United Kingdom Nirex Limited
Nirex Report no. N/108
June 2004

Nirex Report

A Review of the Deep Borehole Disposal Concept for Radioactive Waste

nirex

Nirex Report N/108

A Review of the Deep Borehole Disposal Concept for Radioactive Waste

June 2004

This report has been prepared by Safety Assessment Management Ltd. under contract to Nirex. The report has been reviewed by Nirex, but the views expressed and conclusions reached are those of the authors and do not necessarily represent those of Nirex.

Conditions of Publication

ISBN 1 84029 353 5

Bibliography

If you would like to see other reports available from Nirex, a complete listing can be viewed at our website www.nirex.co.uk, or please write to Corporate Communications at the address below, or email info@nirex.co.uk.

Feedback

Readers are invited to provide feedback to Nirex on the contents, clarity and presentation of this report and on the means of improving the range of Nirex reports published. Feedback should be addressed to:

Corporate Communications Administrator
United Kingdom Nirex Limited
Curie Avenue
Harwell
Didcot
Oxfordshire
OX11 0RH
UK
Or by e-mail to: info@nirex.co.uk

ABSTRACT

This report reviews the development of the deep borehole concept for the disposal of radioactive waste, from its initial development in the 1970s to the present day, and provides comparisons between this concept and more commonly discussed disposal concepts, such as mined repositories.

The review of the development of the deep borehole disposal concept is divided into two parts – early versions of the concept, which were mainly developed during the 1970s and early 1980s, and later versions that have been considered up to the present day.

A substantial part of the report is based on the work which has been carried out by SKB over many years, starting from a review of the geological, hydrogeological and hydrochemical conditions at great depth to an examination of the methods that could be used to emplace the waste canisters. This review also includes the comparisons that were carried out by SKB between the deep borehole disposal concept and other disposal concepts.

The use of the deep borehole concept for the disposal of excess weapons grade plutonium is reviewed. The majority of this work was carried out in the USA, however much of it was essentially based on the work that had been carried out by SKB.

The report ends with an extensive discussion of the issues identified by the review, the key elements of the concept, important questions regarding the disposal zone, a comparison of different concepts and the R&D requirements in order to take this concept further.

EXECUTIVE SUMMARY

This report reviews the development of the deep borehole disposal concept, from its initial development in the 1970s to the present day, and provides comparisons between this concept and more commonly discussed disposal concepts, such as mined repositories. The issues identified in this review, regarding matters such as the key elements of the concept and important questions regarding the disposal zone, are presented at the end of the report.

The development of the deep borehole disposal concept is divided into two parts – early versions of the concept, which were mainly developed during the 1970s and early 1980s, and later versions that have been considered up to the present day. The majority of the work in this area, with regard to the disposal of SF and HLW, has been carried out either on behalf of the United States Department of Energy (USDOE) or by SKB. In addition, this disposal concept has also been considered, mainly in the USA, for the disposal of excess weapons grade plutonium.

The early work on this concept was based almost exclusively on information derived from the drilling of deep boreholes for hydrocarbons and assumed that the technology at the time, i.e. in the 1970s, was already available for drilling sufficiently deep boreholes at the necessary diameters, or that there would be sufficient technological development over the following twenty years that suitable technology would become available. There was little discussion as to what the practical problems might be when employing this disposal concept, nor was there any real discussion on the levels of uncertainty associated with the understanding of the geology, hydrogeology and hydrogeochemistry of rocks at great depth.

It was not until SKB's programme started in the 1980s that serious consideration was given to what the conditions might be at depth in both crystalline basement and deep sedimentary rocks and what the primary advantages might be of using this disposal concept for the disposal of long-lived waste. SKB carried out extensive work during the 1980s, and more so in the 1990s, on the potential for this disposal concept in crystalline basement rocks, using the increased level of understanding that was being developed due to the drilling of deep and ultradeep boreholes, mainly for research purposes. This drilling also provided more information on the capabilities of drilling techniques to reach the depths and at the diameters necessary for the practical application of this disposal concept. Much of this work was concerned with a comparison of this disposal concept with the other disposal concepts that were being, or had been, considered by SKB, such as KBS-3, WP-Cave, medium long hole and very long hole. SKB's work culminated in the late 1990s with two reports, one of which considered the extent of the R&D programme that would be necessary to bring the deep borehole concept up to the level of understanding and development of the KBS-3 concept, and the other in which a systems analysis of the concept is reported.

The 1990s also saw an increased interest in the use of the deep borehole concept for the disposal of excess weapons grade plutonium. The majority of this work was carried out in the USA, however much of it was essentially based on the work that had been carried out by SKB.

More recently, there has been a revival in interest in the use of the deep borehole concept, with alternatives to the normal definition of the concept being suggested, including, for example, the melting or partial melting of the host rock by the waste or the re-use of former hydrocarbon wells.

The report ends with an extensive discussion of the issues identified by the review, the key elements of the concept, important questions regarding the disposal zone, a comparison of

different concepts (specifically between this concept and a conventional mined repository) and the R&D requirements in order to take this concept further.

It is important to emphasise that, although consideration has been given to this disposal concept over a period of many years, no practical demonstration of the application of this concept has taken place. It is also likely that considerable sums of money would be required before it could be brought up to the same level of understanding that already exists for the several different types of mined geological disposal concept that are currently proposed by waste disposal organisations world-wide.

LIST OF CONTENTS

1 INTRODUCTION

The excavation of a deep repository using standard mining or civil engineering technology is limited to accessible locations (*e.g.* under land or near the shore), to rocks that are reasonably stable and without major groundwater problems and to depths of less than about 1000 m. Below 1000 m depth, excavation becomes increasingly more difficult and correspondingly expensive. The present maximum mining depth is in excess of 3000 m for gold mines in South Africa although, at that depth, there can be serious stability problems. The capability of drilling deep boreholes has continued to improve, in particular as a result of technical developments to support the petroleum industry, but also in other areas such as the drilling of super-deep research boreholes, *e.g.* the KTB project in Germany in which a borehole to 9000 m depth was drilled close to the Rhine Graben [1]. In the oil industry boreholes are readily drilled offshore as well as onshore, through unstable rock units, and can deal with high pressure fluids and can penetrate to depths of more than 10 km. This capability to drill to great depths significantly expands the range of locations that could be considered for radioactive waste disposal and could include geological settings which might have advantages in terms of environmental effects or long-term safety over those suitable for a mined repository.

This report reviews the development of the deep boreholes disposal concept to the present day. As a concept, it has always been subsidiary to the more conventional mined geological repository and, although it has been considered in several different countries for the disposal of long-lived waste, sometimes over many years, in comparison it has never been selected as an option for disposal. During the 1990s the concept was investigated for the disposal of excess weapons-grade plutonium and more recently it has been considered in a variety of forms, including the disposal of heat-emitting waste in schemes which involve the melting or partially melting of the host rock. Its most promising use may be for countries which have only small volumes of waste for disposal and where such a concept might prove more suitable than the construction of a mined repository.

It is important to emphasise that, although consideration has been given to this disposal concept over a period of many years, no practical demonstration of the application of this concept has taken place. It is also likely that considerable sums of money would be required before it could be brought up to the same level of understanding that already exists for the several different types of mined geological disposal concept that are currently proposed by waste disposal organisations world-wide.

2 DEVELOPMENT OF THE CONCEPT

The concept of the disposal of radioactive wastes in deep boreholes was initially proposed for the disposal of High Level Waste (HLW)/Spent Fuel (SF) at depths of several kilometres in crystalline rocks. The first such suggestion was probably made in the United States of America in 1974 as one variant of a range of geological disposal concepts that were being considered in the early days of the HLW disposal programme in the USA [2]. The disposal of both solid and liquid HLW was considered, including melting of the rock mass, the disposal of waste at the base of a very deep borehole in a mined cavity and disposal in deep boreholes and extremely deep boreholes to depths of up to 16,000 m. The concept of most relevance to this review consisted of a matrix of very deep boreholes drilled to 6000 m depth and spaced several hundred metres apart, with waste being disposed in the lower 4500 m of each borehole. The concept was further developed in the USA [3] [4] [5][1], with [6] representing the most significant study up to that date. At the same time in the USSR disposal of liquid radioactive waste was taking place at sites such as Mayak and Krasnoyarsk, where liquid Intermediate Level Waste (ILW) and Low Level Waste (LLW) was being injected into aquifers, following the principles set in the USA and Germany for the disposal of liquid hazardous waste into sedimentary rocks and evaporites. The majority, but not all, of the boreholes used for liquid waste injection in the USSR were, however, not very deep. The United States Department of Energy (USDOE) considered several different disposal options in the late 1970s, including disposal in deep boreholes or deep shafts [3]. In considering the concept of deep disposal, two major tasks were performed:

> The definition of the state of knowledge regarding the geotechnical and geophysical attributes of the earth's crust to depths of 10-15 km;
>
> The identification of the state of the art and an estimate of the probable technological development by the year 2000 in drilling a deep borehole or in sinking a deep shaft.

What was meant by very deep was dependent on the geology of a specific site, but probably implied depths of up to 10 km. It was concluded at the time that it would be possible by the year 2000 to drill boreholes with a diameter of 1.2 m to a depth of 4.3 km and boreholes with a diameter of 3 m to a depth of 3 km. Criticality was considered an important issue in disposing of HLW in such boreholes, however it was thought that sealing the boreholes would not prove too difficult, as there was evidence of the successful sealing of oil boreholes against high gas pressures over many decades. The consequences of not sealing a deep borehole successfully were, however, appreciated and it was even considered that monitoring devices could, perhaps, be installed behind such seals. Numerous development needs were specified, but the general conclusion was that there did not appear to be insurmountable obstacles to the development and application of such a disposal concept [3].

The USDOE report [4] considers the disposal of waste at depths of up to 10,000 m in boreholes in either crystalline or sedimentary rocks in tectonically stable areas. It compares and contrasts this disposal concept with others, such as sub-seabed disposal and space disposal, as part of the Environmental Impact Assessment of the disposal of HLW, which was produced as one of the final reports of the then DOE-funded radwaste programme in the USA.

At the same time in the UK an initial assessment was taking place of the different methods that could be used for the disposal of long-lived radioactive waste in the UK up to the year 2000 [7]. This report summarises the work that had been carried out in many countries on disposal concepts and includes the work in the USA on deep borehole disposal. Five

[1] This is synonymous with [6].

different disposal concepts were considered for the UK, including what was termed *deep drilling boreholes*, in which boreholes (or perhaps shafts, it is not clear) could be drilled with diameters of 8 to 10 ft to depths of several miles. It was envisaged that:

> 250 *packages*[2] of waste a year would be generated by the UK civil nuclear programme.
>
> 20 packages would be placed in each hole at 30 ft intervals.
>
> An area of 10 acres would contain between 200 –300 boreholes each 2 miles deep and 8-10 ft diameter.
>
> This would be able to deal with the anticipated amount of waste up to the year 2000.

Five questions were posed:

> Are there suitable geological areas in the UK?
>
> What is the cost of drilling such holes?
>
> Will it be necessary to sleeve (*i.e*. case) such holes?
>
> What method of backfilling would be used to keep groundwater out of the holes?
>
> Is the land above the holes usable for agricultural purposes?

It is unclear where the design of this disposal concept came from, as it clear that it would be impossible to accommodate such a large number of deep vertical boreholes in such a small area. There does not seem to have been any follow-up to this work in the UK.

In Switzerland [8], Denmark (Figure 1) [9] and Sweden (Figure 2); [10] subsequently used as input to the PASS (Project on Alternative Systems Study) [11] similar research was also carried out on this disposal concept. Potential host rocks included intrusive igneous (*e.g.* granite), crystalline metamorphic, and shale or salt (bedded or domed) formations. The Danish concept envisaged very deep boreholes into a salt dome for the very small volumes of long-lived waste involved, as illustrated in Figure 1, and the Swedish concept consisted of boreholes into a granitic or crystalline basement host rock, in which waste canisters of HLW/SF 4.4 m long and 0.5 m in diameter would be emplaced in the bottom 2 km of 4 km deep boreholes with a diameter of 0.6 m (*e.g.* [11] Figure 2). There was also interest in this disposal concept in the Netherlands, at least up to 1989, where boreholes up to 2500 m depth were considered as an option for the disposal of HLW in salt domes [12].

Alternative concepts to that of placing the waste in specific locations in deep boreholes and sealing the waste *in situ* using normal backfilling and sealing materials have been proposed for the deep geological disposal of radioactive waste that utilises the heat from the waste to melt the host rock [13] [14] [15] [16] [17] [18] [19] [20] [21] [22]. These schemes, often referred to as "deep rock melting" (DRM), are most appropriate for high heat generating wastes such as SF, fuel reprocessing waste and high heat radionuclide streams from partitioning and transmutation [23]. However, some do allow for the co-disposal of non- and low-heat generating wastes such as Pu. Some proposals, such as the "deep self-burial" schemes of Logan [13] [14], involve capsules filled with waste sinking through the melted host rock whilst others envisage the waste, whether encapsulated [24] or otherwise [15], remaining static.

Research on the concept of deep borehole disposal has continued, in particular in Sweden, where the concept was under consideration by SKB, at least up to 2000[3]. Joint work in this area between Posiva and SKB ceased in 1996, when Posiva decided not to continue with this option in parallel with the KBS-3 concept [25].

---

[2] This term is not explained in the report.
[3] The current state of work in Sweden on this concept is discussed in Section 4.3.

Interest in the use of deep boreholes for disposal purposes is now believed to be confined to:

Their potential use for the disposal of SF in Sweden, so as to continue the development of an alternative to the KBS-3 concept (see Chapter 4 for further details).

The potential use of such boreholes for the disposal of weapons plutonium [26] (see Chapter 5).

A similar possible use for the disposal of civil plutonium [27] (see Chapter 5).

Their potential use in Japan as part of NUMO's concept development programme which is taking place in parallel with their site selection programme. Although no specific disposal concepts, in addition to the concept presented in H-12, are specifically listed, NUMO do make reference to the studies carried out in Sweden and refer to their programme of work as being analogous to Projects PASS and JADE[4] [11] [28] [29] [30] [31].

The use of very deep boreholes for the disposal of heat-emitting waste at depths in excess of 4 km, where the intention is to cause partial melting and recrystallisation of the rock around the waste. Work is currently being funded by BNFL [20] [21] (see Chapter 6).

Most recently, [32] suggest that the concept of deep borehole disposal needs to be considered more generally for the disposal of fissile material and for countries with small nuclear power programmes and that this disposal option may well have more advantages than disadvantages when compared with mined repositories (see Chapter 6 for discussion).

[4] Project JADE involved comparison of repository systems [28].

Figure 1 Schematic diagram of deep borehole concept suggested in Denmark for the disposal of small volumes of HLW in a salt dome (from Elsam & Elkraft [9]).

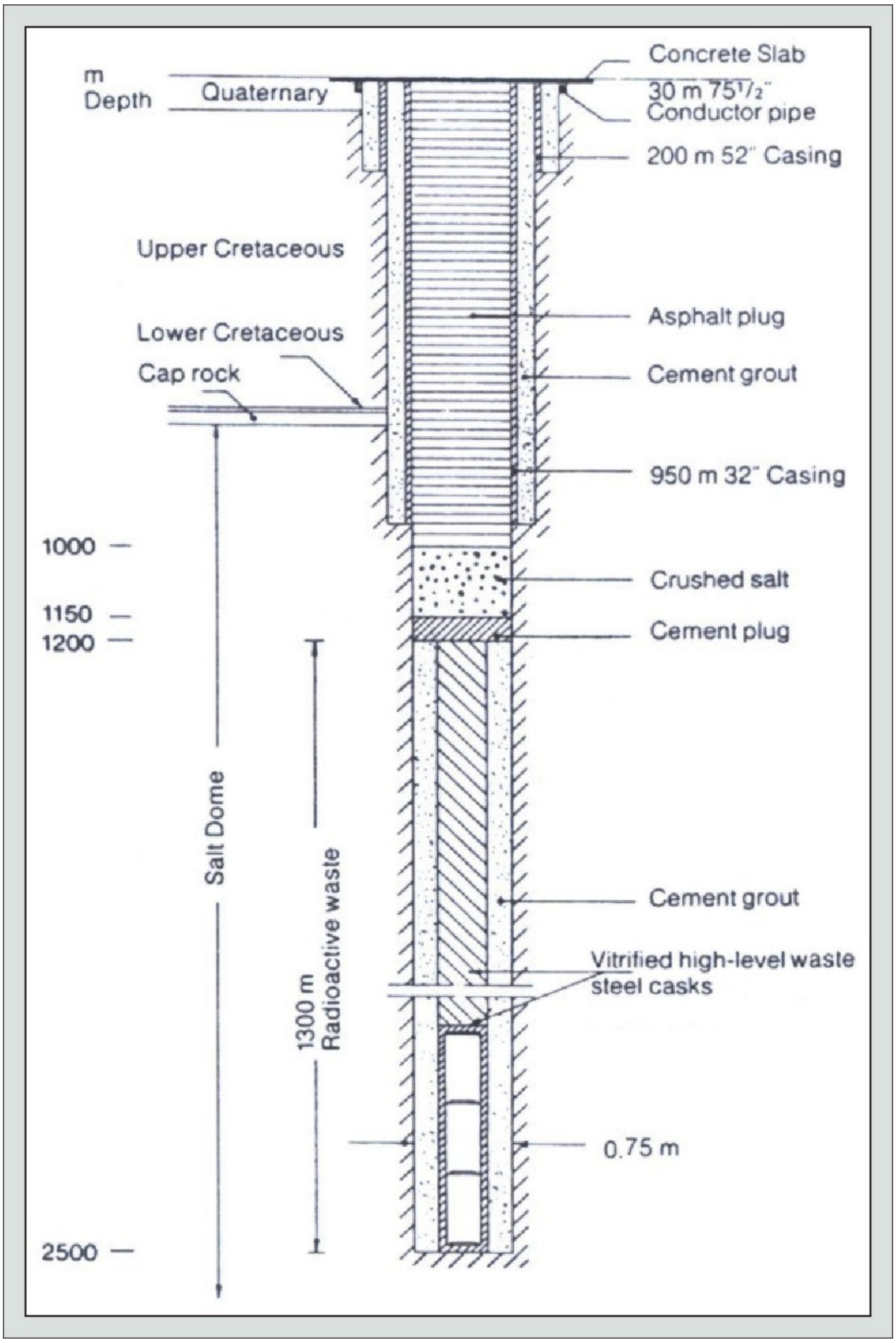
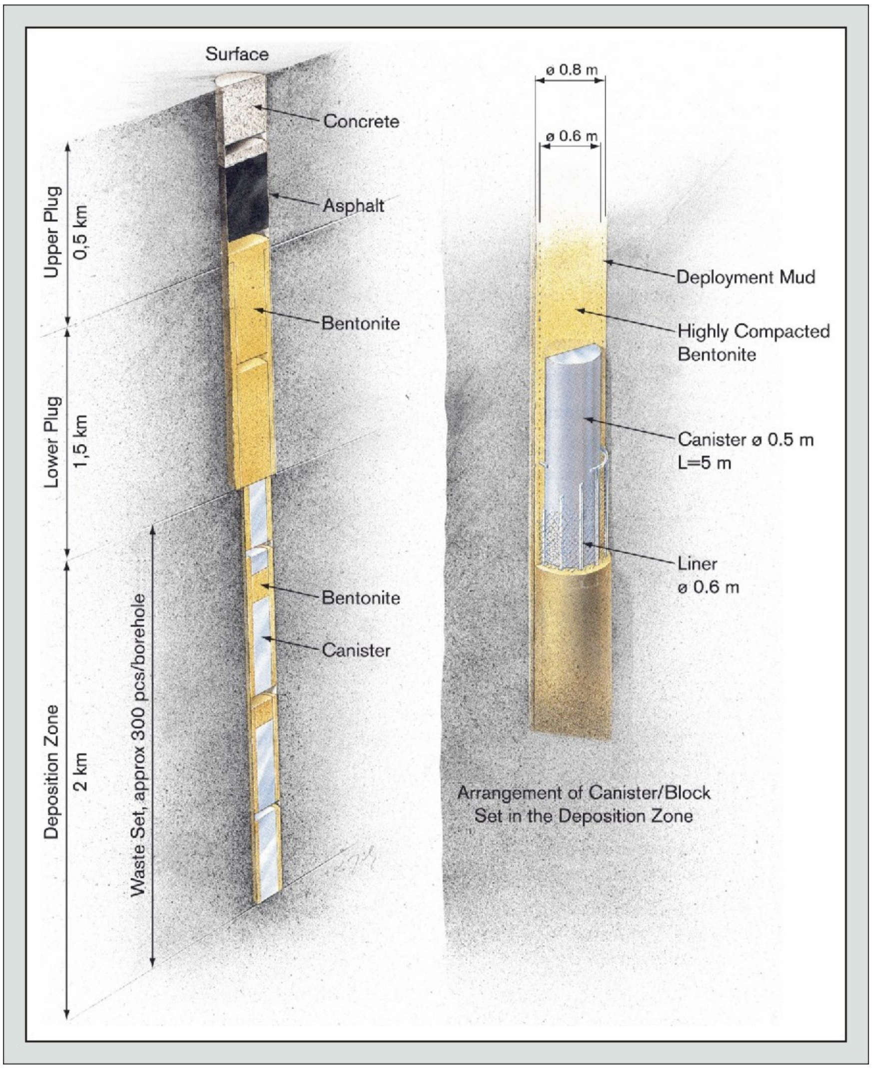


Figure 2 The deep borehole disposal concept, as presented by SKB in their PASS Project [11].



Key to Swedish text: Deponeringszon = Disposal zone; Nedre förslutning = Lower seal; Övre förslutning = Upper seal; Avfallskapslar, ca 300 st/borrhål = Waste capsules, approximately 300 per borehole; Markyta = Ground surface; Betong = Concrete; Asfalt = Asphalt; Bentonit = Bentonite; Kapsel = Capsule; Bentonitslurry = Bentonite slurry; Högkompakterad bentonit = Highly compacted Bentonite; Kapsel = Capsule; Infodring = Lining; Detalj av kapsel/bentonit = Detail of capsule/bentonite in the disposal zone.

3 REVIEW OF DEEP BOREHOLE CONCEPTS

3.1 Early disposal concepts

Early deep borehole disposal concepts were developed as part of the USDOE programme, which commenced in the 1970s, to investigate the disposal of HLW. Closely following on from this work was a limited amount of work as part of an EC-funded programme on the disposal of HLW, which included some work in Denmark on the disposal of long-lived waste in the Mors salt dome in deep boreholes [9]; (Figure 1).

3.1.1 Early work in the USA

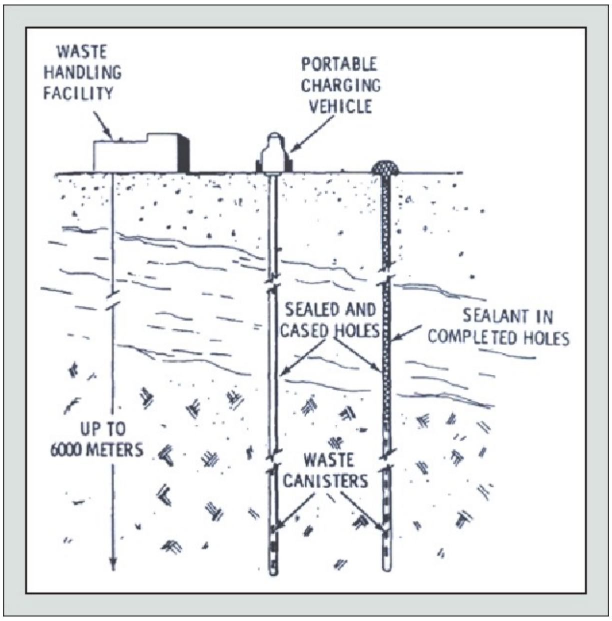
Information on the disposal concepts considered in the USA is presented in [2] and subsequent to that in reports such as [4], and much of the work was carried out by contractors to USDOE who also published their work in reports such as [3]. The deep borehole concept was compared with the other concepts that were also being considered at the time, which included disposal in space and beneath the seabed, as well as more conventional mined repository concepts. Following this initial analysis, the three disposal concepts that were taken forward to the next stage of analysis were what were termed *mined geologic*, *very deep hole* and *sub-seabed* disposal.

It was believed that the main potential advantage of the very deep borehole concept was that its use would place waste further from the biosphere in a location where circulating groundwater was unlikely to communicate with the biosphere. It was appreciated at the time that this would not be an appropriate disposal route for the larger volumes of TRU (*i.e.* ILW in UK parlance) and that there were uncertainties as to whether it would be possible to drill the number of boreholes required to the depths and sizes suggested.

A distinction was made in the USDOE work between the two concepts of *very deep borehole disposal* and *rock melt waste disposal*, however both of these are considered here, at least initially, as the second of these concepts is similar in some respects to the work currently being carried out by Attrill & Gibb [20] [21] in the UK. Only the very deep borehole concept appears to have been taken forward to the next phase of assessment by USDOE, however, there do not appear to be any published reports in the USA that report on any later comparison of concepts. Further work was carried out in the USA on the deep borehole concept, subsequent to the EIA published in 1980 [4], to examine the technical feasibility of the drilling technology and the likelihood of suitable technology being available in the twenty years from 1980 [5]. No further work, however, appears to have taken place in comparing this disposal concept with other concepts and, sometime in the 1980s in the USA, this concept seems to have been discarded.

The three deep borehole concepts discussed in [4] are illustrated in Figures 3 to 5, together with explanatory text. Very little information was provided as to how the waste would be emplaced, other than to suggest that the techniques that had been developed by the oil industry would be employed.

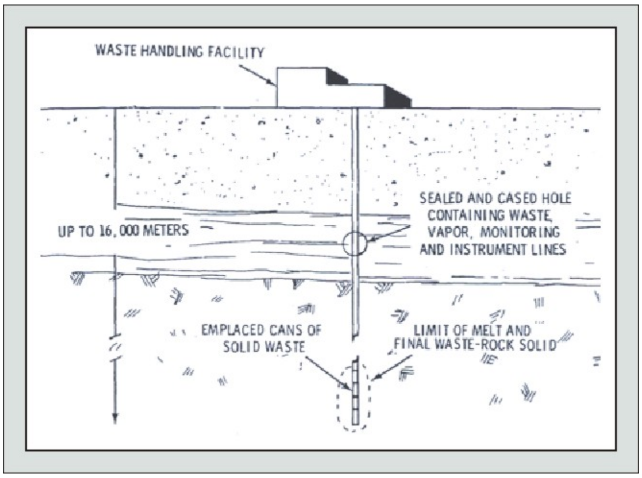
Figure 3 Disposal concept referred to as: Solid waste emplacement in a matrix of drilled holes – no melting (from Schneider & Platt [2]).



The characteristics of this disposal concept were, according to [2]:

Waste Form:	High-integrity solid waste form and canister.
Waste Concentration:	High in waste form; high to low when canister fails. Hole spacing is flexible.
Operational Features:	Surface operations only. Relatively simple.
Candidate Geological Environment:	Might include intrusive igneous, crystalline metamorphic, or possibly shale or salt (bedded or domed) formations.
Retrievability:	Moderately difficult for initial period (up to about 100 years); more difficult with time; might require overboring technology beyond current state-of-the-art.
Monitorability:	Limited; can measure temperatures and released radioactivity within holes for limited time; can detect radioactivity in nearby water-bearing formations if it should occur.
Extent of Knowledge:	Fair. Hole drilling is generally state-of-the-art. Exceptions are long-time proven cementing and casing systems and some hole diameter-depth limits.
Isolation:	Moderately deep to deep geologic isolation, 3000 to 6000 m, or nominal reasonable drilling depths. Depends considerably on effective manmade sealing of numerous manmade penetrations into holes.
Possible Pathways to Man's Environment:	Natural pathways such as fractures if flowing water present, volcanism, seismic activity, erosion, *etc.* Pathways attributed to man's actions such as drilling into repository, sabotage, *etc*.

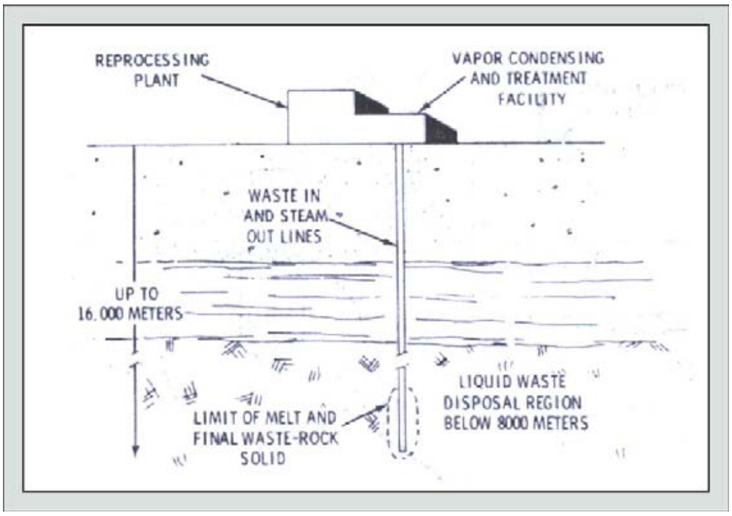
Figure 4 Disposal concept referred to as: Solid waste emplacement in a deep hole with in-place conversion to a rock-waste matrix (from Schneider & Platt [2]).



The characteristics of this disposal concept were, according to [2]:

Waste Form:	High integrity solid waste form and canister. Rock-waste matrix for melting case.
Waste Concentration:	High in waste form; high to low when canister fails.
Operational Features:	Surface operations only. Very difficult to drill to great depth.
Candidate Geological Environment:	Might include intrusive igneous or crystalline metamorphic formations.
Retrievability:	Difficult for initial period (up to about 20 years); very difficult to non-retrievable thereafter. Requires overboring technology beyond current state-of-the-art.
Monitorability:	Very limited; can measure temperatures and released. Radioactivity within holes for limited time; can detect radioactivity in nearby water-bearing formations if it should occur. Can monitor surface support.
Extent of Knowledge:	Limited; hole depth beyond current state-of-the-art in many rocks. Melt-down and cooling knowledge is largely inferred.
Isolation:	Very deep geologic isolation from surface, below about 7000 m. Depends partly on effective manmade sealing of moderate number of manmade penetrations
Possible Pathways to Man's Environment:	Natural pathways such as fractures if flowing water present. Volcanism, seismic activity, erosion, *etc.* Pathway attributed to man's actions such as drilling into repository, sabotage etc.
Other:	Ability to control melt stage must be predicted before starting melt.

Figure 5 Disposal concept referred to as: Liquid waste emplacement in deep hole – In-place drying and conversion to rock-waste matrix (from Schneider & Platt [2]).



The characteristics of this disposal concept were, according to [2]:

Waste Form:	Aqueous waste during emplacement; rock-waste matrix after in-place melting and solidification.
Waste Concentration:	High as liquid; moderate to high as final solid.
Operational Features:	Surface operations only. Surface vapour condensing and recycle system. In-place, self-conversion to melt; eventual self-cooling to solid.
Candidate Geological Environment:	Might include intrusive igneous or crystalline metamorphic formations.
Retrievability:	Essentially not retrievable.
Monitorability:	Limited; can measure some temperatures and released radioactivity within parts of hole for limited time; can detect radioactivity in nearby water-bearing formations if it should occur. Can monitor surface support.
Extent of Knowledge:	Limited; hole depth beyond current state-of-the-art in many rocks. Melt-down and cooling knowledge is largely inferred.
Isolation:	Deep geologic isolation from surface, below about 6000 m. Depends upon mobility of molten column of rock-waste; depends partly upon effective manmade sealing of modest number of manmade penetrations.
Possible Pathways to Man's Environment:	Natural pathways such as fractures if flowing water present, volcanism, seismic activity, erosion, *etc.* Pathway attributed to man's actions such as drilling into repository, sabotage, *etc.*
Other:	Ability to control melt stage must be predicted before starting melt.

3.1.2 Later work in the USA

A more comprehensive study of the deep borehole disposal concept was carried out in 1981 by Woodward-Clyde on behalf on ONWI (Office of Nuclear Waste Isolation) [5] [6] and the whole of Chapter 3.1.2 is based on this report. A general assumption for the study was that the technology for disposal was that that would be required by 2000 (the earliest assumed date for disposal), and certain extrapolations were made regarding the capabilities of drilling systems, in particular (see comments on this approach from SKB in Chapter 4 of this report).

The disposal concept was based on the assumption that radionuclides dissolved in groundwater would have decayed to “innocuous levels” before they reached the biosphere if:

The movement of groundwater is very slow and the flow paths are very long.

The amount and rate of supply of radionuclides to the groundwater is very low.

The radionuclide movement is retarded by chemical interactions with the rocks along the very long flow paths.

The combination of these factors isolates the radionuclides from the biosphere until their radioactivity has decayed to a safe level.

The concepts of *containment* and *isolation* of the waste were defined slightly differently for this concept compared to those associated with a conventional mined repository, in that the containment was redefined to include the whole of the repository zone and not just the waste package, as in the case of a mined repository. The isolation provided by this concept was considered to be provided by the borehole plug (the *isolation plug*) and by the great depth and integrity of the host rock (see Figure 15).

A significant effect that needed to be considered was that of the thermal output from the waste, however, it was proposed to use waste loadings within individual disposal boreholes that would ensure that the temperature rise was the same at in a mined repository and to separate the boreholes by a sufficient distance that their individual thermal fields did not interact.

Two different types of deep disposal concept were envisaged (Figure 6):

One that was *different in degree* from a mined repository, *i.e*. disposal would take place at a greater depth but still, however, in a geological and hydrogeological environment that was similar to that considered for a mined repository.

One that was *different in kind*, in that the waste would be disposed at a depth where the rock would behave semi-plastically so that all groundwater flow would be eliminated.

At the time of the report there was no relevant experience of drilling boreholes in competent rocks to depths where the deformation was semi-plastic and it was concluded that it would take an unreasonable amount of R&D effort to demonstrate that the different in kind concept should be taken any further. An essential difference between the deep disposal and mined repository concepts was that the deep borehole concept would rely to a considerably greater extent on the geological barrier, but that with a stable hydrogeological environment at depth, and one in which there was no upward hydraulic gradient, there should be negligible thermal perturbation to the regime caused by the waste and, therefore, no transport of radionuclides towards the biosphere.

The attributes of the deep disposal concept were stated to be:

Technology had to be available by 2000.

The capacity for developing a sufficient database to allow the concept to be accepted.

Slow moving groundwater and very long flowpaths at depth.

Retardation of the release of radionuclides to the groundwater from the waste.

Isolation of the radionuclides from the biosphere.

Minimal thermal impact.

Potential applications to a diverse range of geological environments.

Limited work force and equipment at the surface.

The isolation of radionuclides from the biosphere, dominantly by the geological barrier, was stated as being the most positive attribute of the deep borehole concept.

Some key issues and considerations were defined during the development of the deep borehole concept in the USA, some of which it was thought would influence its acceptance These issues and considerations were identified in [6] as:

Multiple barriers – generally the same barriers as those in a mined repository, but where the hydrogeological regime is less dynamic and more stable than one associated with a mined repository.

Borehole/shaft stability – needs to be stable during the whole period of waste emplacement and subsequent plugging and sealing procedures.

Retrievability – this is not considered necessary, partly because it was not considered that any corrective action would be necessary once the waste had been emplaced and the boreholes sealed, and partly because it was considered unfeasible.

Isolation – in a suitable geological environment this was considered to be effectively guaranteed by the depth of waste emplacement and the low energy environment at depth.

Containment – the concept was envisaged as relying on containment for about 1000 years within the repository zone.

Waste form and package – the waste package would need to be suitable for handling purposes and be compatible with the other components of the disposal system and the geological environment.

Ability to characterise the down-hole environment – it was admitted that this concept was at a distinct disadvantage compared with a mined repository, but it was considered that a database could be developed that would provide sufficient information on the conditions at depth.

Site selection guidelines – these were considered to be somewhat similar to those applicable for a mined repository.

Feasibility of geological environments – it was considered that the deep borehole concept could be developed in a larger variety of geological environments and that more areas of the USA had suitable environments than those considered suitable for a mined repository.

Repository and facilities – the facilities required would be less than those required for the mined repository, especially as there would be no requirement for personnel to go underground.

Database – the concept has key issues, technical considerations and attributes that are different from those of a mined repository, however it was possible to develop a workable reference system that adequately addresses these.

The performance objectives set for the deep disposal concept were similar to those applicable at the time for a mined repository, and were in fact stated in such a way as to require similar levels of safety during the operational and post-closure phases. The significant differences identified between the two types of disposal concept were in two areas:

> A requirement for the deep borehole concept to contain the waste within the repository zone during the period when radiation and thermal output are dominated by fission produce decay.
>
> A requirement for a minimum depth for the deep borehole concept, so that containment could be defined within the repository zone for a sufficient period, in comparison with the mined repository concept where containment is achieved by the waste canister, (this also required that the geometry of the repository zone would need to be defined).

A reference deep disposal system was defined by Woodward-Clyde [6], as listed in Table 1, and Figure 7 illustrates the reference borehole design, showing the disposal zone from 10,000 – 20,000 ft (approximately 3000 – 6000 m). The capability to drill to 6000 m with a bottom hole diameter of 20 in (0.6 m approx.) was claimed to be within the then current drilling capabilities. The maximum depth was also constrained by the stability of the borehole, with a borehole containing heavy weight drilling mud being stable in crystalline basement to a depth of approximately 6000 m[5]. The plan was to use what was termed big-hole drilling in the uppermost 4000 ft (1200 m) and then to use conventional rotary drilling to the final depth. These assumptions implied that:

> For the case of SF, 850 canisters would be emplaced in each borehole, equivalent to 527 MTHM (Metric Tons of Heavy Metal), so that for a system capacity of 68,000 MTHM, 128 boreholes would be required.
>
> For the case of HLW, 850 canisters would be equivalent to 1785 MTHM and 38 such boreholes would be required.

Two thermally-induced effects were noted, the generation of thermomechanical stresses and an increase in temperature in and around the disposal zone. There appears to be no mention of the effect of thermally-induced groundwater flow and radionuclide transport.

These thermal loadings would produce temperatures greatly in excess of what has been considered as acceptable in any European disposal programmes (Table 2), although these would still be below the maximum acceptable temperatures for the waste forms. Modelling of the temperature rise (carried out only for HLW) indicated that the maximum expected temperature rise at the borehole wall would be 175°C which would take place approximately 3.5 years after emplacement (Figure 8). This calculation assumed a canister string of 10 year old HLW, with an initial power loading of 2.6 kW per canister, with decay rates and thermal properties of the rock being taken from published literature. The far-field temperature rise within 1000 years was stated to be negligible at radial distances in excess of 100 m. The expected ambient temperature in the disposal zone would be likely to lie in the range 85 - 160°C (assuming a geothermal gradient of 25 °C km^{-1} and a mean surface temperature of 10°C), so that the actual maximum temperature could lie in the range 260 - 335°C approximately.

[5] The report uses the units that were prevalent at the time in the oil drilling industry, such as *ksi* (1000 pounds per square inch) and drilling mud weights in pounds per US gallon, and it is difficult to convert these to modern metric units.

Table 1 Summary of reference deep borehole disposal system (from ONWI, [5]).

Attribute of the system	Description
Waste characterisation	10 year old: 0.69 kW per canister SF and 2.6 kW for HLW; canister 32 cm diameter, length 3.05 m
Site	– Part of large pluton with low relief, tectonically stable, minimal mineral resources – Relatively simple homogeneous granite with high strength, favourable thermal characteristics no major discontinuities – Simple groundwater flow and low hydraulic gradient – σ_v (vertical stress) equal to overburden pressure, σ_h (minimum horizontal stress) assumed to have maximum of $1.33\sigma_v$ and minimum of $0.67\sigma_v$ – geothermal gradient of 25°C km^{-1}
Surface facilities and equipment	Canister receiving facility; radioactive waste storage facility etc.; borehole rig (conventional rotary drill rig modified to reach required depth); borehole design as in Figure 7; borehole spacing 0.8 km at surface and lateral separation of disposal zones a minimum of 180 m
Emplacement facility	Rail vehicle transporter; emplacement rig
Borehole plug	Alternating tremied[6] sequence of bentonite pellets, gravel slurry and grout
Monitoring	Prior to decommissioning Normal environmental monitoring thereafter

Table 2 Maximum allowable and expected temperature increase (°C) for the deep borehole disposal concept for SF and HLW [5].

Waste type	Waste	Canister wall
Maximum allowable temperatures (°C):		
SF	700	375
HLW	500	375

Expected temperature increases	Pre-emplacement	Post-emplacement
Only determined for HLW	150	325

[6] Tremied means that the pellets were vibrated into position.

Thermomechanical stresses were calculated for the geometry of a long cylindrical heat source. These demonstrated that, whilst the induced stresses around each borehole would be negligible compared with the *in situ* stresses, significant tangential stresses would be induced to large distances above the disposal zone. The superimposition of the induced tensional stresses with the *in situ* stresses resulted in a net tension above the top of the disposal zone for a distance of approximately 400 m (Figure 9).

The borehole spacing was based on the assumption that although drilling tolerances of approximately 1-2° from the vertical could be achieved, a worse case assumption of a 3° deviation combined with a 1° uncertainty would be applied; so that two adjacent boreholes each deviating 4° from the vertical would need to be separated by approximately 0.8 km at the surface in order to prevent their intersection. This resulted in an area for disposal of approximately 10.9 x 10.1 km (approximately 110 km^2), with an additional area of approximately 1.3 km^2 required for surface facilities.

**Figure 6	The schematic difference between the *difference in kind* and *difference in degree* regarding the deep borehole disposal option and a conventionally mined repository, as proposed in ONWI [5].**

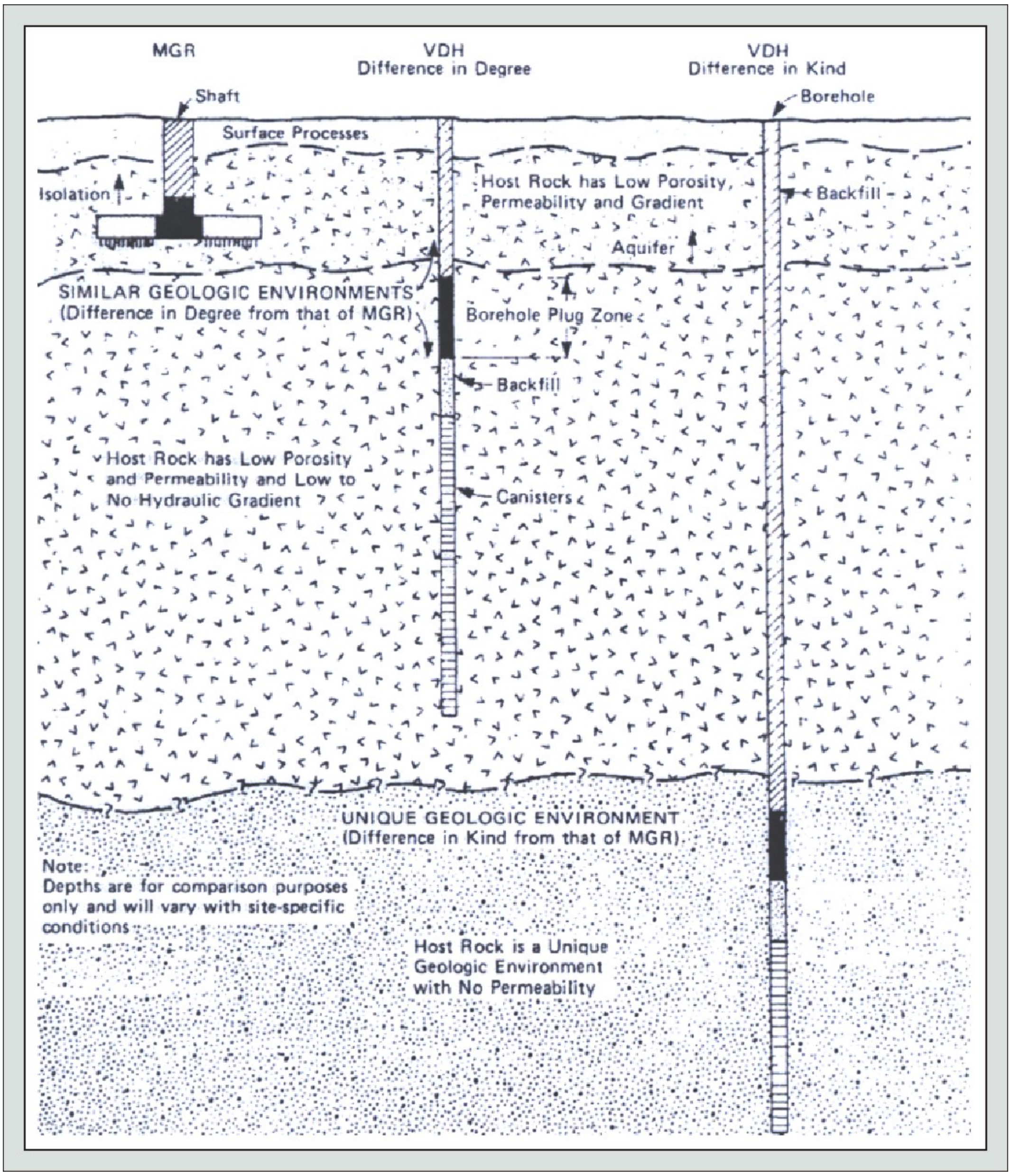


Figure 7 Schematic of reference borehole design for deep borehole disposal concept (from ONWI [5]). The *repository zone*, which includes the containment plug, begins at 6200 ft (1880 m approx.) depth and the *disposal* or *emplacement zone* at 10,000 ft (3 km approx.) depth.

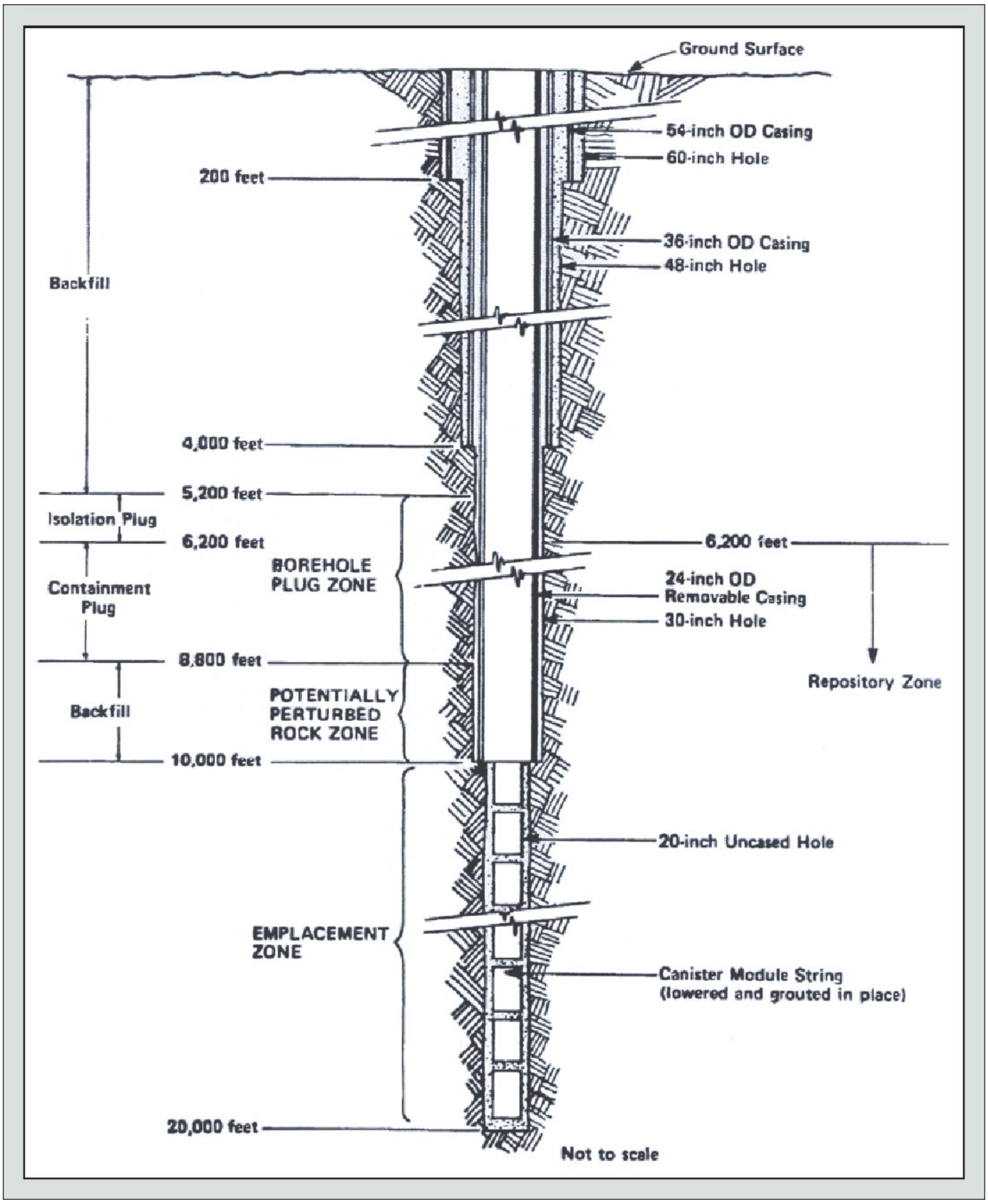


Figure 8 **Borehole wall temperature increase against time for HLW disposed in deep borehole [5]. The expected ambient temperature in the disposal zone is likely to lie in the range 85 - 160°C (assuming a geothermal gradient of 25 °C km^{-1}), so that the actual maximum temperature could lie in the range 260 - 335°C approximately.**

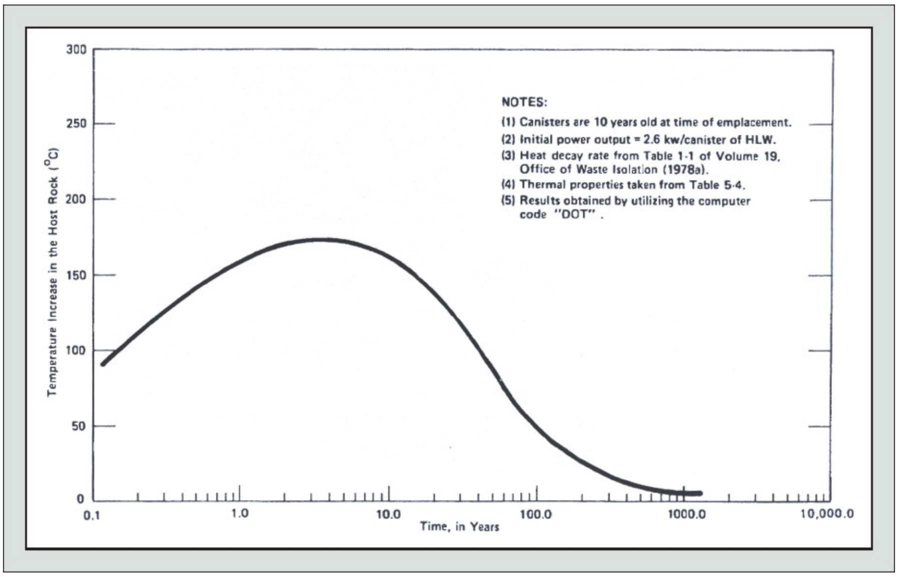
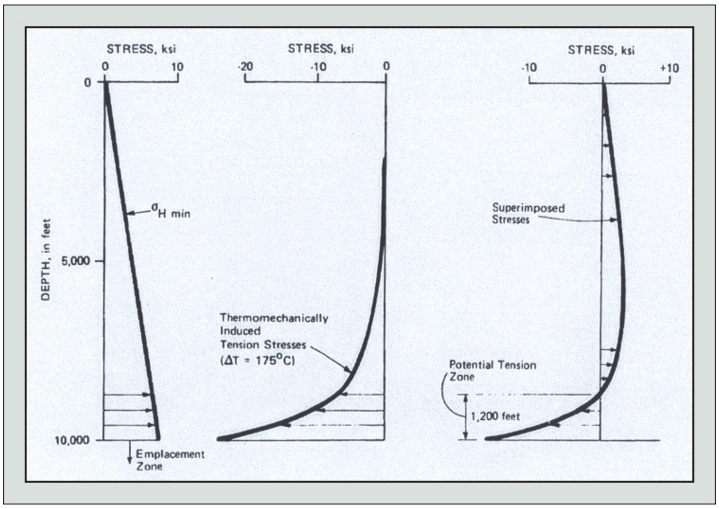


Figure 9 **Thermomechanical stresses induced by the emplacement of HLW in a deep borehole over the depth range below 10,000 ft (3 km). The minimum horizontal *in situ* stress ($\sigma_{h\ min}$) is assumed to equal $0.67\sigma_V$, thermally-induced tensional stresses (in units of ksi) are shown developed above the disposal zone, which when superimposed on the *in situ* stress results in a potential tensional zone for 1200 ft (400 m approx.) above the disposal zone. From [5].**



In the concept, canister modules would be assembled into a canister module string and lowered down the borehole on drill pipe though temporary or removable casing that would extend down to the top of the disposal zone at 3 km (Figure 7). The length of the canister module string would depend on the strength of the drill pipe and, therefore, on the depth where disposal is taking place. This length varies between a minimum value of approximately 95 m at the maximum disposal depth to as much as approximately 270 m at the minimum disposal depth. The canister spring would be lowered into the borehole in a series of steps and, having been emplaced, cement grout would be injected into the annulus between the uncased borehole and the waste canisters using technology and techniques similar to those used in the oil industry. After the grout had set the next canister string would be lowered.

Each canister (whether SF or HLW) has a length of 3.05 m (Table 1), so that the number of canisters per string would vary from 30 to approximately 85, allowing for connectors (of unspecified length) to link the canisters. The plan was to emplace 850 canisters per borehole, with a total length of approximately 2700 m, in a disposal zone with an approximate length of 3000 m. The additional space would presumably be taken up with the grout that was injected between each canister string.

After the disposal zone had been filled the temporary casing would be removed and the borehole plugged using two different plug materials:

A gravel and clay slurry containing compressed bentonite pellets, which was designed to expand and to provide a seal to the migration of radionuclides above the disposal zone.

Cement grout.

The plan being to install alternating 65 m long sections of each plug up to a depth of 5200 ft (1570 m), above which the borehole would be filled with a mixture of slurried rock cuttings and cement. The design for these plugs was based on the designs developed for plugging shafts and boreholes in basalt at Hanford.

It is important to point out that subsequent work in this area by SKB [10] (see Chapter 4.1.1) suggested that this work in the USA was based on anticipated, but non-existent technology, to such an extent that the possibility of actually carrying out the system that was proposed and outlined here should be considered as being highly doubtful. The impact of further advances in drilling technology since 1989 on the feasibility of such deep drilling at the sort of diameter suggested here is discussed in the later parts of Chapter 4 and also in Chapters 5, 6 and 7.

3.1.3 Early work by Nagra

Nagra at one time considered the option of disposing of HLW in deep boreholes. A feasibility project investigated the possibility of drilling deep boreholes to 2000 m depth in northern Switzerland where a granitic basement is overlain by hundreds to more than a thousand metres of sediments [8]. In this study it was assumed that the top of the granitic basement would lie at 1000 m depth and that the diameter of the borehole would be 52 cm at its base. The review concentrated on the feasibility of drilling either a fully or a partially cased borehole to 2000 m depth and did not discuss the techniques that might be used for waste emplacement. It was concluded that it would be possible to drill to 2400 m depth using the oil field drilling equipment available at the time (1979) and that it might be possible to extend the depth of the borehole to 3000 m, if different borehole architecture were used and if the waste emplacement zone were uncased.

The remit given to Forex Neptune was to assume that:

Disposal would take place in the lower 500 m of the boreholes.

These boreholes would not have to be vertical, as long as waste emplacement *etc.* were feasible.

Land availability in Switzerland is restricted, so any disposal site would have to be small.

The disposal zones in the boreholes needed to be separated by at least 30 m for reasons of heat dissipation.

Nine boreholes would be required.

Forex Neptune concluded that a single disposal site could be used at which boreholes that were originally vertical to 300 m, would then be deviated, so that the separation of the boreholes within the disposal zone could be guaranteed. The drilling site itself would need to be no more than 70 x 160 m (*i.e.* 1 Ha), although the area required for disposal would cover an area of approximately 500 x 500 m.

3.1.4 Early work in Denmark

The possible disposal of the small volume of HLW in Denmark was investigated in a series of reports by Elsam and Elkraft [9]. Phase 1 of this work considered the possibility of disposing of HLW by drilling deep boreholes into a salt dome, without considering any specific dome, and demonstrated that, in principle, this would be possible. The basic concept covered [33]:

Type and quantity of waste: Commercial vitrified HLW in steel casks. An overpack with a wall thickness of 15 cm would resist the lithostatic pressure in a plastic salt formation at a depth of 2500 m. The repository design of eight holes would accommodate about 5200 canisters each of 150 L (Figure 1).

Repository design: The conceptual design of a deep borehole repository consisted of eight deep boreholes sequentially drilled to 2500 m, spaced around a circle of radius 500 m. The boreholes would be lined to a depth of 950 m, below which an unlined borehole of 750 mm diameter would be drilled to the total depth. This would allow salt creep to seal the waste after closure.

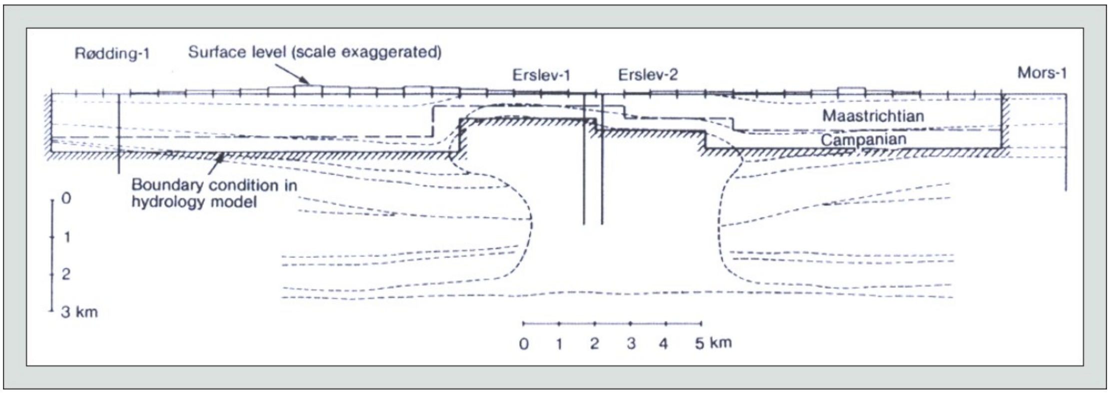
In this design 645 sets of three vitrified waste containers in steel overpacks would be placed in each borehole between 2500 and 1200 m depth. The boreholes would contain saturated brine during their emplacement, but the annular space between canister and the borehole wall would be sealed by pumping cement below the brine.

An advantage of this design was the low cost. There would be no need for mining and all drilling would be carried out from the surface. The volumetric capacity would, however, be limited and would only be suitable for a geological formation with a considerable vertical extent over which it was sufficiently homogeneous so as not to require a detailed investigation. The disadvantage of this concept is the limited possibility that it offers to characterise the internal structure of the salt dome away from the borehole.

Based on the results of this analysis, a limited seismic survey over the Mors dome was carried out and two boreholes were drilled into the dome, which is overlain by Cretaceous limestone, during Phase 2 of the project. This information allowed 2D groundwater flow modelling around the dome to be carried out, *i.e.* examining where and at what rate radionuclides released from the upper part of the dome would subsequently be transported in groundwater (Figure 10). The modelling was made more complex by the large salinity gradient that existed around the dome in the surrounding sedimentary formations, which resulted in a marked groundwater density gradient. Migration times to the surface from the top of the salt dome at 700 m depth were calculated as being in the range 1.4×10^6 to 3.3×10^7 years.

The maximum temperature in the salt at the time of disposal was designed to be 40°C. Calculations were carried out to show that the dissolution rate of the salt at the top of the dome was extremely slow, at a rate of 0.004 mm y^{-1}, even where high permeability faults were present on the dome's margins. Calculations were also carried out to demonstrate that movement on faults below the salt dome would also have no appreciable effects on its stability.

Figure 10 Hydrogeological cross-section of the Mors salt dome, Denmark used in groundwater flow modelling and showing the lower boundary to the model (from [9]).



The only calculational case that showed any noticeable release of radionuclides from the waste was one in which inadvertent drilling took place into the dome, resulting in subsequent leaching of the salt to produce a cavern, which contained the waste. Poor subsequent sealing of this cavern was assumed to allow contaminated groundwater to move up the borehole due to eventual cavern collapse. Even in this very unlikely scenario, however, doses were not particularly significant.

4 MORE RECENT DISPOSAL CONCEPTS

4.1 The SKB PASS Project

An alternative concept to that of KBS-3 was evaluated in the PASS (Project on Alternative Systems Study) project [11]. The alternative concept consists of disposing of SF in very deep boreholes (VDH). The results of this project and the compilation of geological conditions at great depth that was carried out later [10] served as a basis for a report on a research and development programme for the VDH disposal concept that was published in 2000 [34] and a systems analysis of the development of such a concept [35].

As input to the PASS Project and partly in parallel with it, SKB carried out research into the deep crustal structure of the European basement and also the hydrogeological and hydrochemical conditions at great depths, with specific reference to the basement conditions likely to be found in Sweden, by examining the data from three deep boreholes in the Former Soviet Union, the Kola, Krivoy Rog and Tyrnauz boreholes [36]. They also used evidence from the Gravberg-1 borehole, which had been drilled in the Siljan Ring in central Sweden to investigate the possibility of methane from the mantle, and compared the results from the Gravberg-1 borehole with results from other deep boreholes from around the world. This work is reported in Juhlin & Sandstedt [10], Part I. Their report is in two parts, Part I was written first and, in addition to the world-wide review of deep boreholes, includes a review of drilling techniques drawn from work in the USDOE programme, as published in [5][7], which was in part rejected as being too optimistic. Due to the fact that Part I of the report was produced first, it is not in agreement with Part II, which includes further work on the drilling techniques to be used (and which is discussed below, after the sections on the Gravberg-1 borehole and the NEDRA study).

4.1.1 The Gravberg-1 borehole [10]

Part I of Juhlin & Sandstedt [10] was based on the results of the Gravberg-1 borehole, with the review of drilling techniques being based on the report from ONWI [5], which was published as part of the USDOE-funded programme in the USA (see Chapter 3). The disposal concept presented in that report was to a great extent based on expected technical development over the following 20 years. Juhlin & Sandstedt [10] criticised the approach that had been used in the USA [5], (see Chapter 3.1.1) and in its place suggested a considerably slimmer borehole design, based on the then existing technology:

The boreholes should be 5-6 km deep with a disposal zone from 2-3 km depth.

The borehole diameter should be in the range of 300-375 mm at the bottom of the hole.

For reasons of both operational and long-term safety, the boreholes should be cased from top to bottom during emplacement of the waste (i.e. so that the boreholes remained stable and so that there would be fewer problems associated with waste emplacement).

[7] This stage of SKB's PASS project is, therefore, essentially a continuation of the USDOE programme and is based to a large extent on oil field technology. Later in the PASS programme, when more modern drilling technology is considered, there is a movement away from a compete reliance on experience gained in the oil industry to consider other drilling programmes for R&D and geothermal purposes, many of which were in crystalline rock.

Above the disposal zone, a short section of casing should be removed to allow a final seal and plug to be installed.

Additional seals could be provided above the disposal zone at positions where "windows" had been milled in the casing to provide a multiple barrier system, *i.e*. to prevent preferential flow up the EDZ (Excavation Damage Zone) of the borehole and in the annulus between the casing and the rock.

The review of boreholes drilled into crystalline rock to a depth of 1500 m or greater was carried out and the boreholes considered are listed in Table 5. The results from these boreholes [10] showed the following similarities:

The variability of the crystalline rocks in these boreholes.

The rapid increase in P-wave velocity over the uppermost 1000 m, with considerably less change below that depth.

The composition of the rock is the controlling factor in determining the average value of P-wave velocity, whilst fracture zones are responsible for the low velocities encountered over shorter intervals.

The presence of a separate groundwater circulation system below a depth of 700-1000 m.

The boreholes breakouts[8] seen in Gravberg-1, whilst being extreme, are similar to those in boreholes in the FSU.

The importance of *in situ* measurements and the discrepancies that can exist between core data and these measurements.

The most important results from these boreholes are presented in Table 4.

To accommodate the anticipated quantity of Swedish SF, about 31 boreholes would be required and it was suggested that deviated boreholes should preferably be drilled, with a maximum of 7 boreholes from each site. A total number of 5 sites would then be needed for the complete disposal facility.

The location of such a VDH repository was thought, to a large extent, likely to require similar conditions to those considered necessary for a conventional mined repository (i.e. a similar geological environment). The collection of the necessary information was not thought to pose great difficulties and a site investigation programme similar to that required for a conventional repository was thought to be necessary, with perhaps more emphasis on the use of geophysical techniques.

A quick cost estimate was carried out which indicated a cost of SEK 7000-8500 M (£540-650M) (excluding the encapsulation plant and surface waste handling facilities), which appeared to be well within the range of costs for a mined repository using the KBS-3-concept.

Permeabilities were often measured in these boreholes over fairly extensive borehole lengths (approx. 25 m) and the rock within these may be highly variable, with individual fractures within these intervals having permeabilities two orders of magnitude greater. Juhlin & Sandstedt [10] pointed out that Nagra had demonstrated in their hydraulic testing of the Böttstein borehole that if the tests were not of sufficient duration the permeability measured could be too high and that only longer-term testing, where lower hydrostatic heads were applied, resulted in reliable permeability values.

[8] In a breakout part of the borehole wall collapses due to a stress concentration that exceeds the strength of the rock.

Table 3 Boreholes drilled into crystalline rock to a depth of 1500 m or greater and included in Part I of [10]. [P = petroleum exploration; G = geothermal; H = hot dry rock; S = scientific]

Borehole Number	Name	Dated started	Depth (m)	Crystalline portion	Reason for drilling
USA-I	Mobil I-A, Nevada	1979	5962	2440	P
USA-2	Nellie-I, Texas	1983	5822	1748	P
USA- 3	Pinal County A-I,	1980	5490	1180	P
USA-4	Arizona	1983	5418	1980	P
USA-5	Paul-Gibbs-I, Montana	1981	3810	520	P
USA-6	Haraway 1-27,	1984	3506	?	P
USA-7	Oklahoma	1984	3366	1000?	P
USA-8	1-12 Boulder, Wyoming	1979	4663	730	H
USA-9	TXO Henley F-I,	1977	3854	174	G
USA-I0	Oklahoma	1987	3472	500	S
USA-II	Fenton Hill, New Mexico	?	3050	0	?
USA-12	Roosevelt Hot Springs,	1987	1829	0	S
FRG-I	Utah	1979	3334	1602	H
FRG-2	Cajon Pass, California	1987	4001	0	S
FRA-I	Wind River, Wyoming	?	3500	940	S
SWT-I	South Hamilton, Mass	1983	1501	315	S
UK-I	Urach-3, Swabia	1981	2800	0	H
CAN-I	KTB, Bavaria	1982	3500	0	G
JAP-I	Sancerre-Couy	1979	1804	1300	G
URS-I	Nagra, Böttstein	1970	12060	0	S
URS-2	Rosemanowes, CSM	?	3500	0	S
URS-3	Measer MT, BC	?	4008	?	S
URS-4	Higrori, Tohoku	?	3508	?	S
URS-5	SG-3, Kola	?	8300	?	S
URS-6	DB-3000, Ukraine	?	4000	?	S
URS-7	Ural SG-4	?	3700	?	S
SWE-I	Krivoy Rog SG-8	1986	6600	6600	P/S
IT A-I	Saatly	?	4094	1450	G
	Central Asia				
	Caucasus				
	Gravberg-I, Orsa				
	Sasso – 22, Lardello				

Part I of [10] developed a geological model for the Swedish basement to a depth of 6 km, based on the results from the Gravberg-I borehole, which can be compared with the other boreholes listed in Table 3. Their most significant findings regarding this Swedish borehole are summarised below:

> The rock mass is generally extensively fractured down to a depth of about 1200 m. Below this depth fracture zones, which typically extend over 2-20 m lengths of borehole, have a separation of approximately 200-300 m.
>
> Hydraulic measurement between 1250 and 3200 m depth indicate a hydraulic conductivity within this interval of 10^{-9} - 10^{-10} ms^{-1}, which is almost certainly determined by the most permeable zones in the rock mass, *i.e*. the transmissive parts of the fracture network.

Highly saline fluids (salinities of 10-15%) are present below 6 km depth.

Isotope data on calcite fracture infills indicate that meteoric or glacially-derived groundwater has in the past infiltrated to great depth.

A temperature gradient of 1.61°C per 100 m was measured.

Data from various sources including the Gravberg-1 borehole indicate a stress field where the vertical stress is lithostatic, the minimum horizontal stress is 2/3 of the vertical stress and the maximum horizontal stress is somewhat larger than the vertical stress.

Table 4 The most important results from the review of deep boreholes as presented in [10]. Where the circulation depth was not explicitly stated the depth was inferred from velocity information.

Borehole	D	D to HS	MHSG	k	ΔT	DB	P
USA-8	-	-	18	-	80	Minor	
USA-9	817	-	-	-	90	-	
USA-10	900	1800	-	0.1	30	1750-3510	+5
USA-11	460	-	-	-	17	-	
FRG-1	-	-	15	0.3	35	-	+
FRG-2	500	3500	-	-	27	0.2500	-10
FRA-1	-	3200	-	100	-	-	+
SWT-1	1050	1326	-	.001-10	34	-	+4
UK-1	-	-	12	0.1-6	34	none	
URS-1	800	1200	-	0.01	13	major	+4?
SWE-1	1200	>6000	17	1-10	16	1500-TD	0

D = Depth of meteoric water circulation (estimated) (m)

D to HS = Depth to highly saline groundwater (brine) (m)

MHSG = Minimum horizontal stress gradient (MPa km^{-1})

K = Permeability below 1000 m depth (10^{-10} m s^{-1})

ΔT = Temperature gradient (°C km^{-1})

DB = Depth interval where borehole breakouts are present (m)

P = Fluid pressure (% above hydrostatic)

The review of the data available from the other deep boreholes in crystalline rock listed in Table 3 confirmed, in general terms, the geological model based on the Gravberg-1 borehole. On the basis of this review, the following model for crystalline rock in the upper crust was proposed by Juhlin & Sandstedt [10];

The upper 1000 m (this depth could probably vary from 500-2000 m) contains extensively fractured rock with average permeabilities several orders of magnitude greater than that of the rock at greater depth.

This zone also has a separate or distinct groundwater flow system with generally lower salinities than the fluid at greater depth.

> Below about 1000 m the rock is less fractured and its seismic velocity is dependent mainly upon its composition.
>
> Fracture zones will be present at all depths and have considerably lower (seismic) velocities and may have significantly higher permeabilities than the surrounding rock. These fracture zones may contain different groundwater systems that are not in good hydrogeological contact with one another.

Juhlin & Sandstedt [10] concluded from their study that the results from the deep boreholes showed the necessity of a deep investigation borehole in Sweden and that, even for the KBS-3 disposal concept, a location below the upper heavily fractured zone (approx. 1000 m) should be considered. They suggested that a borehole to approximately 3000 m could well answer many questions discussed in their report.

Juhlin & Sandstedt [10] also discussed the different methods for investigating a rock mass at great depth, both from the surface and from deep boreholes. They concluded that:

> The siting of a deep borehole disposal site is likely to be based on surface geophysical investigations, with a small number of deep boreholes.
>
> In comparison with investigations at shallower depths, deep boreholes will be more dependent on geophysical borehole logging. For studies of, for example, fracture density and orientation at great depth *in situ* measurements would be preferable to core logging. Stress release, core losses and drilling-induced fractures would make any interpretation based on core logging rather uncertain.
>
> Recent advances in wireline logging, as well as in borehole seismic techniques, would allow investigation of the rock mass well away from the borehole itself. These techniques, together with cross-hole seismics, should make it possible to identify any major fracture zones running parallel to the borehole itself, as well as make it easier to identify ones that intersected the borehole.
>
> Compared with investigations at shallower depths it would be much more difficult and expensive to make hydraulic measurements in deep, large diameter boreholes and the accuracy of such data is unlikely to be equal to those at shallower depths.
>
> It was recommended that an analysis should be carried out of the deep boreholes that had been drilled in the Soviet Union[9] and that information should also be obtained from the deep boreholes that were planned in Germany and elsewhere.

4.1.2 The NEDRA study

NEDRA [36][10] compiled geoscientific data from three superdeep boreholes - the Kola borehole, with a depth at the time of 12261 m located on the Kola Peninsula, the Krivoy Rog borehole, with a depth of 5000 m located in the Ukraine, and the Tyrnauz borehole, with a depth of 4001 m located between the Black Sea and the Caspian Sea.

These boreholes are separated by several hundreds of kilometres and have been drilled into different geological and tectonic environments. The Kola and Krivoy Rog boreholes penetrate ancient (2.3 billion years) Lower Proterozoic and Archaean complexes. The Tyrnauz borehole is located at the junction of the young (Cenozoic) Caucasian fold belt and the ancient Skif-Turansky plate.

The boreholes penetrate a variety of rock types: Proterozoic volcanogenic-sedimentary deposits in the Kola borehole, Proterozoic metasedimentary complexes and Archaean granitoids in the Krivoy Rog borehole and young (2 million years) granite in the Tyrnauz borehole.

---

[9] This was carried out; see [36] and Chapter 4.1.2 of this report.

[10] NEDRA is the Scientific Industrial Company on Superdeep Drilling and Comprehensive Investigation of the Earth's Interior.

The geothermal characteristics of the three areas are very different. In the Kola and Krivoy Rog boreholes the temperature at 4000 m depth does not exceed 70°C, whereas the temperature in the Tyrnauz borehole at the same depth is 230°C. This difference is due to the type of geological terrain in which each of the boreholes is located and to the extent of radiogenic heat production.

Major differences were observed in the *in situ* stress conditions in the three boreholes. The Tyrnauz borehole is located in a zone of active horizontal stresses - fracture zones detected over the drilled interval dip steeply and high horizontal stresses initiated intense core discing[11] throughout the borehole. The Kola and Krivoy Rog boreholes are located in areas of horizontal stress relief and the stress field is mainly governed by gravitational forces. Each borehole, over the depth interval of 3800-4800 m was cut by a low angle shear zone. Such zones should be expected at depth in the crust, as its shear strength reduces with depth and as brittle-based deformation mechanisms begin to be replaced by those that result in ductile deformation.

Structural conditions

In the Kola borehole, a relationship between fracturing intensity and rock type was established, with the intensity decreasing in a sequence from metamorphosed sedimentary to basic and ultra basic rocks[12]. A similar reduction in fracture widths was noted. Neither the fracture frequency nor the width of fracture zones depended significantly on depth. A more distinct depth dependency was noted, however, in the relative proportions of shear versus tension fractures, with a general increase in the proportion of shear fractures with depth.

The width of individual fractures rarely exceeded 10 mm, and the width of fracture zones ranged from some metres to 50-80 m. On the basis of geophysical investigations, fracture zones were found to extend up to 10 km from the boreholes. Most fractures were filled, with the dominant filling minerals being quartz, calcite or chlorite, regardless of rock type. Additional minerals infills were associated with the rock types being penetrated and depended on the composition of the host rock; they included minerals such as talc, chrysotile, albite, epidote, actinolite, hematite and magnetite. NEDRA [36] reported that the information available from the Kola borehole suggested that fracturing, crush zones and zones of extensive hydrothermal mineralization should be expected in crystalline basement to a depth of 15 km.

It was concluded that a generalised structural model of the rock mass to the depths intersected by these deep boreholes should include a system of fracturing and fracture zones over the entire depth interval. It was also suggested that sub-horizontal or gently-dipping fracture zones should be expected at a depth of 3-4 km and that more evenly distributed fracturing, with fracture widths up to 1.5 mm, should be expected to depths of at least 12 km. Furthermore, relatively wide fracture zones, with widths up to a few metres, should almost invariably be present in the uppermost few hundreds of metres in any model.

Hydrogeological and hydrochemical conditions

The geothermal gradient increased markedly with depth and specific intervals of the thermal gradient could be distinguished. For the Kola and Krivoy Rog boreholes these intervals coincided - a geothermal gradient less than 10°C km^{-1} corresponded to depths less than 1000-1200 m; from this depth down to 2500-3000 m the value was 10-15°C km^{-1}; down to 4000 m it was 17°C km^{-1}, and below 4000 m it again increased to 20°C km^{-1}. In the

[11] A process by which the core breaks into relatively thin discs as a result of stress relief, due to the release of the core from high in situ stresses. In high angle and vertical boreholes core discing is as a result of high horizontal stress.

[12] Basic and ultra basic rocks are dark, heavy rocks with a silica content of less than about 53% and containing magnesium and iron minerals but not quartz. An example of a basic rock is basalt.

Tyrnauz borehole two distinct intervals were distinguished - above 2800 m and below 2800 m. In the upper interval the value was 40°C km^{-1} and in the lower interval values up to 60 K km^{-1} were measured.

Another feature common to all boreholes was the vertical hydrogeological zonation. Three major *hydrogeological zones* were distinguished:

> Zone 1: a zone of free circulation characterised by fresh or slightly mineralised meteoric groundwater (TDS (Total Dissolved Solids) up to 50-60 g l^{-1}) in fractures.
>
> Zone 2: a zone of reduced circulation characterised by weak or medium brines with values of TDS up to 200 g l^{-1}.
>
> Zone 3: a zone of deep groundwater, characterised by strong basement brines, indicating a long period of water-rock interaction, or groundwater with a metamorphic origin with TDS values up to 350 g l^{-1}.

The presence of the first two zones was observed in all three boreholes, whereas the third zone was seen only in the Kola borehole at a depth of 4500 m. The higher parts of Zone 1 were characterised by relatively dynamic groundwater systems with turnover times of tens of thousands of years or less.

Although the first two zones could easily be seen in the boreholes, determining their boundaries was more difficult. In the Kola and Krivoy Rog boreholes, the transition from the first to the second zone could be seen at 800-1200 m depth and the geothermal gradient also increased at a similar depth. The groundwater type in Zone 1 was dominantly Ca-HCO_3 or Na-Cl-SO_4. In the Tyrnauz borehole the groundwater chemistry, the presence of carbonate fracture infills and the change in the geothermal gradient all suggested that Zone 1 extended to a depth of as much as 2500 m. In the Kola borehole, the boundary between Zones 2 and 3 was found to be located at a depth of 4500 m, based on groundwater chemistry, which again coincided with an increase in the geothermal gradient.

Zone 2, therefore, comprises the interval from 1000-2500 m to 4500-5000 m. It is characterised by Ca-Cl, Na-Cl or Na-Cl-SO_4 brines with TDS of 50-200 g l^{-1}. Within the zone, groundwater circulation is assumed to take place between Zone 1 (with dominantly meteoric groundwater) and Zone 3 (with old basement brines). The data available suggested that circulation rates were unlikely to be less than several tens of thousands or hundreds of thousands of years. The lithostatic stress over the depth interval of 3600 – 4500 m, when compared with the expected compressive strength of the rock, suggested conditions which could result in failure. NEDRA [36] suggested that deformation and failure, with the initiation of sub-horizontal fracturing might result and that this could be substantiated by the presence of low velocity zones in both the Kola and Krivoy Rog boreholes at these depths. Zone 3 was found to be characterised by very old basement Ca-Cl or Na-Cl brines which were assumed to be disconnected from the groundwater in Zone 1. Groundwater circulation times in Zone 3 were expected by NEDRA to be in excess of hundreds of thousands of years and the zone to be characterised by high geothermal gradients.

Summary of NEDRA study

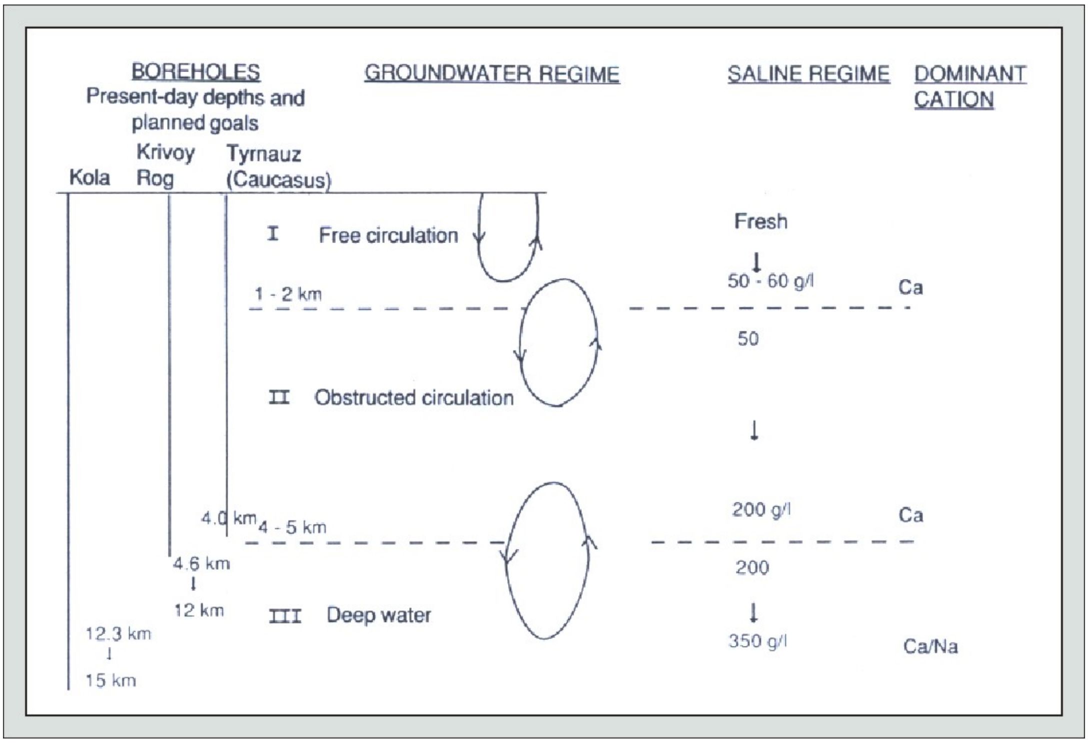
NEDRA [36] condensed the observed hydrogeological and geothermal characteristics in these crystalline basement formations into a generalised model, with the rock mass encountered to a depth of 5 km and greater being envisaged as a three-layer medium, which reflected the vertical hydrogeological and geothermal zonation (Figure 11):

> The first, upper zone (Zone I) encompasses the interval down to 1-2 km depth. It is characterised by active water circulation, minimum geothermal gradients, intense brittle fracturing, mainly as a result of tectonic activity, and contains fresh or slightly mineralised groundwater (up to 50-60 g l^{-1}) under continuous circulation with the atmosphere.

The second zone (Zone II) forms an intermediate zone between the upper and lower zones, in which groundwater circulation reduces with depth. Within this zone the groundwater salinity (with TDS up to 200 g l^{-1}) and the geothermal gradient also tend to increase with depth. The upper parts of the zone are considered to have hydraulic communication with Zone I, where active groundwater circulation takes place, and the lower parts of this zone appears to be weakly connected to Zone III, which is characterised by very low rates of circulation.

The third, lowermost zone (Zone III) has its upper boundary at a depth of 4-5 km, corresponding to the occurrence of deep chloride brines (up to 350 g l^{-1}) which are hydraulically disconnected from Zone I. The depth to the boundary of Zone III is greater in younger fold belts than in areas where older basement structures are present. The geothermal gradient is essentially stable within this zone and data from these three boreholes suggests that at depths in excess of 4-5 km the geothermal gradient remains essentially constant.

Figure 11 Conceptual model of the hydrogeological and geochemical regimes present in the three deep boreholes in the FSU examined by NEDRA on behalf of SKB, illustrating the three zone model [36].



As explained above, the review by NEDRA [36] of the geological and hydrogeological conditions at depth provided input into the PASS study [11], in which the VDH concept was compared with three other concepts, which all involved disposal at an assumed depth of 500 m. The disposal interval of 2000 – 4000 m assumed for the VDH concept in this study was based on two premises:

The groundwater flux at depths in excess of 2000 m would be considerably less than that associated with the KBS-3 disposal concept at 500 m depth, so that the expected return of radionuclides to the biosphere would also be considerably reduced.

It would be technically feasible to drill boreholes to a depth of 4000 m at the required diameter of 800 mm, thereby allowing a waste canister of diameter 538 mm to be emplaced inside a perforated lining.

4.1.3 Juhlin & Sandstedt [10] – Part II

The first of these premises was based on the result of the reviews by NEDRA [36] and Juhlin & Sandstedt [10] and the second on the knowledge of drilling techniques [10]. Juhlin & Sandstedt [10] carried out an analysis of the technical feasibility of deep borehole drilling and the associated plugging and sealing that would be required. They also investigated the hydrogeological conditions at depth and modelled the temperature fields that would be generated by the emplacement of waste in different configurations at depth in a series of deep boreholes with different diameters. Three disposal options were considered in Part II of [10]:

Option A: a borehole with an ID of 800 mm in the disposal zone where waste would be emplaced in a zone from 2 – 4 km.

Option B: a borehole with an ID of 375 mm in the disposal zone where waste would be emplaced in a zone from 2 – 5.5 km.

Option C: a borehole with an ID of 375 mm in the disposal zone where waste would be emplaced in a zone from 2 – 4 km.

Option A, which was preferred for economic and technical reasons, was considered to require shaft drilling technology and possible to construct at the time. It would, however, involve a major innovation in casing technology, especially in the disposal zone, where the casing would have to be non-reactive and be designed so as to allow the borehole to be sealed to a high standard using bentonite. It was estimated that the drilling time for the first option would be approximately 535 days, which would include investigations specific to the borehole, with an additional 365 days for emplacement of the canisters and sealing of the uppermost 2000 m of the hole. This implied that the borehole could be drilled, the waste emplaced and the borehole sealed in less than three years. The costs for one such borehole were estimated to be 388MSEK (approximately £30 million) at 1988 prices.

From their investigations regarding the feasibility of the VDH concept Juhlin & Sandstedt-Part II [10] considered that it offered advantages over the KBS-3 concept in five areas:

Geological aspects.

Multiple disposal sites.

Adaptability to technological innovations.

Possible economic advantages.

Retrievability.

Geological aspects

The advantages in this area were considered to be the lower permeabilities in the rock at the depths at which the waste is to be emplaced, a greater natural barrier (2 km *v*. 500 m) and the probable presence of saline water at the depths being considered [10]. Considerably less movement of groundwater was expected at the greater depth due to lower natural permeabilities and the greater separation of the fracture zones. It was understood at the time, from evidence from deep boreholes, that meteoric groundwaters circulated to depths of possibly as much as 1200 m. For example in the Kola borehole this zone of circulation had been found to extend down to 800 m, in the KTB borehole down to 500 m and in the Gravberg-1 borehole down possibly to 1200 m. The potential increase in salinity of the groundwater below this zone would be an additional factor of advantage to the VDH concept, ensuring that no appreciable quantities of radionuclides would be transported to the surface. Another advantage was that the VDH concept would not be as dependent upon the near surface geological conditions as the KBS-3 concept, thereby allowing a greater flexibility in the choice of a disposal site or sites.

Multiple disposal sites

It was considered as advantageous that the VDH concept offered the possibility for waste to be disposed of at two or more repositories if needed or requested. This was considered to be “a great advantage” if land use problems arose or, if during the development of a disposal site, it was found that not all of the site was suitable as had originally been thought.

Adaptability to technological innovations

Since the waste would probably be disposed over a long period of time it would be possible to take advantage of technological innovations in the field of shaft/borehole drilling. This would increase the possibility of reducing costs for each borehole drilled. It would also be possible to change to an entirely different concept of waste emplacement if so required, whereas, in the KBS-3 concept it would be more difficult to take advantage of technological innovations as they occurred.

Possible economic advantages

Although it was admitted that the large diameter borehole option (Option A above) of the VDH concept was more expensive than the KBS-3 concept there were, nevertheless, a number of economic advantages with the former. Firstly, the initial investment would be considerably less, since one or two boreholes could be drilled at a time, whereas in the KBS-3 concept most of the repository would have to be constructed before any waste could be emplaced. Secondly, the low initial investment in the VDH concept meant that interest costs (*i.e*. discounted costs) should be taken into account when comparing the two concepts.

If it were determined that the maximum allowable temperature in the bentonite close to the waste could be increased to 150°C, it would be possible to use consolidated assemblies (where the fuel assemblies are dismantled, and the fuel rods rebundled, so that more waste can be put in each canister). Consolidated assemblies would allow almost twice as much waste to be emplaced in each borehole, thereby reducing the number of boreholes required from 35 to 19, and reducing costs and time. It was considered that the greater flexibility in selecting a site for the VDH concept could also help in finding a location close to a harbour and thus reduce the cost for transportation. It was also suggested that cost savings in the order of 3000 MSEK (£230 M) would apply if a suitable location could be found close to CLAB, SKB’s underground store for spent fuel.

Retrievability

The report stated that, although it was thought initially that the VDH concept would not allow the canisters to be retrieved once they had been emplaced, further consideration of this matter had indicated that this was not the case. It was concluded that there was no reason why the plugged section could not be drilled or washed out with high pressure fluids. Once access to the canisters was possible they could be removed using overshot tools, a standard oilfield practice. This procedure did assume, however, that the canisters were still intact. The comparative level of difficulty of retrieving waste canisters from deep boreholes was, however, not compared with that expected from a KBS-3 type mined repository [37].

4.1.4 The PASS study

The decision to consider the depth interval and borehole diameter discussed in the previous section had important implications for the associated PASS study [11]:

The groundwater in contact with the waste canister would be considerably more saline than that likely to exist at 500 m depth.

The consequence of this higher salinity would be that the corrosion rate of the VDH waste canisters would be considerably greater than that experienced by a normal copper/steel canister in the KBS-3 concept.

The VDH waste canister would have to be considerably smaller (538 mm diameter) than that envisaged in the KBS-3 concept (840 to 920 mm, depending on the design).

The smaller VDH waste canister would contain fewer SF rods, thereby requiring a considerably greater number of canisters (though this number could be reduced if *consolidated assemblies* were used). These consolidated assemblies would require the fuel assemblies to be dismantled and the SF rods to be consolidated so that they fitted inside a special container. In this manner the number of waste canisters in the PASS study believed necessary for the VDH concept was reduced from 11,235 to 5,548. This compared with the assumed number of canisters for the KBS-3 concept of 3745.

The PASS study carried out a comparison of four disposal concepts – the KBS-3, MLH (Medium Long Holes), VLH (Very Long Holes) and VDH concepts were ranked by comparing the canister alternatives that were possible within each concept and between concepts, *i.e.* five canister alternatives were considered for the KBS-3 concept and three for the VDH concept. These were ranked with regard to long-term performance and safety, technology and cost. The disposal systems were ranked with respect to the same three factors.

For the VDH concept it was assumed [11] that:

The canister could consist of either a titanium canister with a concrete fill (with either intact BWR (Boiling Water Reactor) assemblies or consolidated assemblies) or a copper canister fabricated using HIP (Hot Isostatic Pressing). In both cases the external dimensions of the canister were the same.

The canisters would be stacked on top of each other, separated by compressed bentonite (Figure 12).

The analysis carried out in the PASS study concentrated primarily on the concrete-filled titanium canister. The handling of the SF in order to assemble these canisters is very different from that required for the KBS-3 concept at the hot cell and the welding cell stages[13], and these phases of the process were not studied in detail by SKB. A flow diagram illustrating the encapsulation of the consolidated assemblies is shown in Figure 13. The encapsulation of non-consolidated assemblies was not, however, assumed to differ in functional terms from the encapsulation envisaged in the KBS-3 concept.

[13] This is during the active stage when, for example, welding is carried out in a concrete shielded enclosure.

Figure 12 Canister design for use in the VDH concept assumed in the PASS study [11].

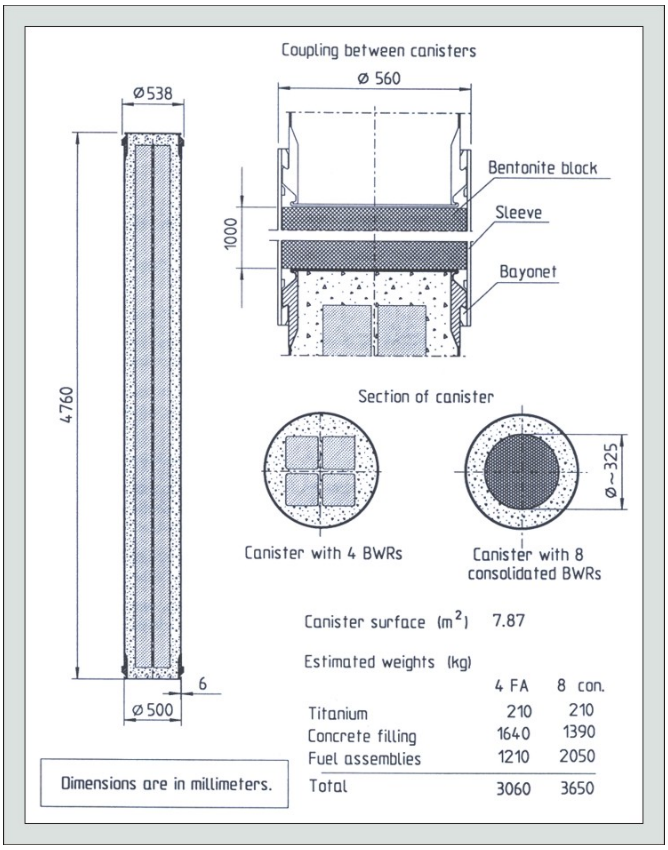
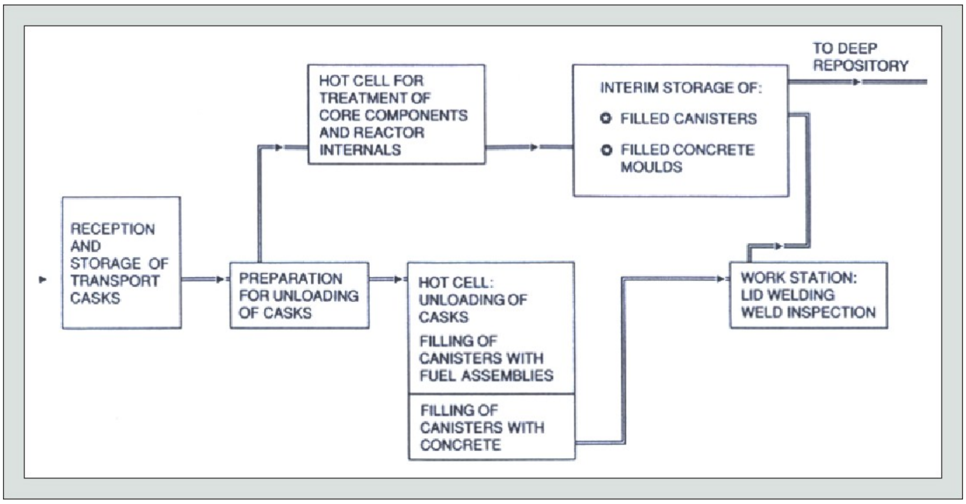


Figure 13 Flow diagram presented in the PASS study illustrating the encapsulation of consolidated assemblies for use in the VDH disposal concept [11].



In the case of the non-consolidated assemblies, after the fuel assemblies have been lowered into the titanium shell the canister is transferred to a special cell where it is filled with concrete. When the concrete has cured, the canister is transferred to the welding cell, where the top surface of the cement is first evened off before the lid is put on and welded down.

In the case of consolidated assemblies, the cell where unloading the transport casks takes place contains units for dismantling the fuel assemblies and for consolidating the fuel rods, so that they fit into a special container which, after sealing, is lowered into the canister. The canister is then filled with cement and welded shut in the same way as for the canister with non-consolidated assemblies. Other metal parts are compacted in a special cell and encapsulated in separate canisters of the same type as those used for the fuel.

A schematic division of a borehole in the VDH concept into *deposition* and *plugging* zones is shown in Figure 2, based on work in [10]. It was intended that no disposal should take place where the boreholes were intersected by transmissive zones (most likely fracture zones or more transmissive parts of the fracture network) and these sections would be filled with bentonite. The preferred design for the VDH concept, which was based on work by Juhlin & Sandstedt [10], consisted of a number of deep boreholes spaced 500 m apart. Two options were presented in [10]:

> **Option A:** large diameter boreholes in which 4 BWR or 1 PWR + 2 BWR fuel bundles would be placed in each canister, which would have an outer and an inner diameter of 0.5 and 0.39 m respectively. The maximum temperature at the canister-bentonite interface would be 120°C and a total of 38 boreholes would be required for the volume of Swedish SF.
>
> **Option B:** the same boreholes as option A, but the fuel elements would be rebundled and consolidated assemblies produced using the same type of canisters as above. If this system were of interest the maximum allowed temperature at the canister-bentonite interface would have to be increased to 150°C from 120°C and a total of 19 boreholes would be required.

Option A was the preferred concept advanced in [10], however both options were considered in the PASS study [11].

The result of the hydrogeological modelling presented in [10] using data from the Gravberg-1 borehole, show that at least 80% of the length of each borehole could probably be used for waste emplacement. This figure was considered conservative but was nonetheless used for cost estimates. It was also assumed that the SF for disposal would be stored for 40 years in CLAB. The total amount of SF was assumed to be 6000 tonnes uranium from BWRs and 1800 tonnes uranium from PWRs.

Figure 13 shows a schematic drawing of a deposition area with 19 boreholes (for consolidated assemblies) or 38 boreholes (for non-consolidated assemblies). The site covers an area of about 3 km^2 or 7 km^2, respectively, if the boreholes are positioned as shown in the figure, with a road, power and water supply running to each borehole site. The reason for the large borehole separation was not explained in the PASS study, however in later SKB reports [35] it was indicated that at the time of the study there was some concern in the ability of drilling systems to be able to control the orientations of boreholes at these great depths, with the result that a considerable margin of error was introduced into the design so as to prevent interactions between the boreholes. Again, it is unclear from the PASS study and from subsequent SKB studies, what the separation of the boreholes would need to be from a thermal standpoint or so that their mechanical interaction was minimised. This large borehole separation and the resulting large size of the repository had several important impacts:

> A larger volume of the rock would have to be investigated, (considerably larger than that envisaged for the KBS-3 concept).

The environmental impact of the repository would be greater than originally envisaged.

These factors resulted in the VDH concept been given lower scores in comparison with the other concepts with regard to these two attributes.

The drilling concept was based on oil well drilling technology with the additional experience gained from the deep borehole at Gravberg (see Chapter 4.1.1). It was assumed that the borehole would have an ID (internal diameter) of 0.8 m within the deposition section, which was the largest diameter that it was considered possible to drill to a depth of 4 km. Drilling would be carried out using bentonite as a drilling fluid. It was proposed to use bronze casing instead of the normal steel grade used within the oil industry, thereby reducing corrosion and avoiding the production of hydrogen gas from the anaerobic corrosion of steel. The casing would be made sufficiently perforated within the deposition zone that the bentonite could fill the void in the borehole behind the casing and between the casing and the canister, as discussed in Chapter 4.1.3.

The method for emplacing the canisters was taken from [10]. The method was based on the use of the same rig as that used for drilling the borehole. The principle was that the canister would be connected to the drill pipe where the bit would normally be located and be pushed down in the liner to the position for disposal. Before waste emplacement commenced, the bentonite drilling mud used during drilling would have been replaced by a thicker bentonite emplacement mud, as thick as could be allowed. The two main factors that would need to taken into account in determining the thickness of the mud would be:

It must allow the canister to be pushed through the mud without causing excessive resistance (the annulus between the canister and the casing/lining is only small in the disposal zone, so that mud velocities cannot be too great).

The mud cannot be so heavy that it results in excessive penetration of the rock mass around the borehole within the disposal zone where the lining is perforated.

Two or more canisters would be inserted at a time as a string, together with intervening sections of highly compacted bentonite. The bentonite proportion would be adjusted so that the average bentonite density is sufficiently high for the bentonite to hold each canister in place when it swells (this is the main purpose of the bentonite in this design). The ability to check on the canister's position in the borehole is important, and it was believed this could be achieved with the aid of methods and instruments developed in the oil industry[14]. It was considered that a suitable waste emplacement rate would be about 200 m of borehole per month per borehole, which is equivalent to approximately 85 canisters per month.

The uppermost 2000 m of the hole would be plugged to prevent axial water transport along or in the borehole and, at one or more points along the borehole, "windows" could be milled that intersected the EDZ around the borehole. Two different plugging sections were distinguished. The lower section, from 2000 m to 500 m depth, would be filled with compacted bentonite blocks inside the perforated casing, with the blocks being inserted in as thick a bentonite mud as possible. The upper part of the borehole, from 500 m depth to the surface, would be filled with asphalt capped with a concrete plug.

Summary

The overall results of the PASS study [11] are summarised in Table 5. The VDH concept was given the lowest ranking in all three interim comparisons – Technology, Long-term performance and safety and Costs. For both "Technology" and "Costs", the outcome was, according to SKB, clear and indisputable. With regard to "Long-term performance and safety" the judgement was less clear, with its lower ranking being due mainly to the fact

[14] No specific information is provided as to how this might be achieved and no references are provided of the use of such techniques in the oil industry.

that the system's long-term isolating capacity was associated almost exclusively with only one barrier, the geosphere. The level of knowledge of the geosphere at the depths of interest in Sweden was limited, thereby increasing the level of uncertainty associated with its properties and behaviour.

An improvement in the engineered barriers was thought to be possible, though it was not stated what these improvements might be, but at the price of increased costs for this disposal concept. As SKB pointed out, there was, however, no margin on the cost side as the VDH concept analysed was already the most expensive of the alternative systems.

The higher costs associated with the VDH concept and the other disadvantages displayed by the concept in comparison with the three other concepts were considered significant. SKB also considered that the study had not indicated any uncertainty in the analysis that might alter the situation in such a way that the VDH concept could be ranked first.

4.2 Follow-on work to PASS

As a follow-on to the PASS Project, SKB carried out more work on the deep borehole concept [38]. This work began with a plan to develop a better understanding of the conditions at depths of 1000-5000 m in crystalline rock, with specific reference to Sweden. Evidence from deep boreholes throughout Europe (including the Former Soviet Union (FSU)) was considered. This study was concerned only with geological and hydrogeological matters and did not consider the implications of these conditions with regard to the feasibility of deep disposal. It is unclear how this work subsequently fed into the later work that SKB carried out on the VDH concept.

4.3 Progress since RD&D 98

In conjunction with their review of SKB's RD&D-Programme 98, Kasam[15] expressed a wish for a system analysis and a safety and performance assessment of the VDH concept. Kasam also called for SKB to specify the scope and contents of the RD&D programme that would be needed to judge the VDH concept on an equal basis with the KBS-3 concept. This specification had to include an idea of the time and resources that would be needed.

The VDH concept is included in the system analysis that was published by SKB in 2000 [34] that included four disposal concepts – KBS-3, VLH (Very Long Holes – these are horizontal, not vertical), WP-cave[16] and VDH. A comparison was made between these four concepts based on five factors:

Overall requirements.

Environmental requirements – represented by the consumption of materials for the EBS and the volume of extracted rock and also by the overall environmental requirements.

Safety requirements – represented by the number of movements involved in canister handling and by the overall safety requirements.

Radiation shielding requirements.

[15] Kasam is the government-funded review body for radioactive waste management in Sweden.
[16] The Swedish concept of geological disposal developed in the 1980s and based around the concept of the hydraulic cage.

Figure 14 The layout of deep boreholes assumed for the VDH disposal concept in SKB's PASS study and used for cost calculations and estimates of environmental impact [11].

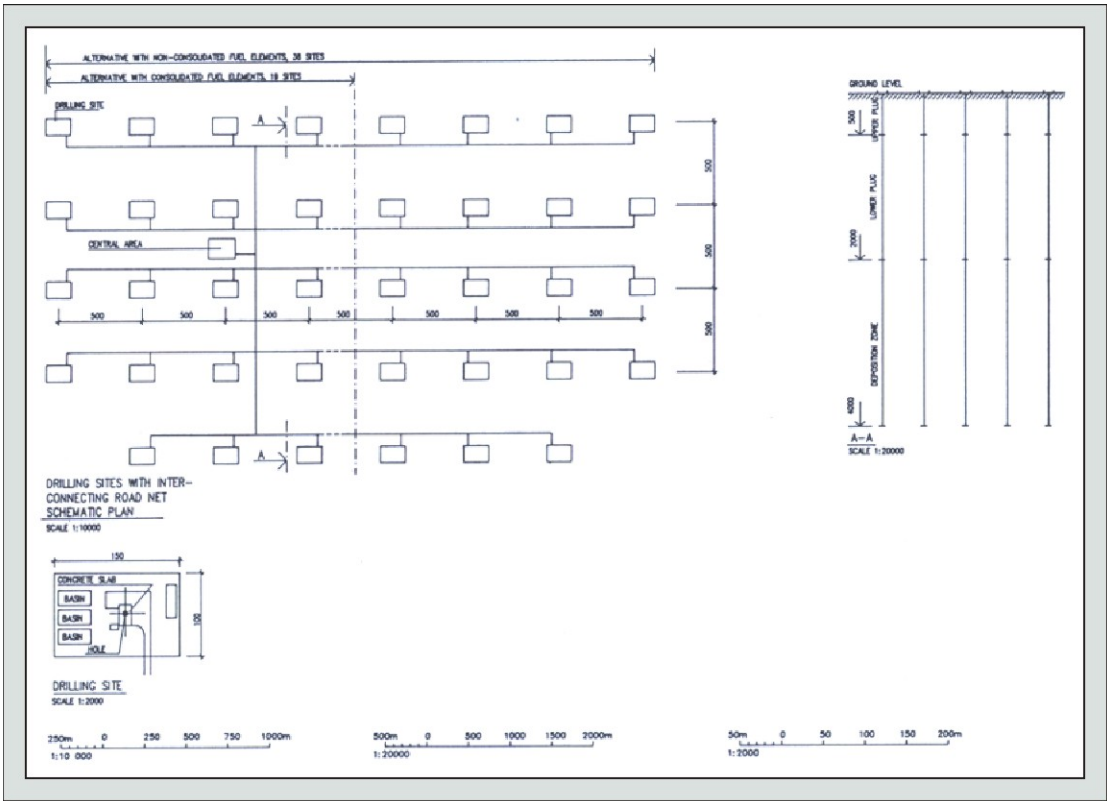


Table 5 **Summary of results of the SKB PASS study [11] in which four disposal concepts were compared under the subject areas of Technology, Long-term performance and safety and Costs. [MLH = Medium Long Holes; VLH = Very Long Holes; VDH = Very Deep Holes]**

Repository concept	Technology	Long-term performance and safety	Costs
KBS-3 (copper-steel canister)	1	1	2
MLH (copper-steel canister)	2	1	1
VLH (copper-steel canister)	3	1	2
VDH (concrete-filled Ti canister)	4	4	4

Several of the organisations (*e.g.* University of Gothenburg, Swedish Society for Nature Conservation, University of Uppsala, Greenpeace, Waste Network, Swedish Anti Nuclear Movement, KASAM) who reviewed SKB's 1998 R&D programme indicated that the VDH concept could have advantages over those concepts at lesser depth as a result of increasing the isolation of the waste from the biosphere and the increased difficulty of human ingress [35]. As a result of these views, the Swedish Government ruled that SKB should carry out additional work on the VDH concept so that it could be compared properly with the KBS-3 concept before potential disposal sites were selected for investigation.

4.3.1 Proposed design of the VDH concept

The outline of the VDH concept presented below is based on that published by SKB in 2000 [34]. The latter parts of Chapter 4.3.1 are based on a parallel study by SKB of the VDH concept, in which the R&D programme and development costs are considered [35]. A considerable part of the design and operation of such a facility is similar to that described in Chapter 4.1.4 in the PASS study. The aspects of the design which are essentially the same as those in the PASS study are not repeated here, except where necessary to explain the attributes of the disposal concept.

Facility design and safety functions

In the reference design, the facility consists of about 40 boreholes some 4000 m in depth drilled at a minimum separation of about 500 m. Their diameter is 1400 mm to about 2000 m depth, and thereafter 800 mm, and their separation is determined by the heat output of the SF. Consideration has also been given to the fact that the boreholes will probably not be drilled completely vertically, but are expected to deviate by a few degrees.

The SF is encapsulated in what SKB term a *leak-proof canister*. Several alternative canister designs are presented as possibilities: the PASS study [11] recommended a titanium canister with concrete filling, an alternative is a homogenous copper canister and a steel canister is also a possibility (something that was not considered in the PASS study). The canisters are deposited on top of each other in the borehole between 2000 and 4000 m depth and are surrounded by a buffer, the primary purpose of which is to fix the canister in position in the surrounding rock. The proposed design is shown in Figure 2, *i.e*. the overall design has not change since the PASS study. The most important safety function in the VDH concept is to delay the release of radionuclides which takes place mainly within the rock. During an initial period the facility must also isolate the SF, and this is achieved by the use of a leak-proof canister that is designed to remain intact for at least 1,000 years.

The delay is achieved primarily by disposing the waste at great depth so that the return times for radionuclides to the biosphere are so long that the activity has had time to decay to insignificant levels. The radionuclides will also be diluted over the long transport path and their transport will be delayed by the effects of matrix diffusion. The rock, therefore, is the principal barrier, with the canisters and other parts of the EBS being of less importance.

The reasons given for believing that the conditions at depth would be suitable for disposal were related to the fact that:

The permeability of the rock mass is likely to be lower.

The separation of fracture zones is likely to be greater.

The high groundwater salinity, in association with a density-stratified groundwater system, and when combined with the low permeability of the rock mass, would mean that groundwater fluxes at depth would be considerable less than those at 500 m – the design depth for the a KBS-3 type repository.

Site selection and site investigations

The concept is based on the idea that it is possible to locate a volume of rock in which the exchange of groundwater with the surface is insignificant during the relevant periods of time. A research programme would be needed to explore the requirements that must be met by the rock if this is to be achieved. Surface geophysical seismic, magnetic and gravimetric measurement techniques are regarded as having the potential for use in the future as important tools in assessing the rock mass at depths down to 5 km, but are likely to require further development.

Construction

Structure, flexibility and safety

Experience of deep drilling is available from the oil industry, and relates mainly to sedimentary rock types, though examples of deep boreholes in crystalline rock do exist in Sweden, Germany and Russia. Nevertheless, holes with diameters as great as 800 mm have never been drilled to these depths (i.e. at least and possibly in excess of 4 km), and technological development is required for such drilling[17]. To ensure a straight borehole and to facilitate investigations of the rock mass, a technique is proposed in which a pilot hole would be drilled first and then expanded to the final diameter. The stability of the borehole will be determined by the stress conditions in the rock mass and methods of measuring and estimating stresses at great depth would need to be developed. The borehole would have to be filled with a drilling fluid, to prevent it collapsing as a result of high *in situ* stresses and the density of this fluid must be sufficient to balance these stresses, but not so great that it is forced into existing fractures, widening them and flowing into the rock surrounding the borehole [35]. The drilling fluid must be able to carry away the rock cuttings and it must also be possible to replace it with a different fluid before waste emplacement, unless the drilling fluid is suitable for both purposes. Further development and testing would be required to find a suitable drilling fluid.

The drilling of deep boreholes includes several operations during which accidents may occur, for example the lowering and raising of drill bits and rods in the borehole and the

[17] A report at the time, on behalf of SKB, emphasised the fact that, although such boreholes could possibly be drilled, they were at the limit of drilling technology, mainly due to their diameter.

handling of feed pipes and pressurised borehole fluid. Routines and equipment are designed to minimise the risks to personnel.

The flexibility of a deep borehole facility is limited by factors such as the maximum and minimum depths for disposal, but the disposal depth can be adapted to regional or local geological conditions. It will be possible to avoid unsuitable sections within the borehole by plugging them, but the long-term stability of such plugs would have to be demonstrable, and this is considered problematic. In reality, a borehole would probably have to be approved or rejected in its entirety. If the borehole position is approved, no further adaptation to variations in local geological conditions would be required. The options for inspecting the borehole and its effects on the surrounding rock are inferior to those associated with a KBS-3 repository concept.

Use of land, contaminants and consumption of resources

The boreholes may be located with a minimum separation of 500 m and, depending on how the boreholes are arranged, they will extend over an area of about 7-10 km^2. Each drilling site would require an area of between 100 x 100 to 200 x 200 m, giving a total land requirement of about 1 km^2. Since the drilling sites are spread over a large area, the environmental impact will be spread widely, although not very much land is needed for drilling. Each borehole requires its own electricity supply *etc.* (drilling equipment would be moved from hole to hole). Land requirements for rock spoil, service buildings and bentonite preparation are less than for any tunnel-based disposal concept and the total volume of drilled rock is anticipated to be approximately 160,000 m^3.

Assuming that a canister made of titanium with concrete filling is used (the alternative recommended in the PASS study [11]); over 3,000 tonnes of titanium and about 2400 tonnes of concrete would be needed for the canisters. Bentonite will be used as a buffer material, and when waste emplacement is complete the borehole will be plugged with bentonite from a depth of about 2 km to about 500 m. The hole will then be filled with asphalt topped with a concrete plug. About 190,000 tonnes of bentonite are required in total (an estimate based on [10]. The asphalt filling and concrete plug quantities have not been determined; and SKB assume the specifications provided in [10], *i.e.* asphalt from 250 to 500 m depth and concrete from 250 m to the surface, implying that about 15,000 m^3 each of asphalt and concrete would be needed.

Operation

Implementation and operating safety

The canister design for the VDH concept and its various alternatives, together with encapsulation plane *etc.* have been described in Chapter 4.1.4.

It was originally intended that the borehole would be lined (cased) with brass, which would protect the walls of the hole and permit repeated lowering and raising of material and equipment [10], however further work by SKB indicated that steel casing may be sufficient. In the disposal zone the lining consists of a liner with a high void ratio, so to protect the boreholes walls whilst at the same time allowing bentonite to move freely to fill up all the void space [10].

Two or more canisters are deposited together separated by 1 m thick blocks of compacted bentonite. Before the canister package is emplaced, the drilling fluid is replaced with a deposition fluid consisting of bentonite slurry. The density of the deposition fluid should be as high as possible, so that it functions as a buffer, but it must be possible to push canisters and bentonite blocks down through it using the drill rods. The canister package replaces the drill bit on the drill rod and is pushed down to its correct position in the borehole. It is important to check that canisters all reach their correct depths.

The proposed equipment is designed to keep the breakdown rate as low as possible. Though a certain amount of experience is available from the oil industry, the proposed method of waste emplacement is largely untested[18] and major technological development would be required before its use, for example in the replacement of borehole fluid with deposition slurry. The following critical elements were identified by SKB in the deposition process itself:

Connection (of the waste package) to the drill bit.

Loss or tilting of the drill rod during lowering.

The transition from the wider to the narrower part of the deposition hole (*i.e*. where the casing size changes).

Deposition at the correct depth.

Problems in releasing the canister package from the drill rod.

Being able to guarantee safety during the waste emplacement process deposition is essential if the method is to be adopted, and development and testing would be required to bring this about.

According to SKB, other problems might ensue during waste emplacement if a canister were released in the borehole during deposition, due perhaps to failure of a drill rod. This is because deposition fluid is of such high density and viscosity that any released canisters would sink very slowly, and the drill rod might even float in the deposition fluid. Canisters could also become tilted and jam during deposition. It is not likely that this type of accident would lead to the canister being damaged to the extent that a radioactive release would occur, however if this did occur it would be difficult to resolve. A visual check of the dropped/tilted canister would not be possible, and radioactive substances could be released to the deposition fluid. It is likely that damaged canisters could be retrieved and brought to the surface for checking, and the deposition fluid could need replacing, however it could be difficult to arrange proper radiation shielding during such a manoeuvre [35][19].

When deposition in a borehole is complete, the uppermost section (2000 m) is plugged to prevent the passage of groundwater along or into the borehole. The feed pipe is removed from a section nearest the deposition area and the entire deposition hole is filled with compacted bentonite [10]. In the remaining section to 500 m depth, the feed pipe is allowed to remain and blocks of compacted bentonite are pushed down into the bentonite slurry in the same way as for the emplacement of waste canisters. At some point or points, recesses are created, by cutting holes in the casing, to interrupt any preferential flow along the disturbed zone around the borehole. From 250 to 500 m depth, the borehole is filled with asphalt, and the rest of the borehole with concrete and the feed pipe removed. Plugging with asphalt and concrete may be performed under conditions similar to those of shaft backfilling in the tunnel-based concepts, thereby allowing the drilling rig to be moved on to the next borehole site. It is envisaged by SKB that at least two drilling rigs would be required if waste emplacement is not to take an unreasonably long time.

The recovery of waste canisters would require special equipment. Grab tools are currently used in boreholes to bring up objects from considerable depths during oil field drilling (i.e. as great as the depths considered here for waste disposal) and SKB propose that modifications to these would be necessary to lift canisters in these boreholes. The very dense deposition fluid might, however, be problematic; its density would probably have to be reduced to get the equipment down, which in turn would compromise the stability of the borehole. In the proposed canister design with the fuel elements cast in concrete it is not

[18] No waste emplacement has taken place by the oil industry but substantial objects have been emplaced at depth in boreholes using similar equipment to that proposed for use here.

[19] It is important to compare the difficulty of retrieving such a canister, or group of canisters, from a deep borehole with the situation of a damaged canister or waste package that might require retrieval from a conventional mined repository.

possible to open the canister and lift out the fuel elements. Should this be a requirement, however, SKB consider that alternative canister designs would be possible.

Contaminants, radioactive substances and radiation doses

This method of deep disposal would cause no dissemination of radioactivity under normal operating conditions, however, in the event of serious, less probable events; radioactivity might be spread by means of the borehole fluid. Personnel might also be exposed to radiation during handling. SKB assume that doses would, nevertheless, be extremely low, although they made no specific estimates. Increased doses to personnel could be expected in the event of breakdowns and mishaps. Other contaminants are likely to be generated by transport and from the handling of bentonite, asphalt and concrete.

Safeguards

The deposition area in this concept is considerably larger than in the other disposal concepts. In the KBS-3 concept the part of the repository at the surface is of limited extent and can be fenced off and monitored. Transport containers and canisters are handled and stored in special buildings or underground. In the case of the VDH concept the canister reception section must be mobile, or the canisters must be transported from a central area out to the boreholes. The canister is considerably lighter and less robust than in the other alternatives, weighing about 3 tonnes in comparison with the 25 tonnes of the KBS-3 canister and the 48 tonnes of the VLH canister. In combination with the extensive handling above ground, this poses special requirements for the design of any monitoring systems. The large deposition area and the relative vulnerability of the canister may also be factors in increasing both the likelihood and consequences of sabotage[20].

Long-term safety

The conditions at great depth, in combination with the need for a technically-feasible deposition technique, mean that the buffer properties of the bentonite will be considerably inferior to when it is used in concepts at 500 m depth. To achieve good buffer properties for bentonite under the conditions at great depth, a high density is required and this cannot be achieved at the same time as allowing canister deposition. SKB conclude that it would not be possible in a safety analysis to assume any barrier function for the buffer in the longer term. They also conclude that it would not be possible to design a canister that could be expected to last for 100,000 years (as is the base case assumption in the KBS-3 concept), but that a reasonable design requirement would be a canister that remained intact for 1000 years. This time was considered important as, after 1000 years a large proportion of the fission products that move relatively easily in geological environments have decayed to approximately the toxicity of the uranium ore from which they were originally derived.

The large number of canisters (unless consolidated canisters were used) means that the probable number deposited with undiscovered initial defects is likely to be considerably greater than in the KBS-3 concept. Deposition would subject the canisters to great stresses and neither during nor after deposition would visual inspection be possible. SKB conclude that in a safety analysis it would, therefore, be assumed that a relatively large number of canisters would be deposited in a damaged state. During the initial period when the temperature is high, the temperature gradient would result in fluids being driven upwards, though to what extent this might be important in generating significant upward transport of radionuclides is unclear. Over the long-term the canister and the buffer would be subjected to such large stresses that the retention of any barrier function could not be guaranteed.

---

[20] Although this subject is not discussed by SKB, it needs to be pointed out that, once emplaced in a deep borehole, especially one that has been backfilled and sealed, the difficulty of retrieval is likely to be considerably greater than from a mined repository, especially from one that has not been completely backfilled and sealed.

Safety would then rest with an effective delay by the rock mass, which in turn would rely on the very low anticipated groundwater flux and the high salinity with a marked density stratification of the groundwater. Any analysis of long-term safety would, therefore, need to demonstrate that the geological barrier was adequate and stable over long periods of time.

Safeguards

Excepting the need to supervise a larger area on the surface than would be necessary in the KBS-3 concept, the safeguards conditions are likely to be similar or superior to other disposal concepts. The great disposal depth and the greater probability that the canisters could be damaged would make retrieval of the waste considerably more difficult.

The overall assessment of the VDH concept is shown in Table 6 and discussed below.

Table 6 Combined comparison of the four disposal concepts considered by SKB in their systems analysis [34].

	Overall requirements	Environmental requirements	Safety requirements	Radiation shielding	Safeguards
KBS-3	+	=	+	=	=
VLH	=	+	=	=	=
WP-Cave	-	-	-	-	=
VDH	-	+	-	-	+

Where: + is better: the method has advantages in terms of this basis for comparison

= Neutral

- Worse: the method has disadvantages in terms of this basis for comparison

A summary of the conclusions of the systems analysis, as it applies to the VDH concept is [34]:

> The VDH concept requires comprehensive technological and theoretical development to become a realisable alternative, and it is thought that this could take some time.
>
> The VDH concept is considered to have environmental advantages, partly due to a small volume of extracted rock, partly to potentially fewer restrictions on the future use of the disposal site.
>
> The VDH concept is thought to have disadvantages relative to the other methods, both in terms of safety during operation and in terms of long-term safety after sealing.
>
> Both the KBS-3 and the VLH concepts are considered to fulfil the radiation shielding requirements, but neither the WP-Cave nor the VDH concept do so. With sufficient knowledge it may be possible to demonstrate that these alternatives also meet these requirements, however, the VDH concept would require major technological and theoretical development to do so. This makes both these alternatives more expensive than KBS-3 and VLH.
>
> As regards safeguards, the alternatives are regarded as equal during the operating stage, whilst the VDH concept is considered superior to the tunnel alternatives after the facility has been sealed.
>
> The safety and radiation shielding requirements weigh most heavily in an overall assessment. The result of the systems analysis was that KBS-3 was chosen by

SKB as the principal concept for the management of SF. For both the WP-Cave and VDH concepts it was considered that it was more difficult to demonstrate long-term safety; both alternatives are regarded as more expensive than KBS-3 and VLH, and neither has any obvious advantages.

In an accompanying study SKB [35] showed that it would take about 30 years and cost over SEK 4 billion (approximately £270 M) to raise the level of knowledge of the VDH concept to that of the KBS-3 concept, with the geoscientific studies being the rate-determining factor for the programme (Table 7). The development of the necessary drilling technology is associated with considerable uncertainties and could prolong the total time required and further increase the total cost.

Table 7 Cost estimate (at 2000 prices in Sweden) from SKB for an R&D programme to bring the VDH disposal concept up to the same level as that of the KBS-3 concept [35].

Items in SKB's R&D programme	Cost (£M converted from SEK at SEK 13/£)
General geoscientific R&D	42
Studies within three type areas	23
Safety analyses	3.8
Siting of a rock laboratory for deep boreholes	4.6
Studies using the SKB deep borehole rock laboratory in two 4000 m deep deposition holes	108
Development of drilling technology for the drilling of deep boreholes	10
General R&D for technological barriers	42
Development of deposition technology for deep boreholes	7.7
Development of buffer material for deep boreholes	10.8
Development of canisters and canister manufacture for deep boreholes	7.7
Design planning for deep boreholes	6.2
Design planning for encapsulation plant	3.1
Total estimated cost	**£269M**
Supplement of 20% for unforeseen expenses	**£323M**

It was calculated that it would take 32 years to carry out the R&D programme, with the rate-controlling processes being the siting, drilling and testing of the two experimental boreholes to 4000 m depth.

The proposed R&D programme presented in SKB [35] contained five main sections:

State of knowledge and geoscience research programme

State of knowledge and research, development and demonstration programme related to technical questions.

State of knowledge and research programme related to engineered barriers.

State of knowledge and development programme for safety assessment.

Timetables and costs.

The similarities between the VDH concept and KBS-3 made it easier, SKB believe, to assess the initiatives that must be carried out to develop the VDH concept to the same level of knowledge as that for KBS-3. The analyses of long-term safety and the scope of the geoscientific research and development initiatives are broadly similar. On the other hand, the concepts have different needs in terms of engineering and demonstration and Table 8 sums up the most important differences.

Table 8 Differences between the KBS-3 and VDH disposal concepts with reference to engineering development and demonstration (from [35]).

Process/engineering activity	KBS-3	VDH
Geological characterisation (major discontinuities)	Known and tested technology, option of seeing the rock at the detailed examination stage.	Development required for the characterisation of rock at great depth.
Geological characterisation (fissure distribution)	Known technology, tested data collection methods, development going on in many disciplines touching on the representation of distribution and properties.	Studies at great depth must take place in vertical boreholes. Limited options for observing fractures other than those that intersect the holes. Increased knowledge required to contribute to the data for the assessment of the conditions/risk of structurally-controlled borehole wall fractures and as a basis for process understanding relating to the degree of fracture development.
Hydraulic and hydrochemical characterisation	Known and tested technology. Increased problem at great depth because of denser rock.	Presumably only possible with reference to discontinuities, i.e. fracture zones.
Rock mechanics characterisation	Known technology from the construction industry applicable to 500-1500 m, but increasing problems with mechanical characterisation and stress measurement at increasing depth.	Known technology from the oil industry, but not developed for crystalline bedrock. Increased knowledge required regarding the effect of high stress levels at great depth on test results.
Canister construction	Established construction, development of manufacturing methodology ongoing.	Conceptual sketch available. Choice of canister material, design and manufacturing methodology.
Drilling of deposition holes	Tested technology.	Holes to a depth of 4000 m at a diameter as great as 0.8 m have never been drilled. Increased knowledge required regarding drilling equipment of

		relevant dimensions and equipment handling systems (control *etc.*), as well as for the design of drilling fluid, the management of possible borehole wall failure and the installation of borehole casings and linings.
Canister deposition	Prototype machines undergoing test run in Äspö.	New and untested technology, but a conceptual deposition process has been described. This includes the necessary equipment. Staged development is required, including testing at full scale to the intended depth. Fault and risk analyses are important sub-elements.
Buffer	Experience of several trials, *e.g.* Stripa. Full-scale trial planned in Äspö. Insertion under controlled conditions.	Replacement of drilling fluid with deposition slurry or bentonite blocks to great depth is a new and untested technology. Increased knowledge required regarding a suitable buffer in saline groundwater and on practical procedures for achieving the desired quality.
Recoverability	Untested technique with expanded bentonite, but full-scale trial is planned.	Tested technology in the form of "fishing" in boreholes, but development required for the mechanically-sensitive conditions that apply to canisters containing SF (the canister must not be damaged). Development requires full-scale testing.

SKB [35] concluded that in any future, more thorough analysis that they might perform, practical interests should be given more prominence than in their previous studies. They concluded that they should avoid methods that are untested and may be thought likely to produce problems, and concentrate on simple and practical procedures.

The first step identified by SKB [35] would be to optimise the concept with regard to drilling technology, choice of materials and the insertion of deposition slurry, casing and bentonite blocks (see Figure 2). The function of the system of components defined in this way must be described numerically, which would require that the associated geotechnical processes (swelling, consolidation, the ultimate bearing resistance of the canister (i.e. the maximum allowable stress applied to the canister as it is emplaced) and canister movements) should be modelled with reference to chemical effects.

A second step would be to investigate appropriate possible alternative formulations of the concept and the following steps were considered by SKB to be important in this regard:

> Optimising the current formulation of the concept in terms of its geometry and implementation. For example, it is becoming easier by the year to drill large diameter vertical boreholes and to control their orientation.

Using casings of steel instead of copper bronze.

Improving the isolation capacity of the clay buffer by increasing the density of the deposition slurry. One proposed way of bringing this about might be to mix highly-compacted bentonite pellets into the slurry by pushing them in after deposition. Another proposal was to produce slurry of a higher density by mixing bentonite granulate with a weighed quantity of calcium chloride solution, so that the highest possible density is achieved while still retaining a slurry that can be pumped.

Eliminating the risk of major internal movements in the deposition zone by replacing the original concept's system of canisters with highly-compacted bentonite blocks between a continuous stack of canisters.

A more radical possible variant of the concept would be to change the depth of the borehole. This would require improved knowledge of how the properties of the rock mass (in particular the hydraulic conductivity and the potential for tectonic displacements) change with depth. It may then be possible to justify a reduced depth, for example a 2.5 km deep borehole with a 1.25 km plug zone and a 1.25 km deposition zone. A solution such as this should mean that the problem of borehole stability should decrease and that the borehole diameter in the deposition zone could be increased, thus making space for larger canisters. However, an analysis of such an alternative concept does presuppose that it would be possible to determine the hydraulic conductivity of the rock mass and the transmissivity of discrete flow paths as a function of the depth, whilst also taking the groundwater chemistry into account. SKB concludes that, if after further research, it was found that understanding of the rock remained poor, they could decide to take the opposite approach and increase the borehole's depth to about six kilometres, though increasing the depth would results in greater difficulties in terms of borehole stability. SKB considered that the following projects should be considered important in developing and assessing variants of the VDH concept:

Performing a more thorough analysis of the groundwater turnover in the rock mass with a variety of assumed structural properties.

Performing a more thorough analysis of borehole stability as a function of rock mass structure and borehole diameter.

Optimising the concept in terms of the depth and diameter of the boreholes and in terms of canister dimensions and waste quantities.

The choice of buffer material would also have to be subjected to scrutiny and, since its principal task is to keep the canisters in place (and not act as a barrier), it is by no means clear that bentonite is the best choice, especially if it should prove that the TDS of the groundwater far exceeded 100 g L^{-1} or 10%.

The areas which SKB [35] saw as requiring the greatest research and technology development were:

The characterization of the bedrock.

Measurement of groundwater flow and determination of the chemistry of the groundwater.

Drilling technology.

Canister design.

Methods to be employed for emplacing waste canisters.

Buffer design.

Retrievability.

The geoscientific questions would require drilling of pilot holes to a depth of at least 4000 m on three selected sites. Equipment and methods for measurement and investigation would be developed in these boreholes and on these sites. Active participation in international deep drilling projects would also be necessary.

For the purposes of technology development and demonstration, one of the sites would have to be selected and an additional two very deep holes be drilled. These holes would be drilled at the full proposed emplacement diameter of 800 mm and be used for the development of deposition and retrieval technology and equipment.

The engineered barriers and their performance are closely associated with the assessment of long-term safety. High hydraulic pressures, mechanical loads, temperature and salinity make different demands on the engineered barriers from those that apply in a KBS-3 repository. Research and development would be required for the design of a canister and the choice of encapsulation material as well as for the choice of a buffer around the canister. Fuel dissolution at high temperatures and salinities would require work aimed at improving analytical techniques and knowledge of the state of radionuclides in such a highly saline environment.

SKB [35] concluded that there was no evidence (in 2000) that disposal in very deep holes would increase safety or reduce the cost of disposing of the SF. SKB therefore decided not to plan to carry out an RD&D programme for VDH, but instead to concentrate its resources on developing a repository based on the KBS-3 method in the relatively near future.

SKB also stated that they would continue to follow developments in the field of deep borehole disposal, since the results and experience obtained could also be beneficial for understanding the conditions in a KBS-3 repository at a depth of about 500 m. A recent review of the geoscientific information on conditions at depths of up to several kilometres in the earth's crust is provided by [39], as part of this continuing interest in the concept.

5 DISPOSAL OF PLUTONIUM

The disposal of Pu in deep boreholes has been considered by a variety of countries, but dominantly by the USA and Russia, and by far the largest amount of published material concerns the programme which took place in the USA, mainly in the 1990s. The problem of excess weapons-grade Pu in an international context has also been studied by institutions outside the USA, such as the work by [26] at Chalmers University in Sweden.

5.1 USDOE weapons-usable Pu disposal

5.1.1 Introduction

In 1996 a decision was made at the Moscow Nuclear Safety Summit by the Russian Federation and the leaders of the seven largest industrial countries (G7) to render surplus fissile materials, both highly enriched U and Pu, in Russia and the USA in a form that was resistant to proliferation. As part of this work the USDOE developed a Spent Fuel standard: "*A concept to make the plutonium as unattractive and inaccessible for retrieval and weapons use as the residual plutonium in the spent fuel from commercial reactors.*" A programme of work was initiated to examine the options for achieving this standard and, as part of this work, the disposal of Pu and enriched U in deep boreholes was considered. In anticipation of the possible disposal of Pu, other work had already been carried out, for example by the National Academy of Sciences [40], and this is discussed below in Chapter 5.3.

Two alternative disposal deep borehole concepts were considered by the USDOE [4] with each being defined as the

"*Entire sequence of processes and facilities necessary to convert stable stored weapons-usable plutonium into forms to be disposed ultimately in government-owned deep boreholes*".

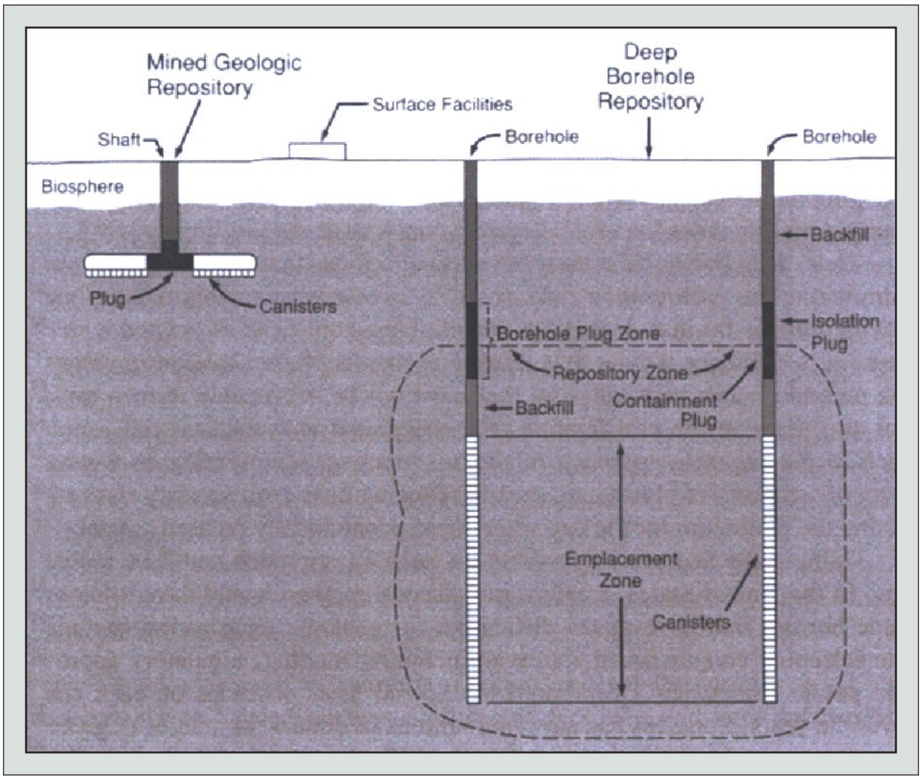
and the description of Pu disposal below is, unless otherwise stated, based exclusively on [41].

These deep borehole alternatives were compared with various other alternatives which involved a variety of different types of waste immobilisation techniques and subsequent disposal in a "standard" HLW repository. It was proposed that the Pu for the deep borehole disposal concepts would not be spiked with radioactive waste to provide a radiation barrier and that the geological barrier by itself would provide a level of proliferation resistance and supply the major barrier to the migration of the Pu to the biosphere.

The plan was to emplace the waste material in the lower part of one or more deep boreholes drilled in tectonically, hydrogeologically, thermally and geochemically stable rock formations and based, effectively, on considerable early work on the disposal of HLW and SF in the USA, as discussed in Chapter 3 (Figure 15). It was assumed that the boreholes would be sited on non-DOE sites, unlike all other alternatives which would be carried out on DOE-owned land. Once the emplacement zone of the boreholes was filled with Pu materials, the *isolation zone* extending from the top of the emplacement zone to the ground surface would be filled and sealed with appropriate materials. The assumption was that at the emplacement depth the groundwater would be relatively stagnant, highly saline, hot (75-150° C), and under high pressure. A considerable barrier to radionuclide transport would be provided by the isolation zone because of its low permeability and high sorptivity, the stability and low solubility of the disposal form, and the high salinity and the lack of driving forces for fluid flow. It was stated that:

"*Thus the disposed material is expected to remain, for all practical purposes, permanently isolated from the biosphere*".

Figure 15 The deep borehole disposal concept considered by the USDOE for the disposal of plutonium [41]. The concept is, in fact, taken from a considerably older report on the disposal of HLW and SF [6].

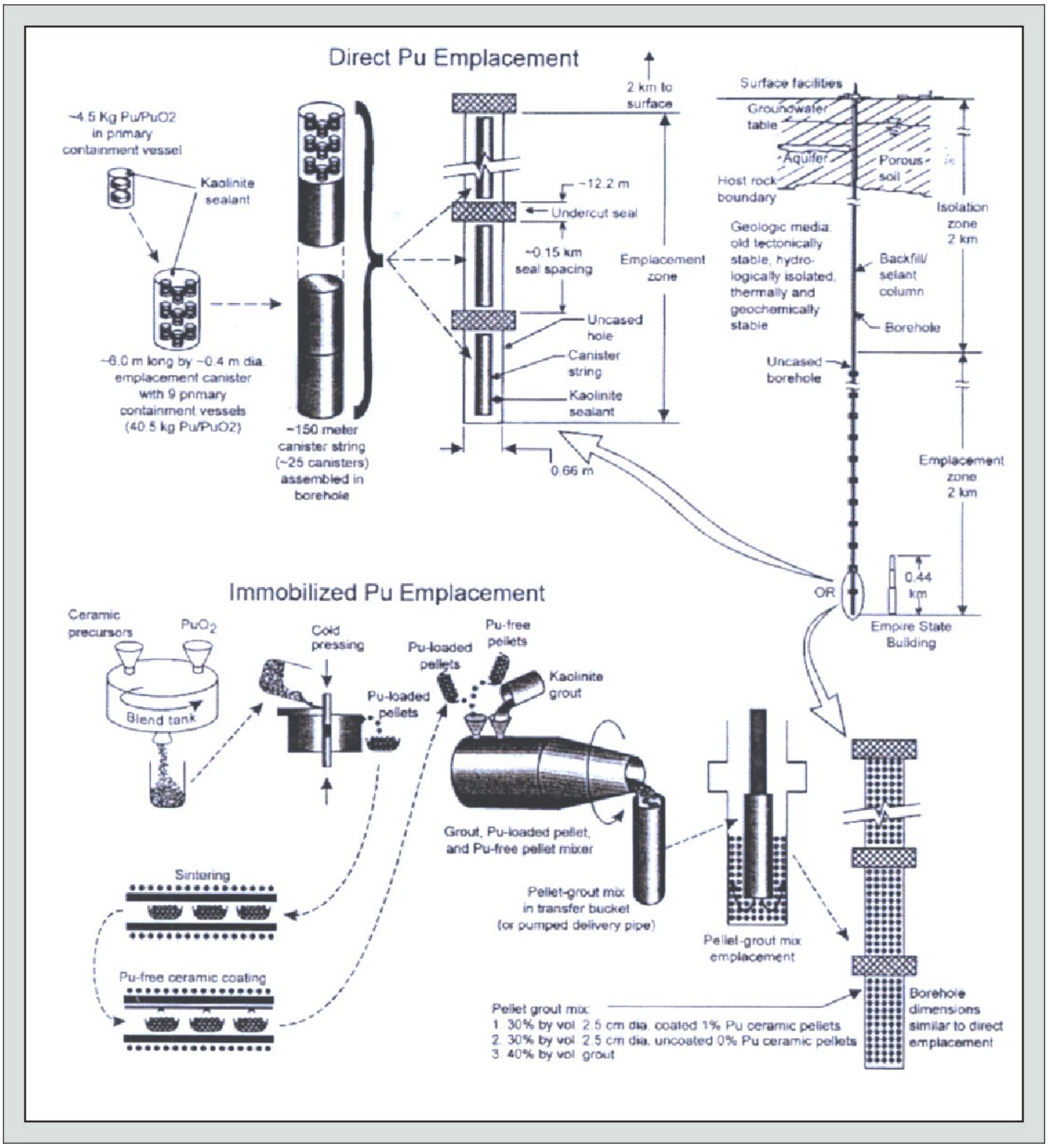


The characteristics of the two alternative deep borehole disposal concepts, either *direct emplacement* or *immobilised emplacement* are summarised in Table 9 and illustrated in Figure 16. Both alternatives assume a disposition rate of 5 tonnes per year over a ten year operational period, although it was assumed that accelerated cases could allow emplacement in three years with the simultaneous rather than the sequential drilling of boreholes.

Table 9 Deep borehole disposal alternatives, either *direct emplacement* or *immobilised emplacement*, considered by USDOE [41].

Alternative	Description
Direct emplacement	Disposal form is Pu metal or Pu oxide
	Emplacement at >2 km depth in four 4 km deep uncased boreholes with diameters from 0.91 - 0.66 m
	In containment vessels within 0.4 m 6.1 m long canisters (with voids filled)
	No radiation barrier
Immobilised emplacement	Disposal form in Pu immobilised in SYNROC-like titanate ceramic pellets with thin Pu-free coating
	Ceramic pellets containing Pu have 1% Pu loading
	Pu pellets mixed with equal volume of Pu-free ceramic pellets and kaolinite grout and emplaced directly without any canisters (mixing Pu-loaded and Pu-free pellets creates an average Pu loading of 0.5% by weight)
	Emplaced at 2-4 km depth in four deep 0.66 - 0.91 m diameter uncased boreholes
	No radiation barrier

Figure 16 The deep borehole disposal alternatives, either *direct emplacement* or *immobilised emplacement*, considered by the USDOE [41].



5.1.2 Direct Emplacement Alternative

As shown in Figure 16 in the direct emplacement alternative, Pu metal and oxide is received and, without further purification, is packed in metal product cans which are then sealed in primary containment vessels and delivered by SSTs (DOE's Safe Secure Trailer System) to the deep borehole disposal facility. The product cans are placed in a container which holds plutonium product cans containing approximately 4.5 kg of plutonium with double containment. These transportation containers are directly encapsulated in large (0.4 m diameter, 6.1 m long) emplacement canisters with filler material mixture without being reopened. Each emplacement canister contains 40.5 kg of plutonium. The emplacement canisters are then assembled into 152 m long canister strings with 25 canisters per string. The canister strings are lowered into the emplacement zone of the boreholes (at a depth of >2 km) and are grouted in place with kaolinite clay. Finally, the isolation zone is sealed from the top of the emplacement zone to the surface with appropriate sealing materials.

In the direct deep borehole alternative, the criticality safety of the plutonium-loaded product cans and the transportation containers during transportation to the disposal site, processing, emplacement and post-emplacement performance are ensured by ensuring the spatial separation of the Pu material. The USDOE [41] concluded that[21]:

> The low solubility of the plutonium metal/plutonium oxide disposal forms and the very slow groundwater fluxes expected at depth would provide sufficient resistance to mobilisation by groundwater.
>
> The heat generated by the plutonium is so small that the temperature rise due to alpha decay of the plutonium would be negligible.
>
> The high salinity of the groundwater would completely suppress any buoyancy-related fluid flow due to temperature changes arising from both the heat generated by plutonium decay and geothermal heat.
>
> Estimates of fluid flow velocities due to water level fluctuations at the surface and earthquake-generated fluid pressure fluctuations appear to be negligible, as a result of the great distance from the surface, the low permeabilities of fractured rocks at depth and the stabilising effect of the high salinity gradients.

5.1.3 Immobilised Emplacement Alternative

As shown in Figure 16 in the immobilised emplacement alternative, plutonium oxide is formed into plutonium-loaded ceramic pellets by a cold press and high temperature sintering process. The plutonium loading of the ceramic pellets is kept at the very low level of 1% by weight to assure criticality safety during processing and after emplacement. To provide a barrier to contamination during handling, the sintered ceramic pellets are subsequently coated with a thin impervious layer of ceramic that is free of plutonium. The ceramic material is a tailored, SYNROC-like titanate-based ceramic with the mineral phases zirconolite and perovskite as the primary constituents. The pellets contain 98% ceramic and have a density of approximately 4 g cm^{-3}.

The ceramic pellets are then transported by SSTs to the deep borehole disposal facility and here the plutonium-loaded ceramic pellets are mixed uniformly with an equal volume of plutonium-free ceramic pellets (to yield a pellet mixture with an average plutonium loading of 0.5% by weight) and a 'grout' (i.e. kaolinite). This additional dilution of the plutonium-loaded pellets with plutonium-free pellets increases the criticality safety margin. The mix is then emplaced in the uncased emplacement zone of the boreholes. No metal canisters, packaging materials, or borehole casings that could compromise the hydraulic sealing of the waste form in the borehole are left in the emplacement zone, thereby providing, according to the USDOE [41], superior sealing of the waste within the borehole compared with the direct emplacement alternative. Finally, as in the case of direct disposal, the isolation zone of the borehole is sealed from the top of the emplacement zone to the surface with appropriate materials.

[21] No calculations are provided in [41] to justify these statements.

The combination of the very low solubility and high thermodynamic stability of the ceramic waste forms is expected to provide superior long-term performance compared with the direct emplacement waste form. The low solubility of the ceramic pellet waste forms and the very slow groundwater flow velocities expected at depth indicate, according to the USDOE [41], that many millions of years would be required to mobilise even one millionth of the emplaced plutonium.

5.1.4 Technical status and assessment

Whilst no deep borehole disposal facilities for plutonium disposal have ever been developed, the USDOE [41] considered that many of the technologies needed for deep boreholes were quite mature, as the basic concept had been considered previously for disposal of other forms of radioactive waste.

The USDOE [41] concluded that the technical unknowns regarding deep borehole disposal centred on an understanding of the conditions at depth and the post-closure performance and a regulatory environment against which performance objectives could be measured. They concluded that suitable rock formations could be found in several areas in the USA, that these could be adequately characterised and that the long-term evolution of the disposal system could be assessed adequately so as to ensure long-term safety.

The immobilised emplacement alternative was considered to differ from direct emplacement in terms of technical unknowns. The extra cost of immobilising the plutonium could be accepted, in part, to give added assurance of long-term safety and a simplified licensing safety argument, with the result that this alternative had fewer uncertainties than the direct emplacement alternative.

The reasons for this increased confidence in the immobilised emplacement alternative with respect to long-term performance were stated to be:

> ***Reduced post-closure contaminant mobilisation:*** The ceramic pellet disposal form used in the immobilisation alternative is the best performing, most geologically compatible and thermodynamically stable disposal form available. The solubility and plutonium release rate from this disposal form is at least three to four orders of magnitude lower than that of other competing disposal forms, including the Pu metal or Pu oxide disposal forms of the direct disposal alternative.
>
> ***Increased confidence in emplacement zone sealing:*** The degree of isolation of the plutonium from the biosphere will depend not only on the geological barrier but also on the nature of the transport mechanisms and the resistance to transport up the deep borehole past the borehole seals. It is necessary to seal properly not only the isolation zones in the upper half of the deep boreholes but also the emplacement zones. The immobilised emplacement alternative reduces uncertainty in the sealing of the emplacement zone by eliminating long, vertical canisters which could degrade, thereby providing potential flowpaths.
>
> ***Increased post-closure criticality safety:*** The plutonium loading in the ceramic pellet option has been kept to a very low 0.5% effective loading (for a 1:1 mix of 1% loaded pellets and plutonium-free pellets) to drive the criticality coefficient down to a value of 0.67 under the worst possible brine-saturated conditions and without any addition of integral neutron absorbers. This is far below the value of 0.95 specified for the safe storage of plutonium metal.

Siting guidelines and procedures for selecting a site were considered by the USDOE [41] to represent the greatest area of uncertainty. It was appreciated that site suitability guidelines consistent with the safety concept of deep borehole disposal would require development. The direct disposal of separated fissile material in significant quantities had never been previously considered and a regulatory framework to address this disposal concept did not exist. Regulatory uncertainty was identified as a risk that affected the viability of this disposal concept, however, preliminary discussions with licensing experts indicated that a licensing regime could be developed, given sufficient time and a suitable mandate.

It was concluded that the equipment requirements for drilling deep boreholes and emplacing the waste were within current capabilities or were viable extrapolations from existing mechanical engineering designs. A demonstration of the techniques would obviously be required; however the drilling and other mechanical design factors were not expected to represent a significant technical risk.

USDOE [41] states that the potential for very long-term geochemical processes in the deep borehole environment to mobilise and redistribute fissile isotopes into critical configurations was a subject of current research and development at the time, however, it is not known where, or if, the results of this research have been published. Preliminary research and development results had indicated that there were characteristics of the deep borehole environment that provided a very strong safety argument against both post-closure criticality and post-closure contamination of the biosphere. The high safety margin was considered to arise from:

- The great depth of burial.
- The high resistance to mobilisation of the selected disposal forms.
- The properties of the subsurface rock and brines.
- The low permeabilities of fractured rock at great depths.
- The lack of driving forces for fluid flow at sites selected according to the site selection criteria developed for deep borehole disposition[22].

5.1.5 Costs

Investment costs, operating costs, non-discounted life cycle costs and discounted life cycle costs for the deep borehole alternatives were estimated and are listed in Table 10, assuming that 50 tonnes of weapons-grade Pu would need disposal [41].

[22] See discussion in Section 5.2.

Table 10 Deep borehole alternative costs in constant and discounted form [41].

	Constant US$ (millions)				Discounted US$ (millions)		
Alternative	Facility	Investment	Operating	Net life cycle costs	Investment	Operating	Net life cycle costs
Direct emplacement	Front-end	240	800	1040			
	Borehole	870	670	1540			
	Total	**1110**	**1470**	**2580**	**800**	**700**	**1500**
Immobilised emplacement	Front-end	580	1510	2090			
	Borehole	770	720	1490			
	Total	**1350**	**2230**	**3580**	**990**	**1060**	**2050**

As indicated by the data in Table 10, the non-discounted life cycle cost of the direct emplacement borehole alternative is $1 billion less than immobilised borehole cost. These rather precise costs seem at variance with those costs implied from the table in [42], where the potential number of boreholes for these two disposal options is shown as having large ranges (Table 11). No explanation is provided by Halsey *et al*. for these large ranges (and their resultant cost implications) or their contrast with those provided by the USDOE in the same year, though these groups were working on what appears to be the same programme.

Table 11 Number of deep boreholes required to dispose of 50 tonnes of Pu [42].

Disposal option	Range of Pu loading	Potential number of boreholes
Direct disposal	1-14 kg m^{-1}	2-25
Indirect disposal	0.25-12 wt%	1-100

In the USDOE work [41] the borehole alternatives were considered, initially, to be a potentially desirable alternative because of their apparent relatively low cost. Their assumed relatively low cost was thought to be mainly due to the use of relatively low-technology processes and equipment that would be inexpensive compared to the highly-specialised MOX fuel fabrication equipment (required for the other disposal options considered by the USDOE). It transpired, as a result of this work carried out at the USDOE [41], that costs of this option were understated due to two significant factors:

Firstly, the borehole site facilities would be likely to be situated at non-DOE sites, unlike all other alternatives which would be carried out on DOE sites with greater or lesser amounts of infrastructure. As such, large costs would be required to develop the infrastructure to support the borehole facilities. (The reason for this was that only sites that met strict site selection guidelines could be used for deep disposal purposes, and it was thought unlikely that any DOE sites would prove to be suitable).

Secondly, while the borehole disposal processes are relatively low technology operations, they still would have to be performed in expensive Category I plutonium handling facilities.

The greater cost of the immobilised emplacement alternative is due to the large costs associated with the front-end processing, which is, in turn, due to the greater amount of material processing required.

5.2 Site selection

Heiken *et al*. [43] prepared a site selection guide for selecting suitable sites in the USA where the deep borehole concept could be applied. They took the borehole designs discussed above, but with a possible additional modification that large amounts of DU (Depleted Uranium) might be added to the backfill within the deposition zone in the borehole to provide isotopic dilution of U, as it increases due to the alpha decay of Pu.

The type of disposal environment considered suitable was based on the answers to the key performance indicator, namely: Can the borehole system effectively isolate the waste from the accessible environment?[23] This was also be expressed [43] as: “If an isolated system can be found, is it possible to emplace the waste without disturbing the natural isolating features and will these features continue to provide isolation for an equivalent geological time span?” These questions spawned several other questions regarding the performance of the disposal system, such as [43]:

Can the system really contain the wastes forever? If not, how long is the actual containment period?

Under what scenarios, both expected and abnormal, can a release occur, and what is the magnitude and timing of the release?

If a release occurs, will it reach the accessible environment, in what amounts, and with what effects on the biosphere?

^{239}Pu decays to ^{235}U - what effect does this have on the borehole system and natural transport phenomena?

Are there any credible scenarios leading to criticality, and if so, how would a criticality event affect isolation?

Even if there is never a release, how does the system evolve over time?

The above questions were used to guide the definition of what these authors considered a suitable disposal environment and Heiken *et al*. [43] listed four factors which they considered defined the ideal site for a deep borehole disposal facility:

Crystalline rock at the surface or within 1 km of the surface.

A region that is tectonically stable.

An area located away from population centres.

---

[23] A term used in the USA, which is incorporated within the NRC regulations for the disposal of radioactive waste and whose approximate equivalent in the UK would be the biosphere.

A region not near international borders (*i.e*. >200 km).

Why these particular factors were selected is not discussed.

Following on from the definition of these factors, they defined a suitable environment as one lying within Precambrian crystalline rocks, most likely in the central part of a granitic pluton, in particular one that had not been deeply eroded, so that the deep boreholes would not penetrate its base. Using information from previous deep boreholes, including the Gravberg-1 borehole (see Chapter 4.1.1), and the "*qualifying conditions*" derived from the NAS report [40][24] they came to the conclusion that the following conditions were required of the host environment:

Rock characteristics:

Disposal over the depth range of 2 – 4 km.

Free of vertical faults.

Very low permeability.

Crystalline rock.

Absence of faults.

Absence of faulting for many million years to come.

Tectonics:

Free of geological activity.

Geochemistry:

Very saline groundwater of the disposal depth, preferable with fresh groundwater above.

Homogeneity of rock properties.

Several of these conditions were not clearly defined in the reports reviewed, (for example, what is meant by "free of vertical faults", within what distance of the boreholes would this apply and how large a fault would be considered problematic?). The difference between this and the factor "absence of faults" is also unclear. Neither [43] nor [44] on deep borehole disposal, both of which are based on information from SKB's deep borehole programme, provides clear justification for the conclusions reached.

5.3 National Academy of Sciences Report

Much of the NAS [40] report appears to be based on the results of the previous work by SKB (mainly using [45]) but it is not always clear that this is in fact the case. Reference is made to the fact that modelling of the effect of transmissive faults and fracture zones on the safety of the deep borehole concept has been carried out, however, no results of this modelling are presented and the effect of such structures on the safety of this disposal concept is only referred to in passing.

If the deep borehole(s) used for disposal were connected at depth to a large, near-vertical fault and a similar connection were available nearer the surface, density differences between the fluid in the borehole and that in the fault (for instance, due to fission product decay heat

[24] Although Heiken *et al*. [43] state that these *qualifying conditions* are taken from [40], another, unspecified, source has also been used.

in HLW or SF - but not in weapons plutonium) would drive fluid circulation, leading to far more flow than would be available from circulation confined to the pore fluid of the borehole itself. For this reason, the NAS [40] concluded that it would be necessary to characterise candidate regions for deep boreholes (perhaps using normal seismic techniques), and to make measurements from one or more pilot boreholes, in order to avoid emplacing containers in regions of major faulting. The possibility of major future faulting over many millennia was also one important area of uncertainty that the NAS indicated required further study. For similar reasons, they considered it important to choose drilling methods that minimised fracturing the surrounding rock.

Another important issue they considered was avoiding transport up through the borehole itself, and in this they agreed with the conclusions of SKB [45] in the types of methods that should be employed to seal the boreholes, *i.e.* 2000 m of clay, asphalt, and concrete. The majority, if not all, of the borehole is likely to be saturated with groundwater, and it was concluded that it was important to ensure that there would be no ready means for convection in this groundwater that would allow the transport of radionuclides upwards. For example, dissolved gas, heat, or differences in salinity could, in principle, reduce the density of the groundwater in the part of the borehole where the waste was emplaced, resulting in groundwater moving slowly upwards through the borehole plug. The NAS [40] concluded that it was important to choose materials for the waste package that did not generate more gas in the borehole (due to corrosion) than could be dissolved in the groundwater (which would be determined by the solubility limit at that depth and temperature).

The NAS agreed with conclusions of the SKB study [45] that the increased salinity of groundwater at great depth (*i.e*. in excess of 2-3 km) was likely to eliminate upward convection; probably even in the case where heat-emitting waste is disposed at sufficient depth[25]. The conclusions of the SKB study are relevant in this regard:

> *"Clearly, a repository in a saline environment with fresh water above is highly desirable. If the water is highly saline, it appears that no radionuclides at all will be transported to the surface by convection."*

The sorption of plutonium on to the kaolinite or bentonite used to seal the borehole would provide another major barrier to its transport to the biosphere. Simple calculations by the NAS, using the known solubility of Pu in reducing conditions, a K_d of 10^5, a groundwater transit time of 10^3 years from the disposal depth to the surface and a distribution coefficient between the Pu dissolved in the groundwater and that sorbed onto the bentonite, would mean that it would take millions of years, in theory, for any Pu to reach the surface, if transport took place only up the borehole. The NAS admitted that more complex calculations would be required to assess the degree to which Pu might migrate via transmissive faults and fracture zones, which would not have nearly the retarding capacity of the bentonite-filled borehole. They emphasised, however, that if high salinity at depth could be guaranteed, even the presence of such extensive faulting would result in the transport of Pu to the surface through a marked salinity gradient taking place only extremely slowly, over a period of millions of years.

The NAS [40] concluded that if the deep borehole site were chosen appropriately, and the material emplaced correctly, the only natural processes that could result in Pu being

[25] If the material to be disposed of generated substantial quantities of heat (as is the case with HLW and SF), the decrease in density resulting from the warming of the surrounding groundwater could lead to some upward convection, if the salinity were not sufficiently great. Such convective processes would, however, not operate where a major salinity gradient existed, as the density stratification would remain stable.

transported to the biosphere were volcanic activity and meteorite impact or extensive uplift and erosion - and that proper site selection should be able to guarantee the absence of both volcanic and erosive effects, especially as the waste had been disposed of at such great depths. They emphasised that the risks from any of these types of natural event were considerably lower for deep boreholes than they would be for a conventional repository at a depth of approximately 500 m.

The deep borehole option would, however, have to be analysed for various accident scenarios during waste emplacement, in order to help define the facilities and procedures required to reduce their likelihood and to provide means to proceed in case of an accident. Borehole collapse during drilling would require re-drilling, but collapse after waste emplacement would represent a more complicated problem that would need to be addressed during a development programme for this option. A set of open questions and major outstanding issues regarding the deep borehole option were considered to be:

Mechanisms for possible transport of radionuclides to the surface.

Advantages and disadvantages of different geological environments and sites for deep borehole disposal.

Methods of collecting data on the characteristics at depth of potential sites, sufficient to permit analysis necessary for site selection and licensing.

Approaches to monitoring and retrieval of emplaced waste.

The pre-processing required to create an acceptable waste form for disposal and to prevent criticality in the boreholes.

Techniques for emplacement of the waste and other material in the boreholes.

Potential failure modes, particularly during emplacement, and their possible consequences.

Costs, including those for site selection, data collection, analysis, licensing support, drilling of the boreholes, emplacement, and post emplacement monitoring [40].

5.3.1 Cost

The NAS [40] used the cost estimates provided by SKB [45] to estimate the cost of the deep borehole disposal of 50 tonnes of Pu in the range of $100 million per borehole (assuming that the boreholes were drilled using US-based technology and US-based companies – the NAS reported that an unnamed Russian group advertised that it would drill a set of boreholes at a considerably lower cost). The NAS also pointed out that there would clearly be less processing necessary to transform weapons-grade plutonium to a suitable waste form and to handle the resulting canisters than would be the case for HLW or SF, because of the intense gamma radioactivity of these latter products (however, see the comments on cost which accompany Table 10 above and the report by the USDOE [41]) which is not in agreement with this statement). The NAS concluded that it appeared certain that in the United States, at least, the costs of development of the deep borehole option, and particularly of gaining the needed licensing and approvals (if they were eventually obtained), would substantially exceed the costs of the actual emplacement.

5.3.2 Retrievability

The NAS [40] considered that the ability to monitor and retrieve the waste canisters, once emplaced, would be desirable from the point of view of ensuring that the system was working as expected, but that retrievability was not a virtue if the goal of the disposal method were to create major barriers to reuse of the plutonium in weapons. They referred to the fact that, at various times, deep borehole disposal of HLW and SF had been described as being irretrievable, when this attribute was considered desirable, or retrievable, when it was regarded as a virtue. Quoting SKB [45] they stated that:

> *"It was initially thought that the VDH [Very Deep Hole] concept would not allow the canisters to be retrieved once they had been deployed. Further consideration of this aspect of the concept indicates this not to be the case. There is no reason why the plugged section [of the original hole] cannot be drilled or washed out with high pressure fluids. Once the canisters have been reached they could be fished out using overshot tools, a standard oilfield practice. This procedure assumes that the canisters are still intact."*

It was concluded that, as this quotation suggests, the simplest retrieval approach would involve re-drilling the borehole(s), which would be relatively easy for the section filled with bentonite and, in this way, the string of canisters could be reached and retrieved, assuming the canisters remained intact. The only major differences from conventional drilling would be the requirement to follow the pilot hole and the details of access to the canister. If the operation were to be conducted at a time when the canisters had ruptured or dissolved, a more complex approach requiring greater safety and health precautions would be required, but the NAS considered that the waste would remain retrievable at "somewhat greater cost".

The NAS concluded that, however, it would not be possible for anyone to retrieve the plutonium without the permission of the host country, as long as political control in the host country remained intact[26]. Moreover, because such drilling activities would be highly visible, the host country could not retrieve the plutonium without detection. To make retrieval more difficult in the future, the NAS considered that one might make the boreholes harder to redrill by embedding extremely hard material in the mud and concrete with which the hole is backfilled. One might also make it more difficult to find the precise location of the boreholes by choosing a site in which the hard rock, in which disposal had taken place, began at a depth of hundreds of metres or more, and by filling the zone above the sealed boreholes in the rock, and the region between there and the surface with rubble. The NAS admitted, however, that if the approximate location of the boreholes were known, it could eventually be found. If the goal of retrieval were only to acquire a few tons of plutonium and reactors and reprocessing facilities were available, it might turn out to be easier to make new plutonium or to separate reactor-grade plutonium from SF; but since the borehole would only have to redrilled once, retrieval from the deep borehole would probably be a cheaper route by which to acquire a large volume of Pu.

5.3.3 Policy issues

While disposal in very deep holes appeared to the NAS [40] to be technically feasible, and appeared to offer the potential for superior isolation of plutonium from the biosphere, they noted that it had received far less critical study than had disposal of SF and HLW in conventional repositories. A substantial additional research and development effort would, therefore, have to be focussed on the deep borehole option if this were to be a leading contender for plutonium disposal. The NAS made reference to the programme of R&D set

[26] It needs to be remembered here that at the time there was considered to a political imperative to find a method of rendering Pu in an inaccessible form as soon as possible, in particular because there was concern regarding the stability of the Russian Federation. The work on Pu disposal, therefore, needs to be viewed in this light, which is somewhat different from that in which the disposal of SF or HLW is normally viewed.

out by SKB, as outlined in Chapter 4, and concluded that the deep borehole option was not ready for "development" and that, in the absence of a crash programme (designed to accomplish an aim rapidly), it would take more than a decade to formulate a plan, carry out research on drilling and emplacement, and use existing boreholes to evaluate the effectiveness of sealing techniques.

They considered that a critical issue, at least in the USA, would be the likely difficulty of gaining the needed licences and approvals for a deep borehole disposal approach, based on the time that it had required to develop a repository at Yucca Mountain. In the case of the deep borehole disposal concept, the relevant data would generally be more difficult to acquire than those required for a conventional repository. In the course of drilling the borehole itself (and the smaller diameter pilot hole), a great deal of data on the properties of the rock being drilled through and the geology of the site could be acquired. To assess the homogeneity of the site would, however, probably require drilling a number of additional boreholes to comparable depths in the immediate vicinity, and means would have to be provided to ensure that these additional exploration boreholes (if they were not to be incorporated into future disposal boreholes) did not provide a potential means of transport of radionuclides to the surface. However many exploration boreholes were drilled, the degree of detail available on the geology of the rock mass over the depth range of 2000 - 4000 m would be unlikely to match that for a repository at 500 m depth. Finally, developing a technical licensing approach that did not rely on monitoring and retrievability, which is possible with a mined repository concept, would be difficult and time-consuming.

6 ALTERNATIVE DISPOSAL OPTIONS IN DEEP BOREHOLES

A recent review of deep boreholes disposal options by [32] includes a considerable number of different deep borehole disposal techniques for solid radioactive waste that have been considered since the 1970s. These options can be placed in seven generic categories, which are shown in Table 12, and are discussed in more detail below.

Table 12 Summary of the seven generic categories of the deep borehole disposal schemes (options) included in the review by Chapman & Gibb [32] and in this review.

Deep borehole disposal scheme (option)	Description and comments
In situ melting	In situ melting is similar to Deep Underground Melting (DUMP), initially suggested in the USA in the 1970s and 1980s (see Chapter 3.1.1), but involves encapsulation of the waste. Multiple small metal containers are placed at the bottom of a borehole (or in an excavated cavity) and sealed in with host rock rubble. In time, the heat from the HLW fuses the waste, containers, and rubble together [24].
Deep self-burial	Concept, proposed by Logan [13], involves heavy, possibly cooled or refrigerated, metal containers filled with heat-generating waste being lowered to the bottom of a cased borehole up to 2 km deep in a crystalline host rock. After any cooling is stopped, the waste packages heat and melt the enclosing rock through which they then sink under the influence of gravity, coming to rest only when the heat budget of the waste is used up.
Low temperature (encapsulated) borehole disposal	As proposed by SKB (Chapter 4), *etc*.
Disposal in former hydrocarbon boreholes	The re-use of depleted oil reservoirs accessed by deep boreholes, suggested by [46].
High temperature (encapsulated) borehole disposal	Gibb [18] [19] proposed that heat-generating HLW in special containers be positioned in the lower part of a 4 to 5 km deep, large-diameter borehole drilled into granitic continental crust. Radioactive decay would gradually heat the waste packages to peak temperatures sufficient to generate a substantial zone of partial melting in the surrounding granite at about 850°C [20].
Hybrid (encapsulated) borehole disposal	The sealing of deep boreholes by partial meting of the rock using HLW packages situated above the main disposal zone, or by the use of electrical heaters.
Spent sealed source disposal	The use of boreholes for the disposal of spent sources. Not included in this review, but currently under investigation by the IAEA.

6.1 Comparison of disposal concepts

6.1.1 Disposal concept from Chapman and Gibb

The review by [32] also provides a comparison between the concept of deep disposal, in general, and the more commonly considered disposal concept of a mined repository. In order to carry out this comparison, they present a "model deep borehole disposal concept" that they suggest would work best for small volumes of waste in compact packages. The presentation of their concept allows a comparison to be made between different designs of the deep borehole concept and between the common elements of this concept and a mined repository.

The essential elements of the concept presented by [32] are:

- Deep, vertical boreholes (or possibly a fanned borehole array) in which waste would be disposed of in the depth interval of approximately 3000 – 4000 m.
- Disposal zone located in crystalline rocks in area of normal geothermal heat flow.
- Crystalline rocks possibly overlain by thick sedimentary sequence.
- Long borehole seals, as in SKB's VDH concept [11] [34].
- Thin-walled waste packages about 0.5 m diameter and 1 m long, containing about 0.17 m^3 of waste (approx. 0.5 tonne).
- Waste canisters emplaced in borehole using a centraliser/roller cage.
- Approximately 250 tonnes of waste per borehole (with a nominal emplacement pitch of 2 m and a 1000 m long disposal zone).

They suggest that vitrified HLW or surplus plutonium in a glass or ceramic matrix would be the most obvious candidates for this concept, as package size and design could be easily controlled; whereas SF would be an unlikely candidate, as typical reactor fuel assemblies require long packages (*e.g*. 4.76 m in the case of SKB; Figure 12) that would be more difficult to handle, and reasonable borehole diameters would permit only single (or a few) assemblies in a package.

Chapman and Gibb [32] assume a disposal concept in which the borehole diameter is 0.8 m in the disposal zone (the same as used by SKB; Chapter 4.1.4) but, in contrast to SKB, propose smaller canisters and a different waste form (proposals from SKB and other organisations are for substantially longer canisters containing SF and a disposal zone of 2000 m (*i.e*. 2- 4 km) with the assumption, based on the evidence from the Gravberg-1 borehole, that 80% of this zone would be suitable for disposal).

Chapman and Gibb [32] suggest that the waste canister would have a "significantly smaller diameter" than that of the borehole in the disposal zone, i.e. 0.5 m compared with 0.8 m. In their proposal, canisters would be fitted with a simple, flexible, centraliser/roller cage to allow them to be lowered (or pushed) down the borehole, and the cage could be left in the borehole with the canister. In the upper, wider diameter, sections of the borehole, the cage system would be contained in a robust, reusable transfer container and then lowered through this into the disposal section. Although such a process would facilitate the emplacement of the waste canisters and may well decrease the likelihood of problems during operation, it would result in less waste being disposed in each borehole (as the diameter of the waste canister would have to be reduced to accommodate the centraliser) and, therefore, would increase both disposal costs and the size of any repository, by the requirement for additional boreholes.

Calculations by SKB (Chapter 4.1.4) already suggest that the number of individual canisters (*i.e*. non-consolidated) in the VDH concept required for disposal of Swedish waste would be considerably greater than that required for the KBS-3 concept, and this was for a situation in which the canisters were as large as possible. The suggestion from [32] would result in an even greater number of canisters, although probably not by a large amount.

Chapman and Gibb [32] conclude that their proposed design is likely to be a reasonable proposition only for disposal programmes involving relatively small volumes of HLW. For example, all the vitrified HLW from the Swiss disposal program could fit into one or two boreholes, whereas it would take perhaps 20 boreholes to dispose of current UK commitments of HLW, and the Japanese program would need about 60 to 70 such boreholes for its approximately 16,000 tonnes of vitrified HLW. In the SKB design, where SF rather than HLW is disposed, the number of boreholes originally believed to be required varied from 19 to 40, depending on the option selected (Chapter 4.1.4), however, this was later re-assessed to be 40 boreholes (Chapter 4.3.1, [34]).

As suggested in Chapter 5, the greatest attraction of the deep borehole disposal concept is perhaps for the disposal of small amounts of fissile material (surplus stockpiles or from weapons decommissioning); in this way the safeguards problem could be effectively removed because the wastes could be made practically irretrievable. The dilution required to remove criticality problems still requires a large disposal volume, as discussed in Chapter 5.1.4, and excess plutonium declared as waste (rather than being recycled as mixed oxide or MOX fuel), could be incorporated in a glass or ceramic waste form, as proposed by USDOE [41].

One suggestion from [32] for the disposal of fissile material that is different from the concepts considered by the USDOE [41] or the NAS [40] would be to place canisters containing fissile material in the lower sections of very deep boreholes, using the upper regions to dispose of HLW canisters. They suggest that this would ensure the effective irretrievability of the fissile waste canisters without any need to tailor each package to meet the *spent fuel standard* that is aimed at meeting safeguards requirements (Chapter 5). The *can-in-canister* method [47] whereby small containers of plutonium are positioned inside larger packages of HLW would be an alternative approach to achieving the same objectives.

6.1.2 Alternative approaches to deep borehole disposal

Alternative approaches to the deep borehole disposal concept have recently been suggested by Chapman and Gibb [32]. The *conventional* model, as suggested by SKB and others (including the “model concept” of Chapman & Gibb described above), relies on the geological environment to provide almost, if not all containment, once the boreholes have been sealed (the design life of the waste canisters suggested by SKB, for example, is approximately 1000 years). Chapman and Gibb [32] suggest that the advent of deep shaft construction technologies makes conceivable the emplacement of larger waste packages with an integral EBS (Engineered Barrier System) at depths up to 3000 m. Design optimisation studies by NUMO for conventional repositories in Japan [29] are currently looking at integrated waste packages (IWPs) that consist of the waste containers and the associated EBS in a prefabricated unit that is taken underground and emplaced in tunnels that are around 3 m in diameter, *e.g*. using an IWP design such as that suggested by Toyota and McKinley [48]. Such packages might be about 2 m in diameter and 3 m long.

At 3003 m, the 9 m diameter South Deeps shaft in South Africa is the single deepest shaft in the world, Kidd Creek in Canada has a subsurface shaft extending from the 1200 m level of the mine down to more than 3000 m depth and mining technology is, apparently, capable of extending to greater depths. It may, therefore, be feasible to emplace IWPs in shafts of dimensions similar to South Deeps; and such shafts might also allow Nirex-size ILW packages to be disposed of at great depths. It is acknowledged that for deep shafts, transporting heavy loads to great depths is a problem; however, [49] find no significant problems with emplacing the concrete and steel used for liners and support at great depths, and at temperatures up to 50°C. At present, it is unclear what the absolute maximum depth might be for the transport of heavy, possibly shielded, waste canisters in a vertical shaft.

The problems in the use of deep shafts appear to lie in five areas:

1. Operational conditions in deep shafts would require the use of refrigerated air supplies to make them workable.
2. The construction of mined shafts, even to depths considerably less than that suggested here, is dangerous and may result in injuries or deaths. Such deaths occurred in the construction of the shafts at Gorleben and Bure and in both these cases deaths led to substantial delays in both these programmes. This could represent a considerable problem if several very deep shafts for disposal were envisaged.
3. Very deep shafts are likely to be associated with stability problems during their construction and operation. Rockbursts[27] may be the primary concern and a considerable EDZ (Excavated Damage Zone) may form around the shaft that could represent a problem in demonstrating long-term safety.
4. The mechanical load of a column of packages would also require consideration in this concept. IWP technology is intended for conventional repositories at shallower depths (500-1000 m), where the groundwater regime is more dynamic. The benefits of the integral EBS are unlikely to add much to containment at depths greater than 2000 m. For this reason [32] suggest that it may thus be most appropriate to consider large diameter deep shafts with IWPs for intermediate depths (1000-2000 m), where the transport of radionuclides in groundwater may still be a key factor in safety assessment. In the case of Nirex ILW packages, they are also not designed to be stacked more than 4 or 5 high, so that a load-supporting backfill around such packages emplaced in a very deep shaft, combined with structural concrete, would be required to present package failure. In addition, for the shaft concept, it is likely to be necessary to cut large bridge plugs into the surrounding rock mass, so that it takes some of the load. Such load support would mean that retrieval of the waste is likely to be impossible.
5. In the case of heat-emitting waste, the thermal evolution of the system; for example, a 9 m diameter shaft could contain four or more IWPs (of the design proposed by [48]) at the same level, if excessive temperatures were not produced.

6.1.3 Comparison of different concepts

All the suggestions above are sensitive either to the capabilities of deep borehole drilling or deep shaft construction (see Chapter 6.1.2) and also, therefore, to the dimensions of the waste canister or package. Drilling 800 mm boreholes to 4000 m depth would stretch drilling

[27] A rockburst is a sudden, violent dislocation of slabs of rock, usually from the walls, but also potentially from the floor, of the shaft.

technology, but was considered potentially feasible a few years ago [50], although to be at the technological limit. An optimisation study would indicate whether smaller diameter boreholes might offer greater potential, if canister dimensions could be reduced, whether even larger diameter boreholes to the same or perhaps slightly lesser depths would be achievable, and how canister handling technology could be developed for different canister sizes and weights.

The deep shaft concept discussed above might be most appropriate for the disposal of large ILW packages, but it might also be suitable for HLW and SF. It is not feasible to make wastes in wide diameter shafts totally irrecoverable, as the space available would allow remote recovery methods to be deployed, and this concept might not, therefore, be suitable for the disposal of Pu[28]. Any waste retrieval is likely, however, to be extremely difficult, particularly if the mechanical integrity of packages to loading and the stability of the shaft cannot be guaranteed. The larger diameter of a shaft permits a greater flexibility for the disposal of different waste types, including perhaps Nirex ILW packages and other forms of long-lived waste within IWPs.

There are considerable uncertainties in several areas, for example in the cost and the extent of detailed characterisation data on the rock mass to several kilometres depth in the case of deep borehole disposal. The majority of these uncertainties are due to the fact that substantially less work has been carried out on deep borehole disposal than on other repository concepts, as was acknowledged by SKB (Chapters 4.2 and 4.3). Much is conditional on the assumptions, such as the assumed capabilities of the drilling systems, the methods that might be employed to emplace waste canisters and the extent to which certain attributes of the concept are sensitive issues for their long-term performance. Without a considerable amount of R&D it will not be possible to resolve the majority of these issues (see Chapter 7.4).

6.2 Comments on alternative disposal options

Deep self-burial, whilst theoretically possible, suffers from a general lack of constraints on its final outcome, with the result that it would be difficult to develop any convincing safety case. The use of depleted oil and gas reservoirs suffers from a considerable problem that these reservoirs might be re-used for other purposes (for example, it has recently been suggested by the DTI that they might be used for CO_2 sequestration) and they might also be re-investigated, for example, when oil recovery techniques have improved. What [32] refer to as high-temperature schemes (Table 12) are still at the early phase of development and the possible uncertainties associated with the generation of high *in situ* temperatures could well preclude their use. Chapman and Gibb [32] conclude that it is the low temperature encapsulated schemes, of the type investigated by SKB for example, that show most promise – and it is dominantly these schemes or concepts that have been considered by waste disposal organisations and have been discussed above. It would appear that, if the deep borehole disposal concept is applied anywhere it would be of this low temperature type and not some form of deep self-burial.

---

[28] Retrieval of Pu from a deep shaft is, however, still likely to be more difficult than its retrieval from a mined repository and, from a safeguards standpoint, the disposal of Pu in deep shafts may still be an alternative that merits consideration.

7 SUMMARY OF ISSUES IDENTIFIED

7.1 Introduction

A low temperature deep borehole disposal concept, *i.e*. one that does not include melting or partial melting of the rock, of the type referred to by Chapman and Gibb [32] and investigated by, for example, SKB with encapsulated wastes, could take a number of forms. Chapman and Gibb [32] and SKB (Chapter 4) assume the drilling of multiple deep disposal boreholes to about 4 km in depth (in the case of Chapman & Gibb) and 5 km (in the case of SKB) into stable crystalline basement rocks in regions with average (Chapman & Gibb) and low (SKB) geothermal heat flow. Such basement rocks might extend to the surface, as in Proterozoic shield terrains (*e.g*. Scandinavia and Canada) or major granitic intrusions (as are common in many countries), or be buried under thick sequences of Phanerozoic sediments (see Figure 13; [32]). The latter situation has the added advantage, according to Chapman and Gibb [32], that younger, argillaceous sediments, such as Mesozoic and later mudrocks, shales and clays, can provide a high degree of hydraulic isolation to the basement, effectively further decoupling its hydrogeological regime from more dynamic, shallower groundwater zones. There may be doubts, however, as to the necessity of providing such additional decoupling, when this effect may be achieved by the presence of the crystalline basement alone (see Chapter 4.1.2). The possible disadvantages of having to drill through thick (c. 1000 m) of sediments before reaching the basement lie in two areas:

- It is more difficult to provide stable borehole conditions in sedimentary sequences in which there is a succession of alternating sedimentary formations with different mechanical properties, as the design of the borehole casing programme is made more complex (a good example of this is provided by some of the deep boreholes at Sellafield). In addition, each reduction in casing size means that the initial borehole diameter will need to be increased.

- It is more difficult to investigate the basement if it is overlain by a sedimentary succession (again Sellafield provides a good example, as do the investigations for Andra's potential URL site near Limoges in the 1990s).

In a UK context, however, considering both basement outcropping at the surface and basement covered with such thick sediments is likely to increase substantially the area of land that might prove suitable for the development of the deep borehole disposal concept.

Understanding shallower groundwater systems (*i.e*. within the uppermost 500 – 1000 m) is generally a central issue in safety assessments for conventional repositories and is likely to prove similar for any form of deep borehole disposal concept, regardless of whether the flow takes place in sedimentary or crystalline rocks. In the majority of deep borehole disposal concepts considered to date the disposal zone ranges in length from 1000 m ([32]; Chapter 6) to 2000 m (SKB, Chapter 4). In the proposal from [32] the shallowest waste package would be situated at about 3000 m depth, whereas in SKB's proposed concept the top of the disposal zone would be at about 2000 m depth.

The safety concept for deep borehole disposal, in all cases and for all forms of waste, whether it is Pu, HLW or SF (also ILW), is based almost entirely on *containment in the natural geological barrier*, with the concept being one of essentially *complete containment within the host formation*. In the normal evolution scenario, therefore, there would be zero release of radionuclides by groundwater (beyond the rock mass immediately surrounding the disposal zone), perhaps for periods of more than 1 Ma; although there would still be the possibility of gaseous releases. This makes the deep borehole concept fundamentally different from any disposal concept involving a mined geological repository, although in such a repository the relative importance ascribed to different parts of the multi-barrier system does vary considerably (*i.e*. the difference between disposal in plastic clay at Mol (*e.g*. the SAFIR-2 safety case [51] and that in crystalline basement in Sweden (*e.g*. the SR 97 safety case [37] where the *relative* importance ascribed to the host rock varies considerably).

7.2 The key elements of the deep borehole disposal concept

The key elements of this containment concept are as follows. These elements are either facts that are substantiated by direct evidence or represent expectations as to what would be required, or what would be considered reasonable to assume:

1. The rate of fluid movement in the rock in the disposal zone is expected to be so slow under undisturbed conditions that any mass transfer will be by diffusion or by advection at rates approaching those of diffusive transport. Pore fluids are expected to be highly saline, from groundwaters with TDS (Total Dissolved Solids) values around that of seawater to true brines. Elevated fluid densities and the presence of a chemically-stratified (*cf*. density-stratified) groundwater system, combined with low hydraulic gradients suggest that these fluids will be hydrogeologically stable, with residence times of millions of years. This is consistent with observational evidence from the very deep crustal boreholes at Kola, Gravberg-l, KTB (Germany, 4 km pilot and 10 km main boreholes) and, in fact, all deep and very deep boreholes in basement rocks anywhere in the world (see Chapter 4.1).

2. The wastes for disposal would be only weakly heat emitting or would be sufficiently cooled prior to disposal, so that the thermal load they impose on the rock-fluid system over the first few hundred years after burial would not cause fluid convection sufficient to destabilise the density- and chemically-stratified groundwater system. Clearly, this will need to be evaluated carefully. The thermal load can be controlled by the spacing of waste containers.

   In fact, it is unclear at present what problems might ensue were the waste to generate higher temperatures. Whilst such elevated temperatures might be assumed to cause a problem, especially with respect to thermally-driven groundwater that might be forced up the borehole, no one has carried out any relevant calculations. It is unclear, for example, what level of heat generation from the waste would be necessary to create fluid convection by destabilising the expected marked density stratification of the groundwater.

3. A long system of borehole seals isolates the disposal zone from overlying rock formations and groundwater systems. The length of the seal zone and its design would be highly site-specific (see, for example, Chapters 4.1.4 and 4.3.1 and Figure 2). A host formation in basement rocks buried under 1000 m of sedimentary cover could allow the upper 1000 - 2000 m of the borehole within the basement rocks (depending on the assumed upper limit for disposal) to be sealed, along with further, probably different, seals in the top 1000 m comprising different sedimentary formations [32].

4. With a sufficiently powerful rig, the wider diameter upper casing sections could be cut above their casing shoes and withdrawn or perhaps, as suggested by SKB

(Chapter 4.3.1), sections of the casing could be cut so that a good seal is obtained between the borehole seal material and the rock mass, isolating any EDZ or annulus behind the casing. If the casing were to be removed completely, the borehole would collapse, unless it were stabilised during its removal, using high density mud, and subsequently backfilled to reconstitute as closely as possible the natural hydraulic properties of the rock.

5. It might be necessary only to disguise the position of the top of a disposal borehole(s) and destroy the upper tens of metres of the borehole to make re-entry very difficult[29]. It would also be possible to backfill a borehole with a mixture of hard, angular rock pieces and a softer matrix, so that any attempt to re-drill the hole would be foiled (as the drilling bits would be likely to break). The repository site would not be lost, and the area in which disposal has occurred could be marked and recorded, as with conventional repositories.
6. Waste packages could be emplaced without the need for any of the additional engineered barriers (overpacks and buffer) that are familiar in conventional repository concepts. The wastes could be in sealed, relatively thin-walled metal containers intended only to facilitate emplacement (see Chapter 4.1.4 and Figure 12 for a proposed SKB canister design). It is appreciated that it will not be possible to design canisters to remain intact for long periods under the extreme conditions of high stress, high temperatures and high salinity at depth, although the strength of any canister and the length of time for which it is designed to remain intact would depend on any requirements there might be for retrievability, either during or post-emplacement. Depending on the waste being considered, surface handling of these canisters might require shielded facilities at the borehole site to transfer the packages from their transport casks into the borehole using remote handling equipment.
7. The size of the waste packages is dependent on many factors, including:

    The types of waste being emplaced.

    The diameter of the borehole.

    The presence of any additional equipment that might be emplaced with the waste canister to permit its easy movement to its disposal location and to ensure that it is emplaced and centralised in the borehole.
8. There are significant limits on the maximum diameter that a borehole can be drilled in hard rock to depths of about 4 km, so that, to allow the maximum amount of waste to be disposed of in any one borehole, it seems that it will only be possible to have a relatively small annulus between the canister and the borehole wall (see, for example Chapter 4.1.4 and Figure 12; but also see Chapter 6 for design of [32]), thereby limiting the possibility for thick, low permeability backfill or buffer around the canister.

[29] Old iron ore site investigation boreholes near Sellafield, whose locations had not been deliberately disguised, but whose exact locations were not known, were found to be extremely difficult to locate, even after an extensive search.

7.3 Important questions regarding the disposal zone

The important questions regarding the disposal zone itself are:

Whether the disposal zone of the borehole should, or even can, be unlined (uncased) at great depth.

The impact of borehole fluids on the waste emplacement procedure.

The effect of the mechanical load on the column of waste canisters during and following their emplacement.

Whether the boreholes should be vertical.

A lined (cased) borehole may be the only feasible option regarding its stability, the ease of waste emplacement and the possibility of retrievability. Harrison [50] describes an approach to the emplacement of SKB type canisters in a lined deep borehole in which the drilling fluid filling the borehole is displaced as part of the waste emplacement process. Whether it would be possible, or desirable, to maintain the borehole free of fluid during the phase of waste emplacement needs to be investigated. A dry borehole would allow some form of dry grout/backfill to be emplaced to stabilise the void space around the canisters and act as a fill/spacer between them. This grout could be composed of, for example, compressed bentonite granules which would swell on contact with groundwater and seal the borehole.

An unlined disposal zone might be beneficial, as the presence of a degraded liner, together with the annulus between the rock and the liner, may form a potential pathway for vertical fluid movement along the disposal zone, at least up to the base of the overlying sealed sections. In an unlined borehole, a dense grout could be used to provide a good seal against the rock. It will be impossible to ensure that any backfill material is uniformly emplaced, but this lack of uniformity and any resulting effect this might have on, for example, the stability of the borehole or the efficacy of the backfill to act as a seal, is unlikely to be critical (unless retrieval of canisters is considered important). The main function of the backfill may be to facilitate continued emplacement and to provide a good thermal contact with the rock, so that the temperature on the canister surface is minimised. Fluid movement along the length of the disposal zone may well occur after it is sealed, but the depth of disposal and the long sealed zone above the waste may make this no more important a factor in the performance of the concept than the equivalent release of radionuclides from a mined repository, as is suggested in Chapter 7.4.

The mechanical integrity of the canisters during their emplacement may be an issue. The weight of a long column of canisters may lead to the failure of some at the base of the borehole, unless either the borehole is backfilled with material that can provide support to the canisters or if bridge plugs are emplaced at intervals throughout the disposal zone to transfer some of the load to the borehole walls before further canisters are emplaced. Whilst failure of the canisters after completion and sealing of a borehole might not detract from the containment capacity of the disposal system, it could be a problem during waste emplacement in situations involving heat-emitting wastes in fluid-filled boreholes without bridge plugs. The failure of canisters would also preclude their retrieval. This is likely to be considered beneficial when considering the disposal of Pu, but might be considered as a problem if other waste types were being disposed. The subject of retrievability has been discussed in Chapters 4.1.4 and 5.3.2.

Vertical boreholes may provide the greatest confidence in the ease of canister emplacement, however, it might be feasible to drill an array of deviated boreholes from the same location to allow more waste to be emplaced using the same surface facilities and minimising the area needed for the repository infrastructure; as has been suggested by [32]. Even a small deflection in drilling angle would make a huge volume of rock accessible at depths greater than 2 km from the same location and might allow many boreholes to be constructed from a small surface site. There could be problems, however, in drilling such deviated boreholes to depths of 4 km in crystalline rock at the diameters suggested (*i.e*. 80 cm), as, according to the report from Deutag [50] drilling vertical boreholes to this depth is probably at the limit of current drilling technology. Drilling deviated boreholes and controlling the deviation to precise amounts may prove too difficult. There is no problem in emplacing canisters in a deviated borehole, as long as the angle of deviation is within acceptable limits. The majority of oil wells are deviated and very large objects are often lowered down them.

7.4 R&D requirements

There are two aspects of the deep borehole disposal concept that require thorough evaluation:

- The performance of the disposal system, especially the thermal and hydraulic environment around the disposal zone and its seals.
- The engineering aspects of borehole construction and package handling, which will require thorough evaluation of safety during the operational phase.

For post-closure safety, standard performance assessment techniques, as applied to numerous conventional repository safety studies, would serve to identify and scope the sensitive factors in system behaviour. An initial analysis of the problem suggests that much of the performance of the concept may hinge on the behaviour of the borehole seals. It might be expected that zero release occurs from the disposal zone into overlying rock formations over millions of years. Simple safety evaluations of SF disposal in analogous, low-energy, stratified brine systems at much shallower depths (*cf*. the Pangea *High-isolation concept* developed for stable, arid desert environments; [52]) indicate this to be the case, with only minute fractions of the ^{129}I inventory escaping after millions of years.

For both the High-isolation and deep borehole concepts, the waste is expected to decay completely *in situ*, with the exception of the longest-lived natural series radionuclides, so that after a few hundred thousand years, the repository will have similar characteristics to a very deeply buried uranium ore deposit.

Even if movement of groundwater containing dissolved radionuclides did take place up, or perhaps around the long borehole seal into the overlying rock mass, the system could be considered to be performing similarly to a mined repository, located at 500 to 1000 m depth. Mined repositories have already been subject to safety analyses that show the presence of extremely low, radiologically-insignificant releases under undisturbed conditions. A deep borehole disposal zone in basement rocks, if overlain by sedimentary rocks, would have the advantage that any releases up the borehole would be dispersed and diluted in the deep regions of the groundwater system in the overlying sediments (this refers to times in the future when any casing that might have remained in the borehole has corroded)[30]. The main R&D requirements concerning safety performance are thus for analyses of the thermal, geochemical, and hydrogeological evolution of the rock around the disposal zone.

---

[30] This could be a good reason for selecting a site where the basement rocks in which disposal takes place are overlain by an alternating sequence of sedimentary rocks. A good example of such a situation might be provided by substantial portions of eastern England where the basement is at depths of less than 1000 – 1500 m. However, this potential advantage needs to be weighed against the potential disadvantages of using such an environment, as discussed in Chapter 7.1.

The second subject area above is similar to that suggested by SKB in Chapter 4.3.1 and listed in Table 7 and relates to the engineering aspects of the concept. Key areas that need to be examined, as suggested both by SKB and [32], include:

- Drilling, stabilising, and maintaining precisely located, very deep boreholes with diameters of at least 500 mm and more likely up to 800 mm. SKB recommended drilling two 4000 m deep boreholes at 800 mm at their base and carrying out the testing of drilling and waste emplacement techniques – in fact this was by far the most expensive and time-consuming part of their proposed R&D programme [35]. This may be the greatest barrier to the possible development of this disposal concept, as it will be expensive to carry out such drilling and without such R&D considerable uncertainty will remain regarding the possibility of drilling such large diameter, deep boreholes. There is no precedent for drilling such boreholes and, in this sense at least, the deep borehole disposal concept can be considered to be very different from a mined repository, which will be constructed using proven techniques.
- General geoscientific research associated with developing a better understanding of the hydrogeological and geochemical conditions at great depths – this was the second largest part of the SKB's programme.
- Design of sealing and backfilling systems and their installation at depth in boreholes, including methods for the removal and/or cutting of casing, so that the borehole can be sealed more effectively.
- Management of borehole fluids during waste emplacement and sealing.
- Maintenance of package integrity during the emplacement phase – canister design and manufacture of canisters.
- Canister or package handling systems at depth, including recovery from jams.
- When considering very deep shaft disposal, methods for transporting heavy waste packages to depth.
- For very deep shafts – construction limits, stabilisation of shaft walls, operational constraints regarding waste package emplacement.

In the development of their R&D programme, SKB [35] concluded that in any future, more thorough analysis that they might perform, practical interests should be given more prominence than in their previous studies. They concluded that they should avoid methods that are untested and may be thought likely to produce problems, and concentrate on simple and practical procedures.

Finally, as Chapman and Gibb [32] also point out, the economic aspects of borehole or shaft disposal need analysing. Throughout this report it can be seen that there has been considerable disagreement as to the comparative costs of the deep borehole and mined repository concepts. This disagreement has persisted from the early days of the development of this concept in the 1970s at least up until the cost comparisons carried out as part of the Pu disposal programmes in the USA in the mid-1990s (Chapter 5). Chapman and Gibb [32] expect the solution to be less expensive than a conventional repository for small amounts of waste. Gibb [19] estimated the drilling cost of a large diameter 4 km deep borehole at £1 million per kilometre (based on data from the Cornish "Hot Dry Rock" project), while Harrison [50] put the cost of a 0.8 m diameter, 4 km deep borehole at 4.65 million Euros (£2.8 M). Advances in deep and deviated borehole drilling technology, largely from the hydrocarbon industry, are likely to lead to continual reductions in costs. In addition, the increased interest in the search for oil in crystalline basement rocks is likely to mean that more deep boreholes are drilled in the types of rocks that are of greatest interest for the deep borehole disposal concept.

Nevertheless, although construction costs may be low, when compared with a conventional mined repository, the deep borehole concept will require significant R&D expenditure on the engineering aspects. SKB's estimate (Table 7), made in 2000, was for an expenditure in excess of £300 M to bring the deep borehole concept up to the level of KBS-3, and they now believe that costs are likely to be considerably in excess of this estimate.

8 REFERENCES

1 Chur, C, Sperber. The Drilling Concept of the Continental Deep Drilling Program of the Federal Republic of Germany. in: Boden, A, Eriksson, K G (eds): *Deep drilling in crystalline bedrock. Volume 2: Review of deep drilling projects, technology, sciences and prospects for the future*, 2:224-234, 3. International Symposium on Observation of the Continental Crust through Drilling, Mora and Orsa, 7.9.-10.9.1987. 1998.

2 Schneider, K J and Platt, A M (Editors). *High-level radioactive waste management alternatives. Battelle Pacific North-West Labs., Richland, Washington, USA, Report BNWL-1900 (Four Vols.) Vol. 1: Section 1 Summary, Section 2 Background and Data Base, Section 3 Evaluation Methodology: Vol. 2: Section 4 Geologic Disposal: Vol. 3: Section 5 Ice Sheet Disposal, Section 6 Sea Bed Disposal: Vol. 4: Section 7 Waste Partitioning, Section 8 Extra Terrestrial Disposal, Section 9 Transmutation Processing*. 1974.

3 O'Brien, M T *et al. The Very Deep Hole Concept: Evaluation of an Alternative for Nuclear Waste Disposal*, Report LBL-7089. Lawrence Berkeley Lab., Berkeley, California. 1979.

4 USDOE. *Management of commercially generated radioactive waste. Final Environmental Impact Statement*, Report DOE/EIS-0046F. 1980.

5 ONWI. *Very deep hole systems engineering studies*, US Office of Nuclear Waste Isolation, Report ONWI-226, Battelle Laboratories, Columbus, Ohio. 1983.

6 Woodward-Clyde Consultants. *Very Deep Hole Systems Engineering Studies*, San Francisco, California, USA. 1981. [This report is synonymous with ONWI, 1983].

7 Smith, E T and Grove-Palmer, C O J. *Geological disposal of highly radioactive wastes: First report of the study group*. AERE Report AERE–R 8000. 1976.

8 Forex Neptune. *Feasibility Study for Large Diameter Boreholes for the Deep Drilling Concept of a High-level Waste Repository*. Nagra Technical Report 80-04. Switzerland. 1980.

9 Elsam/Elkraft. *Disposal of High-level Waste from Nuclear Power Plants in Denmark*; Salt Dome Investigations. 5 vols. ELSAM Frederica, Denmark and ELKRAFT Baler, Denmark. 1981.

10 Juhlin, C and Sandstedt H. *Storage of nuclear waste in very deep boreholes: Feasibility study and assessment of economic potential*. Part I Geological considerations. Part II Overall facilities plan and cost analysis. *SKB Technical Report* TR 89-39. 1989.

11 SKB. *Project on Alternative Systems Study (PASS) Final Report*, October 1992. SKB Technical Report TR 93-04. 1993.

12 Montfrans, van H M. Research program on geological disposal of radioactive waste in the Netherlands. In: *Geological problems in radioactive waste isolation – A world-wide review*. Proceedings of Workshop W3B of the 28th International Geological Congress, Washington 1989. Report LBL-29703, p103-114. 1991.

13 Logan, S E. *Deep self-burial of radioactive wastes by rock melting capsules*. Nuclear Technology, 21, 111-117. 1976.

14 Logan, S E. *Deeper geologic disposal: a new look at self-burial.* Proceedings of Waste Management *'99*, WM Symposia, Tucson, Arizona, U.S.A. 1999.

15 Klett, R D. *Deep Rock Nuclear Waste Disposal Test: Design and Operation*. Sandia National Laboratories, Albuquerque, NM, USA. SAND-74-OO42. 1974.

16 Heuze, F E. *On the Geotechnical Modelling of High-Level Nuclear Waste Disposal by Rock Melting*. Lawrence Livermore Laboratory, Livermore, CA, USA. UCRL-53183. 1981.

17 Kascheev, V A, Nikiforov, A S , Poluektov, P P, Polyakov, A S. *Toward a theory of self-disposal of high-level waste*. Atomnaya Energiya 73, 215-221. 1992.

18 Gibb, F G F. *High-temperature, very deep, geological disposal: a safer alternative for high-level radioactive waste.* Waste Management 19, 207-211. 1999.

19 Gibb, F G F. *A new scheme for the very deep geological disposal of high-level radioactive waste*. Journal of the Geological Society (London) 157, 27-36. 2000.

20 Attrill, P G and Gibb, F G F. *Partial meting and recrystallisation of granite and their application to deep disposal of radioactive waste. Part I – Rationale and partial melting*. Lithos, 67, 103-117. 2003.

21 Attrill, P G and Gibb, F G F. *Partial meting and recrystallisation of granite and their application to deep disposal of radioactive waste. Part II – Recrystallisation*. Lithos, 67, 119-133. 2003.

22 Gibb, F G F and Attrill, P G. *Granite recrystallisation: The key to the nuclear waste problem?* Geology, 31, 657-660. 2003.

23 Forsberg, C W. *Rethinking high-level waste disposal: separate disposal of high-heat radionuclides* ^{90}*Sr and* ^{137}*Cs*. Nuclear Technology 131, 252-268. 2000.

24 Angelo, J A. *Nuclear waste management by in situ melting*. Unpublished PhD thesis, University of Arizona, Tucson, USA. 1976.

25 Autio, J, Saanio, T, Tolppanen, P, Raiko, H, Vieno, T and Salo, J-P. *Assessment of alternative disposal concepts*, Report POSIVA-96-12, POSIVA OV, Finland. 1996.

26 Swahn, J. Retrievability and safeguards concerns regarding plutonium in geological repositories. In Merz, E R and Walter, C E (eds.), *Disposal of weapons plutonium – Approaches and prospects.* NATO ASI Series, Disarmament Technologies, Volume 4, 9-22. 1996.

27 NEA/OECD. *Management of Separated Plutonium, The Technical Options*, Nuclear Energy Agency, OECD. 1997.

28 SKB. *Project JADE. Comparison of repository systems*. Executive summary of results. SKB Technical Report TR-01-17. 2001.

29 Umeki, H, Ueda, H, Naito, M, Konishi, T and Danda, H. *The NUMO approach for development of a repository concept*. Proceedings of the HLRWM Conference, Las Vegas, 2003.

30 Umeki, H, McKinley, I and Masuda, S. *Alternative repository design options for HLW disposal in Japan*, (Submitted to PSAM / ESREL 2004, Berlin, June 2004). 2003.

31 Umeki, H, Masuda, S and McKinley I. *Advanced repository concepts required for NUMO's volunteering approach to site selection*. Global 2003, November 2003.

32 Chapman, N and Gibb. *A truly final waste management solution – Is very deep borehole disposal a realistic option for HLW or fissile material?* Radwaste Solutions, July/August, p 26-35. 2003.

33 NEA/OECD. *Geological Disposal of Radioactive Waste*. 1984.

34 SKB. *Systems analysis. Choice of strategy and systems for the management of used nuclear fuel* (in Swedish). SKB Report R-00-32. 2000.

35 SKB. *Waste disposal alternative: Very Deep Boreholes. Contents and scope of the research, development and demonstration (RD&D) programmes required for a comparison with the KBS-3 method* (in Swedish). SKB Report R-00-28. 2000.

36 NEDRA. *Characterisation of crystalline rocks in deep boreholes*. The Kola, Krivoy Rog and Tyrnauz Boreholes", SKB Technical Report 92-39. 1992.

37 SKB. *Deep repository for spent nuclear fuel. SR 97 – Post-closure safety.* SKB Technical Report TR-99-06. 1999.

38 Juhlin, C & Leijon, B. *Geoscientific appraisal to conditions at large depths – Project outline and deep borehole inventory*. SKB Project Report PR D-95-016. 1995.

39 Smellie, J. *Recent geoscientific information relating to deep crustal studies*. SKB Report R-04-09. 2004.

40 NAS (National Academy of Sciences). *Management and Disposition of Excess Weapons Plutonium*, Committee on International Security and Arms Control, National Academy Press, Washington, DC, USA. 1994.

41 USDOE. *Technical summary report for surplus weapon-usable plutonium disposition*. Office of Fissile Materials Disposition. Report DOE/MD-0003 Rev 1. 1996.

42 Halsey, W G, Jardine, L J and Walter, C E. Disposition of plutonium in deep boreholes. In Merz, E R and Walter, C E (eds.), *Disposal of weapons plutonium – Approaches and prospects.* NATO ASI Series, Disarmament Technologies, Volume 4, 237-247. 1996.

43 Heiken, G, Woldegabriel, G, Morley, R, Plannerer, H and Rowley, J. Disposition of excess weapons plutonium in deep boreholes – Site selection handbook. *Report of the Los Alamos National Laboratory*, Report LA-13168-MS. 1996.

44 Ferguson, K L. *Excess plutonium disposition: The deep borehole option*. Westinghouse Savannah River Report WSRC-TR-94-0266. 1994.

45 SKB. *WP-cave assessment of feasibility, safety and development potential*. SKB Technical Report 89-20. 1989.

46 Watts, T H. Locating and Engineering Hydrologically Secure HLW Repositories. A Proposal for Disposal of the United Kingdom's High Level Nuclear Wastes in Sub-Seabed Reservoir Repositories. pp 467-490. In: *Geo-Engineering of Hazardous and Radioactive Waste Disposal*, 3rd European Engineering Geology Conference, 33rd

Annual Conference of the Engineering Group of the Geological Society, University of Newcastle upon Tyne, UK. 1997.

47 Kuehn, N, Brault, J, Herman, D et al. *Can-in-canister demonstration at DWPF*. *Radwaste Magazine*, 4, 20-22. 1997.

48 Toyota, M and McKinley, I. Optimisation of the engineered barrier system for vitrified HLW – Fabrication and emplacement aspects. *Proceedings of the 8th International Conference on high level radioactive waste management*, American Nuclear Society, p 648-653. 1998.

49 Kilbride, M and Stringer, N. Ultra-deep shaft construction. *Tunnels and Tunnelling Internationa*l, June 2002, p38-40. 2002.

50 Harrison, T. *Very deep borehole - Deutag's opinion on boring, canister emplacement and retrievability*. SKB Report R-00-35. 2000.

51 Niras/Ondraf. *SAFIR 2 – Safety Assessment and Feasibility Interim Report 2*. NIOROND 2001-06E. 2001.

52 Apted, M J, Smith, P A and Chapman, N A*. Engineered barrier design strategy for a High isolation repository site*. Proceedings of the 9th International Conference on High Level Waste Management. Las Vegas, American Nuclear Society. 2001.

Certificate No 0772938

Certificate No 0772938

United Kingdom Nirex Limited
Curie Avenue
Harwell, Didcot
Oxfordshire
OX11 0RH

t +44(0) 1235 825500
f +44(0) 1235 831239
e info@nirex.co.uk
www.nirex.co.uk

ISBN 1 84029 353 5