Final Deposition of High-level Nuclear Waste in Very Deep Boreholes

An evaluation based on recent research of bedrock conditions at great depths

Karl-Inge Åhäll

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MKG Report 2

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About the Swedish NGO Office of Nuclear Waste Review (MKG)

The Swedish NGO Office of Nuclear Waste Review (Miljöorganisationernas kärnavfallsgranskning in Swedish), MKG, is a Swedish non-governmental environmental organization dedicated to the environmental aspects of nuclear waste management. MKG was founded in the autumn of 2004. Member organizations are the Swedish Society for Nature Conservation SSNC (SNF), Oss - a Public Opinion Group Dedicated to Safe Final Diposal of Radioactive Waste in Östhammar community, Nature and Youth Sweden (Fältbiologerna), the Swedish Society for Nature Conservation in the Uppsala county administrative province and the Swedish Society for Nature Conservation in the Kalmar county administrative province.

The work of the organisation is financed out of the Swedish Nuclear Waste Fund. MKG takes an active part in the ongoing public consultations related to the plans of the nuclear industry to construct a final repository for high-level nuclear waste. The objective of MKG is to promote the best long-term environmentally option for the management of the radioactive waste from the Swedish nuclear reactors.

About the author

Karl-Inge Åhäll, associate professor in geology, is based at Karlstad University, Sweden. He has done extensive research on the formation of Swedish bedrock and has served as co-ordinator of an international research group with a focus on the origins of, and changes in, the continental crust.

Karl-Inge Åhäll is a member of the SSNC (Swedish Society for Nature Conservation) Expert Advisory Panel and the Swedish chapter of the International Lithosphere Program (ILP). He is a member of MKG´s expert council.

Karl-Inge Åhäll is the author of numerous scientific papers, and as also written a book for laymen on the geology of Dalsland (1993), a report commissioned by Svensk kärnbränslehantering AB (SKB) on dating of young granite intrusions in eastern Småland (R-01-60), and a policy platform for the Swedish Society for Nature Conservation (SSNC) on valuable geological features in Sweden (1998).

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Preface

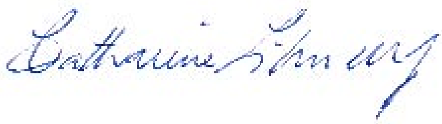
The objective of the Swedish NGO Office of Nuclear Waste Review, MKG, is to promote the long-term environmentally best option for managing the radioactive waste from the Swedish nuclear reactors. The high-level nuclear waste in the form of spent nuclear fuels is very hazardous and long-lived waste needs to be isolated from living organisms for more than 100,000 years. With this report MKG presents an up-to-date and comprehensive evaluation of the concept of disposing high-level nuclear waste in very deep boreholes. With the report MKG wants to broaden the discussion as Sweden approaches its choice of method for disposal of high-level nuclear waste.

Since the 1970s the Swedish nuclear industry has advocated a method, KBS, for final disposal of nuclear waste where the spent nuclear fuel is placed in tunnels at the depth of 500 m, i.e., at a relatively shallow depth. Alternative methods do exist; the one addressed by this report involves disposing of waste at a depth of 3-5 km.

According to the statutes of the Swedish Environmental Code, an application for permission to carry out activities that might affect the environment or human health must be preceded by an evaluation of all feasible alternatives. Since the early 1990s, the Swedish environmental movement has urged that the very deep borehole concept should be further examined. There have been repeated calls from the environmental NGOs, the Swedish regulatory authorities and the Government for an independent and unbiased comprehensive evaluation of the alternative method very deep boreholes. Such a study still does not exist but this review is a step on the way.

The report is written by Associate Professor Karl-Inge Åhäll, a bedrock geologist, who has surveyed and evaluated recent research on the hydro-geological conditions in Sweden. The conclusions presented in the report are those of the author.

The report was initially commissioned by the local chapter of the Swedish Society for Nature Conservation in the Uppsala county administrative province and Oss, a local public environmental NGO dedicated to safe final storage of radioactive waste in Östhammar municipality. The present report is a substantially expanded version commissioned by MKG and the english version is a translation of the Swedish version.



Catharina Lihnell Järnhester
Chair person of MKG

Johan Swahn
Director of MKG

Summary

This report evaluates the feasibility of very deep borehole disposal of high-level nuclear waste, e.g., spent nuclear fuel, in the light of recent technological developments and research on the characteristics of bedrock at extreme depths. The evaluation finds that new knowledge in the field of hydrogeology and technical advances in drilling technology have advanced the possibility of using very deep boreholes (3-5 km) for disposal of the Swedish nuclear waste. Decisive factors are (1) that the repository can be located in stable bedrock at a level where the groundwater is isolated from the biosphere, and (2) that the waste can be deposited and the boreholes permanently sealed without causing long-term disturbances in the density-stratification of the groundwater that surrounds the repository.

Very deep borehole disposal might offer important advantage compared to the relatively more shallow KBS approach that is presently planned to be used by the Swedish nnuclear industry in Sweden, in that it has the potential of being more robust. The reason for this is that very deep borehole disposal appears to permit emplacement of the waste at depths where the entire repository zone would be surrounded by stable, density-stratified groundwater having no contact with the surface, whereas a KBS-3 repository would be surrounded by upwardly mobile groundwater.

This hydro-geological difference is a major safety factor, which is particularly apparent in all scenarios that envisage leakage of radioactive substances. Another advantage of a repository at a depth of 3 to 5 km is that it is less vulnerable to impacts from expected events (e.g., changes in groundwater conditions during future ice ages) as well as undesired events (e.g. such as terrorist actions, technical malfunction and major local earthquakes). Decisive for the feasibility of a repository based on the very deep borehole concept is, however, the ability to emplace the waste without failures. In order to achieve this further research and technological development is required.

Contents

1. The Swedish program for nuclear waste management

Ever since the first Swedish nuclear power reactor came on line in 1972, Sweden has been producing high-level radioactive waste. The accumulated waste has been stored for cooling in a dedicated installation, CLAB, adjacent to the nuclear power station just north of Oskarshamn. Efforts to arrive at an acceptable method for processing and/or final deposition of Sweden's high-level nuclear waste has been in progress some thirty years. Having abandoned plans to reprocess the spent fuel, in 1983 the nuclear power industry presented the outlines of a method for direct final deposit, known as KBS-3. Briefly, the method involves packing all high-level waste in metal canisters, which are then deposited in gallery-like tunnels in Swedish bedrock at a depth of approximately 500 m. In the interval since 1978, the Swedish nuclear power companies, acting through their jointly owned subsidiary, Svensk kärnbränslehantering AB (known internationally as "SKB"), have concentrated their efforts on two things: finding a suitable location for the final repository and specifying its design so as to minimize short- and long-term risks.

2. Background

The idea of depositing nuclear waste in deep boreholes at depths of several kilometres is not new, but only in the 1990s did the research community at large recognize the implications of new hydro-geological findings that indicated the presence, at least in some areas, of density-stratified groundwater at great depths, the stratification of which is so stable that it lacks contact with the biosphere.

For example, William G Halsey, project leader at the Lawrence Livermore National Laboratory, University of California at Berkeley, highlighted these findings from an American study concerning final deposit of high-level nuclear waste from military programs (Deep Borehole Disposition 1996) in an evaluation commissioned by the Department of Energy (Fissile Material Disposition Program).

"The basic safety argument is permanent isolation in deep, old and stable rock from which water does not communicate with the accessible biosphere."

Christopher Juhlin, Uppsala University, was among the first in Sweden to recognize the new findings, but they first reached a wider audience when included in a survey of deep bedrock research performed by Juhlin et al. for SKB and published in 1998 (SKB TR-98-05).

More recently, new and more detailed documentation of conditions at great depths in continental bedrock of the kind found in Sweden has been presented. Major factors are the higher pressure and higher temperatures that prevail at these depths.

Other factors are the mineral composition of the rock, the presence of cracks and the rock's cracking properties, and the chemical composition of the groundwater, its stratification and bacterial content. By measuring these and other parameters it is possible to assess the feasibility of the deep borehole concept, addressing the following items:

How deep does one have to drill to find sufficiently stable density-stratified groundwater that permits localization of a final repository below an "upper zone", where groundwater does have contact with the biosphere?

What other hydro-geologic criteria have to be met?

What factors impede the diffusion of radioactive substances at great depths?

What hazards, in the short and longer term, can be identified?

Does current technology afford the drilling precision required for safe disposition and long-term storage of nuclear waste in deep boreholes?

New insights into conditions deep down in continental bedrock have been gained primarily from measurements taken in deep boreholes in Europe, North America and Japan:

- Kola Peninsula: -12.3 km, deepest in the world (SG-3 project)
- Ural Mountains, Central Russia: -5.4 km (SG-4)
- Southern Germany: two boreholes, -4 and -9 km (KTBV- and KTBH-project)
- Eastern France: two boreholes, -3.6 and -5 km (GPK 1 and 2)
- Central France: several boreholes, 1-2 km deep (Sancerre-Couy, Cezalier)
- Cornwall, England: several boreholes 1-2 km deep (RH 11, 12 and 15)
  USA: four boreholes, -4 to -6 km (Mobile-1, Nellie-1, Fenton Hill, Haraway 1-27)
- Japan: -1.8 km (Nojima Fault Zone)

In addition to published research findings, oil exploration has produced extensive data, albeit they are not readily available for reasons of commercial secrecy. Furthermore, mining operations in South Africa and Canada have reached depths in excess of -2.5 km. Other pertinent data derive from seismic studies conducted in conjunction with earthquakes.

In Sweden, deep boreholes have been drilled in three areas:

- the Siljan region (Gravberg and Stensberg): two boreholes about -6 km deep, exploration for fossil gas
- Southern Sweden (near Lund, Skåne): -3.7 km, geothermal project

- The south east part of Sweden (Laxemar, Småland): -1.7 km, SKB's nuclear waste program.

Mining operations and exploratory drilling have reached the -1 km level in several areas, e.g., the Kiruna region, the Skellefteå field, and Bergslagen.

All this experience allows us a more detailed evaluation of pros and cons of repositories in deep boreholes than was possible when the nuclear power industry and Swedish authorities first agreed on the framework of the KBS program, with its focus on a relatively shallow disposal (about -500 m). The most important new knowledge relates to the discovery of areas at depths of -3 to -5 km that have highly stable bodies of density-stratified groundwater the stratification of which radically hampers upward vertical migration (transport) through the bedrock.

Furthermore, recent technological advances have made it possible to drill holes at great depths of diameters that can accommodate canisters of high-level waste. Accordingly, it is now possible to reach more precise estimates of costs for such undertakings.

Also, there is more widespread understanding the value of using so-called "forgiving technologies" to minimize risks that always accompany technically complicated systems (and human fallibility). The choice of more robust technological systems is also in line with the precautionary principle and the use of BAT (Best Available Technology) and BEP (Best Environmental Practices) — two concepts that are of focal importance in Swedish environmental protection legislation.

In sum, these new hydro-geological insights, technological advances and international obligations make it more feasible to seriously assess the advantages and drawbacks of final deposition in deep boreholes relative to other high-level waste management systems.

The need to update the nuclear waste management program is, of course, not confined to Sweden. In the USA, for example, a comprehensive interdisciplinary study conducted by a team at the Massachusetts Institute of Technology (MIT 2003, p 11) concluded:

"A research program should be launched to determine the viability of geologic disposal in deep boreholes within a decade."

This new interest in the deep borehole concept in the USA was partly motivated by the relative security such repositories were peceived to give. The researchers adresses (MIT 2003, p 57) some organizational and technical problems still need to be worked out, but concludes:

"... Despite these obstacles, we view the deep borehole disposal approach as a promising extension of geological disposal, with greater siting flexibility and the potential to reduce the already very low risk of long-term radiation exposure to still lower levels without incurring significant additional costs".

3. Final storage in deep boreholes — an overview

All bedrock changes character with increasing depth; and below -1.5 km there are marked changes in the rock pressure, fracture systems and groundwater chemistry. Deposition of canisters with high-level waste at great depth presumes sophisticated drilling technology that can drill holes of a diameter that accommodates the canisters. Furthermore, an extensive exploratory drilling program is required to establish the hydro-geological properties surrounding the prospective repository.

The advantage of a deep geological deposition resides primarily in the markedly lower permeability to water and gases and the much more stable stratification of groundwater at depth. In addition, the higher pressure and temperature at deeper levels may be expected to promote geochemical sorption processes (adhesive capacity) in micro-fissures in the event that radioactive substances leak out of the repository (SKB T-98-05, SKB R-04-09). All three factors enhance safety as they, singly and in combination, inhibit the transport of radioactivity long distances from the repository. In particular, transport upward toward the biosphere is inhibited inasmuch as all vertical migration is inhibited, themore stable the stratification of local groundwater is.

3.1 How deep should a nuclear waste repository be located?

One crucial parameter from the point of view of security is the localization of the repositories by a good margin under the "upper zone" of the bedrock, where relatively open and water-conducting cracks and fissures predominate. Under this zone the fractures are increasingly closed, which renders the rock more homogeneous; this is reflected in rising seismic wave velocities (cf., for example, SKB TR-98-05, Section 14.1). This first "criterion" of the deep borehole concept implies a repository depth of at least 1.5 km.

The need to establish a thick "hydrological buffer" between the waste repository and the rock above with its more mobile groundwater implies a second "criterion" relating to the depth of the repository. In this connection one can make use of the increasing stability of stratification that groundwater displays as one progresses deeper down under this "upper zone" in order to create a substantial buffer zone. The stratification of groundwater is related to the water's density and reflects the progression from slightly saline subsurface groundwater to successively saline, and therefore heavier, brines. Swedish data from the Siljan region (Gravberg 1) indicate that in some areas this "criterion" will not be fulfilled until depths of -5 to -6 km (Juhlin et al. 1991), whereas other areas display density stratification from depths of -1 km and down (Laxemar, eastern Småland, SKB TR-01-11). Moreover, data from bedrock studies outside Sweden (SKB R-04-09) indicate that there are areas in Sweden where it would not be necessary to drill deeper than 2.5 km, even to meet the need for a buffer zone of 1 km between the waste repository and the overlying bedrock with open fractures and mobile groundwater.

In their reports the Swedish nuclear fuel waste company, SKB, has considered a deep borehole disposal with deposition at depths ranging from -2 km to -4 km (SKB R-00-28). However no more detailed analysis as to the thickness of the buffer zone or the most appropriate depth for the repository is undertaken in these very cursory reports. The prospects of coming ice ages, for example, cast doubts on the advisability of storing nuclear waste as high up as -2 km.

In view of the fact that drilling costs rise sharply at greater depths, there is reason not to deposit the waste any deeper than is necessary. At the same time, there are parameters (such as the density-stratification of groundwater) that suggest greater safety, the deeper the waste is stored. These conflicting values, economy versus safety, may be expected to result in a variety of ambitions for different actors as to the optimal depth, at depths exceeding -2 km.

In order to not underestimate the problems this assessment of the value of depositing spent fuel waste in deep boreholes relates to depths of between -3 to -5 km. Continued advances in wide hole drilling technology may render storage at depths greater than -5 km economically attractive.

In addition to the repository boreholes, a number of exploratory holes will be required to measure the various parameters relating to the geological and hydrogeological properties of the bedrock. Some parameters can be measured from the surface, but not all. For example, measurements of the length of time that groundwater at these levels has been isolated from groundwater nearer the surface requires access via exploratory boreholes. These exploratory boreholes need not be as wide as the deposition holes, but at least some must extend beyond the level of the repository since it is important to know what is at play immediately under the repository, as well. Exploratory boreholes should extend several hundred meters past the intended level of the repository.

3.2 Two alternative borehole concepts

Today there are two contrasting concepts for final disposal of high-level nuclear waste in deep boreholes. Most research to date has focused on so-called Low Temperature (LT) systems, but data on High Temperature (HT) storage has been produced these past few years. HT-solutions call for denser concentration of the waste (see Section 3.2.2), which reduces the number of boreholes required, and therewith the volume of the repository as a whole.

3.2.1 Low Temperature storage (LT repositories)

The LT storage concept revolves around limiting the heat impact on the surrounding bedrock by packing the canisters with relatively low concentrations of radioactive substance. Furthermore, the heat released due to radioactive decay inside the canisters may be more widely diffused by placing buffering material between the canisters in the boreholes and localizing the repository in bedrock with favourable heat-conductive properties. Such measures make it possible to regulate the heat impact on the surrounding rock, which means that once the repository boreholes have been filled and sealed, the repository may be expected to be surrounded by ordinary groundwater, which in turn makes it relatively easy to model the future function of the nuclear waste repository.

Thus, the idea is that the bedrock outside the repository will be as little impacted as possible, so that the groundwater present will retain its stable density-stratification and thus be able to hinder radioactive substances from migrating upwards to the biosphere, even in the event of failure of several canisters.

The principles of an LT repository in deep boreholes are illustrated in figure 1. The dimensions of both boreholes and canisters may need some modification for reasons of cost (SKB R-00-35, p 45), as may the, by SKB, specified repository depth of -2 to -4 km. Furthermore, other materials than bentonite have been considered for the buffer between canisters — at greater depths in any case (cf. SKB R-00-28, p 64f).

It should be noted that the deep borehole concept does not necessarily require containment of the waste in canisters as it might also be deposited in the form of smaller "rods" enclosed in fluid cement that hardens after deposition. But, for lack of comparable data that allow an assessment of the reliability of this alternative the author confine the present discussion to deposition using canisters, as illustrated in figure 1.

The specification of low concentrations of radioactive substance should pose no problems for the Swedish radioactive waste program (SKB R-00-28), which entails intermediate storage at CLAB near Oskarshamn for a period of 15-50 years. By the

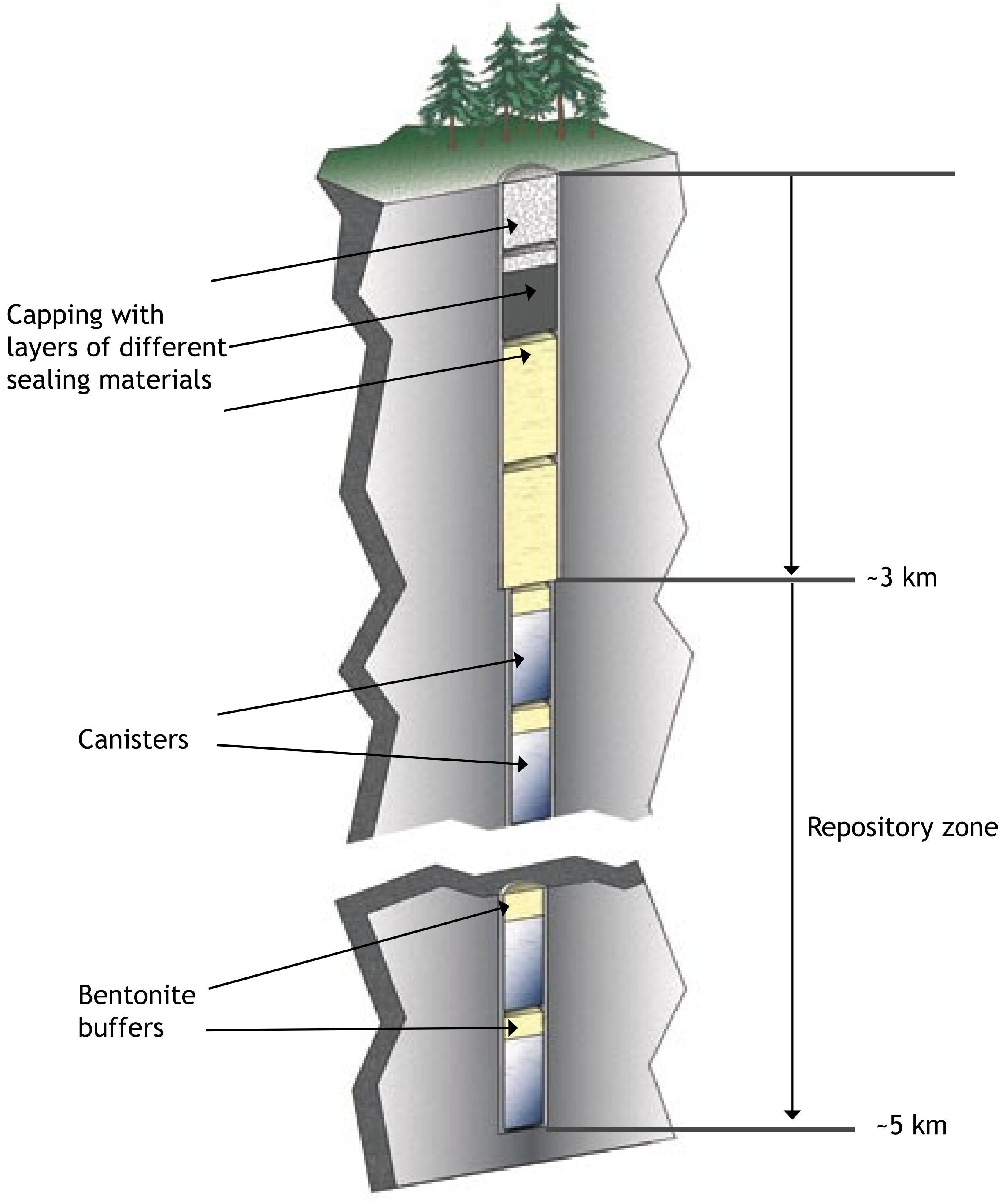


Figure 1. The concept of final storage of canisters of high-level nuclear waste deposited in deep boreholes. The canisters are about 5 m long and have diameters of 0.5 m. The illustration is based on a figure in SKB R-00-28, page 8. The SKB document discusses borehole diameters of 0.6-0.8 m.

time of final storage, the waste has cooled so that it should be suitable for storage in LT repository boreholes as outlined in figure 1.

Earlier SKB reports (TR-98-05 and R-00-28) have estimated that 20-40 boreholes would be required, depending on how the waste is pre-processed. It would take a single drilling rig about 10-15 years to complete such a repository, and before that, a good number of exploratory boreholes would be needed to guide the selection of the site(s). Given SKB's estimated cost of approximately 40 million SEK per borehole (SKB R-00-35), total drilling costs for the repository would land in the range of 1.5 billion SEK. The calculations should, however, be updated as technological advances may have influenced the cost of drilling. What is more, drilling operators today can drill with greater precision to create, for example, so-called "fanned arrays" of holes extending downwards from a central borehole deep down in the bedrock (Chapman & Gibb 2003). See figure 2.

3.2.2 High Temperature storage (HT repository).

The HT concept presumes more concentrated packaging and storage of the waste in the repository than in a LT storage. This may be achieved by concentrating more radioactive substance in each canister and allowing less space between canisters. After the boreholes have been filled and sealed, the heat generated by continued decay may be expected to partially melt the immediately adjacent rock. Initially, the heat generated will gradually purge a good area surrounding the repository area of all liquids and gases. As the melted mineral cools, the fuel waste will be encased in a zone of dry, newly crystallized rock, the outer perimeters of which are surrounded by multiple physical and geochemical barriers. Together, these barriers should impede all exchange between the content of the repository and the rock outside the now crystallized melt zone closest to it. This kind of HT system has been described most fully by researchers at the University of Sheffield (cf. Gibb 2000 and Atrill & Gibb 2003a, 2003b).

Figure 3 shows the geochemical zones of "thermally sealed rock" that may be expected to surround an HT repository once the melted mass has crystallized. The rationale of the HT system is not only to enclose the repository in a zone of dense, newly crystallized rock, but that both will in turn be surrounded by several outer zones of metamorphosed rock, the liquid and gaseous content of which has either been purged or chemically bound in newly crystallized mineral.

One significant advantage of HT systems is that they allow compaction of nuclear waste, which would reduce the cost of drilling. In addition, the method is believed to be suitable for storage of plutonium and other ingredients in nuclear weaponry, which would give UN (United Nations) agencies like the IAEA (International Atomic Energy Agency) and individual nuclear powers a means to effectively keep fissionable material out of the hands of terrorists.

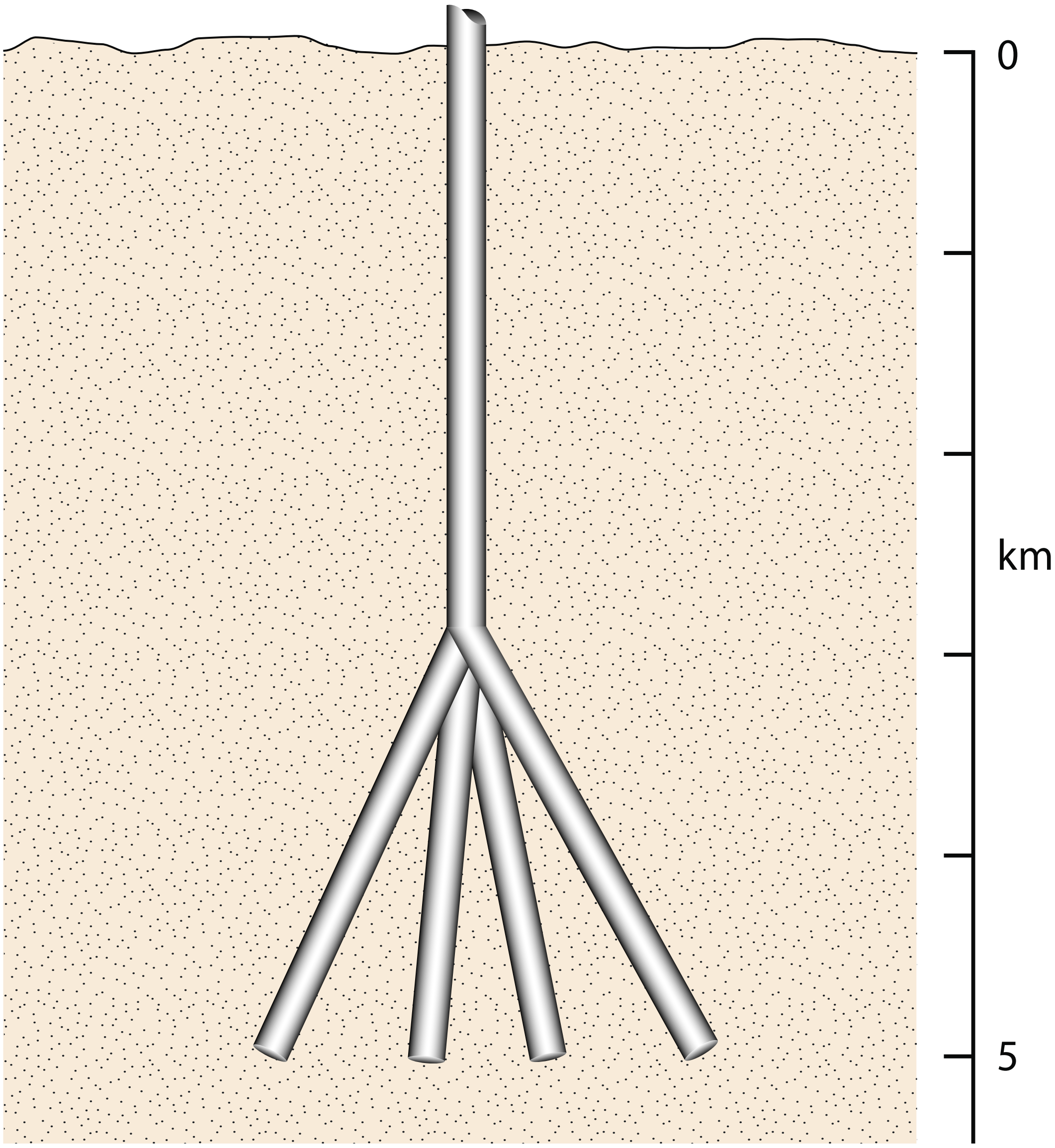


Figure 2. Example of technically advanced deep drilling, a so-called fanned array, with four repository holes fanning out from a common central borehole in the upper region (illustration adapted from Chapman & Gibb 2003, page 32).

HT systems of the kind described here are a relatively new concept (Gibb 1999), and more safety-related research is required before their advantages and drawbacks relative to LT systems can be assessed. The team at Sheffield has, however, been able to verify the model presented in experiments. They have, for example, demonstrated that the basic functions do work as regards energy, provided host rock having an appropriate mineral composition is selected (Attrill & Gibb 2003a, 2003b). Appropriate rocks (granites of S-type) are quite common in continental bedrock, including the Swedish.

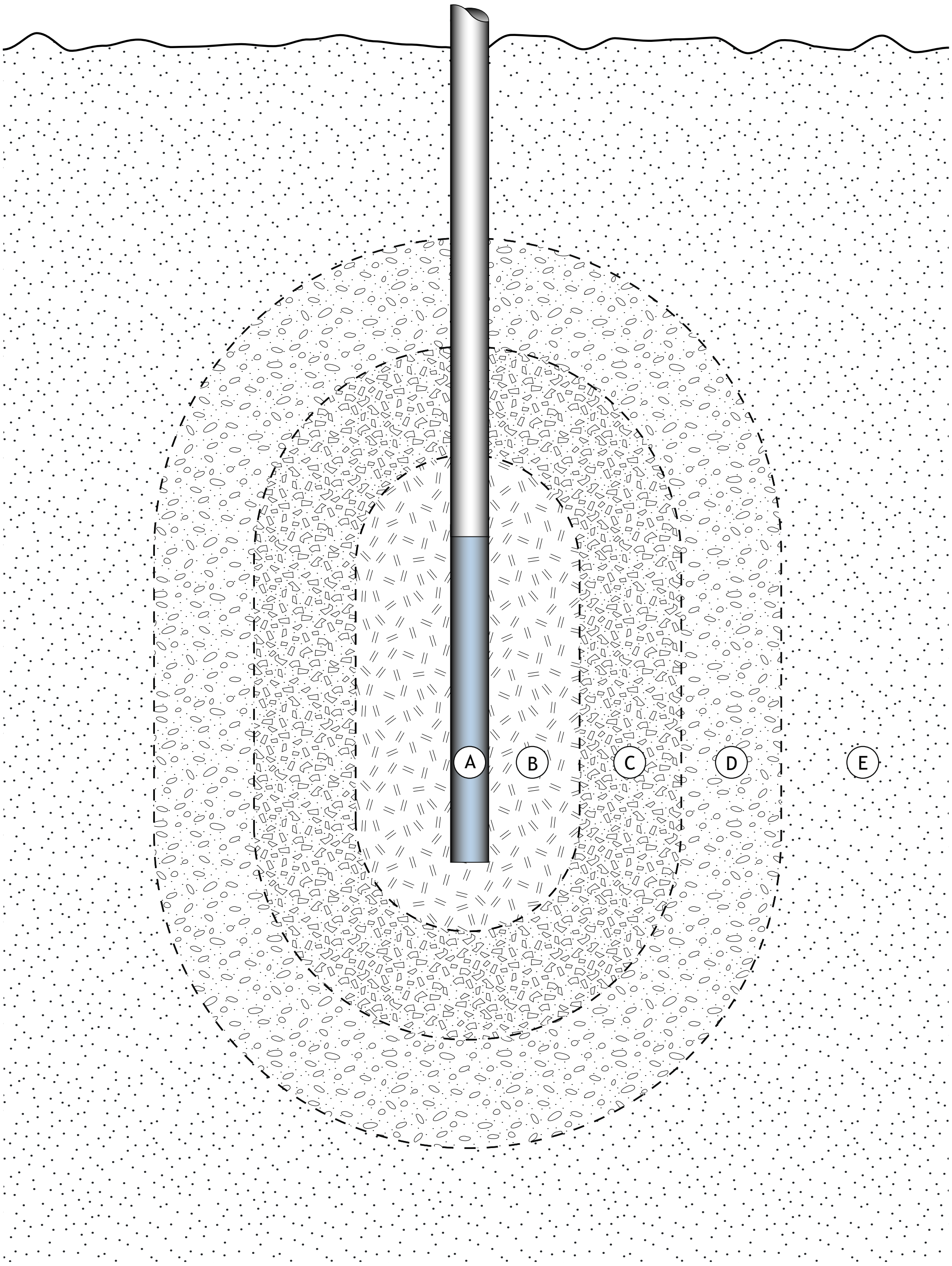


Figure 3. The principle of a high-temperature repository (adapted from Gibb 2000, page 29). A = canister of spent nuclear fuel; B = inner zone consisting of dry, newly crystallized rock that subsequently surrounds the waste; C = zone of metamorphosed, re-crystallized rock; D = zone with rock of higher density after hydrothermal processes in micro-pores etc; and E = unaffected bedrock.

4. Conditions at depths of -3 to -5 kilometres

A report by John Smellie, Conterra AB (Recent geo-scientific information relating to deep crustal studies; SKB R-04-09) summarized what is known about conditions at depths of -3 to-5 km. This study may be taken as an update of a similar report from SKB in 1998 (Juhlin et al. 1998; TR-98-05). The above-mentioned researchers at Sheffield University have published additional data and assessments (cf. Gibb 2000, Atrill & Gibb 2003a, 2003b), as have a multidisciplinary team at Massachusetts Institute of Technology (cf. MIT 2003, pp 53-63.)

As these studies provide useful surveys of the literature on the subject, I have concentrated my evaluation on the most crucial factors for the long-term safety of a high-level waste repository in deep boreholes. First, there are three factors presumed to impede the diffusion of radioactive substances at depths of 3 to 5 km, before proceeding to examine the factors that might facilitate diffusion.

4.1 Factors that impede the diffusion of radioactive substances

Research has shown that the bedrock and groundwater hinder or delay the diffusion of radionuclides at greater depths.

4.1.1 Near-impermeability of the rock

The permeability of rock to groundwater and gases declines sharply at greater depths and can be less than 10^{-16} m/s at extreme depths. These data from deep boreholes in southern Germany correspond well to data from the Kola Peninsula (less than 10^{-16} m/s, measured over a 1 km-wide zone), although differences in the measures prevent direct comparison of the findings. The studies are documented in a report from SKB (R-04-09, pp 9-13).

These low values mean that the areas studied exhibit practically no groundwater mobility at depths of 3 to 5 km. The low permeability at extreme depths is interpreted as due to extreme pressure, forcing existing cracks together so that no open transport routes are available to the groundwater present in micro-cracks and pores. This hampers all migration of water and gases through the rock at depth. By way of comparison we should note that permeability at -1 km is several powers of ten greater in the "upper zone" where subsurface groundwater circulates.

The permeability data presented so far suggests, generally speaking, that it is only in major fracture zones that bedrock at depths of 3 to 5 km will display a degree of permeability that would allow transport of groundwater and gases. Such mobility would, however, be confined to the fracture zone and its immediate surroundings.

Overall, the findings indicating generally low permeability of ordinary bedrock at depths are so congruent that areas of older continental bedrock as predominate in Sweden outside major fracture and fault zones may be presumed to lack mobile groundwater at depths of 3 to 5 km (cf. SKB R-04-09, p 24f). These assumptions are supported by data from deep drilling at Siljan, where the deepest series of data (exceeding 5.4 km, Gravberg 1) indicated very low permeability (cf. Juhlin et al. 1998, SKB TR-98-05, ch. 10). Unfortunately, there are no data for depths between 3 and 5 km at Gravberg or from deep drilling projects elsewhere in Sweden.

4.1.2 The stratification of groundwater

The groundwater in bedrock at levels below 3 km can be so saline, and thus heavier, that it remains density-stratified extremely long periods of time; indeed, millions of years (cf. SKB R-04-09, p 24f). The discovery of this stable stratification over time is important because it indicates that there are extensive, contiguous areas at depths of 3 to 5 km that lack all form of interaction with groundwater at lesser depths, which interfaces with the biosphere.

Stable density-stratification of groundwater over time is a significant safety factor for deep repositories of all kinds. In connection with nuclear waste, the phenomenon was highlighted as early as 1996 in the American study, Deep Borehole Disposition, in an evaluation (Fissile Material Disposition Program) by the U.S. Department of Energy. It first reached a wider audience in Sweden when these findings were included in a survey of deep bedrock research performed by Juhlin et al. for SKB AB (SKB TR-98-05) and summarized, in the following words:

"The chemistry, isotopic character and high gas content shows that these brines have been stable for periods of millions to possibly hundreds of millions of years."

Other, more recent studies confirm these observations (see under "Hydraulic conductivity" and "Hydrochemistry" in the literature review in SKB R-04-09, p 24f). It should also be noted that measurements of several other parameters, including water chemistry and isotopic composition, affirm these findings. Furthermore, there is supportive evidence in the form of fracture minerals and so-called fluid inclusions. The density-stratification of groundwater at greater depths in Sweden has yet to be systematically inventoried. Local data from Gravberg 1 in the Siljan region (Juhlin et al. 1991) and from Laxemar in Småland (SKB TR-01-11) indicate, however, that existing density stratification in both areas has been stable as long as a million years (SKB TR-98-05, p 92).

All in all, research to date shows two things. First, the existence of areas of bedrock with stable density-stratification of the groundwater at great depths, and secondly, that this stratification can prevail very long periods of time. The combination of stable density-stratification and low permeability at depths of 3 to 5 km represents an important safety factor: Even if there should turn out to be fracture zones with high permeability near the repository, the stable density-stratification would significantly hamper all upward mobility of groundwater.

Painting in broad strokes, one might consider the analogy of the density-stratification of sea water that hampers heavier water below the termo-cline (thermo-haline boundary layer) from rising and merge with the subsurface water. In the sea, a certain mixing occurs across this boundary layer over time — but not without some input of energy in the form of wave action or currents. In normal continental bedrock at depths of 3 to 5 km, that is, outside fault zones and areas of recent volcanic or other geothermal activity, there is no energy available for groundwater mobility across any individual density-stratifaction. As a consequence, the density-stratification of groundwater at great depths can remain stable for several millions of years.

4.1.3 Geochemical processes

The high pressure and temperatures at depths are believed to imply a more rapid adsorption (adhesion) of possible leakage from the repository. This is because the increased temperature (60 °C - 105 °C) generally promotes geochemical processes like the formation of fracture minerals. Interestingly, several geochemical studies of such minerals and the gaseous substances contained therein have confirmed the stability of the groundwater stratification at depths of 3 to 5 km (SKB R-04-09, p 25; Möller et al. 1997).

What is more, particularly long-lived nuclides like technetium-99 and neptunium-237 seem to be virtually insoluble in the anaerobic groundwater found at extreme depths (MIT 2003, p 56). Preservation of anaerobic groundwater environments in the vicinity of repositories is therefore an important safety factor. This calls for mindfulness at several stages in the process: in the choice of drilling strategy and technology, canister material,the dimensions of buffer zones, and borehole sealing procedures.

4.2 Factors that facilitate diffusion of radioactive substances

Just as there are rock characteristics at great depths that hamper diffusion of radioactive substances, there are also properties that can facilitate diffusion.

4.2.1 The presence of major cracks, fissures and faults

Cracks and fissures are present everywhere in the planet’s upper crust. Recent research has indicated fracture zones at great depths, as well. In some of the larger zones, mobile groundwater has even been indicated at extreme depths, e.g., on the Kola Peninsula (Popov et al. 1999).

As a safety precaution, therefore, no waste repository should be sited in areas characterized by open fracture zones, even if risk of leakage to the biosphere diminishes, the deeper the waste is deposited. This is because all upward mobility of groundwater at depths of 3 to 5 km are impeded by the greater stability of density stratification at these depths, compared to higher up in the bedrock. Vertical transport of radionuclides from a repository at a depth of 3 to 5 km is therefore considered impossible over any longer distance without input of some kind of energy. This implies that LT-repositories should be given such dimensions as to minimize the heat impact of the high-level waste on the surrounding bedrock (see further, Section 4.2.2).

4.2.2 Heating of the rock surrounding the repository

Some impact on the rock closest to a high-level waste repository is inevitable, due to the ongoing decay process in the canisters. Heat will generated and released for thousands of years, which may result in the development of thermal convection cells in the bedrock, which might set the groundwater in motion, which in turn might facilitate the upward transport of radioactive substances.

Thus, in an LT-repository the density of the canisters in the repository should be kept low. Low density means that the impact on the rock and the density-stratification of groundwater can be confined to a more limited area. A second precondition is that the buffer zone between the repository and the "upper zone" with mobile groundwater is thick enough, cf. Section 3.1.

In the case of a Swedish LT-repository the heat generated and heat impacts on the surrounding bedrock do not imply any major problem, since there are several ways to minimize the impact. First and foremost, the total heat will have been reduced through intermediate storage some 15-50 years at CLAB outside Oskarshamn. Then, there are several ways to adjust the amount of heat generated to match the heat-conductivity of the surrounding rock. The heat can be reduced by packing the most radioactive waste less densely and by leaving a buffering distance between canisters in the boreholes. This latter strategy involves a conflict, however, in that more extensive (as opposed to dense) packing increases the number of boreholes required, which in turn means higher drilling costs.

In the case of an HT-repository, the point is to create enough heat (approximately 800 °C) to partially melt the rock surrounding the repository, which — once the heat has been conducted away — would leave the repository in the midst of a zone of newly crystallized rock that is both dry and free of gases and is surrounded by several additional protective zones (Figure 3). The presumption in all HT-repositories is that the canisters can be placed in close enough proximity as to generate an appropriate amount of heat.

4.2.3 Sealing of the boreholes

The deep borehole concept involves drilling cores to check the properties of the rock and groundwater and wider boreholes to accommodate the storage process. Any borehole represents a risk inasmuch as it may serve as a channel for upward transport of groundwater or gases containing radionuclides to the biosphere.

The decisive factor here is how well the boreholes are capped and sealed. Today there are several procedures that are deemed adequate, so that the problem no longer poses a hindrance to storage in deep boreholes (SKB R-00-35, p 32). In addition, as mentioned above, the density-stratification of deep groundwater hampers upward transport, which suggests that leakage from a waste repository would not get very far. It is therefore crucial that the repository be given proper dimensions so that the heat from the decay process does not convey enough energy to the surrounding groundwater to generate upward migration. Thus, in this connection, too, the density stratification of the groundwater combined with an adequate buffer zone (cf. Section 3.1) is an important factor for safety.

Containment of gases requires more detailed study, albeit the oil and gas industry has accumulated considerable expertise when it comes to sealing holes to contain gas. These industrial methods cannot, however, be simply lifted over and applied to final storage of nuclear waste in deep boreholes since (1) the boreholes must be rendered 'gas-tight' at depths of 3 km and greater, and (2) the time frame in the case of nuclear waste extends thousands of years.

4.2.4 Biochemical influences in the repository

Recent research has found living microorganisms deep down in the bedrock. These organisms can influence the geochemical environment up to temperatures of 115 °C, which is believed to be the limit of tolerance for these forms of life (Pedersen 2001, Sand 2003). Thus, there is a certain potential for bacterial influence on repositories in deep boreholes as the temperature at depths of -3 to -5 km normally does not exceed 105 °C in the kind of older continental bedrock that predominates in Sweden (SKB TR-98-05, pp 63f; SKB R-04-09, p 21). The heat generated by the continued decay of the high-level waste will, however, raise the temperature above the tolerance of the bacteria rather soon after the borehole is sealed, which means that the repository would be surrounded by a zone that is devoid of biological activity.

On the basis of existing knowledge, the influence of bacteria is presumed to be limited; for example, the risk is discounted in SKB's latest study on the subject (SKB R-04-09, p 25). Nonetheless, materials should be chosen so as to prevent bacterial activity that might alter the reducing (non-oxidizing) groundwater environment around the repository.

4.2.5 Changes in connection with future ice ages

The prospect of future ice ages poses a complex of problems for all kinds of repositories in bedrock. First, there are direct risks, e.g., earthquakes and faulting and displacement of the bedrock due to changes in pressure caused by expanding glaciation or melting (see, for example, SKB TR-05-04). Secondly, there are indirect risks in the form of hydrogeological changes as a result of climate change or changes in patterns of groundwater infiltration and drainage channels (cf. SKB TR-99-05). These patterns may, for example, change as a consequence of expansion of permafrost or ice coverage over areas of groundwater infiltration. What is more, such factors might also change the hydrostatic pressure in previous discharge areas. For example, a reduction of infiltration or drainage due to permafrost or glaciation might result in the rise or fall of the interface between subsurface and heavier groundwater (Herbert Henkel, 2005, personal communication).

As it is highly likely that Scandinavia will experience at least partial glaciation before the radioactivity in the high-level waste has dissipated entirely, an ice age scenario implies risks for all kinds of final repositories in Sweden. There is not enough data to permit closer analysis of these risks, save the inference that these risks decline the deeper the repository is located. Above all, there is a need for more data to ensure that final repositories are not located in or near run-off areas or in areas that are likely to become run-off areas after a future ice age (Voss & Provost 2001).

5. Criteria for final storage in deep boreholes

The criteria for establishing an LT repository in deep boreholes include geological, geohydrological, technological and economic/political factors. Taking into account recent research findings, I consider the following nine aspects most important:
1) political and social acceptance of the execution of the project and its costs over the coming 15-30 years;
2) the existence of a sufficiently large area at a depth of 3 to 5 km having groundwater, the density-stratification of which is stable;
3) the availability of reliable technology for measurements and analyses that can localize areas at -3 to -5 km having groundwater, the density-stratification of which is stable;
4) sufficient knowledge of geodynamic and hydrogeological conditions as to permit the identification of areas at depths of 3 to 5 km, where the effects of future ice ages will not impinge on the long-term safety of the repository;
5) the availability of technology for the precision drilling required for both exploration and deposition;
6) the ability to deposit filled canisters and, during the period of deposition, to retrieve canisters in order to exchange them or to test materials and technological solutions;

7) the feasibility of drilling boreholes, depositing the canisters, and sealing all of the boreholes without corrupting the long-term stability of the density-stratification of the groundwater around the repository;
8) the feasibility of storing high-level radioactive waste in canisters for extremely long periods of time so that neither the heat nor the radioactivity generated by the decay process corrupts the stability of the density-stratification of the groundwater around the repository; and
9) the selection of drilling equipment, canisters and sealing materials with a view to avoiding chemical reactions that might give rise to gases in the repository area.

The criteria pertaining to HT storage are very similar in terms of drilling technology, deposition and how the boreholes are sealed, whereas hydrological characteristics of the rock would appear to be less important since the main point of HT systems is to localize a large enough area of suitable host rocks, amenable to melting and recrystallization so as to form protective zones around the repository (cf. section 3.2 above).

6. Can these criteria be fulfilled in Sweden?

It is not yet possible to fully evaluate all risks involved in storing high-level nuclear waste in deep boreholes. More data are needed. But it is possible to use existing functional criteria related to a final disposition in Sweden to analyze and compare the risks associated with different kinds of repositories. For example, it is possible to compare the risks associated with a KBS-3 repository at -500 m with those associated with boreholes at depths of 3 to 5 km. But such comparisons also entail ethical judgments to reconcile present contradictions, such as the strong desire to keep fissionable materials out of human reach versus the advisability of being able to retrieve them, should the need arise. Plus if these aspects should be open for changes in future societies.

Such considerations lie beyond the scope of the present bedrock-related evaluation. The following discussion is therefore limited to the nine above-mentioned criteria and whether and to what extent the concept of disposition in very deep boreholes fulfils them. Moreover, I only consider the LT alternative, as there is not yet enough reference material to evaluate the HT concept on an equal footing.

<u>1) What will be the costs?</u>
Earlier objections to deep borehole alternatives were founded, among other things, on high drilling costs (SKB R-00-28). However, the most recently published estimates for a repository at a depth of 2 to 4 km (SKB R-00-35) notes cost of about 40 million SEK per deposit borehole. Assuming a need for 20-40 boreholes and including anticipated inflation, the total drilling cost for the deposit holes would be less than 2 billion SEK. Adding an estimate for drilling to depths of 3 to 5 km

brings the cost of deposit boreholes up to 3-4 billion SEK. In addition there are costs for the exploratory drilling, which would probably bring the total to at least 5-6 billion. Finally, there are developmental costs, earlier estimated by SKB at app. 4 billion (SKB R-00-28, p 9) and the costs of loading and sealing.

The reliability of these rough estimates must, of course, be checked. Until then, all we can say is that the cost of a repository in deep boreholes will hardly exceed those of a KBS-based solution at a depth of 500 m. A KBS repository also involves greater costs for both encapsulation and future surveillance.

The economy of deep borehole solutions is also noted in the MIT study, The Future of Nuclear Power (MIT 2003), albeit the prime arguments for deep boreholes in that study have to do with safety/security and flexibility with regard to the choice of locality.

Thus, it appears that neither the establishment costs nor operating costs weigh against the deep borehole concept. Particularly the long-term costs for surveillance and security are much lower than for all solutions involving repositories nearer the surface. Instead, we should perhaps expect that HT systems, despite the need for considerable further study, may well be touted as a "low budget alternative", relative to LT solutions and repositories on the KBS model.

2) Are there areas at depths of 3 to 5 km that have groundwater, the density-stratification of which is very stable?

First of all, already existing technology is enough for measuring and analyzing the bedrock to determine whether there is stable, density-stratified groundwater at these depths, as demonstrated by the research programs carried out in southern Germany (cf. for example, SKB R-04-09). This leaves to distinguish areas large enough for a repository by measurements in several exploratory boreholes in the area concerned.

On the basis of existing data, we may presume that stable density-stratification of groundwater is the rule in nearly all continental bedrock of shield character like that predominating in Sweden outside the Scandinavian Caledonides and its flanks. Other exceptions would appear to be areas with major fracture zones. Mobile groundwater has, for example, been found in proximity to such zones in very deep borholes on the Kola Peninsula (SKB R-04-09).

A third risk factor to be borne in mind is the occurrence of mafic dykes (diabases) having geochemically unconsolidated interfaces with surrounding bedrock. In Sweden, most young diabase intrusions are non-metamorphosed and, hence, of that type. Moreover, most are near-vertical and extend to great depths. Consequently, all such mafic dykes form potential planes of weakness in rock that can be activated by even small disturbances. Areas with young, non-metamorphosed diabase intrusions thus imply a higher risk of groundwater mobility at great depths. Concentrations of this type of mafic dykes occur in several parts of Sweden — in Skåne to the south, in the Göteborg region in the southwest, and in a swath across southern Sweden, stretching north-east from Blekinge toward Dalarna. That this risk factor has not yet been taken into account is surprising, particularly since leakage from a KBS-type repository and movements along a subvertical interface at a depth of 500 m would occur within the "upper zone" of the bedrock, where the groundwater is mobile and part of the biosphere.

The extent of the areas in Sweden that are characterized by stable density-stratified groundwater at depths of 3 to 5 km is not yet known. To date only a few deep boreholes have been drilled in Europe as a whole. But, considering that the available data represent geologically complex areas, there is no reason to believe that density-stratified groundwater would be less prevalent in normal Swedish bedrock at these depths — save areas with major deformation zones, young mafic dykes, and near the Caledonides. The facts of the matter can only be determined, however, by a program of exploratory drilling to the depths in question.

It ought to be possible to make general characterizations to define the boundary between subsurface and heavier groundwater via electrical and electromagnetic measurements above ground. These must be followed up, however, with measures taken in exploratory boreholes to determine how stable the density stratification may be. Any assessment of deep boreholes for depositing high-level nuclear waste requires a relatively extensive program of exploratory drilling to ascertain the presence of stable density-stratification of groundwater at depths of 3 to 5 km.

In recent years, the Geological Survey of Sweden (SGU) has published regional inventories of the bedrock, including the occurrence of deformation zones, in most Swedish counties. These summaries provide a useful starting point for selection of promising areas for exploration. There is reason to believe that extensive areas of relatively homogeneous bedrock without mafic dykes exist in many parts of the country.

<u>3) Is there adequate technology for measurement and analysis in very deep boreholes?</u>

The need for technology adapted to measurement and analysis in deep boreholes recurs at several stages. First, to explore and assess the geological and hydrological properties of the prospective repository area requires measurements of several parameters in exploratory boreholes. For reasons of cost, exploration is performed using narrow boreholes. Later, measurements are needed to steer the drilling in the desired directions and, during and after the loading phase, to monitor the performance of the repository.

Here, too, major technological advances have been made in the last few years in the context of comprehensive research programs in Germany, Russia and North America (SKB R-00-35). Published data indicate that there are both instrumentation and a capacity for analysis that a deep borehole project requires. What is more, technological development is a continuing, ongoing process.

Probably the most challenging task from a methodological point of view is the need, when drilling, to avoid contaminating the groundwater to be analyzed, as the drill progresses deeper down into the rock. Adding an isotope "tracer" to the drilling fluid makes it possible to verify the reliability of serial data gathered at different levels in the borehole.

In his report to SKB (SKB R-00-35), consultant Tim Harrison, Deutag/Well Engineering Partners BV, stresses the importance of mindfulness in one's selection of drilling strategy and analytic instrumentation in order to ensure reliable results from each core, thereby keeping the number of exploratory boreholes to a minimum.

4) Do we have enough geodynamic and hydrogeological knowledge to identify areas at depths of 3 to 5 km where the effects of future ice ages will not impinge on the long-term safety of the repository?

As the problems raised by the prospect of an ice age have only been touched on briefly in recent years' documentation (SKB R-00-28, R-04-09) or by general modelling (SKB TR-99-05, TR-04-25, TR-05-04), there remains some uncertainty as to long-term safety, even if the likelihood of direct impacts at depths of 3 to 5 km is minimal. Indirect effects may, however, influence the safety of the repository. The pattern of groundwater may, for example, change so that the interface between subsurface and heavier groundwater rises or falls.

Having consulted experts in the fields of hydrogeology and geodynamics, it is the authors judgment that the evaluation of various risk scenarios will require further, more specific study. Presently, there are some borehole data from Laxemar in eastern Småland that demonstrate density stratification (SKB TR-01-11, pp 143ff) and that the groundwater under a depth of -1.1 km does not appear to have been affected despite repeated glaciation over the past million years (SKB TR-98-05, p 92). It remains, however, to establish how regionally generalizable these local data may be.

The prospect of future ice ages implies that the choice of the depth of a final repository should be based on precautionary estimates as long as there is uncertainty as to how deep the effects of future glaciation may extend. It is, for example, essential to establish that no future ice age scenario implies patterns of groundwater mobility at deeper levels (cf. Section 4.2) so that the mobile groundwater of the "upper zone" might disturb the stratification of the groundwater in the repository area.

In sum, the prospect of future ice ages underlines the need for a sufficient "hydrological buffer zone" between the high-level waste repository and the bedrock above, where mobile groundwater is prevalent (cf. Section 3.1). Further study of glaciation scenarios is also required to determine whether a deep borehole repository should be allowed to extend as high up as 2 km below the surface (Figure 1).

<u>5) Is the requisite drilling technology for wide deposit and narrow exploratory boreholes available?</u>

The answers to this question are crucial to the feasibility of the deep borehole alternative. Several years ago, consultant Tim Harrison of Deutag/Well Engineering Partners BV evaluated various drilling approaches in the light of recent years' experience. Harrison concludes that there are no longer any technical impediments to disposal of high-level nuclear waste in deep boreholes (Abstract p 3):

"It is the author's conclusion that it is possible to drill the well with currently existing technology, although it represents one of the biggest challenges to be presented to the drilling industry."

The conclusions seem well-founded, which is hardly surprising considering that Harrison was one of the team in charge of the drilling program that reached -9 km in southern Germany. The realism in his assessment is also supported by his calculation of the savings (180 thousand euro per borehole) that might be realized by modifying certain dimensions in the drilling plan SKB had proposed (SKB R-00-35, p 45).

Neither does the American evaluation (MIT 2003) point to any major technical problems in executing the drilling program required for deposition in deep boreholes.

All major drilling operators possess technology to allow precision steering of drills at the depths in question here (SKB R-00-35). For example, it is now considered entirely feasible to drill so-called "fanned arrays" of boreholes (Chapman & Gibb 2003), cf. figure 2.

<u>6) Do we have technology that allows safe deposition of the canisters and their retrieval for testing or replacement during the loading phase?</u>

The Harrison report also outlines strategies and technology for the deposition and retrieval of waste canisters (SKB R-00-35, sections 4 and 5). The review leads to the conclusion that proven techniques and equipment can handle both tasks, albeit some apparatus will need to be scaled up relative to the existing equipment used by oil companies (op. cit., pp 41, 44). Some modifications may also be required for retrieval of damaged canisters. Harrison also points out that some adjustments in the procedures and materials specified by SKB for keeping the canisters in place may be required to ensure safe retrieval during the loading phase (pp 43f).

The risks that deposition and retrieval of canisters entail need further study. It would appear that several hazards can be overcome if the borehole is simply sealed after forcing a problematic canister down; then, deposition continues in the next borehole. Such procedure would, however, add to the drilling cost, and more economical procedures might be developed.

The deep borehole concept does not envisage retrieval of the waste canisters once the borehole has been sealed. Given the waste will be physically isolated at depth, there would be no reason for any kind of retrieval. The concept presumes, however, siting in an area where the density-stratification of groundwater may be expected to remain unchanged for thousands of years, a criterion crucial to the long-term safety of this concept.

<u>7) Does available technology permit drilling, loading and sealing of all boreholes without corrupting the density-stratification of groundwater in the area around the waste?</u>

Harrison (SKB R-00-35) covers these aspects, as well. Even if Harrison sees no major hindrances (Sections 3, 4 and 5), more detailed studies are required to optimize the method so that presently conflicting objectives, such as trade-offs between cost and choice of materials, do not compromise the long-term safety of the high-level waste. Among other things, the program of drilling and borehole measurements that will be necessary before and during the deposition needs to be specified.

<u>8) Can high-level nuclear waste be stored in 3 to 5-km deep boreholes long periods of time without the heat and ionizing radiation generated by the decay process impacting on the density-stratification of groundwater around the repository area?</u>

In the case of standard Swedish nuclear waste, this kind of environmental impact would not appear to be a problem (SKB R-00-28). For one thing, the heat remaining in the waste will have diminished to manageable levels in the interval of 15-50 years' "intermediate storage" at CLAB near Oskarshamn. Secondly, there are several ways to steer the heat impact on surrounding rock. The boreholes might, for example, be drilled at enough distance from each other that the heat impact will be negligible. Secondly, heating of the host rock may be moderated so that it matches the conductivity of the rock, i.e., its ability to abduct heat; this may be achieved through the choice of appropriate rock and by packing an appropriate buffer material between the canisters (cf. figure 1). The buffer material has to maintain its volume so as to fix the canisters in place. Here, too, there is a conflict, inasmuch as fewer canisters in each borehole implies higher drilling costs.

All in all, no insurmountable problems are anticipated with respect to the heat and radiation impact (see, for example, SKB R-00-28, for an outline of a possible Swedish LT storage facility). Further specification of the solution is required, however: e.g., the size of the canisters, the selection of buffer materials, and the distance between canisters in the repository.

<u>9) Are there drilling equipment, canister materials and ways of sealing the boreholes that can inhibit the generation of gas in the repository area?</u>
These points, too, need further study. SKB registers no major doubts in SKB R-00-28 other than the observation (p 65) that corrosion of some metals generates hydrogen. These metals should be avoided, as should materials that might impair the anaerobic environment in the repository area, which contributes to safety by hindering the transport of long-lived radionuclides like technetium-99 and neptunium-237 (MIT 2003, p 56).

7. The concept of deep boreholes — a closing assessment

In addition to some uncertainty regarding the risks associated with future ice ages (Section 6, item 4) and with the choice of materials for drilling and sealing boreholes (Section 6, item 7), there is a need to determine if there is groundwater at depths of 3 to 5 km in Swedish bedrock that is sufficiently reliably density-stratified — that is, whether or not the fundamental hydrological precondition for the deep borehole concept can be fulfilled in Sweden. Available data on old continental bedrock of the kind that predominates in Sweden suggests that such density stratification is rather the rule than the exception, apart from areas with major deformation zones, young mafic dykes and in the vicinity to the Scandinavian Caledonides. Actual conditions can only be determined through borehole measurements at the depths in question, however. The feasibility of such measurements and analyses using present technology has been proven.

That no hydrogeological surveys at greater depths have been undertaken in Sweden is somewhat remarkable. For many years now, the two Swedish regulatory agencies — the Swedish Radiation Protection Institute (SSI) and the Swedish Nuclear Power Inspectorate (SKI) — have called for more research and development efforts to explore the feasibility of a Swedish nuclear waste repository in deep boreholes. The authorities renewed their urgings in their comments on SKB's two latest progress reports on their R&D work (the so-called "FUD-reports", published at three-year intervals) in 2001 and 2004. The Government, commenting on Fud-04 (Government decision M2005/3965/Mk, 11 Dec 2005), seconds their view:

"In their comments both SKI and SSI call upon SKB to elaborate on alternative [storage] methods as the time for environmental impact assessments draws nigh. A comparison with the KBS-3 method, that makes use of security analysis methodology, should be made. The Government shares that opinion."

SKBs lack of interest in the deep borehole concept, most recently manifested in FUD-04, is to be lamented. There is one advantage, however, namely that experiences from research teams in other countries are now available. We know, for example, what serial data need to be gathered to evaluate the stability of the stratification of groundwater. Secondly, an arsenal of proven measurement and analytical instrumentation is also now available. Both these factors facilitate give future Swedish R&D efforts.

Whether existing deep boreholes in Sweden can be used for reliable measures of density stratification and so forth remains to be seen. There is a risk that the drilling operations have corrupted the surrounding rock; these holes were, after all, drilled with other purposes in mind. Nonetheless, the possibility is worth looking into. By the same token, the possibility of using very deep lift wells in closed-down mines for this kind of hydrogeological research should also be explored.

As for technological feasibility, after Harrison's report (SKB R-00-35; section 6, above) there would not seem to be any major impediments to establishing a repository for nuclear waste in deep boreholes. Most of the prerequisites seem to be in place (Section 6, points 3, 5, 8), and the remaining technical criteria can most likely be satisfied through traditional R&D (Section 6, points 6, 7, 9). More detailed data is needed to verify Harrison's essentially positive assessments relating to drilling technology. The principal challenge from the point of view of engineering and technology development concerns techniques for loading/packing the canisters into, and retrieval of canisters from, deep boreholes. Relatively large canisters are envisaged. Harrison, who has extensive experience of comprehensive drilling programs at extreme depths, seems to be optimistic about the concept's feasibility although he recognizes it as "one of the biggest challenges to be presented to the drilling industry".

In conclusion: The cost of establishing a repository for Swedish high-level nuclear waste in deep boreholes would hardly exceed those calculated for a KBS-type deposition, with gallery-like tunnels at a depth of about 500 m (cf. point 1 in section 6 , above). Even the development costs seem reasonable compared to the KBS alternative, as the concept can essentially rely on existing drilling and analytical procedures. What is more, the deep borehole alternative can also utilize much of the R&D work that has been done within the KBS program, albeit with certain modifications — in the areas of logistics, canister design, and safety analysis, for example.

Another significant factor that speaks for the deep borehole concept are the considerably lower costs for surveillance and safeguards for final storage in deep boreholes, compared to the costs for any concept that includes retrieval as an option (Swahn 1996, Peterson 1999). This is because retrievability implies some degree of accessibility, which means costs of guarding the repository against intrusion, whether accidental or deliberate. Unauthorized persons must not gain access to any nuclear waste.

On balance, this evaluation shows that recent years' advances in hydrogeology and drilling practices have rendered deep boreholes as an alternative for storage of Swedish high-level nuclear wastes more feasible. Two crucial aspects are (1) identifying localities where a final repository may be created in stable bedrock at levels where the groundwater lacks contact with the biosphere, and (2) the ability to deposit and seal the repository without disturbing the long-term density-stratification of the groundwater around the repository area.

One advantage of deep boreholes, compared to subsurface alternatives like the KBS-3 concept, is that deep boreholes can prove to be technologically more robust as a consequence of the depths the concept affords. In the borehole concept the high-level waste would be deposited in bedrock, the groundwater of which is reliably density-stratified and lacks contact with levels above it, whereas a KBS-3 repository would be surrounded by mobile groundwater that interacts with subsurface levels. This hydrogeological difference has direct bearing on the safety and security of the repository, as scenarios involving leakage from the repository clearly demonstrate. A deep borehole repository at a depth of 3 to 5 km is less vulnerable to impacts from anticipated events (such a changes in groundwater levels during and after future ice ages) and unanticipated events (such as local earthquakes, theft, terrorist attacks and technical malfunction). Decisive, however, is an ability to execute the concept without major failures, and this requires further research and technological development.

It is conceivable that SKB's lack of interest in the deep borehole concept is due to the great amount of energy and resources the company has put into developing its own concept, ever since the KBS method was first presented in the 1970s. Should this disinterest prevail, the only remedy is for the responsible authorities, the Swedish Nuclear Power Inspectorate (SKI) and the Swedish Radiation Protection Institute (SSI), to find another operator to take on the task of determining whether or not the hydrogeological preconditions for the deep borehole concept can be fulfilled in Sweden. In other words: to determine the existence at depths of 3 to 5 km of groundwater in Swedish bedrock that is reliably enough density-stratified. One suitable candidate for an R&D project of this kind is the national authority in geological matters, the Geological Survey of Sweden (SGU).

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