

Also in this case, the removal of bentonite buffer material (fully or partially) leads to generation of sludge. The bentonite microstructure is subjected to salt water, whereby most of the fine structure swells but some parts shrink. Such a differential expansion causes the pore structure to open, so that further salt water can enter into the bentonite structure. Contrary to the situation in fresh water, no tightening gel (of face to edge arrangement of primary clay particles) is formed preventing the deterioration of the bentonite microstructure.

In parallel with this process, flushing takes place whereby the softened surface is readily removed. This removal frees previously comparatively little affected bentonite and thus makes it available for attack by the salt water.

Further details on the mechanisms for the low pressure hydrodynamic technique can be found in /6/.

The low pressure hydrodynamic technique is characterized by the following properties:

- The low pressure hydrodynamic technique is very efficient if the medium used is a salt water solution containing between 4 and 6 percent by weight of sodium chloride.
- The need for power is very low.
- The volume of sludge generated for one deposition hole is about 50–60 cubic metres.
- The time required for removal of the bentonite in one deposition hole is estimated to about 20 hours.

The management of the sludge generated is described in section 4.2.3.

The conceptual outline of a tool for the low pressure hydrodynamic technique is presented in Figure 4-8. (See section 7.1, Figure 7-1, for possible applications of the low pressure hydrodynamic technique to vertical as well as horizontal disposal.)

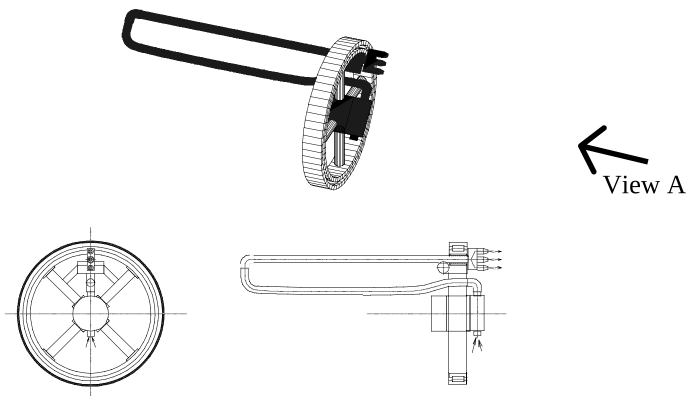

Figure 4-8. *The low pressure hydrodynamic technique. A possible realization of the key components for the present purpose.*

4.2.3 Sludge management

The characteristics of the sludge is dependent on the technique applied. When the low pressure hydrodynamic technique is applied, the flush water contains a few percent of salt, in which case the separation of solids and water is expected to be greatly simplified.

Obviously, the addition of salt to the flush medium would improve the possibilities of separating liquid and solids, also in the case of the high pressure hydrodynamic techniques. In such a case, the improved rate of removal of bentonite, appearing as a result of the increased pressure would be of minor interest since ample rates of removal would be obtained at lower pressures.

The canisters which are to be retrieved are assumed to be located at a depth of about 500 metres in crystalline rock. Thus, the freeing operation is to be conducted in an underground mine environment. These prerequisites were considered in an analysis leading to an identification of the following alternative solutions for the sludge management.

1. The sludge is pumped from the retrieval position to the surface. The solids are separated from the liquid by one of the following methods:
   a. Sedimentation in a pond by means of gravity.
   b. Separation in a process:
      - sedimentation,
      - separation by means of flocculation,
      - filter pressing,
      - centrifugation.
2. The sludge is pumped from the retrieval position to a central facility at the level of the repository. Separation would be achieved by means of flocculation, filter pressing or centrifugation.
3. Treatment of the sludge at the retrieval position. It would be an ideal solution if retrieval and sludge management could be carried out in parallel, i.e. the clear solution from the separation would be re-used in the local freeing process.

It should be emphasized that the need for “infrastructure” is very different in the three main alternatives above.

For alternative 1 (pumping to the surface), the following may be needed:

- A system of permanently installed main piping (horizontal) at repository level.
- A vertical main pipe between the repository level and the surface. The system would include either a number of stations at different levels with a tank, a mixer and pumps, or a tank, a mixer and pumps at repository level.
- A facility at the surface including process facilities and a store for sludge.

In the design of such a facility, it should be considered that bentonite slurry may be a strongly non-Newtonian liquid. This implies that the resistance against shear may vary very little with the rate of shear, and that gel may form if the slurry is left unstirred. Formation of gel during a stand-still might imply that it could be very difficult to get the flow to start again.

The following may be needed for alternative 2 above (central facility at repository level):

- a network of pipe installations (horizontal) at repository level,
- a process facility at repository level.

The following may be needed for alternative 3 above (retrieval position):

- no fixed installations
- centrifugation or filter pressing can be identified as suitable methods for the separation of solid and liquid

The following issues need to be dealt with before any of the three alternatives above is selected:

- The capacity and the results of the dewatering, i.e. primarily moisture content of the solids generated.
- The composition of the clear liquid obtained in the separation process.
- The possibilities of reuse and recirculation of the reprocessed liquid (e.g. composition and availability).
- The possibilities of integration between the generation and separation of sludge. In order for such an integration to be achieved, a number of parameters for the two processes (sludge generation and sludge dewatering) have to be known. Examples of parameters of interest are the water content of the solids after separation for various dry contents of the sludge.
- The possibilities for integration between the two processes also depends on the prerequisites of the hardware.

Alternative 3 is assessed to be the method which has the highest potential for the present application. The reason for this is that alternative 3 provides the best prerequisites for an integrated process in which the water is being recycled, and in which the transport is as undemanding as possible. The transport concerns only the bentonite itself and a moderate content of water. In view of these characteristics, this alternative is assessed to be cost effective. It was said above that this alternative presupposes that centrifugation or filter pressing can be used as separation techniques.

4.3 Thermal techniques

The different materials in and around a deposition hole have different thermal expansion coefficients. The change in dimension as a function of temperature is particularly large for bentonite with its high content of saturation water (typically above 20% by weight). Heating or cooling will thus give rise to stresses, strains and perhaps also separation, depending on the following:

- The magnitude of the heating or cooling.
- Where it is applied.
- The geometries involved.
- The length of time that the heating or cooling has been applied.

A necessary prerequisite for separation involving bentonite is that the swelling pressure is overcome and that tensile stresses develop. It can be expected that the potential for separation is largest in the borders between different materials. On the other hand, such a pattern can by no means be taken for granted.

Separation between the bentonite and the rock is of limited value in the present context for several reasons:

- None of the deposition alternatives studied by SKB offers enough space in the tunnel for the entire bentonite and canister entity. (There are disposal alternatives in which the canister and the surrounding bentonite is one entity, but there is also a separate plug of bentonite for the part of the buffer which is nearest to the tunnel). Thus, it cannot be feasible to retrieve the canister and all of the bentonite in one operation.
- The rock surface is expected to be rough with variations on the order of plus or minus 1–2 centimetres. Thus, the separation would have to be of a considerable magnitude in order for retrieval to take place.
- Water may enter from fractures in the rock and cause swelling of the bentonite. The magnitude and positions of such an inflow cannot be expected to be the same as measured during the disposal phase since the rock has been subjected to the swelling pressure of the bentonite in the meantime.
- Pieces of rock may have come loose after the hole was closed (again due to the swelling pressure of the bentonite). They may obstruct the retrieval of a canister/bentonite entity.

For these reasons, retrieval involving the full diameter of the bentonite buffer is excluded from further consideration.

Instead, separation between the canister and the surrounding bentonite, or alternatively, in the bentonite close to the canister will be the focus of attention.

This assessment means that thermal techniques are not considered for the removal of the plug between the canister and the deposition tunnel. Such an operation will therefore have to be carried out by some other technique.

Thus, the question is under what conditions tensile stresses and possible separations may appear at, or near, the canister surface. Modellings have been made of heating as well as cooling. Subsequently, experiments have been conducted on cooling. The modelling calculations were carried out under the assumption that the bentonite is fully saturated. This was also the case in the experiments. Details on heating are given in section 4.3.1 and on cooling in section 4.3.2.

The heating and cooling were simulated in the modelling in four different ways:

1. No heating or cooling other than that which normally exists in a deposition hole. (Heat is continuously being transferred from the canister to the surroundings as a result of radioactive decay occurring in the spent fuel).
2. External heating of the buffer so that the temperature is increased by 50°C.
3. External cooling of the buffer (around the mantle surface of the canister) so that the temperature is decreased by 50°C.
4. External cooling of the canister gable so that its temperature is decreased by 50°C.

In the calculations, the following assumptions were made regarding the types of interaction between the bentonite buffer and the canister:

- Neither separation nor shearing takes place in the border between the canister and the bentonite buffer. Any fracturing will therefore have to appear within the bentonite. The interaction between the canister and the buffer (shearing) depends on the swelling pressure of the bentonite.
- Separation but no shearing takes place in the border between the canister and the bentonite buffer. This means that relative movement in the border takes place only when the total pressure is ≤ 0. Shearing in the buffer depends on the swelling pressure.
- Separation as well as shearing can take place in the border between the canister and the bentonite buffer. The shearing depends on the total pressure together with the coefficient of friction.

It was also assumed that rotational symmetry was maintained throughout.

The study includes comprehensive modelling of the bentonite behaviour. This implies that the result can be expected to reflect, in a reliable manner, the actual mechanical behaviour of bentonite under the conditions in question.

The main results of the calculations were as follows:

- In the case of no external heating or cooling, a force of 110–800 tonnes may be required to pull the canister out of the gripping of the bentonite. The magnitude is very sensitive to the type of interaction assumed, see sections 4.3.1 and 4.3.2.
- The potential is higher for cooling than for heating.
- The potential for development is higher for cooling of the buffer than for cooling of the canister.

It should be recognized, however, that the difference in potential for development is closely related to the outline of the realization. It should e.g. be observed that in the present calculations the cooling of the buffer is assumed to be not only centrosymmetric but also uniform along the canister. No studies have been made regarding the implications of realizations, however.

The experiments were carried out on a small block of saturated bentonite The block was cylindrical with a hole such that rotational symmetry was maintained. The following variations were made:

Cooling:

- from the mantle surface (by 50°C),
- from the inner surface (by 50°C).

Shearing:

- along the mantle surface,
- along the inner surface.

The main conclusions of the experiments were as follows:

- Cooling can be expected to decrease the pressure on both the rock and the canister, and thereby also the resistance against shear in the border surface.
- The results indicate that the buffer pressure on the rock may be sufficiently released in order for the buffer and canister entity to be moved relative to the rock, at least if the temperature decrease is large.
- The results also indicate that the buffer pressure on the canister might not be suficiently released in order for the canister entity to be moved relative to the buffer.
- The reason for this difference between the inner and the outer surface of the buffer is that the contraction which occurs as a result of the cooling takes place inwards so that pressure may be maintained onto the canister.

In conclusion, cooling appears to be more advantageous than heating. Simulations in combination with experiments indicate that the grip on the canister can be expected to be substantially reduced if the buffer is cooled. It cannot be assessed whether or not a separation can actually be obtained.

In view of the various uncertainties and variabilities involved, the prospect of developing a thermal process for the freeing of the canister is assessed to be uncertain.

4.3.1 Heating

The prerequisites for a realisation of a thermal technique based on heating are as follows:

- The bentonite between the canister and the tunnel have been removed through the application of some other technique.
- The gable of the canister facing the tunnel is freed and available for the application of a thermal technique.

- The heating of the bentonite takes place entirely through conduction from some other entity.

A conceptual outline of a thermal technique based on heating may be as follows. The heating is achieved by heating elements which have been put in holes drilled through the buffer in a direction parallel to the main axis of the canister. Bentonite has been removed from the area between the canister and the tunnel prior to the operation.

The following prerequisites apply for the simulations made:

- full saturation of the bentonite,
- rotational symmetry,
- three types of interaction between canister and buffer;

  type A: no separation and no shearing,
  type B: separation but no shearing,
  type C: separation and shearing.

The main results of the simulations are as follows.

No heating of the bentonite buffer in combination with canister/buffer interaction type A (no separation and no shearing)

Removal of the volume of bentonite between the canister and the tunnel leads to a reduction of the pore pressure from 3 MPa to 3.5 MPa. The effective pressure undergoes reduction from 6.5 MPa to values in the range 3.6–5.7 MPa. No separation occurs between the buffer and canister.

No heating of the bentonite buffer in combination with canister/buffer interaction type B (separation but no shearing)

The result is identical to that above for interaction type A where no separation occurs between the buffer and canister.

No heating of the bentonite buffer in combination with canister/buffer interaction type C (separation and shearing)

The result is identical to that above for interaction type A where no separation occurs between the buffer and canister.

Heating of the bentonite buffer by 50°C in combination with canister/buffer interaction type A (no separation and no shearing)

The pore pressure varies from its initial value of –3.5 Mpa before heating to values between –3.0 MPa and 8.5 MPa after heating. At the same time, the effective pressure is reduced only slightly. No separation occurs between the buffer and canister.

Heating of the bentonite buffer by 50°C in combination with canister/buffer interaction type B (separation but no shearing)

The result is identical to that above for interaction type A in that no separation occurs between the buffer and canister.

Heating of the bentonite buffer by 50°C in combination with canister/buffer interaction type C (separation and shearing)

The total pressure is higher than the effective pressure and also higher than the total pressure before heating. No separation occurs between the buffer and canister.

The force needed for loosening the canister has been calculated for the different combinations above and the results are given in Table 4-4.

Table 4-4. The force needed for loosening the canister calculated for the case of a thermal technique based on heating.

The force needed to loosen the canister (tonnes)	Type of interaction A No separation No shear	 B Separation allowed No shear	 C Separation allowed Shear allowed
No cooling of the buffer	800	800	110
Cooling of the buffer by 50°C	650	650	800

4.3.2 Cooling

Simulations

The prerequisites for a realisation of a thermal technique based on heating are as follows:

- The bentonite between the canister and the tunnel have been removed through the application of some other technique.
- The gable of the canister facing the tunnel is freed and available for the application of a thermal technique.
- The cooling of the bentonite takes place entirely through conduction from some other entity.

A conceptual outline of a thermal technique based on cooling of the bentonite may be as follows. The cooling is achieved by cooling elements which have been put in holes drilled through the buffer in a direction parallel to the main axis of the canister. Bentonite has been removed from the area between the canister and the tunnel prior to the operation.

A conceptual outline of a thermal technique based on cooling of the gable of the canister may be as follows. The cooling is achieved by cooling elements being pressed against the gable of the canister. Bentonite has been removed from the area between the canister and the tunnel prior to the operation.

The following prerequisites apply for the simulations made:

- Full saturation of the bentonite.
- Rotational symmetry.
- Three types of interaction between canister and buffer, c f section 4.3;

  type A: no separation and no shearing,
  type B: separation but no shearing,
  type C: separation and shearing.

The main results of the simulations are as follows.

For results regarding no cooling, see section 4.3.1

Cooling of the bentonite buffer in combination with canister/buffer interaction type A (no separation and no shearing)

The pore pressure varies from its initial value of –3.5 Mpa before cooling to values around 11.5 MPa after heating. At the same time, the effective pressure increases slightly (with less than 1 MPa). No separation occurs between the buffer and canister.

Cooling of the bentonite buffer by 50°C in combination with canister/buffer interaction type B (separation but no shearing)

The pore pressure becomes somewhat lower (by about 3 MPa) while the effective pressure increases slightly (with less than 1 MPa). The canister is separated from the buffer almost completely.

Cooling of the bentonite buffer by 50°C in combination with canister/buffer interaction type C (separation and shearing)

The result is similar to that of interaction type B above.

Cooling of the gable of the canister by 50°C in combination with canister/buffer interaction type A (no separation and no shearing)

The pore pressure varies from its initial value of –3.5 Mpa before heating to values between –3.3 MPa and –7.5 MPa after cooling. At the same time, the effective pressure is essentially unaffected. No separation occurs between the buffer and canister.

Cooling of the gable of the canister by 50°C in combination with canister/buffer interaction type B (separation but no shearing)

In this case, the reduction in pore pressure becomes slightly smaller, while the effective pressure remains about the same. Separation takes place along about half of the length of the canister (the part closest to the gable from which is cooled).

Cooling of the gable of the canister by 50°C in combination with canister/buffer interaction type C (separation and shearing)

The pore pressure is reduced by 0.4 to 2.0 MPa while the effective pressure becomes slightly increased. The buffer is still in contact with the canister along the entire length.

The force needed for loosening the canister has been calculated for the different combinations above and the results are given in Table 4-5.

Table 4-5. The force needed for loosening the canister calculated for the case of a thermal technique based on cooling.

The force needed to loosen the canister (tonnes)	Type of interaction		
	A No separation No shear	B Separation allowed No shear	C Separation allowed Shear allowed
No cooling of the buffer	800	6	0.5
Cooling of the buffer by 50°C	650	700	5

Experiments

Samples of bentonite (diameter 50 millimetres and height 20 millimetres) were placed in oedometers and allowed to saturate. The samples were "heat treated" at 70°C, and then cooled. Temperature and swelling pressure were recorded during the cooling. After cooling, a load was applied on the sample, or on a copper tube installed in the sample, so that displacement took place at a rate of 0.1 millimetre per minute. The load and the displacement were measured and the interaction between bentonite and steel, alternatively copper, was determined.

Four different types of tests were performed as illustrated in Figure 4-9.

The main results of the tests are summarized in Table 4-6.

The following observations can be made:

- The largest effect was observed in test series 1b (sliding along the outer surface in combination with cooling from the outer surface). The radial swelling pressure was decreased by at least a factor of five and the maximum shear stress fell to very low values.
- Significant effects were also obtained in test series 2 where the radial swelling pressure was reduced by a factor of about 5–10 and the maximum shear stress by 25–30%.

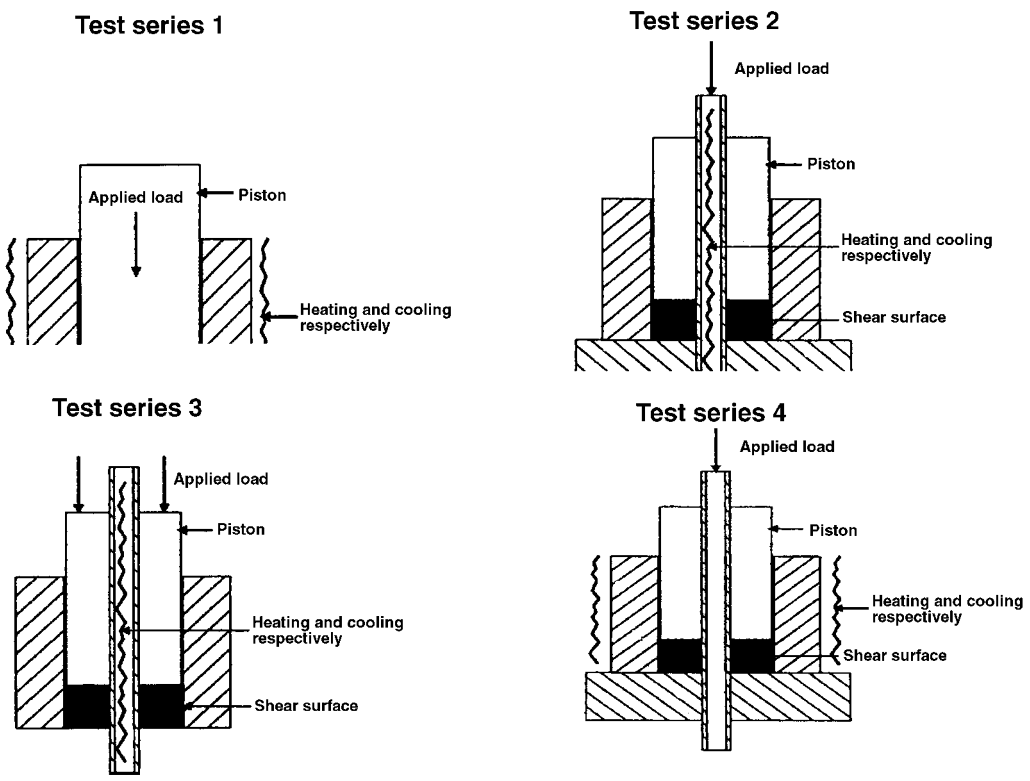

Figure 4-9. *Schematic drawings of the four types of tests performed. The figure has been supplied by Clay Technology AB.*

Table 4-6. A brief summary of the results of the experiments on cooling. The experimental arrangement for the different test series are shown schematically in Figure 4-9.

	Sliding along outer surface		Sliding along inner surface	
	Radial swelling pressure Mpa	Maximum shear stress Mpa	Radial swelling pressure Mpa	Maximum shear stress MPa
No cooling	**Test series 1a**		**Test series 2a**	
	≈ 6	≈ 0,3	≈ 5	≈ 0,85
Cooling from outer surface by around	**Test series 1b**		**Test series 4**	
	≈ 0,00–0,02	≈ 0,05	< 0,6	≈ 0,5
	≈ 1	≈ 0,00		
Cooling from inner surface by around 60°C	**Test series 3**		**Test series 2b**	
	≈ 0,7	≈ 0,5	≈ 0,6	≈ 0,5
	≈ 1,2	≈ 0,3	≈ 0,7	≈ 0,6
			≈ 1,2	≈ 0,7

4.4 Electrical techniques

In certain applications, electrical techniques might be used for freeing or for separation of different parts of a system. Thus, high frequency alternating current (microwaves) can in some cases be used for demolition of concrete. Direct current can be used in order to loosen metal posts from the ground.

The purpose of the experiments summarized below is to determine if direct current and microwaves might affect the bentonite buffer in such a way that freeing could be promoted.

The principles of the interaction with bentonite are different for the two potential techniques.

When direct current is applied to bentonite, a static electric field is developed. This influences ions and dipoles, which are present in the field. The strength of the interaction is related to the strength of the electric field, the charges of the ions, and the electric moment of the dipoles. Electrical interaction with ions and dipoles (non-uniform field) may give rise to a macroscopic transfer of matter which, in turn, can be conceived to be of significance in connection with freeing.

The application of alternating current means that alternating electric and magnetic fields develop in the bentonite. In this process, energy is continuously transferred to and absorbed by the bentonite. The primary effect of this absorption of energy is heating. This may lead to secondary effects, which depend on the characteristics of the target material. The magnitude of the effect depends on the power as well as on the frequency.

4.4.1 Direct current

The primary expectations of the experiments was to attempt to influence and move ions in the bentonite so that a redistribution would be achieved. Water would then also be redistributed and the swelling pressure reduced.

A conceivable realization of an electrical technique involving the application of direct current may include the following.

Bentonite is removed from the area between the canister and the tunnel. Holes are drilled through the bentonite around the mantle surface of the canister, and electrodes are applied. A direct current (DC) source is applied between the electrodes and the canister so that the bentonite becomes subjected to the electric current and acts as an electrolyte.

Laboratory-scale tests have been performed on two fully saturated cylindrical specimens of bentonite with a diameter of 50 millimetres and a height of 30 millimetres. The specimens contained rods of copper, which simulated canisters. They were subjected to direct current and the potential difference between the electrodes was 10 Volts. The copper was connected to the minus pole and the oedometer to the positive pole. The electrical current was approximately 1 Ampère. The current was disconnected after eleven days and the cell opened for analysis after another 20 days. During this entire time, the swelling pressure was logged.

The analyses after the opening of the cell included pH, cationic exchange capacity (CEC), x-ray diffraction (XRD), chemical composition and water content.

It was determined that changes in pH took place at the electrodes, indicating transfer of ions as expected. It was also found that a little water had been lost which concords with the generation of heat and of hydrogen and oxygen observed during the experiment. No change of structure could be determined.

Some reduction of the swelling pressure took place during the course of the experiment. This can be explained by the loss of water caused by the generation of heat and the electrolysis of water.

It was concluded that the generation of a stoichiometric mixture of hydrogen and oxygen, which is highly explosive, in connection with a conceivably leaking canister introduces highly undesirable difficulties with this technique. The electrical technique involving the application of direct current is thus not recommended for further studies.

4.4.2 Alternating current at very high frequency

The primary expectation of the investigations regarding alternating current at very high frequency was to achieve such modifications of the structure of the bentonite that it might affect the swelling pressure and have a potential to be of significance in connection with freeing of the canister.

A frequency range of 300 MHz $\leq f \leq$ 300 GHz, i.e. microwaves, was selected on the grounds that waves in this range are utilized in many applications. It was also assumed that it would be advantageous if the waves would be readily absorbed by the bentonite. Therefore 2.45 GHz was selected, since this is a frequency often used in commercial microwave ovens.

The investigations comprised literature studies as well as contacts and interviews with specialists with relevant profiles at different commercial companies.

The conclusion is that no knowledge seems to exist regarding the heating of bentonite using microwaves. It could be concluded, however, that economic considerations could motivate that this technique is given a low priority.

The largest magnetometer available commercially today has a capacity of 60 kW. It would hardly provide sufficient power, let alone that its efficiency (input electricity to microwave output) is only 50 per cent, and the expected penetration depth of the microwaves a couple of centimetres.

5 Detection and determination of the position of the canister

Freeing of the canister is a necessary step, since the swelling of the bentonite implies that the canister is held in a solid grip by the buffer attaching it to the surrounding rock. This grip may be so firm that attempts to move the canister without previously freeing it may result in unacceptable damage.

The basis for the evolution of the swelling pressure is uptake of water by the bentonite. The uptake of water together with associated processes in the bentonite (e.g. homogenization) will probably continue for decades or centuries after the closure of the repository.

It is possible that such processes will not be entirely symmetrical in relation to the initial rotational symmetry of a deposition hole. This deviation from the initial symmetry may be related to the uneven uptake of water from the surrounding rock which may give rise to a pressure on the canister surface which varies with the position. Such effects may cause the canister to move away from its initial position in a manner which may be very difficult to predict.

Substantial damage might be inflicted on the canister if an freeing operation is initiated under the assumption that the canister is in its initial position while its actual position is substantially removed. It was indicated in Chapter 4 that the damage imposed may vary considerably depending on the characteristics and realization of the particular technique used.

Moreover, the requirements on the knowledge about the position of the canister varies considerably between the different techniques studied.

Ideally, it is desirable to use a technique whereby the exact position of the canister can be determined without opening the deposition hole. If this turns out to be difficult to achieve, or unattainable, then it might still be of value to be able to determine the position of the canister before some part of the equipment comes into actual physical contact.

In view of these needs, a study has been conducted with the purpose of identifying, describing and evaluating different potential techniques based on different physical principles for the detection and determination of the position of the canister in the deposition hole.

The study has included mechanical, electromagnetic, thermal and acoustic modes of interaction. The main conclusions are as follows.

- None of the methods studied was assessed to have a potential to attain a sufficient precision in the determination of the position in a deposition hole which has not been opened.

- The anticipated properties of bentonite imply that methods based on acoustic waves and non-ionizing electromagnetic waves were assessed to have negative prognoses, at least for cases in which a detailed determination of the position is desired or required.
- Nevertheless, techniques based on the utilization of acoustic waves were assessed to be the most promising.

Consequently the travel of ultrasonic waves through compacted and water saturated bentonite was studied specifically. The result is that, at a frequency of 500 kHz and for an attenuation of 100 dB, a penetration depth of 65 millimetres can be attained. If the emitter and receiver are on opposite sides of the specimen, a distance of 130 millimetres can be managed. However, a deeper penetration can be obtained if a lower frequency is used. The resolution is then lower.

Detection might be achieved by applying two electromagnetic fields (inductive metal detectors). It is assessed that this method would not provide sufficient precision if the deposition hole is not opened. It might, however, be possible to use with adequate results during an ongoing freeing operation. The detection can then be carried out in the vicinity of the canister.

A comprehensive assessment should include what has been compiled regarding the freeing processes as well as regarding the detection. In such an assessment, due consideration must be given to the circumstance that no detailed information can be obtained regarding the position of the canister unless the system for freeing of the canister is made considerably more complex than otherwise. This leads to the conclusion that the selection of techniques for freeing of the canister should focus on such techniques which do not require any detailed information regarding the position of the canister.

6 Comparisons between the different techniques for freeing the canister

The different techniques investigated and evaluated for the purpose of freeing canisters in a repository for nuclear waste are compiled in Table 6-1. In the table, reference is given to the respective sections in which the different techniques are described.

These descriptions of the different techniques have included comparisons between the techniques only to a limited extent. Instead, a simplistic but systematic comparison is presented below. It should be emphasized that the purpose of the comparison is to identify one or a small number of techniques for further investigation. Consequently, the ambition is limited to a simplistic categorization of the different techniques into the following three groups:

- Techniques which have a *high potential* for the development of a system for freeing of the canister.
- Techniques which have a *low potential* for the development of a system for freeing of the canister.
- Techniques which are *not recommended* for further investigation.

The scoring of the different criteria, with regard to the techniques listed in Table 6-1, is therefore qualitative in nature.

Table 6-1. A compilation of the different techniques investigated and evaluated for the purpose of freeing canisters in a repository for nuclear waste. Reference is made to the section where each technique is described.

Main technique	Technique		Described in section number	Comments
Mechanical techniques	Full-face boring		4.1.1	
	Milling		4.1.2	
	Core drilling		4.1.3	
Hydrodynamical techniques	High pressure hydrodynamic techniques	Pressure 10–100 bar	3.2.1	Slurrying technique
		Pressure ≥ 100 bar	3.2.1	Jet-technique
	Low pressure hydrodynamic technique (< 10 bar)		4.2.2	Hydrodynamical / chemical technique
Thermal techniques	No heating or cooling		4.3.1	Included for comparison
	Heating	Buffer	3.3.1	50°C
	Cooling	Buffer	3.3.2	50°C
		Canister gable	3.3.2	50°C
Electrical techniques	Direct current		4.4.1	
	High frequency alternating current		4.4.2	Microwaves

The criteria according to which the scoring is made should preferably be generic so that they reflect the essentials of an freeing process in general, and not the outline or even realization of any particular method. The criteria selected and used in the comparison are presented in Table 6-2.

Table 6-2. The criteria used for the comparison between the different techniques for freeing the canister.

Criterion label	Criterion
A	Is the technique in question applicable for the removal of bentonite from the *entire* deposition hole?
B	Is the equipment or process complex or complicated?
C	Are there high demands for energy or power?
D	Is any byproduct or waste product generated?
E	Does the byproduct or waste product require any treatment which is demanding or complex?
F	Is there any inherent risk for canister damage?
G	Is the technique in question sensitive to the position of the canister? Is knowledge required beforehand regarding the precise position of the canister?

The results of the comparison between the different methods for freeing are presented in Table 6-3. The criteria for the comparison are given in Table 6-2. A simplified version of the comparison in Table 6-3 is given in Table 6-5.

The results presented in Tables 6-3–6-4 were used as a basis for classification of the different techniques into the categories given above and the result is presented in Table 6-5. It should be emphasized that the knowledge base as well as the degree of detail of the analysis is such that a ranking is not justified.

The division into categories in Table 6-5 should be interpreted as follows:

- *Techniques which have a high potential for development*

  The reference technique for continued development (and hopefully also the technique to be used) should preferably be selected from this category.

- *Techniques which have a low potential for development*

  The initial expectations on these techniques have not been confirmed. Some obstacle has been identified which would need to be circumvented in order for the technique to be reconsidered. (Alternatively, a selection of optimal parameters would shift the technique described into something close to some other technique).

- *Techniques which are not recommended for further investigations*

  Substantial drawbacks have been identified already at the present stage. This disqualifies the techniques for further studies.

Table 6-3. The results of the comparison between the different methods for freeing. The criteria for the comparison are given in Table 6-2.

Technique	S C O R E						
	Criterion label (c f Table 6-2) for the comparison together with the best answer						
	A	**B**	**C**	**D**	**E**	**F**	**G**
	yes	**low**	**low**	**no**	**no**	**no**	**no**
Full-face boring	no	high	high	yes (α)	no	yes	no
Milling	yes	high	high	yes (β)	no / yes	yes	no
Core drilling	yes	high	high	yes (γ)	yes	yes	no
Hydrodynamic 10–100 bar	yes	medium	medium	yes (δ)	yes	no	no
Hydrodynamic >100 bar	yes	high	high	yes (ε)	yes	no / yes	no
Hydrodynamic <10 bar	yes	low	low	yes (λ)	no / yes	no	no
No heating or cooling	no	high	low	no	no	no / yes	yes
Heating of buffer	no	high	high	no	no	yes	no
Cooling of buffer	no	high	high	no	no	no / yes	yes
Cooling of canister gable	no	low	high	no	no	no / yes	yes
Direct current	no	?	?	yes (σ)	yes	no	yes
Microwaves	yes	high	high	yes (ω)	yes	no	yes

α = disintegrated dry solid bentonite in the form of chips, splinters or lumps.

β = disintegrated dry solid bentonite in the form of chips and splinters together with a considerable fraction of fines.

γ = the same as the previous except that the material is wet.

δ = sludge with a low content of solids.

ε = sludge with a low content of solids or cutting liquid to a small volume together with large and small lumps of bentonite covered with gel.

λ = slurry of bentonite with a high content of solids.

σ = gas (H_2 and O_2 together with water vapour).

ω = water vapour.

Table 6-4. The results of the comparison between the different methods for freeing, simplified presentation. The criteria for the comparison are given in Table 6-2.

Technique	**SCORE**						
	Criterion label (c f Table 6-2) for the comparison together with the best answer						
	A	**B**	**C**	**D**	**E**	**F**	**G**
Full-face boring	-	-	-	-	+	-	+
Milling	+	-	-	-	±	-	+
Core drilling	+	-	-	-	-	-	+
Hydrodynamic 10–100 bar	+	±	±	-	-	+	+
Hydrodynamic >100 bar	+	-	+	-	-	±	+
Hydrodynamic <10 bar	+	+	-	-	±	+	+
No heating or cooling	-	-	+	+	+	±	-
Heating of buffer	-	-	-	+	+	-	+
Cooling of buffer	-	-	-	+	+	±	-
Cooling of canister gable	-	+	-	+	+	±	-
Direct current	-	?	?	-	-	+	-
Microwaves	+	-	-	-	-	+	-

Table 6-5. The results of the classification of the different techniques into the three categories given based on the data presented in Tables 6-3–6-4.

CATEGORY	**TECHNIQUE**
Potential for development of a system for freeing the canister	
Techniques which have a ***high potential***	Hydrodynamic <10 bar
Techniques which have a ***low potential***	Cooling of buffer Cooling of canister gable Hydrodynamic >100 bar Direct current
Techniques which are ***not recommended*** for further investigation	Full-face boring Milling Core drilling Hydrodynamic 10–100 bar No heating or cooling Heating of buffer Microwaves

7 Significance of disposal alternative

7.1 The significance of the choice of disposal alternative

It has been pointed out earlier that the analysis and assessments this far have concerned horizontal disposal only. However, the reference alternative used in most of the studies carried out by and commissioned by SKB is vertical disposal. Consequently, the conclusions made in the previous section needs to be tested against the alternative of vertical disposal.

Thus, Chapter 6 has been revisited and the analyses reiterated from the perspective of vertical disposal with emphasis on potential differences.

One of the results of this exercise was that no reason was found to upgrade any of the techniques classified as “not recommended for further studies”. They will therefore not be discussed further.

The results on the other techniques are discussed in the following.

In the above, the criteria for comparison have not included inflow of water from the walls of the deposition hole or from the tunnel. However, an inflow of water has a greater influence on the assessed feasibility in the case of vertical disposal as compared to horizontal. Therefore, such effects are also included in the subsequent analysis.

7.1.1 Techniques with a low potential

Thermal techniques involving cooling

Cooling actually concerns two techniques: cooling of buffer and cooling of canister gable.

The development of a separation in the border between the canister and the bentonite implies that the transfer of heat is hampered, and that the heat formed as a result of the radioactive decay in the canister will preferably flow through border areas where the canister is in good mechanical contact with the bentonite. In the case of vertical disposal, such conditions exist at the bottom gable of the canister, while in the case of horizontal disposal, the best contact is expected to exist at the lower part of the mantle surface.

In the case of vertical disposal, it might be difficult to provide sufficient cooling around the bottom gable in order for a separation to develop. The absence of a separation along the full length of the canister is expected to mean that canister is still stuck in the bentonite.

For horizontal disposal, the diffusion lengths for heat are shorter. Moreover, separation at the bottom may not be necessary in order for the canister to be easy to move.

Furthermore, leakage of water may take place into the separation formed between the canister and the bentonite. In such a case, the bentonite would absorb water, swell, and perhaps also resume its grip on the canister. The probability of inflow of water is greater in the case of vertical disposal since the holes are drilled from the bottom of the tunnel.

The conclusion is that vertical disposal is less favourable than horizontal for thermal techniques involving cooling.

Direct current

Leakage of water may take place into the separation formed between the canister and the bentonite. In such a case, the bentonite would absorb water, swell, and perhaps also resume its grip on the canister. The potential for inflow of water is greater in the case of vertical disposal since the holes are drilled from the bottom of the tunnel.

The conclusion is that vertical disposal is less favourable than horizontal for the electrical technique involving the application of direct current.

Water jet

This technique is a hydrodynamic technique requiring pressures above 100 bar. The distance between the nozzle and the object to be cut needs to be limited in order for the beam not diverge too much, in which case the technique becomes less efficient.

The requirement on proximity become even more stringent under water, especially in the present case where the water may have a high content of bentonite and also contain lumps. A need to operate the nozzle close to the bentonite adds to the complexity of the system.

In the case of horizontal disposal, it may be possible to evacuate the by-product by flushing it towards the tunnel. Such evacuation is less simple in the case of vertical disposal.

Conversely, the potential for inflow of water into the vicinity of the jet is higher for vertical disposal.

The conclusion is that vertical disposal is less favourable than horizontal for the hydrodynamic technique utilizing a water jet.

7.1.2 Techniques which have a high potential

Only one technique was identified to belong to this category namely the low pressure hydrodynamic technique which may also be called the hydrodynamic/chemical technique.

The description and discussion to follow build on the basic description of the technique given in section 4.2.2. Realizations showing the principles of freeing operations in the case of vertical as well as horizontal disposal are shown in Figure 7-1. The concept for freeing of a canister in vertical disposal was presented at WM2000 i Tucson /7/.

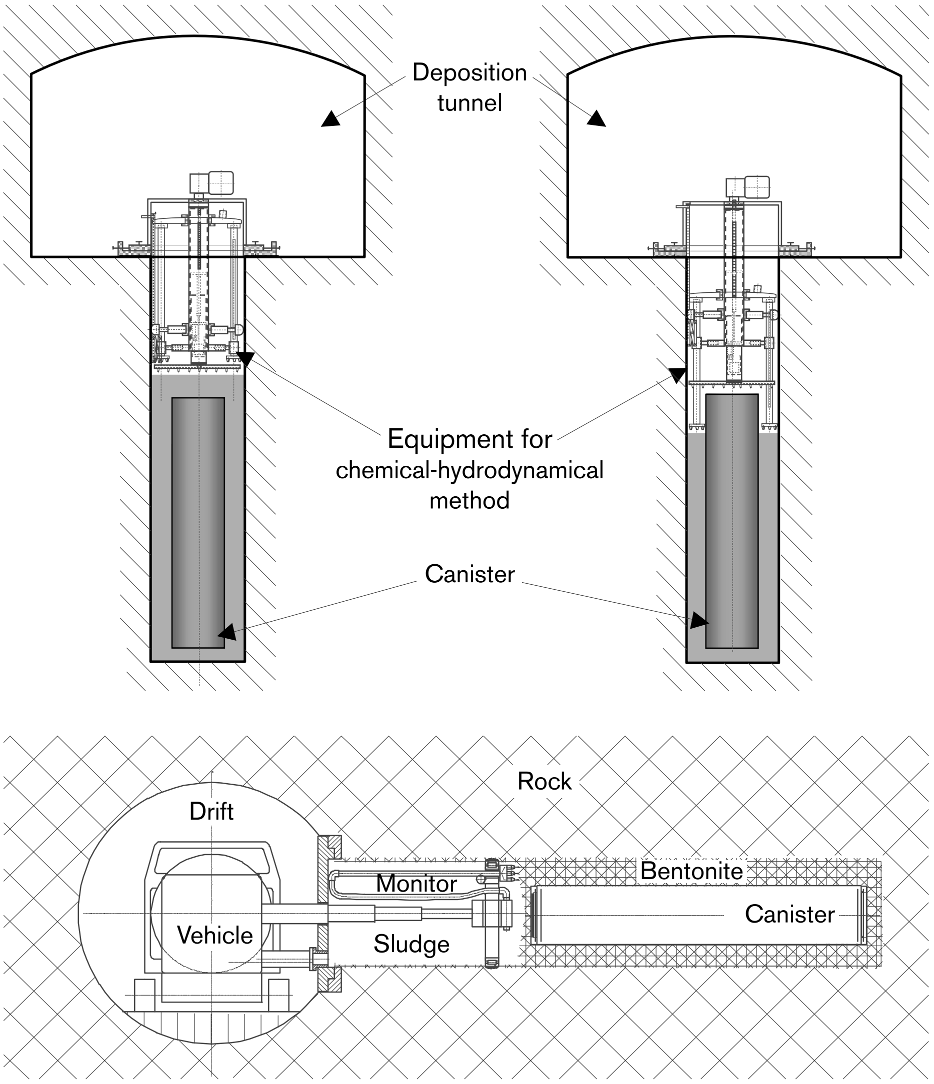

Figure 7-1. *Realizations showing the principles of freeing operations in the case of vertical as well as horizontal disposal.*

The flushing of the bentonite might be orientation-dependent. Such a dependence could be related to the efficiency of the process. Possible effects are as follows:

1. The gel formed on the surface of the bentonite as a result of the chemical attack has a low mechanical integrity and may be influenced by the force of gravity. In the case of vertical disposal, the bentonite surface is horizontal, and the gel is expected to stay in place. In the case of horizontal disposal, where the bentonite surface may be vertical, the bentonite gel might move downwards. The latter case is more favourable for an freeing process.

2. It is also possible that the force of gravity may act on the sludge in such a manner that sedimentation takes place. In the case of vertical disposal, the bentonite surface may be horizontal, in which case, sediment may accumulate on this surface and impede flushing. Such effects are not expected in the case of horizontal disposal. Thus, from the point of view of sedimentation, horizontal disposal is more favourable.

3. A prerequisite for the technique is that a liquid is used in the deposition hole. In the case of vertical disposal, this liquid is held in place by the walls of the deposition hole. In the case of horizontal disposal, additional arrangements are needed in order to keep the liquid in place. Thus, the realization of the method can be expected to be somewhat more complex in the case of horizontal disposal.
4. The prerequisites for the design of the equipment to be used are different in the sense that the stress situations are less complex and the stresses lower in the case of vertical disposal.

Thus, each disposal alternative is favoured in two cases. Moreover, all four of the above mentioned effects are assessed to have a limited significance. The conclusion is that the low pressure hydrodynamic technique is equally applicable to the cases of vertical as well as horizontal disposal.

7.2 Sensitivity of the low pressure hydrodynamic technique

The comparison between the different techniques for freeing the canister was carried out considering only a very limited set of generic criteria, c f Table 6-2.

Consequently, the conclusions made in the previous section need to be tested against various possibly significant influences. A few such analyses are made in the present section.

The analyses are made only with respect to the alternative in the category of high potential for successful further development which is the low pressure hydrodynamic technique, *c f* section 4.2.2. The reason for this is as follows.

It was concluded in section 7.1 that the techniques in the category “not recommended for further studies” would belong to this category regardless of whether horizontal or vertical disposal were considered. It was also concluded in section 7.1 that the techniques assessed to be in the category of “low potential for further development” in the case of horizontal disposal would probably have a lower potential in the case of vertical disposal.

Thus, none of the techniques in the two categories mentioned would appear to warrant development work until new circumstances are identified which would give rise to a more positive assessment.

In the case of the low pressure hydrodynamic technique, it was concluded that the technique is probably quite insensitive to the choice of disposal alternative.

The purpose of the subsequent analysis is therefore to investigate if it might be possible to confirm this positive assessment of the low pressure hydrodynamic method with regard to some factors or criteria not included in the comparison in Chapter 6.

7.2.1 Support of the canister during the freeing operation

As was described in Chapter 4, the issue of the realization of the methods as well as the design and operation of the mechanical systems for the retraction of the canister are still in the inception stage. The issue of support of the canister during the freeing operation will certainly constitute an important part of any such consideration.

In the case of vertical disposal, it may well be that the canister can be retracted before all the bentonite has been removed without any particular precautions. In such a case, it is possible that no support is needed. The same may apply to horizontally emplaced canisters provided that the flushing is carried out selectively so that the canister can be retracted before the support might be questioned.

If support is needed nonetheless, it is assessed that support should be applied only at the gable of the canister which faces the tunnel. In such a case, the application of the support as well as the subsequent docking is assessed to be non-trivial but straightforward.

Thus, no significant obstacle (from the point of view of alternative selection) against applying the low pressure hydrodynamic technique could be identified.

7.2.2 Water entering the deposition hole

Water might enter the deposition hole from the walls of the hole as well as from the tunnel.

Water from the walls of the hole may dilute the flushing liquid somewhat. This can easily be compensated for by increasing the salt content of the make-up salt solution added to the process. The presence of salt in the groundwater entering the process is assessed to be of little significance for the process.

Water from the tunnel is not expected to enter the process water system under normal operating conditions and is therefore expected to have little influence.

In conclusion, water entering the deposition hole is assessed to be of little significance and of essentially no consequence.

7.2.3 Canister dose rate

The canister dose rate is an important consideration for canister retraction and some other process steps for any technique used for the freeing of the canister.

In the application of the low pressure hydrodynamic technique, the flushing water in the process may provide additional shielding. Moreover, the technique readily lends itself to remote operation.

In conclusion, no significant problems associated with the low pressure hydrodynamic technique have been identified with regard to the dose rate of the canister.

8 Conclusions

Material has been presented for the selection of a reference alternative for a technique to be developed to a system for the retrieval of canisters with an emphasis on techniques for freeing.

This material includes identification and description of different potential techniques for freeing together with analyses and comparisons relating to their potential for development. The basis also comprises identification, description, analysis and comparison of a few techniques for determining the position of the canister in the deposition hole.

The comparison was based on a number of generic criteria and resulted in the categorization of the techniques studied into three different groups:

- Techniques which have a *high potential* for the development of a system for freeing of the canister.
- Techniques which have a *low potential* for the development of a system for freeing of the canister.
- Techniques which are *not recommended* for further investigation.

Only one technique was identified in the high potential category, namely the low pressure hydrodynamic technique. Four techniques were identified to have a low potential, namely cooling of the buffer, cooling of the canister, water jet technique and application of direct current. The other seven techniques included are not recommended for further studies.

Since horizontal disposal was assumed in the first step of the analysis, vertical disposal was considered in a second one. The result of this analysis is that the potential for the low pressure hydrodynamic technique is equally high for vertical disposal as for the horizontal, while analyses of the other techniques did not provide any basis for upgrading to the category of high potential.

Since the comparison had to be based on a simple and generic set of criteria, a further analysis was conducted in order to determine whether or not the low pressure hydrodynamic method is robust enough in order to remain in the high potential category even when some other relevant issues are considered. This was found to be the case.

The potential assessed is not the same in all parts of the deposition hole. The low pressure hydrodynamic technique was assessed to be applicable in the entire deposition hole. The techniques in the low potential category are more difficult to apply when the gable of the canister is to be freed as compared to the freeing of the mantle surface.

The low pressure hydrodynamic technique presupposes that the slurry generated can be managed. It is hoped that the clear liquid (that is, the slurry after removal of the bentonite) can be reused in the continued freeing process and that the bentonite recovered can be reprocessed and used for arbitrary purposes. It was assessed that separation of liquid and solid in the slurry may preferably be carried out in the vicinity of the freeing operation.

The conclusion regarding how to determine the position of the canister is that none of the methods studied provides sufficiently detailed information before the deposition hole is opened. This conclusion implies that it is favourable if a technique does not require detailed knowledge regarding the position of the canister.

The efforts spent on the various techniques in a development project have to reflect the potential assessed at the time of the execution of the work. This has been true in the present case even if the main purpose has been to achieve a categorization and identification of one or more technologies with a high potential for development.

In the work conducted, the efficiency of the low pressure hydrodynamic method has come as a surprise. This has prompted phenomenologically oriented studies which are of relevance also for other aspects of the use of bentonite in conjunction with disposal of nuclear waste. It is not inconceivable that the results of such studies may actually be of greater significance for the understanding of the barrier properties of bentonite than for the assurance of the applicability of the low pressure hydrodynamic technique under various conditions.

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