STATUS OF TECHNOLOGY FOR DEEP BOREHOLE DISPOSAL

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Preface

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EXECUTIVE SUMMARY

In October 2006 Government decided that geological disposal is its preferred option for the long-term management of higher activity radioactive wastes in the UK. The Government also decided to make the Nuclear Decommissioning Authority (NDA) responsible for implementation.

Government also recognised the need to take account of developments in storage and disposal options, as well as new technologies and solutions. The NDA are therefore also responsible for monitoring of international Research and Development programmes into safe and secure treatment and storage of waste and geological disposal technology as well as new options that emerge (e.g. the use of deep boreholes for the disposal of some wastes).

United Kingdom Nirex Limited (now integrated with the NDA) commissioned this report on the status of technology for deep borehole disposal as part of this programme of monitoring international R&D programmes. The report considers four cases relevant to deep borehole disposal with clear internal diameters at the final depth of the waste deployment zone at 4 km and 5 km, depending on the geological environment, of 300 mm, 500 mm, 750 mm and 1000 mm

This report reviews the historical experience and status of deep drilling and large diameter borehole construction by reference to the experiences in the oil, gas, gas storage, geothermal and geoscientific drilling industries, drilled shafts, radioactive waste investigations and drilling large diameter boreholes for military purposes and discusses the various deep well engineering issues that are relevant to the concept of deep disposal in boreholes. This includes the issues of casing and cementation or sealing casing both above the waste deployment zone and within the zone itself.

The report gives some guidance on the time scale and cost of construction for such a deep borehole concept and some comment on commercial options.

Risks are discussed and, whilst some risk is considered acceptable during the drilling phase, once the borehole had been constructed, the waste disposal phase would need to be engineered to guarantee waste could be deployed to the desired spatial position in the borehole and sealed. The waste emplacement concept and packaging are not considered in this report and would need to be the subject of other research. However, there would need to be close integration of the concept of disposal and the drilling and casing elements for such a deep borehole concept to be successful. It has been assumed for the purpose of this report that there would be no requirement to retrieve radioactive waste at some future date if disposed of in a deep borehole.

A number of potential future developments in drilling technology are discussed, some of which may impact on the future feasibility of the deep borehole disposal option. A number of research and development requirements are also highlighted.

This limited study has revisited old ideas and experiences but also developed some new ideas, considering new technologies and approaches in relation to the practicability of adopting the deep borehole disposal concept for the disposal of radioactive waste. The key

outcome is that deep borehole disposal is a valid option, under certain circumstances, although a large amount of detailed work would be required to develop the concept into a technically acceptable solution.

The principal conclusion is that drilling deep boreholes with the necessary depth–diameter combination required for deep borehole disposal would be a serious challenge and would be a major project. For the smallest diameter options of 300 mm and 500 mm clear diameters in the waste disposal zone, which are a still a step outside the envelope of historical and current experience, it is considered that such a concept could be successfully designed and implemented.

Boreholes of 750 mm and particularly 1000 mm clear diameter are considered too far outside the envelope of experience and should not be contemplated at this stage. There is caveat that in the 750 mm case, a successful deep borehole may be practical to 4 km with the appropriate development effort and suitable geology.

It is also concluded that only vertical boreholes should be considered at this stage as directional or the more exotic multi-lateral or fanned arrays of wells introduce unacceptable risks during waste deployment.

Large drilling rigs for the more modest diameters considered are within current rig design technology. A separate rig or the use of continuous coiled tubing could be considered for the waste disposal phase.

The weakest element of the deep borehole concept is the casing and cementation or sealing in the casing-rock annulus and this would need extensive research as cementing experience particularly, even in the mature oil and gas industry, is poor especially in large diameter boreholes. It is concluded that some form of permanent casing would be required through the waste deployment zone to assure the deployment of waste, with no risk from borehole instability.

Boreholes of 300 mm and 500 mm finished diameter are estimated to take up to two years to construct and for the waste to be deployed and sealed. The cost of the first borehole(s) are estimated at current prices to be of the order of £15 million to £25 million for the two diameters respectively to drill and be prepared for the waste emplacement phase. This excludes the cost of the waste disposal phase itself. There would be opportunities for significant cost savings as more experience was gained on a particular site with saving of 25% to 50% possible.

1 INTRODUCTION

The Nuclear Decommissioning Authority (NDA) is a non-departmental public body, which began operation in April 2005 with a remit to secure the decommissioning and clean-up of the UK's civil public sector nuclear sites. This remit was widened when the government announced on 25 October 2006 that, following recommendations from the Committee on Radioactive Waste Management (CoRWM), higher activity wastes will be managed in the long-term through geological disposal. Government also announced that it was giving the NDA the responsibility for planning and implementing geological disposal.

Government also recognised the need to take account of developments in storage and disposal options, as well as new technologies and solutions. The NDA are therefore also responsible for monitoring of international Research and Development programmes into safe and secure treatment and storage of waste and geological disposal technology as well as new options that emerge (e.g. the use of deep boreholes for the disposal of some wastes).

The NDA's mission is to deliver safe, sustainable and publicly acceptable solutions to the challenge of nuclear clean-up and waste management. This means never compromising on safety or security, taking full account of the social and environmental responsibilities, always seeking value for money for the tax payer and actively engaging with stakeholders.

CoRWM was set up by Government in November 2003 to oversee a public consultation on the long-term management options for UK radioactive wastes. In July 2006, CoRWM recommended geological disposal as the preferred option for the long-term management of the UK's radioactive waste with a period of interim storage. CoRWM also recommended that other long-term management options for example borehole disposal be kept under consideration [CoRWM 2006]. In response to CoRWM's recommendations, the government announced in October 2006 that geological disposal was the preferred means of long-term management for higher activity waste. [Defra 2006] It proposed that the UK should keep abreast with developments in other countries in respect of possible alternative options such as deep borehole disposal [Defra 2006].

The possibility of disposing of radioactive waste in very deep boreholes has been considered for over twenty five years. A deep borehole disposal concept (DBD) was researched in some detail by the US Department of Energy (USDOE), Office of Nuclear Waste Isolation (ONWI) in the early 1980s and reported in 1983 [ONWI 1983]. At that time, the ONWI report rejected deep borehole disposal (DBD) of radioactive waste on the basis that the necessary sizes and depths were not achievable. Since the 1980s, the technology for drilling and supporting deep boreholes has advanced dramatically such that this may no longer be true. In recent years, the idea of DBD has been considered by several waste management organisations, notably Svensk Känbränslehantering AB (SKB), the Swedish Nuclear Fuel and Waste Management Company in the late 1980s and reviewed again in 2000-2001.

John Beswick, a specialist drilling consultant, was appointed by the NDA to report on the status of technology for deep drilling for deep borehole disposal as part of the NDA programme on monitoring international R&D of alternative options.

There are no known examples of deep drilled boreholes for long-term radioactive waste management. Any such concept is outside the normal construction practices for borehole drilling in the oil, gas and mining industries. Hence, further development of this option has to be based on the principles and practices that control the practicability of the construction of deep boreholes with reference to the supporting petroleum and mining industries where relevant.

Disposal of radioactive waste in deep, large diameter boreholes as a feasible alternative to deep geological disposal involves many elements. This report can only be a summary of key points to highlight the issues and constraints in relation to this concept.

This report focuses on the practical issues that would be involved with constructing deep, large diameter boreholes. Whilst geology will be discussed briefly, this report does not include a detailed analysis on the various geological settings or hydrogeological processes or the case for or against this option on geological, hydrogeological processes merits. Further research and development drawing on experience of the drilling industry would be required to evaluate deep borehole disposal.

The term ‘deep’ borehole is subjective, but a classification that is sometimes used in the context of deep continental drilling is as follows:

Shallow	Up to 1 km
Medium depth	1 km to 3 km
Deep	3 km to 5 km
Very deep	5 km to 7 km
Superdeep	7 km to 10 km
Ultradeep	Over 10 km

Most oil and gas wells fall into the shallow and medium range with a significant and increasing proportion now being drilled in the deep range. Boreholes over 5 km are unusual and the deepest wells have been drilled generally for geoscientific purposes.

Similarly, the nature of the waste, its deployment and isolation and its effect on the borehole construction and long term effects are not considered in detail, but must also be understood in outline, particularly where high temperature waste is considered. The potential for high temperature generation in the deployment zone post disposal is outside the experience of the deep drilling industry. However, the drilling considerations cannot be wholly separated from the disposal proposals in the final concept design.

The application of technology for deep disposal boreholes would need to take account of the current status quo and also attempt to predict what improvements or extension of the knowledge and equipment could realistically be expected during the design and construction of the first few deep boreholes. However, the emphasis for this report is on realistic and practicable ideas. Hence some discussion is necessary on ideas and proposals raised in the literature and these must be tested against the key principles and factors which govern such deep man made holes made by drilling.

Evaluating the limitations and risks, this can be divided into two phases:

A *The well construction phase*

The well construction phase would include risks which cannot be wholly eliminated and 100% success is not certain, but highly probable given that the borehole design would have been thoroughly engineered and all potential problem scenarios rehearsed.

B *The waste deployment phase*

> At this stage, the objective would be 100% success in the deployment of the waste packages or canisters to the predetermined spatial location and the subsequent sealing of the waste within the deep borehole. This focuses the mind on solutions that really have a high probability of eventually being shown to be workable and could be developed into a certain solution.

Mined shafts are not considered in this report other than mention of a mined solution to the '*top abutment seal*' and the possibility that this shaft could or should be constructed in advance of the main deep boreholes. The top abutment seal is effectively a top cap to the borehole. In the SKB concept for deep borehole disposal, it was suggested that this cap should be constructed at the base of a mined shaft and undercut into the surrounding rock with a cap constructed in asphalt and concrete. Typical depths of this top seal are 250 m to 500 m.

2 OBJECTIVES OF THIS REVIEW

Following the recommendations of CoRWM [CoRWM 2006], Nirex developed a technical specification for this study with the following objectives:

- Clarify or reduce the uncertainties associated with deep borehole disposal of radioactive wastes and to provide a suitable basis to support preliminary safety, cost, implementability and environmental assessments to consider the viability, legal and regulatory acceptability of a deep borehole disposal.

- To report on the status of technology for deep borehole disposal of high level waste and spent fuel using the most up-to-date information.

Internationally, the deep borehole option has been considered for high activity, low volume wastes such as high-level waste, spent fuel and stocks of plutonium. Nirex was therefore investigating borehole disposal of these materials as part of its work on waste management options [Nirex 2004]. Borehole disposal is not usually considered suitable for, high volume waste (such as intermediate-level waste).

A method of deep borehole disposal has been suggested by Fergus Gibb of Sheffield University with several scenarios for the disposal of solid wastes [Chapman and Gibb 2003]. In all cases, the approach requires the construction of a deep man made hole to a depth such that there is sufficient space for a commercially realistic volume of waste to be placed and such that an effective sealing system can be engineered. This would ensure that radionuclides could not reach the biosphere as a result of such containment working in conjunction with the hydrogeological and other processes that prevent such migration from depth.

3 DEEP BOREHOLE DISPOSAL OPTION

The concept of disposing of radioactive waste and other hazardous substances at depth in boreholes is not new and indeed there is historical record of research as far back as the 1950s. Liquid chemical waste and radioactive waste were disposed of in deep wells by both the USA [Brookins 1988] and the former USSR [Rybalchenko 1998, Bradley 1997]. This practice has now stopped. In principle such an approach appears simple. However, studies in the 1970s and 1980s in particular in the USA, Sweden and to a lesser degree in Denmark and Switzerland, related to solid waste disposal highlighted some of the problems and constraints of such an approach.

The deep borehole disposal idea was rejuvenated to a degree by the results of deep geoscientific boreholes such as in the former USSR, where an ultra deep well was drilled in stages to 12.22 km between 1970 and 1990 [Kozlovsky 1984], Sweden, where a deep borehole was drilled in the 1980s to 6.6 km (Gravberg-1) [Beswick 1987] to investigate the theory of abiogenic methane after Gold [Gold 1984, Gold 1987] and the Kontinentale Tiefbohrprogramm der Bundesrepublik Deutschland (KTB) pilot (to 4 km) and superdeep well (drilled to 9 km) in Bavaria completed in 1994 [KTB 1996].

The following guidelines for disposal were developed by the NDA to assist in setting realistic boundaries for the study:

- Depth range: 2 km to 5 km.

  Note that one current DBD proposal advocate a minimum depth of burial of 3 km [5]. This report considers a lesser depth as there may be certain environments where a minimum depth of 2 km may be acceptable.

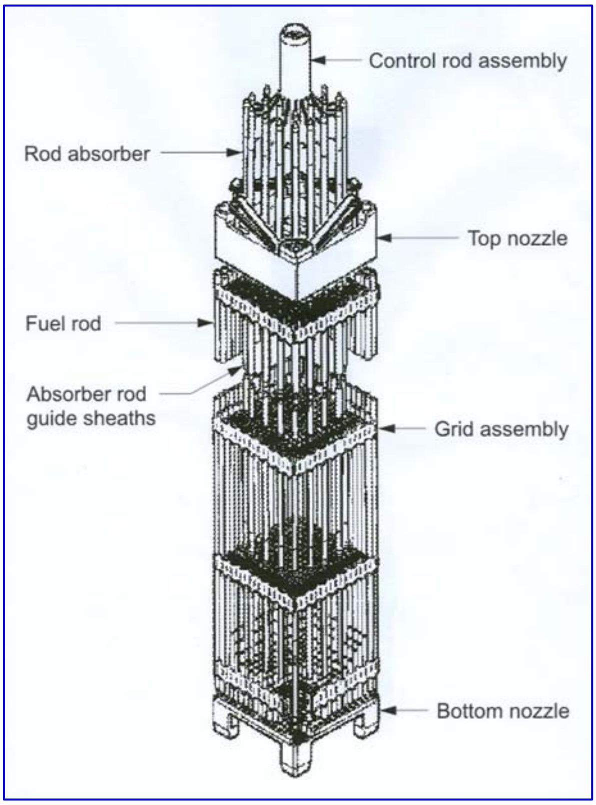
- Diameter (fuel elements and HLW (WVP) canisters) [Nirex 2005a, Nirex 2005b, CoRWM 2005]

  - PWR fuel elements 214 mm square x 4100 mm long (302 mm diameter).
  - AGR fuel elements 240 mm diameter x 1000 mm long (340 mm diameter).
  - WVP (Waste canisters) 433 mm diameter x 1347 mm long.

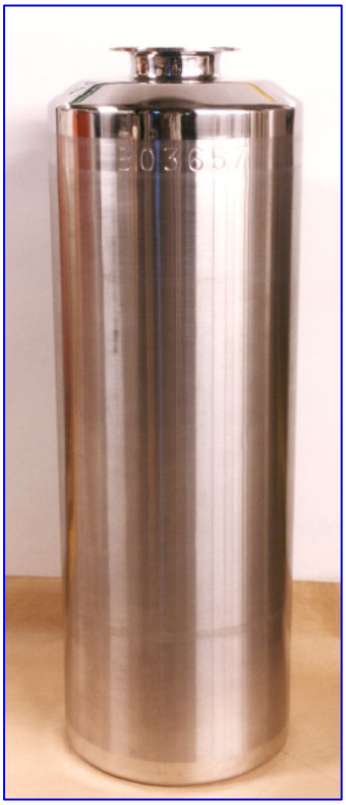
  Examples of these fuel elements and WVP canisters are illustrated in Figure 3.1.

  Whilst concept designs exist for the various types of waste packages for geological disposal, these tend to package multiple elements or canisters into much larger disposal canisters, which are typically 900 mm in diameter. There is potential for development of alternative canister designs to reduce the overall diameter of the package to be ultimately disposed. Similarly there is also the potential to remove fuel rods from the assemblies and close packing in containers to reduce the size of the waste package. Therefore, for the purpose of this study open hole or clear internal diameters of 300 mm, 500 mm, 750 mm and 1000 mm have been considered.

PWR Fuel Element



WVP Canister



AGR Fuel Element

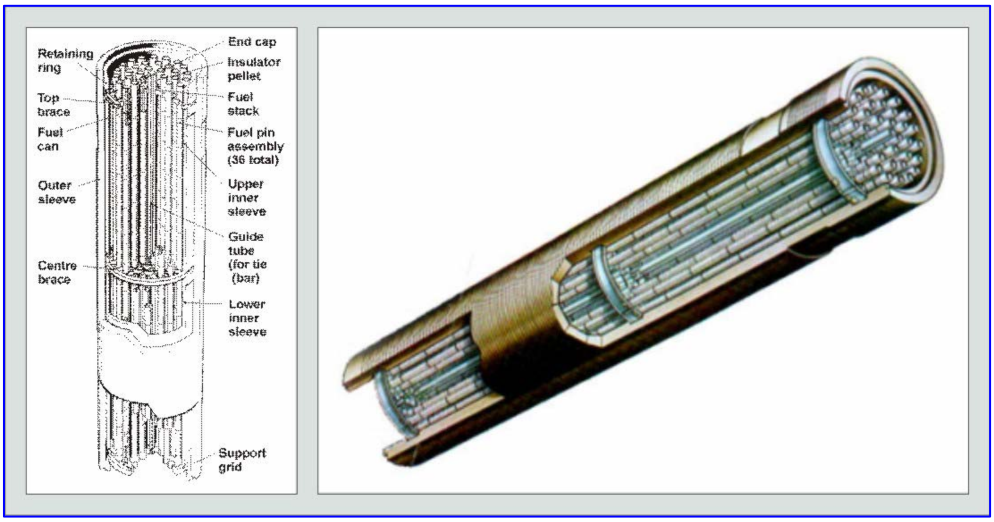


Figure 3.1 : Examples of fuel elements and WVP canisters

- Retrievability of the waste packages would not be required except if difficulties arise during deployment when it would be necessary to fully retrieve the canister.

- Materials that are allowed to be used as part of the permanent borehole construction such as for casing and sealing materials, but not including the waste canisters, canister support and the waste products themselves:

  - steel (for casing etc);
  - cement;
  - clays (eg bentonite); and
  - lead alloy or similar (for canister support).

- Sealing length above waste material: 2 km, but some advocates of deep borehole disposal suggest 3 km is necessary. The actual depth would be driven by geology and assessment of future geological processes.

At this stage the details of containment canisters and the running system for canister deployment are not important other than to give a yardstick to the requirements. This will be discussed later. Firstly, the practicality of drilling such large diameters to relatively great depth has to be considered.

4 DEEP DRILLING STATUS AND CONSTRAINTS

It is important to establish the boundaries set by state-of-the-art technology for deep drilling. The reference industries are:

- Oil and gas exploration, appraisal and development
- Gas storage
- Geothermal (natural high enthalpy, low enthalpy, hot fractured rock)
- Geoscientific and research
- Mining exploration
- Drilled shafts
- Radioactive and other waste geological and hydrogeological investigations
- Military applications

4.1 Oil, gas and gas storage drilling

Oil and gas drilling is the most important source of data, equipment and technology for deep drilling. This is a mature industry with over 100 years of history, but with continuing and relatively rapid developments in technology, equipment, tools, drilling fluids, processes and data transmission over recent years. The impressive progress made, particularly in the last 25 years, has been driven by demand to explore new frontiers often in hostile conditions. The North Sea has played a major role in these developments.

However whilst oil and gas drilling offers a wealth of knowledge, wells drilled for hydrocarbons are of generally small diameter with the diameter at total depth generally in the range of 150 mm (6.00 in) to 215 mm (8.50 in) with some wells drilled in 'slim hole' sizes with typically 121 mm (4.75 in) or smaller. Both units are quoted here for hole diameters as the oil industry still widely uses Imperial measurements for bit sizes.

Gas storage wells by the nature of their service requirements tend to be larger with final hole sizes typically of 311 mm (12.25 in) diameter.

Depths of hydrocarbon wells are generally in the range of 500 m to 5 km with a few wells drilled towards 6 km. Up to the early 1980s, directional drilling in North America accounted for 2% of all hydrocarbon drilling. Today, inclined, long reach and wells started vertically with a final trajectory horizontal are common place. Long reach wells which are started vertically and then deviated to a high angle trajectory have been drilled to over 11 km length such as at the BP Wytch Farm Oilfield in Southern England. The development of downhole rotation devices over the last 30 years such as slow speed high torque positive displacement motors and turbines has made this possible. Data transmission technology, steering system development and improved mud systems coupled with a better understanding of wellbore physics and hole stability have also been important improvements which has made the drilling of these exotic directionally drilled holes achievable.

Oil and gas wells are generally drilled entirely in sedimentary rocks except for some special cases where oil and gas are held in the fractures at the top of the granite basement such as in Kansas and Vietnam. In these cases penetration into granite is for limited lengths to access the reservoir zone where the oil accumulates in the top of the granite in comparison to the extended penetration into granite of some deep geothermal wells and geoscientific boreholes drilled into the crystalline basement.

The extensive experience and maturity of the oil and gas drilling industry where thousands of wells are drilled every year, even though the depth and diameters have not been achieved in combination, gives some comfort that at least for the smaller diameter boreholes of 300 mm and 500 mm finished diameter, the technology can be extended to the required depth-diameter combination required given a demand for a programme of deep disposal boreholes and favourable geology with respect to drilling.

4.2 Geothermal drilling

Geothermal experience also dates back over 100 years. The drilling systems used in this application of deep drilling are largely the same as for oil and gas wells, but the rock conditions are generally more hostile and wells are of course hot providing the catalyst to develop processes and tools suitable for drilling hot, abrasive and fractured rock wells. Some of this experience relates to drilling in competent granite.

Depths of geothermal wells range from about 1 km to 5 km with diameters at the final depth of between 215 mm (8.50 in) and 311 mm (12.25 in). A deep geothermal well designed by the author has recently been completed in Switzerland in 2007 to a depth of 5 km with a diameter at the final depth of 251 mm (9.875 in) with a penetration of 2.4 km into the crystalline basement in the Rhine Graben structure.

4.3 Geoscientific drilling

Deep boreholes drilled for geoscientific and other research purposes have contributed much to the understanding of the geotechnical constraints which apply to deep drilling and the processes that control penetration deep into the basement. A number of very deep, superdeep and ultradeep boreholes (see Section 1 for classification) were drilled between 1970 and 1994, several in the former USSR. The deepest well, Kola drilled in the Murmansk peninsula in the former USSR (Russia) into the Baltic Shield eventually achieved a depth of 12.22 km with a 215 mm (8.50 in) final diameter.

In Europe the KTB superdeep borehole in Bavaria drilled from 1990 to 1994 was drilled to 9.1 km with a final diameter of 165 mm (6.50 in). This deep geoscientific superdeep borehole in Germany was preceded by a fully cored borehole to 4 km at the same location. The KTB superdeep stages are shown in Table 4.1 to give some indication of the scale of this project. Note that main borehole was originally planned to be drilled to 12 km, but the project was stopped at 9.1 km due to funding limitations together with the foreseeable difficulties of drilling much deeper [KTB 1996].

Interval	*Depths (m)*		*Drilled diameter*		*Casing size*		*Days*	*Ave ROP*
	From	*To*	*mm*	*In*	*mm*	*in*	*No*	*m/day*
I	6.0	305.0	711.2	28.00	622.3	24.500	32	9.34
II	290.5	3003.0	444.5	17.50	406.4	16.000	220	12.33
III	3000.5	6018.0	374.7	14.75	339.7	13.375	310	9.73
IV	6013.5	8328.2	311.2	12.25	244.5	9.625	602	3.84
V	7784.8	8729.7	215.9	8.50	193.7	7.625	158	5.98
VI	8729.7	9101.0	165.1	6.50	Open hole		146	2.54
Summary		*9101.0*					*1468*	

Table 4.1 : Operational phases of the KTB superdeep borehole

4.4 Mineral drilling

Mineral exploration drilling is generally confined to small 'slim hole' diameters with extensive coring usually by wireline methods. Final diameters of typically 76 mm or N size in the Diamond Core Drillers Manufacturers Association (DCDMA) nomenclature, or smaller, to approximately 50 mm (B size). The deepest known such borehole was drilled in South Africa in 1985-1986. The borehole was drilled to a world record of 5.42 km and was drilled quickly by deep South African borehole standards in 10 months using an aluminium alloy string [Fortier 1989].

Mineral exploration wells are often deviated into ore bodies and sidetracked to re-enter the mineral resource of interest to optimise the cost of drilling the uppermost section. Sidetracking is generally achieved using a whipstock, a long, curved, taper shaped wedge made of steel that is deployed and oriented just above the blockage in a borehole to allow the next drilling run to deflect into a new trajectory through the side of the borehole. These are rarely used in oil gas drilling except when special problems arise such as sidetracking through windows cut in casing. This is because with such small diameter boreholes and generally hard and strong rock, the traditional oil industry methods of using downhole rotation devices (motors and turbines) with a steering assembly are not practical.

4.5 Shaft or big hole drilling

Drilled shafts, often referred to as 'blind shaft drilling' or 'big hole drilling' has been practiced for many years for such applications as mine access shafts, mine ventilation shafts and other similar civil engineering or mining applications [Rowe 1993]. These drilled shafts are constructed for a variety of purposes including waste disposal (sewage, chemicals, etc) nuclear weapons testing, mine access, mine ventilation and drainage (water and methane). Shafts up to 5 m in diameter and greater have been drilled. Much of the pioneering work in shaft drilling was driven by the underground nuclear explosive testing programmes which started in 1957. A proposal was developed in the USA to drill a shaft of 4.7 m in diameter to 1.2 km in a single pass with enlargement to 6.1 m with a second pass. Also feasibility studies were carried out to asses the possibility of drilling 6.1 m diameter shafts to 3 km in South Africa. These large scale developments have never been implemented as far as is known due to limitations of drilling equipment and hole lining systems.

A 4.4 m diameter shaft was drilled to 0.75 km in the Agnew area in Western Australia which was completed in 1982 and more recently (date unknown) a 5.8 m diameter shaft was drilled to 0.52 km in Australia.

There have been three known drilled shafts in the UK, two at Killingholme in Lincolnshire for a gas storage project and one for a coal mine ventilation shaft at Betws Colliery in South Wales undertaken by Pigott Shaft Drilling in the early 1980s. Whilst relatively shallow compared with the requirement for waste disposal, the Betws shaft experience illustrates many of the features and problems of blind shaft drilling. The shaft was drilled and cased to 0.22 km at 3.75 m diameter in a single pass using a purpose built shaft rig known as the 'Titan' rig [Chadwick 1986]. The Titan rig was a relatively simple rig with a 7.3 m opening to allow the handling of very large tools. The rig incorporated a cutting head transporter. The rotary table had a 2.5 m opening diameter to allow the passage of drill weights, stabilisers and other tools.

The shaft was drilled mainly in mudstone over Pennant Sandstone. Penetration rates of 6 m/hr were achieved in the mudstones, but reduced to 180 mm/hr in the competent Pennant Sandstone. The shaft was drilled with reverse circulation at 260 l/s (4000 gal/min). The mud was circulated by an electrical submersible pump accommodated in the drill string. The drill pipe was 305 mm diameter and flanged. A 20 m deep fore shaft was excavated by drill and blast first. Solids control equipment comprising shale shakers and hydrocyclones conditioned the mud.

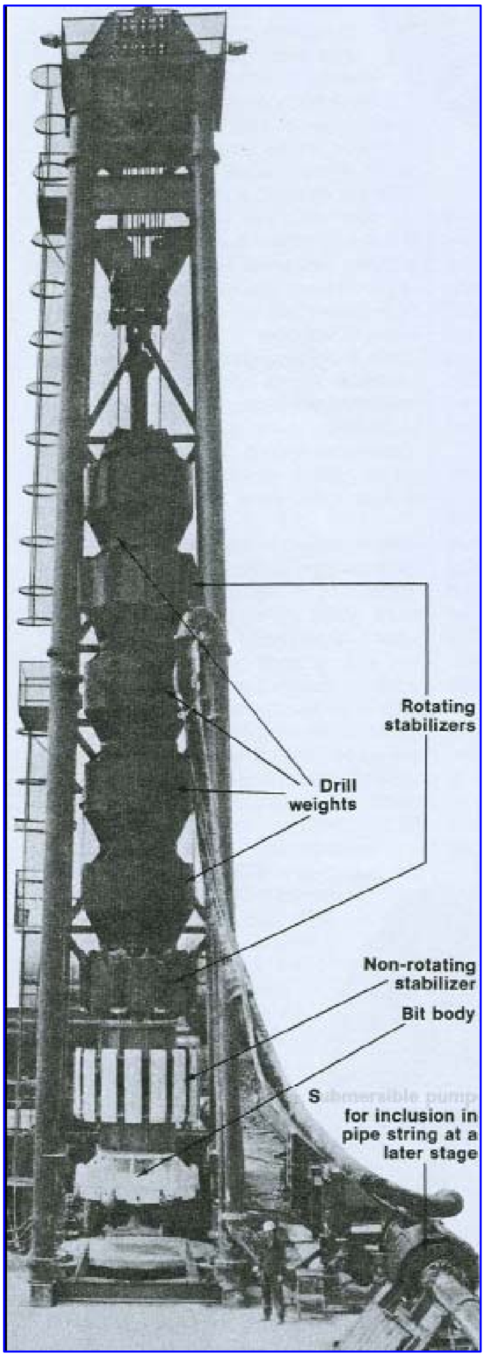


Figure 4.1 : Titan shaft rig

The casing was double skinned steel with a 3 m internal diameter (ID) and a 3.5 m outside diameter (OD) with grout pipes for final cementation. Concrete was poured on site into the gap between the inner and outer skin prior to installation. The casing lengths were welded both on the inside and outside and run in pairs of 6 m lengths. The casing was what is called a 'hydrostatic' casing with a closed end and was floated into the shaft with buoyancy control. The casing weighed approximately 5 tonne/m or about 1000 metric tonnes in total, but installed with a 100 metric ton crane.

Some deviation problems were experienced in the hard Pennant sandstone and so a reamer with extendable cutters was made and available on the site in case the casing 'hung up' during installation.

Large diameter holes of this kind are drilled with rotary methods usually with reverse circulation in either single or double pass depending on the depth, geology and diameter. Drill strings are large with some shafts using 500 mm diameter pipe and rigs capable of lifting 500 tons or more with casing weight approaching 2000 tons. Casing in these relatively shallow shafts is usually 'floated in 'under controlled buoyancy so that the heavy casing weights can be installed with a shaft drilling or oilfield rig or with a suitable crane. Casings are usually composite design (steel and concrete) designed to withstand the hydrostatic forces for 'floating the casing into the borehole to reduce the effective weight.

Reverse circulation or '*reverse fluid-air assist circulating system*' is the opposite of the normal direct circulation used in most oil and gas drilling. In the normal direct circulation system, the drilling fluid is pumped with surface pumps down the drill string and returns up the drill string-borehole annulus carrying the cuttings to the surface for separation and conditioning of the mud before it is pumped round the system again. In the reverse circulation system, the opposite occurs. The drilling fluid is circulated down the annulus and returns through the drill pipe to the surface. The air assist approach is used in many reverse circulating systems to create a lower density in the drill pipe to allow the borehole circulation to occur without pumps which is a significant advantage with the very large volumes of fluid necessary in shaft or large hole drilling. Reverse circulation is commonly used also in some water wells and surface mineral exploration boreholes through overburden.

In the former USSR, shaft drilling was relatively common using both rotary and, in selected cases, the use of multi-head reaction turbine devices up to diameters of 5 m. These devices comprise two, three or four turbodrills mounted rigidly in a heavy collar assembly. The turbodrills are powered by drilling fluid in the same way that an oilfield downhole motor or turbine operates and the assembly is rotated by reactive torque forces.

4.6 Radioactive waste investigations

Radioactive waste disposal investigations to characterise the geology and hydrogeology have been carried out in a number of countries. Investigation methods and the approach has varied widely from the use of oilfield rigs and equipment to the slim hole mineral exploration approach, the latter where hard rock or basement is encountered near the surface such as in Sweden. A combination of oilfield, mining and geotechnical equipment and methods were used for the geological and hydrogeological investigations at Sellafield and Dounreay in the 1990s due to the geological conditions and testing requirements with boreholes up to 2 km deep with a final diameter of 159 mm (6.25 in).

4.7 Drilling for military purposes

The final group is the deep boreholes drilled for military purposed such as the deep large diameter holes for underground nuclear device testing in Nevada and in the former USSR. The US Government drilled 550 big holes totalling 320 km in length at diameters ranging from 1.22 m to 3.66 m with some opened to 6.4 m to depths of 0.15 km to 1.5 km primarily in Nevada. Drilling rates averaged about 30 m per day in the soft rocks with average compressive strengths of 28 MPa (4000 lb/in^2)[Rowe 1993].

The deepest 3 m diameter drilled hole is thought to be the 1.68 km UC-4 hole drilled in Hot Creek Valley in south central Nevada for the US Atomic Energy Commission drilled in about 1967 for a nuclear test detonation. The deepest 2.28 m shaft is the 1874 m (possibly 1905 m depending on the reference) deep UA-1 hole on Amchitka Island in the Aleutians as part of the US Atomic Energy Commission programme in 1969-1970 period.

4.8 Depth v diameter

To summarise the background to deep drilling experience, some examples are presented graphically in Figure 4.2 to illustrate the general relationship between depth and diameter generated by actual practice. Superimposed are the boundary lines of the 1000 mm, 750 mm, 500 mm and 300 mm well borehole diameter cases that have been considered in this report for deep disposal. These are the clear internal dimensions. Drilled diameters would be larger.

Noteworthy is that some of the data are from deep water offshore drilling, particularly the cluster in the 3 km to 4 km range where depths are measured from the rig floor and therefore include the length from rig floor to sea bed. Therefore some of these data may be artificially deeper than the actual drilled depth, although the data do provide a useful insight into the depth vs diameter relationship.

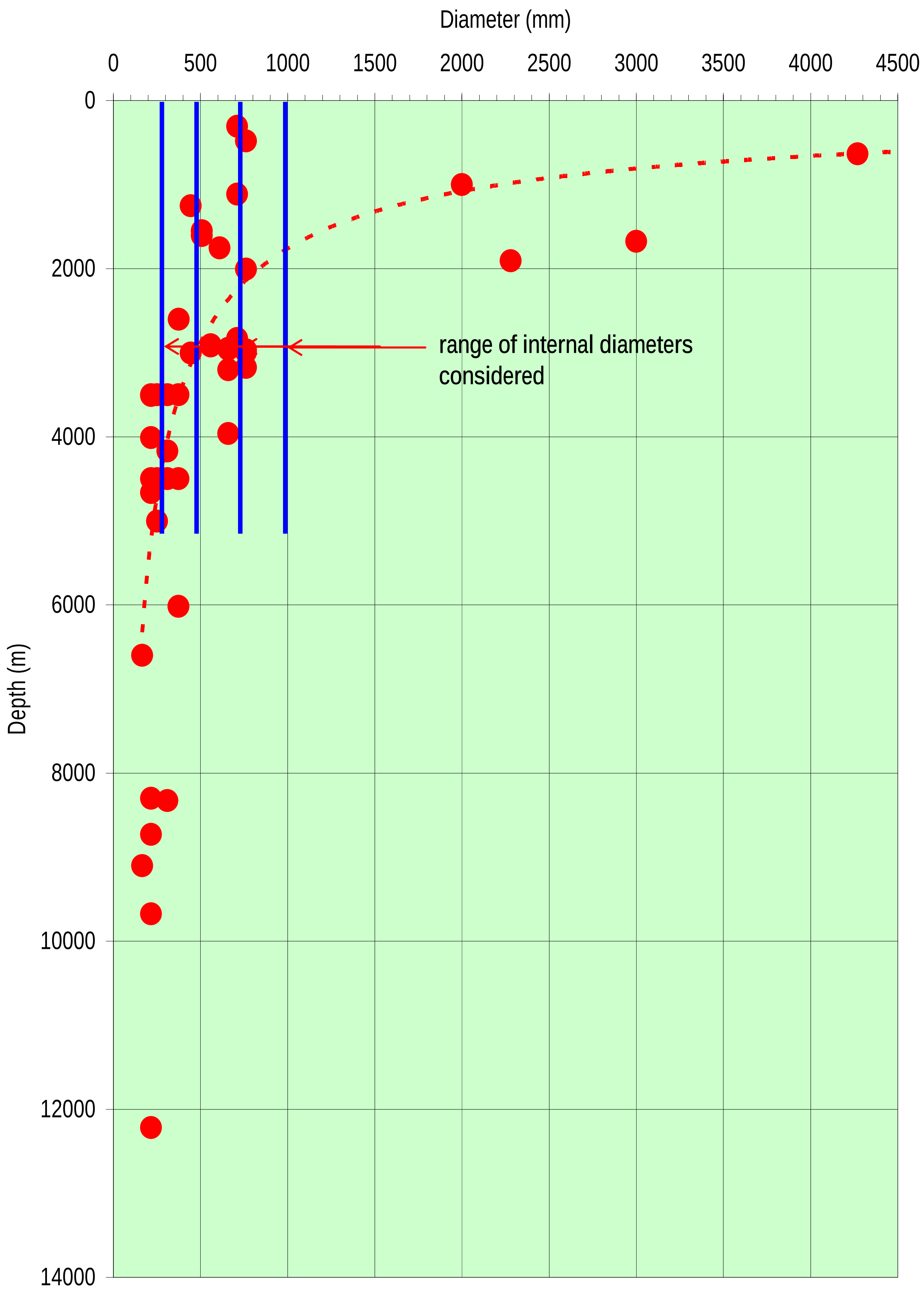


Figure 4.1 : Relationship between depth and diameter generated by actual practice

These data show that the waste disposal boreholes defined in this report and that have been the subject of historical studies by others for this option of waste disposal, are close to or outside the envelope of historical and current drilling experience at the larger sizes. However, at the more modest sizes of a final clear hole diameter of 300 mm and perhaps 500 mm, such boreholes are probably an achievable extension of previous experience.

However, the geotechnical behaviour of rocks at depths of 5 km, particularly in large diameter boreholes, is poorly understood and a major challenge. There is a limited drilling history to provide a confident forecast of the degree of success of deep drilling to these depths and diameters.

There is little useful data for deep boreholes at 3.5 km and 4.5 km that is outside the normal oil industry standards of 216 mm and 150 mm diameter for the lowermost intervals of deep boreholes. The data presented in Figure 4.1 below 4 km include good data from deep, very deep, superdeep and ultradeep boreholes (see Section 1 for classification) primarily in crystalline rock drilling as these are the only data from these depths that are readily available and more relevant to the case under discussion.

Data on the time taken for the drilling of the deep wells illustrated on Figure 4.2 are not useful in anticipating future developments, as development has been slow over the past 25 years or more. Moreover, the current trend is to reduce the diameter of wells at depth where possible, as cost is the key driver. The Basel well, referred to in Section 4.2 which had a final diameter of 251 mm, was the first well other than the KTB well drilled to a bottom hole diameter size greater than the accepted 216 mm in the crystalline basement. This larger diameter was required to accommodate the high flow rates associated with such a geothermal production borehole.

4.9 Constraints

No industry can readily supply equipment and tools suitable for such a challenging endeavour without a serious design and engineering programme. That is not to say that all aspects are in the research and development phase. Some are simply adaptation of known technologies and existing equipment and tools. These issues will be summarised in this section to highlight the status of the technology and where the shortfalls occur.

Moreover, engineering development, design and manufacturing would inevitable introduce long lead times for some items, even if the concept is proven to be practicable. This would apply as much for a pilot or demonstration borehole as for a major implementation programme.

Other constraints relate amongst others things to material engineering, geology, rock mechanics, geopressurised fluids and temperature. Material engineering in this context should not be underestimated as there are physical limitations to the design of large diameter deep borehole equipment and such items as casing and cement.

Geology is very important throughout this debate. Hole stability in some formations is problematic and in large diameter boreholes this can be a major issue. Hole stability is best achieved by drilling in the stronger rocks which are less susceptible to breakdown and instability. The geological scenarios for emplacement of a deep drilled shaft repository will be discussed later.

With reference to the rock mechanics considerations, these can present particular problems in deep boreholes in basement rocks or strong formations. The problems relate to rock stress as the stronger the rock the more anisotropy in stress the rock can withstand with consequential effects as the stress is relieved by drilling. Reference in reports elsewhere on this subject has been made to deep shafts and gold mines in South Africa. The strong host quartzites in South Africa are highly stressed in places and explosive rock bursts occur which illustrates the effect of stress release when the confining support is removed by the creation of an opening. Similarly, many deep boreholes, particularly in the stronger basement rocks exhibit stress breakout creating oval or irregular holes with axes related to the principal stress directions. In a deep geothermal well which has just been completed in Switzerland in the Rhine Graben tectonic structure, the final drilled diameter was 251 mm (9.875 in) at 5 km, but the dimension on the long axis was 430 mm. An image of the bottom of this well is shown on Figure 4.3. An image of the breakout in the KTB superdeep well in Bavaria is shown on Figure 4.4.

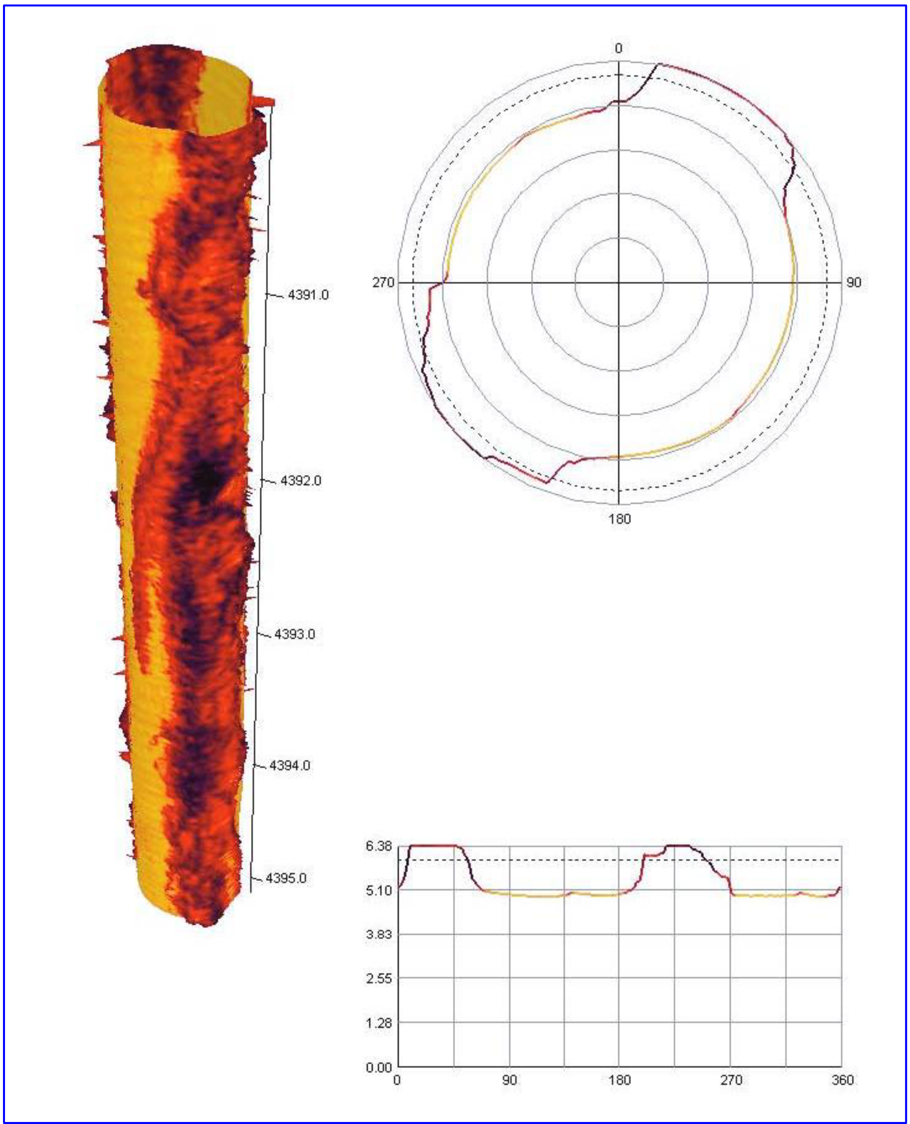


Figure 4.3 : stress breakout in Basel-1 well 4390 m to 4395 m

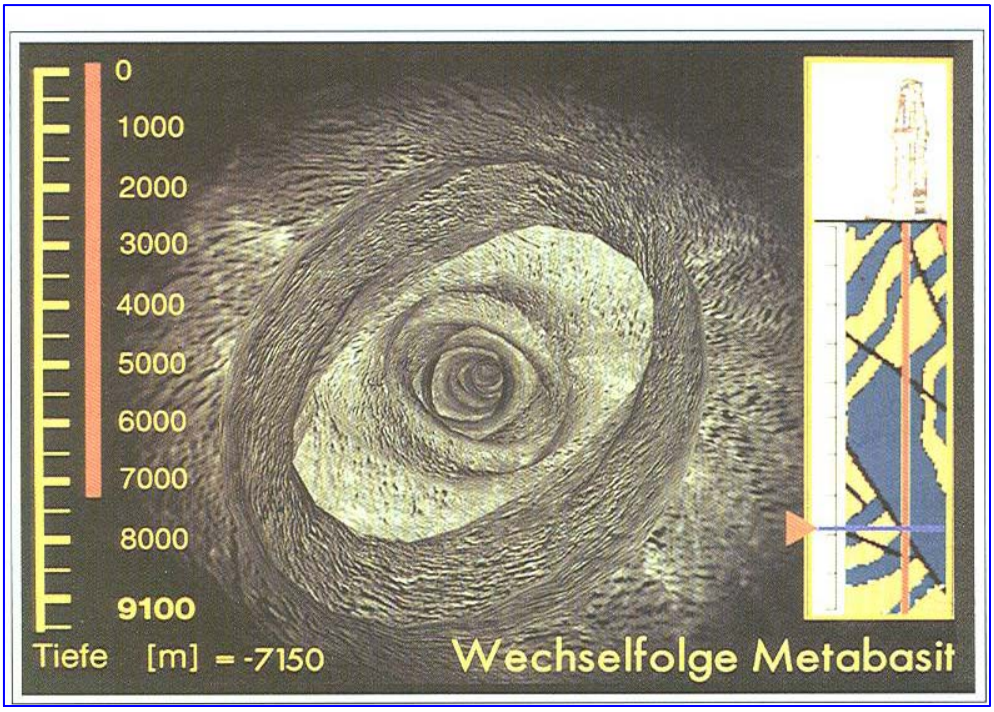


Fig 4.4 : Stress breakout in the KTB superdeep well at 7150 m

Stress and relaxation of the rock mass around the borehole would also result in a 'disturbed' zone with an increase in permeability. The treatment of this zone with regard to sealing is also a concern that has to be considered in the design of the repository and sealing aspects of the concept.

The natural geothermal gradient is also an issue which has to be considered. The normal geothermal gradient is about 25^{o}C/km. In the Baltic Shield (Kola and Gravberg) the geothermal gradient was low at about 16^{o}C/km. In the batholiths of South West England for example, the geothermal gradient is abnormally high at about 35^{o}C/km. Hence, at 5 km depth, assuming a 10^{o}C ambient temperature, the bottom hole temperature can range from say 90^{o}C to 180^{o}C or even higher. High temperature wells create problems with instrumentation and the risk of 'flashing' in the upper part of the wells or at the surface which must be avoided. The term 'flashing' is used to describe the change of state from water or brine to steam within the well itself as the liquid rapidly vaporises as the pressure reduces close to the surface.

Thermal effects on casing must also be considered in the borehole design as expansion and contraction can be significant with large changes in temperature.

This background to deep drilling in all its forms is the start point from which to investigate the possibility of the successful development of a deep borehole disposal solution. It is by no means an exhaustive summary, but illustrates the baseline.

5 DEEP WELL ENGINEERING ISSUES

5.1 Geology

This report is not intended to be a treatise on the details of suitable geologies as this is primarily a site selection issue. It is assumed that any site selected for deep borehole disposal would be in an area not liable to significant seismic activity. For the purpose of this report, three geological scenarios have been in mind as a framework to the discussion:

Case A Sedimentary geology throughout the whole depth.
Case B A sedimentary upper part and a disposal zone in the crystalline basement.
Case C Crystalline basement rock from near or at the surface.

As noted above, hole stability considerations would be a serious issue in some geologies. Strong sandstones or limestones are stable and may be suitable whereas swelling clays and troublesome formations like the Rhaetic formations and Jurassic clays should be avoided. Salt is also a known problem area for deep drilling and should also be avoided, although it is noted that a project to drill into a salt dome in Denmark to dispose of waste was investigated and considered feasible [Nirex 2004].

The other fact that has to be addressed is that any depth of sedimentary cover would introduce the needs for intermediate casing(s) which would add diameter to the surface entry and hence would be more problematic in the context of big hole drilling and more costly. On the other hand, sedimentary rocks would be easier and hence cheaper to drill providing the more troublesome formations were avoided. Of the geological scenarios used as a guide above, Case B, with a limited sedimentary cover, which was relatively easy to drill, and perhaps Case C are the most favourable. If there was a choice, coarse grained granite in the disposal zone with low quartz content would be easier to drill than a fine grained basement complex as the cutting mechanism is one of crushing the large feldspar crystals to break the rock.

A historical summary of depth v diameter examples is presented in Figure 4.2 above. Some hole scenarios that have been considered for this review are presented in Figure 5.1. The deeper the sedimentary cover the more the likelihood of the need for different casing strings in the construction of borehole. Hence, a shallow cover to competent rock scenario is preferable to minimise drilling sizes.

5.2 Depths and diameters

Four cases have been considered:

I 300 mm finished diameter
ii 500 mm finished diameter
iii 750 mm finished diameter
iv 1000 mm finished diameter

The diameter of the borehole must accommodate the various types of packing. Waste container size considerations ideally require a 1000 mm internal diameter completed borehole in the zone of disposal to cover all waste packaging cases. However, repackaged fuel rods and some canister dimensions suggest that disposal in smaller diameter boreholes may be practicable.

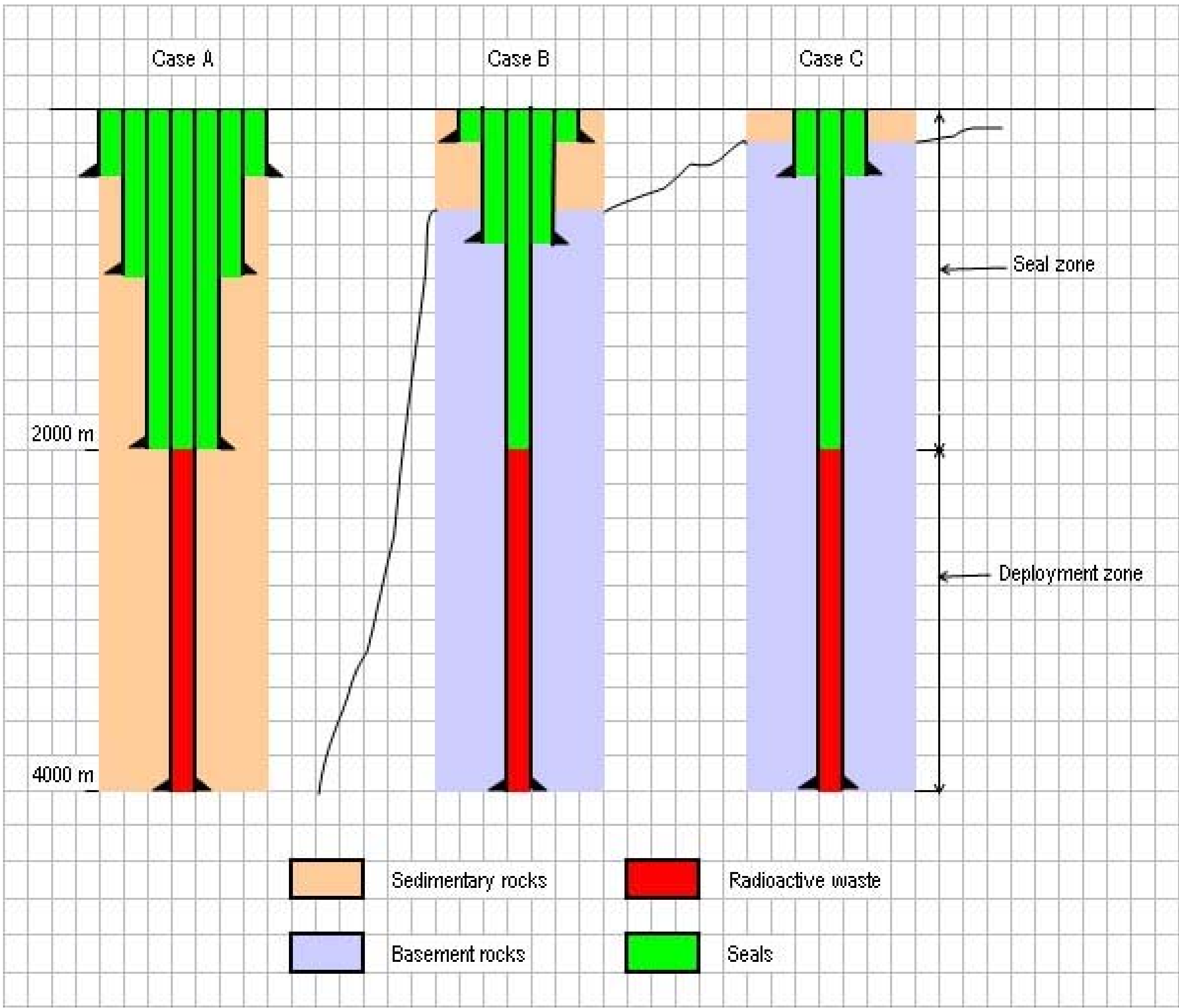


Figure 5.1 : Geological scenarios for deep waste disposal boreholes

The 300 mm clear diameter option to 4 km or 5 km is probably achievable now with current technology, although such boreholes would be easier to construct in competent sedimentary rock or the crystalline basement in a low differential horizontal stress environment. In the Case C, an intermediate casing between the top of the crystalline basement and the top of the deployment zone may be required if drilling becomes troublesome and any design should include this contingency.

The 500 mm diameter option to 4 km or deeper starts to deviate from the known experience particularly in the stronger rocks and a stressed environment. The graph in Figure 4.1 suggests that this is achievable, but the cluster of data at below 3 km at diameters above 251 mm relates to deep water offshore experience so the cluster is deeper than it would be plotted for onshore boreholes. Boreholes to 3 km should be achievable in favourable conditions with the tools and experience available today. Deeper boreholes present an extension of current knowledge, equipment and casing design issues that starts to introduce high risk, but with good engineering and favourable conditions, boreholes to 4 km or maybe should be achievable. In the Swedish case, the review for SKB [Harrison 2002] suggested that an 800 mm diameter hole to 4 km *may* be possible in the strong relatively homogeneous granite with few fractures which are characteristic of parts of the Baltic Shield and are not subject to any overpressure that arise in some parts of Sweden [Juhlin *et al* 1989, SKB 2000]. This proposal was reviewed by Harrison who concluded that with current technology, a borehole with a diameter of 800 mm could be drilled to 4 km in the context of the Swedish geology, although it represents one of the most challenging projects ever to be presented to the drilling industry [Harrison 2002].

It is important to reiterate that the study by SKB for DBD in Sweden was solely related to the Baltic Shield and the geological conditions in Sweden and may not necessarily be directly transferable to other countries or geologies [Juhlin *et al* 1989]. At the Gravberg-1 deep gas well drilled near Mora in Central Sweden, the top 4 km was drilled with water in 311 mm diameter before borehole instability precluded further drilling without weighted drilling fluid. The Gravberg-1 well was located in the Siljan Ring impact crater and the rock had been crushed and reconstituted as a granitic mass and was atypical in texture of an undisturbed granite, although exhibiting the same drilling features and behaviour.

The 750 mm case starts to deviate significantly from current experience and equipment probably below 2 km. Hence more risk is introduced and there would be a need for significant tool and drilling process development to minimise the risks if such a project were considered. The issues associated with casing installation also become a serious concern as the size increases.

The 1000 mm diameter case is well outside current experience or anticipated borehole development in the future except for a relatively shallow borehole. It is considered technically impracticable in the foreseeable future to drill such a large diameter borehole to 4 km.

At these scales, the technology that is applicable to the larger size holes is similar to that required for blind shaft drilling or big hole drilling than the oilfield drilling, but a blend of the two technologies is necessary as the depths concerned are outside that experienced by the shaft drillers.

However, it is being realistic to state that attempting to drill a borehole hole with a finished internal size of 1000 mm to a depth of 4 km to 5 km is far outside the envelope of past experience and probably beyond current technology and realistic drilling equipment design. Everything would be a ‘special’ and the risks would be high. Risks, technical difficulties and cost increase with depth, particularly below 4 km and except in favourable circumstances such as competent, relatively unstressed crystalline rock at depth, deep disposal boreholes to 5 km in large diameters of 750 mm and 1000 mm clear diameter are high risk and too far outside the practicable envelope also.

Depths for waste disposal of 2 km to 5 km have been indicated as being necessary, but it is also suggested that a sealing length of a minimum 2 km is required and in some geological environments it is considered that a sealing length of 3 km is necessary. This increased depth of burial would increase the number of boreholes required to accommodate the waste material if the total drilling depth remains the same. Moreover, increased depth increases risk. For example, stress related problems of borehole instability tend to start to be particularly troublesome below 4 km in the United Kingdom.

Whilst the desire is for a 4 km deep borehole with a 2 km seal cover above the waste disposal zone, consideration should also be given to say a 3 km deep borehole with 2 km of cover perhaps in the intermediate size of say 750 mm as this may be practical and shallow enough not to encounter the same level of stress related borehole breakout problems that are likely to exist at depth. This option is not relevant if the seal cover above the waste has to be 3 km as proposed by Gibb [Gibb 2005]. However, there may be geological environments where a 2 km cover may be acceptable.

To summarise the current status of experience, technology and practicability for the different borehole diameters that have been considered, a simple classification of the feasibility of deep boreholes is presented in Table 5.1 for different diameters and depths.

Depth (km)	*Completed internal diameter (mm)*			
	300	*500*	*750*	*1000*
2				
3				??
4			??	
5				

Key : Green = feasible with current technology and favourable geological conditions.
Orange = may be achievable with tool and process development.
Red = considered impractical in the foreseeable future.

Table 5.1 : Classification of deep borehole feasibility

The diameter depth relationship becomes a trade off both technically and commercially. Whilst more boreholes would be needed for a shallower borehole case to accommodate the volume of waste, the advantages are significant technically. However, the overall cost of more boreholes may be less attractive than designing deeper smaller diameter boreholes. In terms of drilling costs, without doing a detailed design and cost analysis, providing the design is achievable, there is probably not much difference in the overall drilling costs per unit length drilled, but the surface land take and hence handling logistics, site construction, rig moving costs etc, may increase the overall repository cost if a shallow solution was adopted.

In considering the drilling aspects of the deep disposal concept, the borehole has been divided into two parts:

- The upper section of the borehole which would eventually accommodate the upper seal zone (from surface to the top of the deployment zone); and

- The waste deployment zone where the waste materials would be placed for long term disposal.

5.3 Hole advancement and construction

This refers to the method of forming a suitable hole in the earth through the various geological formations and conditions that may arise. The design of the drilling programme needs to consider the following elements:

- A means of cuttings the rock (bits);

- A means of cooling the bit and carrying the cut rock pieces or cuttings to the surface for disposal (drilling fluid);

- The drilling fluid circulation system, either direct (as the oilfield) or reverse (as for shaft drilling) either mud or air assist;

- A machine that can provide the rotation and rotational torque required and the means of lifting and lowering the drilling assembly and drill string;

- A machine and procedure for lowering very heavy casing strings into the borehole;
- A drill string to connect the bit and drilling assembly to the surface and transfer the torque to rotate the bit;
- A means of support to the borehole wall at all times either through a drilling fluid or casing; and
- A machine to handle and deploy the waste packages and service the borehole during the sealing process. This may be the same rig as the drilling rig or different.

5.4 Bits

In the case of oilfield drilling, bit technology for rock roller bits in the size range up to say 762 mm (30 in) is well known and a mature industry. Typically these bits are manufactured for relatively soft to medium formations, but are unusual for granite. Hard formation bits are usually special order. The oilfield also uses polycrystalline bits extensively in certain sedimentary formations and occasionally full face diamond bits. However, crystalline rock drilling is rare and bits used are generally low to medium profile tungsten carbide insert bits to crush the weaker crystals in the rock and often include additional gauge protection for use in these abrasive rocks. These bits require high weight-on-bit (WOB) and penetration rates are slow typically 3-5 m/hr in the size range of 251 mm 311 mm with bit lives of 100 m to 150 m. WOB of 90 kg/mm (5000 lb/in) or higher are typical meaning that for a 762 mm (30 in) bit, the load required to drill granite would be 68 metric tonnes (150 000 lb).

Shaft drilling is usually accomplished by the use of purpose built roller or plate bits which are a combination of rollers or cutters organised in an array covering the drilled area to crush or gouge the formation and so create an excavation. Shaft drilling is not dissimilar to a tunnelling machine approach. Big hole bits can be manufactured in any size and are known to have been used for diameters up to 6 m or more. A typical big hole bit is shown on Figure 5.2.

When drilling began at the Nevada nuclear test site in 1959, a 915 mm hole to 305 m took some 60 days. The process was to use multi-pass drilling. This was a time consuming process. The time was reduced by mounting all three size bits together into a tri-stage assembly which cut the drilling time down to 30 days.

Successive modification stacked the bits closer together and eventually the tri-stage bit gave way to the flat bottomed bit. This resulted in more time saving for the same 305 m hole to 20 days [US DoE 2004].

Bit technology is already developed to a stage whereby a large diameter hole can be drilled so this is not necessarily a limiting factor. There is a caveat to that statement in that much of the big hole drilling experience particularly related to the Nevada test site has been through a simple geology with low compressive strengths to relatively shallow depths and above the water table that allowed relative fast drilling and low bit or cutter wear. For harder and more abrasive formations, such as the crystalline basement rocks, bit design would need careful thought and weight on the bit would need to be significantly increased and may demand multi-pass drilling as against full face drilling to achieve the objective.

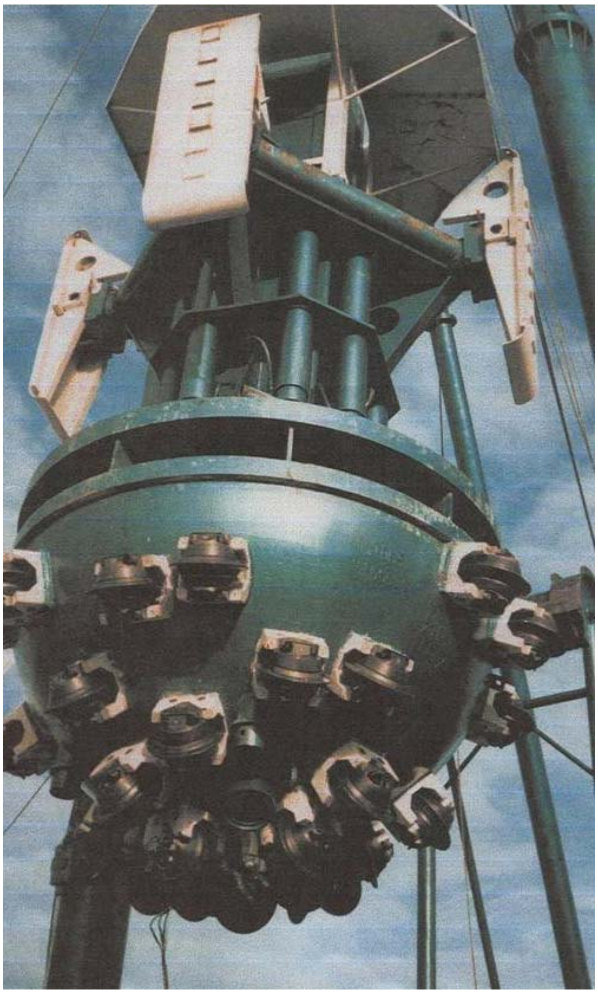


Fig 5.2 : Big hole bit

Large holes in crystalline rock are very unusual and so bit technology and the associated tools and rig requirements would need some significant development.

5.5 Drilling tools

Drilling tools for oilfield drilling are again well developed and generally readily available, although in the larger sizes and when the industry has high demand, lead time may be extended. Tools include drill collars to provide weight to the cutting bit, stabilisers, directional control tools, hole openers, jars for freeing stuck assemblies and an assortment of specialist tools. Again tools in the larger sizes are generally only available for relatively weak rocks and not for hard crystalline formations so some development or special builds would be required.

The shaft drillers use somewhat simpler tools. For weight to make the bit cut they rely on doughnut drill collars with removable weights mounted above the plate bits. For relative shallow holes, this is acceptable and rarely do they have to resort to 'fishing' failed assemblies. Obviously, unstable boreholes can result in material falling behind the bit. Recovery can be achieved by washing the material from above the bit, but sometimes the bit and drilling assembly has to be abandoned and the hole plugged. With deeper boreholes, this risk obviously increases, especially if there is a potential for borehole wall instability. This introduces serious risks to large hole drilling at depth.

A typical big hole drilling assembly is shown on Figure 5.3.

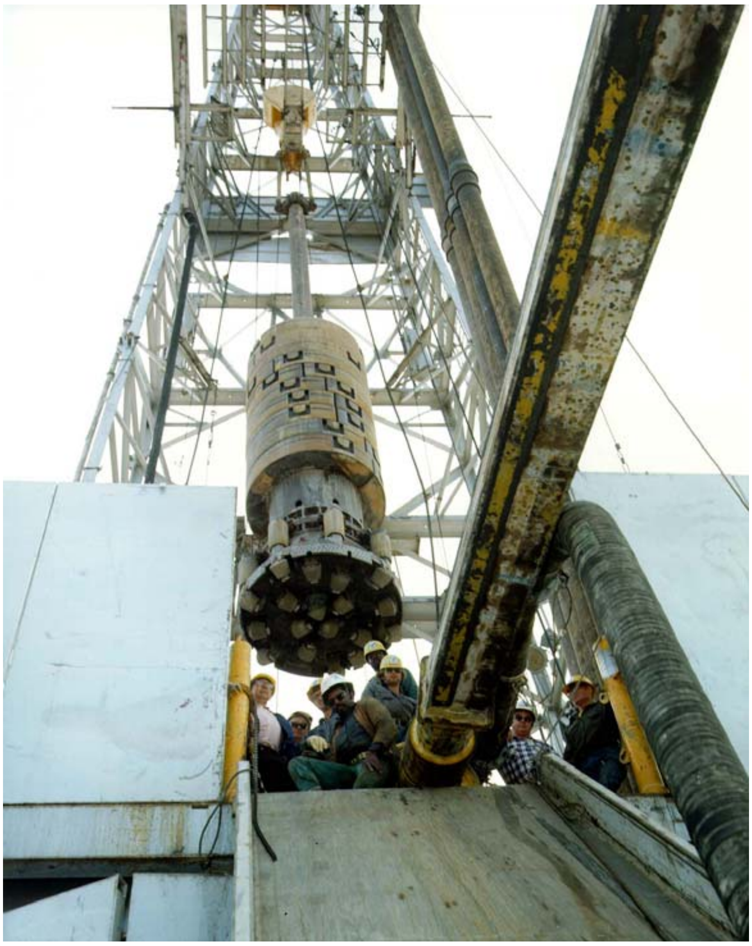


Figure 5.3 : Typical big hole drilling assembly

For larger diameter boreholes, even for oilfield applications, drilling can be approached either as a single pass process, ie drilling the full diameter in one pass, or in dual or multi-passes first drilling a pilot hole to the required depth of the interval then opening up the borehole to a new diameter until the final diameter is achieved. There are both advantages and disadvantages to the multi-pass approach.

Advantages include making sure the well is vertical with some form of verticality control that can be used in relatively small diameter boreholes say up to 445 mm (see Section 5.7) and knowing the formation and conditions through which the larger hole is to be drilled at the actual location of the disposal borehole. It is assumed that at any site selected for a waste disposal borehole that there would be a detailed site characterisation programme and hence the geological and hydrogeological prognosis at the site of any deep disposal well would be based on much better information than is normal for typical oil, gas, geothermal or geoscientific exploration boreholes or in some cases oil and gas development wells.

Disadvantages include the potential of the subsequent hole opening passes to sidetrack from the pilot hole, although a hole finder in the drilling assembly that follows the original pilot hole usually prevents that happening. Poor performance and excessive damage to hole opening tools especially in strong rock is also a feature of multi-pass drilling. However, for large shafts, some form of multi-pass system is commonplace.

Tools are available for large diameter hole construction to the depths experienced to date. There are serious problems of recovery in the event of hole instability which increase with diameter of hole. The harder formation would require heavier drill collar assemblies and, due to limitations on assemblies and rigs may dictate that deep holes in the stronger rocks are drilled using multi-pass process.

5.6 Other methods of advancing boreholes

For some applications in relatively small diameters and in competent rock, the use of down-the-hole hammers (DTH) is widely used particularly in the mining and quarrying industries. Hammers are available in sizes up to about 1095 mm diameter. These hammers require large quantities of air and air pressure to operate. DTH use also has limitations in directional control, although some recent experiences in the USA and Oman have demonstrated that with a heavy pendulum assembly, verticality can be controlled.

However, the use of air, mist or foam drilling with DTHs may be a candidate for use in drilling a vertical pilot hole or opening boreholes for example in granite. There is an added cost of the air requirements. The noise which arises from the air compressors and boosters also has to be addressed, but penetration rates are much higher than using roller cone rock bits in hard rock. The hammers are also problematical if water is encountered in any quantity and the hammer or air supply cannot blow the hole clean. Air and mist drilling also introduce a drilling scenario where there is little support to the rock and in unstable formations, such an approach is not practical.

DTH drilling can also be used with foams for improved cuttings transport from the borehole annulus. The use of DTHs with air, mist or foam was also discussed in the report to SKB by Harrison [Harrison 2002].

A borehole in Pennsylvania drilled to 1.2 km in about 2000 is the deepest large diameter borehole ever drilled with a down-the-hole hammer system. The borehole through shales, sandstones and limestone was for gas storage using a Numa's Champion 240 hammers and special polycrystalline diamond (PCD) carbide bits. The PCD carbide bits are reported to be three to fives time harder, 100% more wear resistant and have a compressive strength 155% stronger than a standard carbide bit [NUMA 2001].

This deep hole was drilled in the following sizes:

991 mm (39 in) to 24 m drilled with reverse circulation
864 mm (34 in) to 230 m drilled with reverse circulation
724 mm (28.5 in) to 693 m with 660 mm (26 in) casing
620 mm (24 in) to 1,188 m with 508 mm (20 in) casing

The air requirement was over 6,136 l/sec (13,000 m^3/min) and necessitated many compressors and five two stage boosters. Since such a large volume of air could not be run through the hammers, a ported sub was run directly above the hammer to bypass some of the airflow.

Penetration rates averaged 18.3 m/hr in the 724 mm diameter interval and 24.4 m/hr in the 610 mm interval. The deviation at total depth was 0.5^o. The rig used for this borehole was a National 1320 UE, diesel electric 2000 HP rig.

A deep borehole has also recently been drilled in Oman using a DTH assembly to 4.7 km at 213 mm diameter in conglomerate [Beare 2007].

Several attempts have been made to develop fluid driven hammers and generally in small diameters over the last 25 years, but none is sufficiently reliable or proven to consider at this stage and not applicable anyway to large diameter drilling.

Hammer drilling systems have significant benefits in terms of rates of penetration if the ground conditions are appropriate. However, the extra cost of the air package has to be considered together with the noise issues from the compressors and boosters. This method is certainty worthy of a more detailed investigation.

5.7 Verticality control

Verticality can now be controlled very accurately with liquid mud systems in the smaller range of hole sizes (up to 445 mm) using '*vertical drilling systems*'. These systems were finessed to a commercial level on the KTB superdeep hole programme where two companies were invited to develop tools to maintain the verticality of the borehole [KTB 1996]. This was technically successful and verticality was maintained within about 1.5^{o} to depths below 6 km in the Bavarian borehole. Problems of hole temperature and batteries limited the use of these tools in the lowermost interval below 7.15 km once the circulating temperature had exceeded the limitation on the electronics and batteries at about $125^{o}C$ to $150^{o}C$, depending on the type of equipment used. The geothermal gradient at the KTB site was approximately $27^{o}C$/km giving a bottom hole temperature at the final depth of 9 km of $250^{o}C$. The circulating temperature is lower and depends on flow rates and circulating time of the drilling fluid which in deep hot wells is usually cooled with a simple heat transfer system in the surface circulating equipment. Once the vertical drilling system could not be used, the well deviated somewhat uncontrollably due to the stress breakout bias which made directional control virtually impossible as has been experienced in other deep crystalline boreholes.

However, the vertical drilling system development together with simultaneous work elsewhere has resulted in a range of sophisticated directional drilling tools now in routine use in the oil industry. This will allow most wells and boreholes to be drilled very accurately and within the resolution of the supporting surveying systems and physics.

The consequence of using these systems is that it allows more confidence in borehole cluster spacing. Maximum departures for boreholes to 4 km for average inclinations of 1^{o} to 3^{o} are given in Table 5.2. Deep boreholes are rarely vertical and this has implications for the location of adjacent boreholes unless verticality is tightly controlled.

Average deviation (deg)	*Departure (m)*
1.0	70
1.5	105
2.0	140
2.5	175
3.0	210

Table 5.2 : Departures for different average inclinations for 4 km borehole

Deviation control with DTH drilling assemblies has also recently been demonstrated to be achievable using heavy pendulum assemblies and light weights on bit as reported in Section 5.6 [NUMA 2001, Beare 2007].

So for any type of disposal borehole, with an accurately drilled pilot hole, borehole deviation control could be achieved providing of course those sites with strong geological bias related to jointing systems, cleavage, folding and stress anisotropy for example do not prevent the verticality control tools from making the hole trajectory corrections.

5.8 Pressure regime

The design of a deep borehole must address the pressure regime into which the borehole was to be constructed. Knowledge of the natural pore pressure gradient in the formations through which the borehole would pass would need to be determined or estimated with reasonable accuracy. The pore pressure is the pre-existing pressure in pores or fractures that occurs in nature and sets the lower bound drilling fluid pressure below which flow of pore or fracture fluid will occur into the borehole.

The fracture pressure is the pressure in a borehole that can initiate breakdown of the rock such that rock will ‘fracture’ or ‘split’ by either the formation of new fractures in intact rock or by opening up existing sealed fractures in the rock. This pressure can be determined by carrying out a formation integrity test, by increasing the pressure in the borehole until a fracture in the rock is initiated resulting in leakage of the wellbore fluid into the formation. This controls the upper bound of the borehole fluid density envelope and the density of the wellbore fluid should never be close to this upper limit otherwise it will promote lost circulation. Noteworthy is that in the Nevada nuclear testing boreholes, the weight of fluid in the borehole was a problem as much of the formation is above the water table and hence the design of reverse circulation methods using dual concentric drill strings was adopted to overcome this problem.

The oil industry has historically drilled ‘over balanced’ to maintain a positive pressure on the pore or fracture fluid, but more recently balanced drilling and underbalanced drilling have become more acceptable to reduce borehole damage.

Balanced drilling is when the fluid density in the borehole is equal to the natural pore pressure. Overbalanced is when the borehole fluid density is greater than the natural pore fluid and if the density is much higher and exceed the fracture gradient, then the fluid will leak from the well as ‘lost circulation’. Movement of fluid from the borehole to the surrounding rock pores and fractures can cause blocking of the pores and fractures which decreases permeability. This is not desirable in a well intended to produce oil, gas or water for example. However, an overbalanced approach has been adopted for most cases historically to control any gas influxes as part of the well control programme.

The desire of reservoir engineers is to drill underbalanced whereby allowing the formation fluid flow into the well during drilling aims to minimise damage to the borehole pores and fractures and to allow a more sensitive identification of gas influxes. Drilling methods for underbalanced operations have been developed in the last 10 years such that drilling and gas production can occur simultaneously with instrumental control, separators and appropriate surface well control equipment. The actual bottom hole pressure which controls influxes and losses is more complicated as friction losses from pumped circulating fluids has to be taken into account.

If gas enters the borehole due to the fluid density in the borehole being less than the pore pressure where gas is present, the gas will quickly expand as it rises and create a ‘kick’ or at worst ‘blow out’ situation which has to be controlled. Hence there is always a need in drilling deep boreholes to address the well control issues by the availability of equipment in the form of blow out preventers and chokes and by having available weighted drilling fluid to increase the density of the fluid in the well to control the gas influx together with trained and qualified drillers and senior site personnel. Control measures can be relaxed if or when the site can be demonstrated to be benign with no risk of gas.

However, where possible for this application, geopressurised formations, ie those where the pressure in the pore fluid is greater than hydrostatic, should be avoided for disposal wells for a variety of reasons, not just related to drilling. For example, if geopressurised fluids are present, then the boreholes would have to be drilled with weighted drilling fluids at a density appropriate to the expected pore pressure in the rock formations and include permanent surface well control equipment. For large diameter boreholes where normal well control equipment was not available, this could present a serious problem.

Whilst the natural pore pressure must be counteracted by the weight of the fluid used for drilling, the fluid density should not be such as to create a situation where significant losses of fluid can occur if the fracture pressure is exceeded.

An accurate geological prognosis can minimise the risk of problems associated with formation pressures and lost circulation.

5.9 Drilling fluids

For conventional oilfield hole sizes, even at the larger end of the spectrum, drilling fluid technology is well understood and caters for most drilling conditions. The oilfield generally uses a direct circulating system whereby the drilling fluid is pumped with special duplex, triplex or quadruplex pumps down the drill string at pressures up to 35 MPa (but sometimes more) and returns up the drill pipe to hole or casing annulus with the drilled cuttings. This system is limited for big hole drilling due to the large flow rates required to produce an acceptable annular velocity.

The shaft drilling industry has adopted a simple mud system using water or light mud with reverse circulation and air lift system. Typically a 340 mm diameter drill pipe is used with a concentric 178 mm pipe to provide the facility to both recover the drilling fluid in a reverse circulation arrangement and to create the air lift in the return line. Water or drilling mud is circulated between the outer pipes and the casing or borehole wall, across the bit cutters to remove the cuttings and is *'sucked'* to the surface through the drill pipe by an air lift process operating on the inner smaller pipe. Circulation rates of 260 l/s (4000 gpm) are typical for big hole drilling.

In principle, a fluid and circulating system design can be achieved using current knowledge together with the surface handling of cuttings and fluid conditioning. Of course, for large holes the volume of fluid to be managed is substantial.

5.10 Borehole wall stability

In any deep drilling operation, wellbore stability is a critically important factor and can be compromised by a number of factors as follows:

- Poorly cemented formations;
- Reactive clay formations where some clays are very susceptible to rapid deterioration on contact with water based fluids;
- Salt which can flow and squeeze into boreholes and highly loads casing, and
- The effects of stress breakout in stronger rocks.

Many of these problems can be overcome in relatively small diameter well or borehole design by the choice of fluids and in the case of larger diameter borehole by the geological conditions.

The one effect that may be more difficult to manage is that of rock stress resulting in what is referred to as 'stress breakout' from the borehole wall as discussed in Section 4.9. To assess the degree that breakout would occur, a knowledge of the in situ rock stress regime would be necessary. In practice, the drilling process removes the constraining force on the rock and the rock relaxes around the borehole controlled by the in situ stresses much as in a tunnel excavation. The problem comes when there exists a strong anisotropy in the magnitudes of the horizontal principal stresses that generate shear stresses which in extreme circumstances create intrinsic instability and borehole collapses. The stronger the rock the more anisotropy it can sustain before failure so that in the quartzites in the South African gold mines, for example, deep mines can be excavated, but if failure occurs it is explosive in the form of rock bursts. Breakout is also time dependent and continues until the borehole develops a stable profile.

The non-isotropic stress regime influences drilling due to the creation of a non-circular hole making directional control less effective. Potential problems can also arise due to instability of the borehole wall resulting in pieces of rock falling in the hole whilst running drilling equipment or on top of tools during drilling. Problems can also arise from borehole instability during the installation of casing due to loose fragments becoming trapped between the casing and rock wall and in some cases by the build up of hole fill at the bottom of the borehole which prevent casing been run to the design depth. Thorough hole cleaning prior to running casing strings can alleviate many of these problems.

The resulting hole shape in an anisotropic stress environment will not be circular and the breakout will continue to occur with time over the early period during and after drilling until a stable profile is achieved. There are many records of the effect of breakout, but the image in Fig 4.3 above from a very recent well where there was 2.6 km of sedimentary cover over crystalline basement drilled to 5 km illustrates the shape of deep boreholes subject to stress breakout.

In larger diameter boreholes, the problems and risks would be worse. There is more potential for discontinuities to be intercepted by the borehole wall which can result in fragments or large pieces of rock spalling from the wall. The photograph in Fig 5.5 shows a typical piece of granite, which has come away on joint planes, that was recovered from a 216 mm diameter borehole. The fragment also exhibits evidence of 'exfoliation' or 'delaminating' as the stress has been relieved. The consequences in a large diameter borehole of this occurring would be more significant. Noteworthy is that core from great depth 'discs' once the confining pressure is released disintegrating into thin slices.

In all scenarios of hole size, stress breakout at depth, even in strong sedimentary rocks, would be an issue not just in drilling, but post drilling until the borehole is permanently lined and supported by casing or a liner. Hence it is considered important to secure the borehole against any risk of instability or collapse prior to waste disposal by the installation of some form of support casing or liner (see Section 7).

Fig 5.5 : Rock fragment from a 216 mm diameter borehole

5.11 Instrumentation during drilling

Surface instrumentation monitoring of drilling parameters that can be measured on the drilling rig are common to all types of drilling and pose no problem. The development of computerised and automatic drilling systems has significantly improved the data available and hence the control of drilling parameters and the reduction of risk.

Down hole data are another matter. In the range of smaller diameter boreholes typical of the oil industry, a sophisticated range of measurement-whilst-drilling (MWD) and logging-whilst-drilling (LWD) tools up to 241 mm (9.50 in) diameter are available allowing the borehole to be steered, surveyed, drill string performance and vibration behaviour monitored and formations logged for basic parameters during the drilling process in quasi real time. These tools are suitable for 311 mm to 445 mm diameter boreholes. The data transmission is based on mud pulse telemetry which affords a continuous record of what is happening in the borehole as it is drilled.

To date, this technology has not been used for large diameter boreholes drilled with conventional direct circulation. Whilst it would not be difficult to develop the tools for larger diameters, even to give basic data, the use of reverse circulation and air lift would make that very difficult if not impossible. However, for pilot holes, which could also be considered reconnaissance holes, the tools could be made available which together with logging and maybe even coring, would give an accurate indication of the drilling conditions for the enlargement of a big hole and allow drill strings and drilling parameters and equipment to be selected with more knowledge.

Electromagnetic telemetry may also provide another means of data transmission via low frequency electromagnetic waves that propagate through the earth and are detected by a ground antenna at the surface and could be considered. This method is worthy of further investigations for large diameter boreholes using different drilling methods. At the moment, this technology is used for monitoring underbalanced drilling operations with air, foam or aerated muds which preclude the use of mud pulse telemetry.

5.12 Drilling rig requirements

For a large programme of waste disposal in deep boreholes, a ‘purpose built’ rig would be desirable based on current designs and equipment that is readily available in the market. The type and size of rig that would be necessary would depend on the diameter and depth of hole to be drilled and to some degree on whether or not a sedimentary or sedimentary over basement geological case would be adopted. The latter point relates to the diameters and casing loads that have to be handled which depends on the number of stages of borehole construction. A ‘purpose built’ rig would incorporate as much standard equipment and components as was possible, but be designed and configured to handle the sizes and loads that would be required as well as any other operating and handling procedures that may require special attention. The design would also draw equipment and equipment designs from both the petroleum and mining industries. There are several companies that have the capability of this type of equipment design and manufacture and two in Europe at least. The term ‘purpose built’ does not mean a unique or grass root design, but use and adaptation of existing well understood concepts and designs.

Historically, large boreholes have been drilled with large oilfield rigs with some modification mainly related to the rotary table size and tool handling arrangements. Special, relatively simple shaft drilling rigs designed to handle the large diameters and heavy loads have been used in recent years.

The drilling rig and associated equipment in this case must be suitable to both drill the holes and to deploy the waste unless a separate rig and equipment is used for the waste deployment. For a programme of deep boreholes, this latter expedient may be appropriate as the waste deployment should be possible with a lighter set of equipment and allow the safety shielding arrangements just to be limited to that special deployment rig. This approach merits further consideration as it has cost saving implications.

The key criteria for rig selection would be the weight of drill string, drilling assembly and any allowance for overpull that the rig has to withstand together with the weight of any casing that has to be installed.

Drilling rigs for oilfield purposes are built up to 4,000 HP size with lifting capacities up to 900 metric tones (2,000,000 lb or 1,000 short ton). These rigs, suitably adapted for this application would probably be suitable for drilling boreholes with a finished diameter of 500 mm to 4 km or 5 km. However, there are only two or three rigs of this capacity in the world today. For the smallest diameter considered, ie 300 mm finished diameter, a smaller rig of the order of 2,500 HP to 3,000 HP would probably be sufficient. There are a number of such rigs operating in various parts of the world today.

Typical heavy rigs are illustrated in Fig 5.6. This shows a traditional oilfield rig built some 20 years ago and a new concept rig with automated pipe handling which has recently been commissioned. The latter rig in its present form is too light for a big hole programme, but the design concept could easily be adapted and the rig upgraded to accommodate the loads and diameters required.

Figure 5.7 shows a typical shaft drilling rig. This particular rig would be too small for the larger diameter hole considered in this report, but illustrates the difference between the oilfield and shaft drilling equipment. A photograph of a large rotary table is also shown.

For the larger borehole scenarios, ie a 750 mm or 1000 mm finished hole diameter, even if this were feasible, the loads required would be enormous. Whilst drilling loads are likely to be up to 750 000 lb (340 metric tons), they can probably be accommodated in existing rig designs. Casing loads for a conventional casing approach could be as much as 2000 metric tons and are considered to be beyond the current capability and rig design. Some other method of lowering casing would have to be considered such as a large casing jack, but this would be a very slow process. Noteworthy is that casing jacks are relatively simple to design and operate, but the limit would be the tensile capacity of the casing or casing connection, the latter usually being the weakest element in the casing string.

The casing loads do depend on the potential for using controlled buoyancy to install casing. The problem comes if for some reason the casing cannot be installed to the desired depth and attempts have to be made to withdraw the casing. Then the whole buoyed weight plus drag have to be accommodated either by a rig or a casing jacking system, which may itself be an incorporated feature of a purpose designed rig. The buoyed weight is less than the dry weight by virtue of the fact that the actual metal volume is displacing fluid in the borehole and hence this reduces the effective weight. Note that some reduction in the effective casing weight by buoyancy can be achieved by the use of a casing shoe incorporating a non-return valve and displacing some of the fluid at the top the casing string to create a net reduction in weight. Whilst this technique of '*floating in*' or recovery of casing could be achieved with significant reductions in small diameter casings where the collapse pressure capacity would be large, this would not possible in large diameter casing as the collapse strength would be very low.

350 ton new concept rig 2007

4000 HP rig 1982

Fig 5.6 : Typical heavy land rigs

Fig 5.7 : Shaft drilling rig and rotary table

Rig pumps, pipe handling systems and drive systems are all readily adapted from current designs. The main issue would be to develop a system for handling the large diameter tools and accommodating a large enough rotary table to suit. Rotary tables of up to 1.26 m (49.50 in) diameter are currently available for oilfield drilling rigs. Shaft drillers are known to have used rotary tables up to 2.5 m diameter or more. The rotary table size must be large enough to accommodate the largest drilling bit to be used or there must be some form of handling mechanism to attach bits, reaming tools and other large diameter drilling assembly components to the drill pipe underneath the rig floor.

Standard, readily available oilfield rotary tables would be suitable for drilling boreholes for the 300 mm and 500 mm clear diameter cases. The 750 mm case could be accommodated with a surface shaft drilling rotary table to say 1 km then a conventional oilfield rotary table. The 1000 mm diameter case would require a purpose designed rotary table.

For the three geological scenarios discussed in Section 5.1 and Figure 5.1 the drilling rig and associated equipment size would reduce in size from Case A, to Case B to Case C as the size of the rig / equipment would depend on the number of sections necessary to construct the borehole, and hence the number of casing sizes to maintain the desired diameter at the final depth.

For a project of this type and scale and the likely extended drilling programme, the development of purpose built or adapted equipment would be highly recommended. In the long term, this approach would assist in improving operational efficiency and productivity as well as providing the best platform for assuring safety at all times.

5.13 Top drive drilling systems

Modern oilfield drilling rigs use top drive systems for rotation as against the use of a rotary table which transmits the torque to the drill string at the surface. However, oilfield top drives are limited in torque and load capacity and may not be suitable except for pilot holes and shallow drilling in modest sizes. Moreover, the possible application of reverse circulation drilling makes the use of traditional oilfield top drive systems impractical due to the limited internal diameter usually restricted to 100 mm maximum. However, top drive systems are available up to about 900 metric tonnes (1000 short ton) capacity for normal circulation drilling.

Top drive systems have also been developed for shallow large diameter holes for civil engineering applications by Fugro Seacore based in Cornwall. They have experience of drilling large diameter holes up to 7.0 mm diameter, but usually to depths less than 100 m. Fugro Seacore has developed a well engineered simple form of top drive system for use with the reverse circulation method. They typically use a 400 mm OD drill pipe to apply the torque to the pipe and a 300 mm sacrificial pipe for the return flow to protect the drill string from abrasion wear. This type of approach may be a foundation for further investigation into the viability of a similar system for much deeper drilling. Reference can also be made to rotary boring machines for tunnelling which employ rotary heads of much higher torques. However, the limit of the application of torque will be the strength of the drill pipe which forms the column connecting the drive system to the drilling assembly at the bottom of the borehole.

Shaft rigs normally use a large rotary table that provides the necessary torque to rotate the large drilling bits and assemblies. For large size boreholes, the use of downhole drilling devices such as positive displacement motors or turbines is not applicable as the torques required are well outside the limit of these tools, although the Russians have used multi-head assemblies driven by an array of downhole motors for shallow shafts in the past.

For the smaller diameter boreholes considered in this report, downhole motors may be applicable for some applications, but the vertical drilling systems, which would be likely to be required for verticality control, are rotary steerable systems whereby rotation is from the surface by a rotary table or top drive. Downhole drilling devices, such as positive displacement motors and turbines, are also expensive to operate and introduce another piece of equipment in the borehole which if it is not necessary should be avoided unless their use is absolutely necessary for technical reasons. These are expensive tools to operate and replace if damaged or lost in hole and are limited in size as they are primarily designed for drilling the normal oilfield suite of drilling sizes up to say 24 in (600 mm). Moreover, any loss of such a device would involve a difficult and expensive fishing operation to clear the well.

5.14 Waste deployment equipment including coiled tubing

Mention has been made above in Section 5.12 of a separate rig to handle the waste during the waste deployment phase. This could be a lighter and smaller automated rig based on currently available equipment.

Another approach that merits serious consideration/monitoring is the use of a continuous pipe or Coiled Tubing (CT) system. This type of equipment is now widely used for well intervention work in the oilfield and some types of purpose designed rigs have been manufactured which combine a standard drilling capability with the use of CT. For example CT equipment can be used for small diameter drilling, milling, minor fishing operations, cutting windows in casing, circulating, testing with data transmission and for placement of cements. The pipe is similar to a standard oilfield drill pipe, but continuous rather than in lengths. Coiled tubing is always run in tension, but can support drill collars and drilling assemblies for slim hole drilling. It cannot be rotated, but drilling tools can be rotated by use of the CT string with a downhole drilling device such as a motor or turbine.

Coils are made in a variety of pipe diameter and coil length sizes. This equipment offers an alternative method of repeated access in boreholes up to 4 km for the placement and release of waste packages, injection of fluids and also for signalling as the coils can accommodate a continuous wireline. These units are manufactured with coils up to 73 mm (2.875 in) although larger coils may be available in the future. Tubing is available up to 6 km. These systems are widely used both onshore and offshore including for testing purposes. CT was used for the testing programmes and the cementing of an investigation borehole using a special grout at Sellafield during the investigation programme in the 1990s and also later for some abandonments [Chaplow 2001, Chaplow 2003].

As with drill pipe over great lengths, there are limitations on slurry density and viscosity that can be pumped through CT equipment. Pumping from the surface with high density sealing mud is probably impractical, but the CT approach may provide an access system for deploying and operating an extrusion device for say high density bentonite slurries for sealing around canisters or waste with relatively fast deployment and removal to save time.

A typical coil tubing operation carried out in Switzerland relating to some remedial work in a 2700 m deep borehole is shown on Fig 5.8.

Coiled tubing equipment was used recently for sealing the deep investigation boreholes at Dounreay [Chaplow 2003].

Fig 5.8 : Coil tubing equipment with 73 mm coil on a 2700 m deep well

5.15 Minimising borehole construction problems

The main risks would be borehole wall stability and stuck pipe together with drill string and drilling assembly failures due to damage, cracks or metal fatigue. The key to success of any deep drilling programme is to adopt a rigorous routine and comprehensive inspection programme for all tools and drill string components that enter the borehole. Then, providing that the drilling system is used well within its design ratings, there is a low risk of failures.

Wellbore stability is strongly dependent upon geology. Rock stress can result in serious problems if allowed to develop. In practice, there is little that can be done to arrest the problem other than to attempt to increase the density of the mud system to provide some more support to the rock, but this is not often successful. Therefore, although geology has a part to play in minimising stress effects, these cannot be entirely eliminated.

Bit failure can occur due to the nature and/or abrasiveness of the rock so careful monitoring of drilling parameters is essential and bits should be recovered in good time to make sure that cones or cutters do not fall off. Recovery of such items is possible and is a routine procedure if it occurs in normal relatively small diameter oilfield wells using near full diameter tools, but inconvenient. This would be more difficult in larger diameter boreholes as the recovery tools themselves would have to be large and cover almost the full face of the drilled borehole to attempt to recover any debris on the bottom of the borehole. These would be specially designed tools as there is no inventory of such tools for deep holes available. Experience would help to optimise bit runs especially if several boreholes were drilled in the same area such that bit failure is minimised.

The very scale of these large diameter holes creates severe stresses and damage to drilling bits and drill string components as a result of the process. Whilst every effort can be made to have rigorous inspection and meticulous design and running procedures for all components, nevertheless, equipment can break due to material fatigue and other reasons and can cause hole or recovery problems and these must be recognised.

Recovery tools would need to be available to ‘fish’ any damaged items that need to be retrieved to allow the drilling process to continue. For the smaller diameter scenarios of 300 mm and 500 mm diameter, where the finished drilling diameter would be close to the largest size of oil and gas drilling, a wide range of tools are available. For the large diameter holes, the shaft drillers have developed specialist tools, but the depths of the disposal holes considered in this report are well outside their experience. Fishing tools generally require further investigation for the larger sizes.

5.16 Rock characterisation issues

Before any programme to construct deep disposal boreholes, obviously a site selection process would need to be undertaken and an investigation to characterise the formations through which the deep large diameter boreholes would be constructed carried out. The degree to which this would be necessary depends on the geology and confidence of any prognosis. However, for other reasons of understanding the post closure behaviour, it is assumed that there would have to be several deep exploratory boreholes with coring, logging and testing to the full depth of the proposed disposal zone. The data from such exploratory boreholes would be invaluable in helping to design any deep borehole programme. The other option would be to drill a full scale prototype borehole which could be used for disposal or abandoned as appropriate. Certainly a full scale trial disposal borehole would be a very desirable element of such a programme and combined with a series of slim exploration boreholes would provide a means of fully evaluating the deep disposal concept.

Such exploratory boreholes ahead of main borehole programme have been drilled before such as in the KTB pilot hole in Bavaria where a 4 km wireline cored borehole (152 mm final diameter with nominal 100 mm core) was fully cored. Whilst the equipment for such a programme may not be readily available ‘on the shelf’, the designs and surface equipment can be organised within a reasonable time frame.

5.17 Environmental issues (related to drilling)

In all the cases of exploratory boreholes, prototype disposal borehole and final waste disposal borehole programme, environmental issues would need to be addressed. However, it may not always be possible to select sites that would be ideal for an environmental perspective, but with care all sites could be operated within reasonable environmental limits. The issues would be:

- Visual impact: not much could be done about a large drilling machine and the associated equipment such as silos and cranes, but the site selection should be such as to provide natural screening where possible. The use of purpose design rigs with shorter mast than the conventional oilfield rigs would help to make the equipment less intrusive. Typical oilfield rigs that can handle the three drill pipes in one stand (triples rig) are 55 m high from the ground to the top of the crown. This can be reduced to about 40 m with a doubles rig and 30 m with a singles rig, ie a rig that can only handle one length pipe at a time. Shaft rigs are generally smaller in height anyway as they normally only work with one drill pipe assembly at a time. Noteworthy is that the 'Titan' rig used by Pigott Foundations for the shaft in Wales referred to in Section 4.5 was 30 m high including the sub-structure.

- Noise: drilling rigs and equipment could be made with low noise footprints which are now a general demand in Europe. Rig and equipment design, mechanised pipe handling systems together with careful site selection and the use of noise screens can almost eliminate the problem of noise nuisance. For a large project, the use of mains power as against diesel generators can also be considered to further reduce noise and this is a known technology. Mains power of 4.5 MW was used for the recent 5000m geothermal well in Basel, Switzerland which has just been completed. Modern drilling rigs are powered by diesel generators which can be designed to operate at 70 dB(A) at 1 m and so provide a very low noise footprint around the rig. Air drilling equipment poses special noise attenuation problems.

- Light: adequate rig and site lighting would be essential on safety grounds, but lights could be positioned to shine downwards not outwards and again site selection and screening can to a degree minimise this potential nuisance. It is essential for any deep drilling that the operation is a 24/7 process and so night working would be necessary.

- Pollution: Site construction and rig design could almost eliminate the risk of pollution. Where possible the geological conditions and borehole design should avoid the need for oil based drilling fluids which give rise to an increased risk of pollution.

- Traffic: A project of this scale would generate a large number of truck movements daily for site construction and drilling waste disposal unless an on site processing plant was practical for the separation of cuttings and disposal. Trucks would also be required for drilling tools and consumables on a daily basis. Hence site selection or management needs to address vehicle routing and nuisance.

- Waste disposal: The handling, storage and disposal of waste drilling fluids and cuttings from this large diameter borehole would present an environmental challenge. The drilling pads would need to be of such size and constructed to a standard of sealing to avoid any ground pollution. Storage tanks and silos would be necessary for the management of the fluids and waste material. The objective should be to achieve a minimum volume approach with a high standard of solids removal equipment. Nevertheless, the disposal of waste would require a relative large number of truck movements during the drilling period.

- Radiation: whilst not part of this review, obviously the handling of radioactive waste and the transport to the disposal location has to be considered.

5.18 Projected frequencies of failures, loss of hole and/or time to recover

Failures during drilling would be very difficult to forecast. If the site section and geological conditions were well researched and a borehole design could be developed that has a high expectation of success, then equipment failures that would threaten any boreholes could be minimised by good drilling rig design with standby power and pumps, a rigorous inspection regime and appropriate drilling, pipe and tool handling procedures. The risk would increase with diameter. For the smallest diameter case (300 mm or 500 mm finished hole diameter), if all the precautions were taken, equipment failures should be minimal if not eliminated altogether. Once a conceptual design had been agreed, a risk assessment for each element of the work could be carried out.

Loss of hole due to borehole wall collapse, spalling or breakout poses the real risk together with unforeseen geological conditions such as penetrating a major fault zone of high angle joint structure that generate a bias to deflect the borehole which cannot be controlled. These can be mitigated by a pre-implementation investigation programme referred to above.

Recovery from failures would be variable depending on the severity. Sometimes hole problems can be resolved in a day, but sometimes up to say a month or more for serious problems such as recovering large downhole tools to allow the work to continue. There would be a constant risk that a borehole may have to be abandoned and plugged and sealed. However, the risk of abandonment would be very small if the site selection and borehole and equipment design were thorough and the borehole is within practical limits of diameter and depth.

6 DIRECTIONAL DRILLING

6.1 Status of directional drilling

Directional drilling in the oil and gas industry has developed to a stage where it is commonplace and used widely for deviated, long reach, slant and wells started vertically with a horizontal trajectory at final depth, referred to as horizontal wells. Accuracies are very good at depths up to 4 km to 5 km. Accuracy depends on the ability to control deviation of the tools and whilst there are examples of directional drilling being achieved to reasonable tolerances at greater depths, there are also numerous cases of difficulties in steering due to stress breakout in deep wells. The new range of rotary steerable tools have the best possibility of achieving accuracy at depth, but these tools are probably limited at the moment to boreholes up to 660 mm (26 in) diameter, which have a typical maximum depth capability of 600 m. For boreholes drilled to depths in excess of approximately 3 km, the maximum borehole size whilst directional drilling is probably limited to 311 mm (12.25 in).

For large diameter boreholes, directional drilling is not normally contemplated and there are no known cases of shafts being drilled other than intended to be vertical except for perhaps the occasional small diameter, short slant shaft. However, tools to adjust verticality have been attempted as verticality is always a critical specification requirement for mine shafts.

Note that accurate directional drilling for oilfield purposes is generally undertaken in sedimentary formations. Directional drilling in hard abrasive crystalline rocks, especially where there is a tendency for breakout, is more difficult. This has been demonstrated in several very deep and superdeep wells where directional control is impractical as the borehole shape changes from round to elliptical as breakout occurs in the crystalline basement.

Accuracy of directional drilling in oil and gas drilling and in some geothermal applications is high with state-of-the-art tools and associated survey instruments and techniques available to achieve high accuracy. Whilst typical North Sea targets are ±50 m, wells to 2 km have been achieved at accuracies of ±5 m which is generally within the resolution of the surveying method at depth. Verticality, which is in effect directional control, has achieved accuracy to 1^o to 1.5^o in deep wells such as the KTB superdeep to depths below 6 km.

As well as trajectory accuracy, the question of borehole tortuosity must also be addressed as a spiral hole or a trajectory with relatively rapid changes in the radius of curvature can prevent the passage of long assemblies so the use of what are called '*packed hole assemblies*' for drilling and/or reaming are necessary to prevent this happening to allow casing and other stiff strings to be run without any problems. Packed hole assemblies and heavily stabilised assemblies with stiff drill collars between the stabilisers which can either be a blade non-rotating type or some form of rotating blade or roller. By making the drilling assembly immediately above the drilling bit as stiff as possible, this gives the best chance of the borehole being drilled straight.

Deep slim hole surveying using gyro instruments and also Measurement Whilst Drilling (MWD) with In Field Reference (IFR) methods are commonly used to provide azimuth and inclination data of the borehole profile. These are accurate and within accepted tolerances and error margins for most applications. MWD, and its counterpart LWD for formation evaluation data, are devices run in the drilling string with sensors for data acquisition which is then transmitted to surface via the drilling fluid in pulses which are presented as quasi real time data for the driller and directional driller.

For shallow shafts or big holes, more simple verticality measurement devices have been developed as most shafts are required to be vertical.

6.2 Fanned arrays

It is relevant at this juncture to mention what are called ‘multi-laterals’ and whether or not the idea of multiple disposal legs from one central borehole is practical in this context. It has been suggested by Chapman and Gibb [Chapman *et al* 2003] that fanned arrays of boreholes may have an application for waste disposal. The idea is elegant, but not recommended at this stage as the sizes envisaged and the need for ‘guarantees’ make this an impractical approach. The reason for this statement is that current technology and experience is restricted to small diameters and also that the introduction of the ‘splitter’ arrangement at depth to direct the access from one branch to another introduces risk in waste deployment.

Multi-laterals are fairly common in small diameters for what are sometimes referred to as ‘drain holes’ to increase reservoir production, usually for oil wells, from a single producing well at the surface. The methods require a ‘splitter’ to access the various legs. These legs are generally no more than 120 mm diameter, but there are a few examples of larger sizes. In some recent examples, a 20 in (508 mm) splitter system in a 24 in (610 mm) hole with two 9.675 in (246 mm) legs from which a 8.50 in (216 mm) hole can be drilled has been run in Wyoming, Norway and the Gulf of Mexico. A 13.375 in (340 mm) splitter system set in a 17.50 in (445 mm) hole with two 7.625 in (194 mm) legs from which a 6 in (152 mm) hole can be drilled were run in Nigeria and Gabon at depths between 1.28 km and 1.525 km.

In the context of radioactive waste disposal, the use of this technology scaled up to suit the depths and diameters, at the present stage of the technology, would compromise the objective that deployment of waste should have a 100% certainty of success.

For deep disposal of radioactive waste in boreholes, a simple vertical borehole should be the only consideration at this stage as all other scenarios introduce other risks and extend the known technology uncomfortably outside the envelope of current knowledge and equipment or anticipated developments in the next few years. If vertical boreholes were to be drilled and proved successful, it could be relevant in the future to monitor R&D and consider the possibility of multi-branch boreholes, but it is considered unwise at the moment to contemplate this approach.

7 CASING AND ANNULUS ISOLATION

7.1 Introduction

The design and construction of deep boreholes for whatever purpose must take into account the stability of the formation, the permeability, potential presence of geopressurised fluids and likelihood of lost circulation during drilling, aquifer security and a range of other factors including the proposed use of the borehole. This will require intermediate casing or zone isolation to be incorporated. This should not be confused with the need for a permanent casing or liner in the deployment zone which may be solid or perforated in some way. The normal method of isolation is to use steel casing which is cemented into the rock over part or the whole length. The casing-cement-rock system integrity is important in providing the necessary bond and isolation.

This is perhaps the most challenging and debatable element of borehole disposal. For relatively small diameter boreholes, such as the 300 mm and 500 mm clear diameter cases, the use of standard steel casing may be possible and installed in a similar way to the casing installation equipment and procedures used daily in the oilfield. For larger diameter boreholes, the loads involved during installation, the stiffness of the string and problems of maintaining 'roundness' of the casing during installation become serious issues. Maintaining roundness would be essential as if the casing becomes out of round due to damage during installation, then the drilling bit and assembly for the next section cannot pass through the casing. Such an eventuality would damage the casing and may not allow the borehole to be continued in the selected size. This may also eventually preclude the deployment of the desired diameter of waste packages. Shaft casing often incorporates strength hoops on large diameter casing strings to give extra strength to maintain the roundness of the casing.

Case C of the geological scenarios where the borehole is almost entirely in crystalline rock from the surface would be perhaps the most favourable if the rock is relatively unjointed and the borehole could be drilled for the most part without casing support. Case B would also be a relatively favourable case, but would need at least one casing string above the deployment zone. Case A would be the least favourable as it would introduce more than one string of intermediate casing and hence would increase the diameter of the borehole at the surface.

One key issue that would need to be faced is the technical need for some form of permanent liner or casing in the actual waste deployment zone to provide a permanent support to allow the waste disposal process to be 'guaranteed'. This is as well as the casing necessary above the deployment zone to support and isolate the formations during drilling. An opening in rock such as a tunnel or borehole is dynamic and can collapse or block at any time by material coming away from the borehole wall for a wide range of mechanical, chemical and stress related reasons. Hence an 'open hole' in rock at depth in a borehole, especially one intended for disposal of radioactive waste, would be an unacceptable risk where a guarantee of access would be required post drilling.

This technical requirement would introduce design and implementation issues especially for the larger scale boreholes, ie the 750 mm and 1000 mm clear diameter cases, as for these depths and diameters of borehole, the cases are well outside known practice and experience. The analysis of what is theoretically required can be calculated using such software as the Tubular Design and Analysis System (TDAS) which has been one of the industry standards for some years. This stress analysis program can determine the combined stresses at each stage of the operation of drilling, running casing and post drilling stages including any temperature effects and determine the size and strength of casing required and hence the steel grade, wall thickness, type of connections, etc.

However, the idea of designing and installing very large diameter casing, particularly for the 750 mm and 1000 mm finished diameter borehole cases to say 4 km or even 5 km, is daunting and is considered to be impractical at the present time.

In the work undertaken for SKB in the late 1980s, two borehole options were considered [Juhlin *et al* 1989, SKB 2000]:

Option A : A 4000 m deep borehole with an 800 mm drilled diameter at total depth.

Option B : A 5500 m deep borehole with a 375 mm drilled diameter at total depth.

In the Swedish case for SKB, the boreholes were to be drilled entirely in granite. For Option A, a 1000 mm nominal diameter casing was planned to be set at 2 km and in Option B a 400 mm diameter casing. In both cases it was intended to set a perforated or high voids ratio liner (rather than a casing to reduce the weight) through the deployment zone to 4 km.

Option A was also considered in a later study for SKB by Harrison [Harrison 2002], although in the authors opinion the casing thicknesses presented are considered too light for such an application. Harrison proposed a 914 mm solid steel casing to 2 km and a 762 mm full slotted casing from surface to 4 km [Harrison 2002]. The argument being that a canister may become snagged at the change in diameter at the liner hanger just inside the solid upper casing.

An explanation of the difference between a ‘casing’ and a ‘liner’ is explained in Section 7.5 below.

There was previous experience of running 1000 mm diameter casing to about 2 km in a deep large diameter borehole drilled on the Amichitka Islands, Alaska in 1969 where 1.875 km string of 1375 mm OD casing with a wall thickness of 63.5 mm was installed. The casing weight was 1850 metric tons.

Noteworthy is that for shallow shaft applications, casing construction is often achieved with composite steel and concrete and heavy casings are ‘floated’ in with controlled buoyancy.

7.2 Holes sizes

Some typical hole and casing sizes for the three cases under discussion are set out in Table 7.1 below. The table sizes are taken for this preliminary review from the current reference tables produced by the various manufacturers of oilfield casing and tubing. The table also illustrates where significant deviation arises from known experience or even a reasonable, extension of that experience by the colour coding.

These depths and diameters are illustrative and are not based on any rigorous analysis or calculation or on any geological profile. The analysis of all loading that a casing or liner is subjected to during the various phases of borehole construction and the post drilling scenarios is a detailed engineering exercise in its own right.

Diameters indicated may not be available except by special order. Standard oilfield casing is manufactured up to 762 mm diameter size with one or two manufacturers offering casing up to 1219 mm diameter normally used for large diameter surface holes in oil and gas wells.

Depth (m)	Hole diameter (mm)	Casing OD (mm)	Casing ID (mm)
300 mm diameter case			
~50	914	762	686
~1000	660	508	473
4000	445	340	307
500 mm diameter case			
~50	1220	1016	927
~1000	914	762	673
4000	660	559	508
750 mm diameter case			
~500	1905	1625	1524
~1000	1422	1168	1067
4000	1016	863	775
1000 mm diameter case			
~500	3048	2670	2540
~1000	2133	1776	1676
4000	1524	1219	1118

Key

Green = within current experience
Orange = an extension of current experience by virtue of the depth/diameter requirement
Red = Outside current experience

Table 7.1 : Typical hole and casing sizes that would provide the desired clear hole diameters taken from current oilfield tubular tables

The green shading indicates what is considered achievable in favourable conditions, the orange possibly achievable and the red considered impractical with current technology, equipment and taking account of the ground conditions at depth. Weights have not been included as there are several wall thicknesses available for pipe and the shaft drillers also use composite steel-concrete lining. However, for the larger sizes the weights become large. Typically, pipe over 762 mm would have a wall thickness of 50 mm thick or more.

7.3 Indicative casing weights

Some indication of standard pipe weights in air for different diameters may be useful in understanding the high loads involved:

Casing OD mm	*Casing ID mm*	*Weight Kg/m*	*Weight per 1 km Metric tonnes*
340	308	115	115
559	493	412	412
863	762	1016	1018
1219	1092	1808	1808

Table 7.2 : Illustrative casing weights per km

Hence, a casing even using oilfield products to 4 km would weigh a significant amount in air.

7.4 Connections

Connections also pose problems of strength (tensile and collapse) and the issue relating to 'making up' the casing as it is installed. Larger diameter casing is often welded and even in some oil and gas applications, such as gas storage, welded connections are becoming more popular as they are stronger and there is less risk of failure during the lifetime of the facility (in oil and gas terms). Welded connections do assume that there is little chance of failure to install the casing to the required depth due to hole fill, differential sticking or other problems of running long, stiff tubular strings in deep boreholes and that has to be taken into account. Welded casing can have the same internal and external diameter throughout the string so allowing a smaller telescopic suite of casing diameters to be adopted. Welded casing does take much longer to install than running threaded connections.

7.5 Casing v liners

The reference to 'casing' and 'liners' is based on the traditional oil industry understanding. A '*casing*' in this context is a continuous lining tube from the casing shoe at the depth of the interval of the borehole interval which has been drilled to the surface and is generally supported at the surface in some form of wellhead hanger system. A '*liner*' is a partial continuous support casing that 'hangs' from the lowermost part of the previous casing to the shoe depth of the interval that has been drilled. This liner is supported by a '*liner hanger*', which is a special device with support slips or dogs that are engaged on the previous casing to anchor the liner in place.

The diagram in Figure 7.1 shows the two types of borehole support.

Liners are often used to reduce the amount of casing, and hence cost, and to lighten the string weight. One disadvantage of a liner system is that for conventional circulation, the hydraulics of cuttings removal is impaired and additional pumping is necessary. This is not the same for reverse circulation where the well profile has little effect.

In the case of boreholes for deep disposal other than at the lower end of the size spectrum, liner hangers would have to be specially designed as these devices are not available or called for in shaft drilling.

A potential problem with liners is that the internal borehole profile is not a consistent diameter so creating a step, which although the 'step' can be tapered to effect easy entry of tools and in this case waste packages, it would however introduce a possible risk. Also material from the casing-rock annulus would have a potential flow path which could allow material to enter the borehole if the liner hanger seal was not effective for any reasons. In the oilfield, packers are used, but are not available for the sizes contemplated.

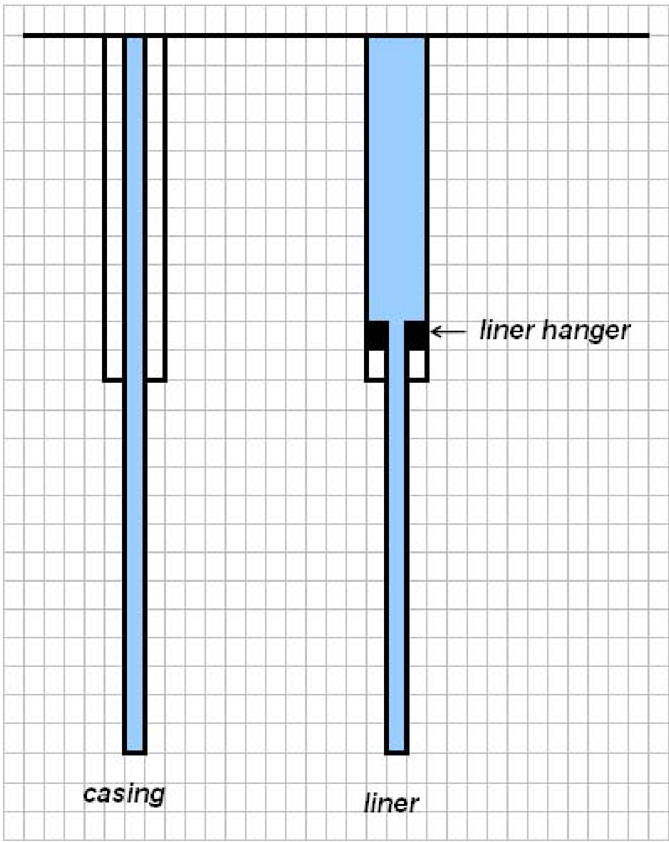


Fig 7.1 : Diagrammatic illustration of casing vs liner support system

However, a design modification could be relatively easily made such that an entry guide could be installed in the liner hanger to facilitate the passage of waste containers without hang up occurring and additional seals installed to assure the liner lap (the annulus between the existing casing and the liner) would be sealed from ingress of material from below the liner.

7.6 Casing materials

Whilst reference so far has been to steel casing in grades which can range from 560 MPa to 1050 MPa (80 000 lb/in^2 to 150 000 lb/in^2) yield strength, it would be possible to introduce other material such as copper or chrome to change the properties if this was relevant.

The acceptance of steel or any other material for any permanent lining must be determined. Note that if there is a likelihood of hydrogen sulphide (H_2S) present, lower strength more ductile steel would be necessary as hydrogen embrittlement from the presence of free hydrogen in H_2S would cause serious deterioration by cracking of the steel. At the higher strengths, the material would become brittle and also introduce handling and site welding problems.

7.7 Temperature

In the context of the post deployment high temperature scenario where reference is made to such high temperatures as to 'melt' the surrounding rock, the presence of a steel or other liner must also be considered. For the high temperature variant of DBD involving partial melting of the rock, the presence of a steel casing should present no problems given the relatively short time the casing would be exposed to temperatures above ~600°C [5, 26]. Thermal changes would create stresses in casing due to the expansion and contraction, the effects of which would need to be considered.

7.8 Cementing and/or sealing

This section relates primarily to the cementation or sealing of the borehole construction above the deployment zone and differs from the process of sealing the actual waste packages. This is discussed briefly in Section 11 below, but some of the methods suggested here would also apply to the deployment zone if a solid casing was used.

In addition to the issue of sealing of the waste in the deployment zone, the casing or zone isolation considerations must also address the other critical issue of how to seal the casing annulus to provide isolation for well control purposes and more importantly for sealing against any risk of migration of radio nuclides through the borehole length above the deployment zone in the casing-rock annulus and also in the relaxation zone immediately surrounding the borehole. Whilst the oil industry can provide many simple and exotic types of cement to cater for a multitude of scenarios, the fact remains that the ability to place high quality cement to a high standard in deep boreholes remains a major problem.

The long term integrity of the cement bond behind the casing would be a requirement, as this annulus could provide a potential pathway for contaminant migration. However, current cementing technology cannot provide total assurance of a high quality cement bond. Placement problems, potential channelling of cement, variable quality of the cement throughout the annulus, fracturing of rock under high cementing pressures, water of hydration loss, thermal and chemical effects on setting times, the shear volume involved, surface mixing volumes and problems of consistency, micro-annulus formation and the deterioration of the cement all contribute to this problem.

The oilfield often relies on relatively short, typically 100 m to 200 m good quality cement (usually referred to as the ‘tail’ cement) around the shoe of a casing string to provide well control isolation. Gas storage wells and geothermal wells often require cement to surface which is rarely achieved and even if the ‘lead’ cement is recorded as ‘returned to surface’ the consistency throughout the column is often poor and erratic. The shaft drillers use a multiple grout injection pipe system on the outside of the casing to try and avoid channelling, but again they are not that interested in a perfect seal. Shafts can be remedially grouted post construction in stages using a grout injection process through holes drilled in the casing once the shaft has been dewatered.

Whilst the sealing in the deployment zone is a key element of deep borehole disposal and not strictly a drilling related subject, nevertheless it does impact on the method of construction and any sealing would need to be achieved with the same type of drilling equipment and processes that would otherwise be used in deep wells. The conventional methods of cementing or effectively sealing boreholes as used routinely by the oil and gas industry and for other deep well applications would be too crude and other methods would be needed and could most probably be developed with research and engineering.

In previous studies for SKB [Juhlin *et al* 1989, SKB 2000], the use of a high void ratio perforated casing was considered. Perforated casing has been used widely for water wells and in some oil and gas installations where screens are not necessary. Typically perforations would be holes of 20 mm to 30 mm diameter drilled in a pattern along the length of casing to allow the passage of fluid. The term ‘*high voids ratio*’ casing was adopted in the Swedish study for SKB to mean a casing or liner where the hole area was much larger than would normally be found in standard perforated casing. This introduces potential, weakness in the casing and therefore a thicker casing is required and a special manufacturing requirement as this would be non standard. The voids ratio required depends on the material that would have to pass through the holes and needs some design and engineering to suit the waste disposal concept.

For the upper casing string(s) above the waste deployment zone, the approach of staged sealing by treating short lengths of casing at a time would have merit as to attempt to cement a large casing over considerable lengths would not likely be successful. However, this would be a laborious process and requires either perforating the casing for each stage of injection and setting packers or using stage collars with packers.

Reverting to a high void ratio casing (a casing with a high proportion of perforations) that allows the flow of a sealing or deployment mud into the annulus as the waste is deployed still has merit and could solve the problem of assured penetration of grouts or sealing materials into the casing-rock annulus and to a degree into the disturbed rock zone around the borehole, the latter depending on the sealing characteristics. Of course, such high voids ratio casing would have to be specially manufactured unless a series of purpose designed stage collars were run at every casing joint in the system to allow access to the annulus.

One approach would be to use a series of stage collars and inject material in stages very much like a *tube-à-manchette* grouting system used for dam sealing and other civil engineer applications. The tube-à-manchette is a sleeved port system in a double packer assembly that allows fluids and grouts to be injected under pressure at different intervals in a borehole. The practice in dam grouting is to systematically grout through ports up the borehole and overlap the injections until such time as the area around the borehole has been satisfactorily grouted. The most suitable sealing material is also an area of uncertainty. Ideally, the materials should be such that the 'grout' does not fail in early time by cracking or allowing the creation of a micro-annulus.

The material that may satisfy most requirements could be a clay based sealing material such as bentonite. The problem with bentonite is that the density has to be high to provide any sort of strength and at high densities it would not flow well and could not easily be pumped, especially any distance. In earlier work for SKB [Juhlin *et al* 1989, SKB 2000], the use of a high density bentonite placed by bottom dumping or extrusion from a special placement tool run into the borehole on drill pipe or coiled tubing was considered as a deployment mud for canister placement. The use of pre-compacted bentonite blocks was also considered.

The advantage of a clay based 'grout' is that it can continue to 'flow' after placement and should have a long liquid or plastic time to allow further injection to be carried out. Bentonite would also continue to swell under hydrating conditions whereas cement would shrink. Any cementation material that 'sets' would not good as it would create solid bridges in the annulus so making any remedial or staged grouting system impossible.

Another approach that is theoretically possible is the use of the new expandable liners which are run then enlarged to fit tight to the borehole wall. These are only available in smaller sizes at present, but should be investigated further and may offer a solution to some of the problems associated with the concept of deep borehole disposal, although the development at these sizes would be a significant development and challenging. The current liners are solid and are expanded by withdrawing an oversize mandrel through the tube to fit closely to the borehole wall and minimise the diameter reduction in borehole compared with using conventional nesting casing systems. The process is illustrated in Figure 7.2.

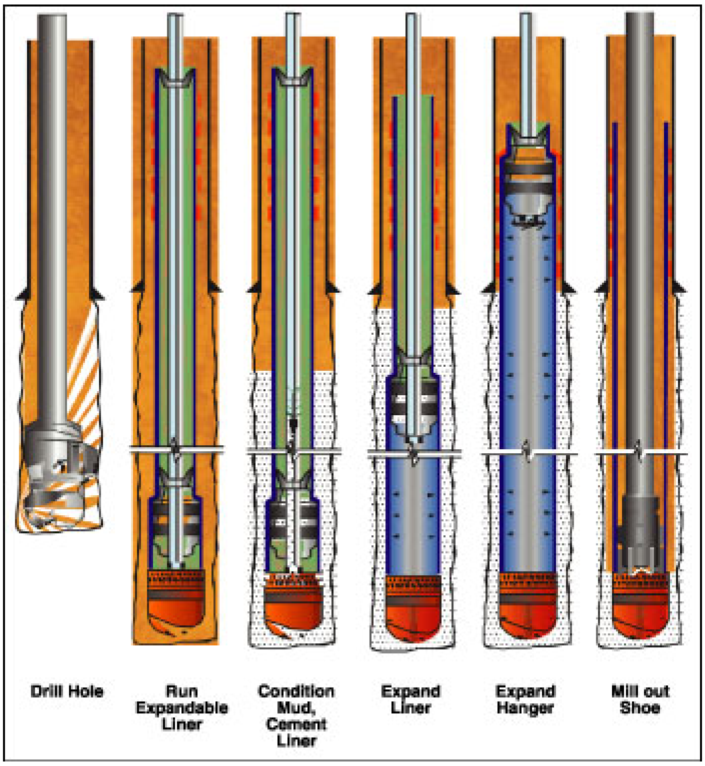


Fig 7.2 : Expandable casing or liner installation

Some recent developments have been made to this process for well screens. The use of an expandable screen with sufficient void area to allow the passage of lead shot, for example, would provide another method of creating the necessary borehole support and sealing facility in the deployment zone. This is an area for monitoring further research and development.

In some variants of waste disposal being considered, the casing in the lower part of the boreholes would be 'withdrawn', after deployment of the waste packages and before the rock melting process begins. This would be really impractical in these sizes and at these depths and over the long intervals concerned.

Moreover, the process is made virtually impossible due to the requirements for the waste packages to be deployed first, then the casing withdrawn. This would eliminate access to the casing length to be cut and so would relie on the ability to pull the casing out around the waste canisters, which would simply not be practical.

Removal of casing at any time in deep wells is very difficult and where 'windows' have to be cut to access the formation, they are usually constructed with casing cutters. These can be mechanical devices or possibly the use of high pressure water jets. The process is slow and for large sizes, it would be likely to be very time consuming.

8 TIME ESTIMATES

Estimating the time required to drill a deep borehole for the sizes considered in this report, if it is feasible, is problematic. However, if some yardsticks are used that have worked reasonably well for holes up to 250 mm, the following illustration in Table 8.1 may be a guide for drilling time for a 4 km borehole assuming some drilling in the crystalline basement. The estimates are based on penetration rates from a variety of wells and assuming that a third of the rig time is spent drilling.

Clear hole size at TD mm	*Penetration rate m/hr*	*Time to drill and complete days*
1000	1.00	500
750	2.50	200
500	3.75	135
300	5.00	100

Table 8.1 : Time estimates for borehole construction to 4 km for different clear borehole diameters at total depth

For boreholes to 5 km, the extrapolation will not be linear and may take a further 30% to 50% more time than the 4 km case.

The drilling time used in this table has been assumed to be 30% of the total time required for the borehole and drilling to take some 18 hr per day (or 24 hr). In general, this percentage is somewhere in the 30% to 45% range for normal wells drilled by the oil industry onshore. In this case, the lower bound value has been taken due to the large diameter of the borehole.

The non-drilling time includes such activities as the time taken to trip the drill string in and out of the borehole between bit and tool changes and at casing depths, make up tools, clean the hole, carry out any surveys, carry out any evaluation or testing and run casing at each level and if necessary provide some form of annulus sealing. The number of casing strings necessary for any borehole is not currently known. Casing and cementing can be roughly estimated as taking 25 days per intermediate casing stage for these operations and assume two stages, then a further 50 days must be included in each total. This does not include the process of providing a final support casing and sealing through the deployment zone in whatever way would be considered acceptable.

The time spent in non-drilling activities is sometime called ‘flat time’. The table shows the estimated *total time* required to drill wells of different diameters ready for waste disposal including the installation of casing and cementing.

By comparison, the Basel-1 geothermal well in Switzerland which was completed in 2007 took 155 days from 32 m (base of a pre-drilled hole) to 5 km with a 2.4 km length drilled in the crystalline basement with a 251 mm diameter hole at the final depth. This included running and cementing all casing. The installation of the final production string to 4.7 km was delayed for a few days by the inability to pull a technical liner. Gravberg-1 drilled in Sweden entirely in granite in the late 1980s took about 100 days to reach 4 km (311 mm diameter) and 175 days to reach 5 km (216 mm diameter), but there were not so many casing strings run in Gravberg compared with Basel-1. By comparison, the KTB superdeep borehole in Bavaria took 220 days to reach 3 km (445 mm diameter) and 350 days to reach 4 km (375 mm diameter).

For the scenarios which appear to be within the boundaries of feasibility at this juncture, ie the 300 mm and 500 mm clear diameter cases, this means that the time to construct a deep borehole would take about 100 to 135 days to drill. If a full depth support casing or liner was installed, which would be recommended, and effectively sealed, this could add another 50 days. If an associated geoscientific programme were carried out in conjunction with the construction of the borehole, estimates in the SKB study suggested this may add a further 50 days or more [Juhlin *et al* 1989]. In broad terms, each borehole would take about nine months to complete before the process of deploying the waste assemblies commences without a geoscientific investigation programme. The first borehole(s) may take longer as the learning process would affect the progress.

The time estimates are very much a theoretical guide in ideal drilling circumstances for the cases of a 750 mm or 1000 mm diameter borehole as these cases are considered too far outside the envelope of practicability at this stage to be possible to be implemented to the full depth of 4 km or 5 km. The 750 mm diameter case may just be possible with some significant development of drilling tools and casing systems in the longer term as technology develops, but more allowance should be made for casing which would give an overall borehole construction time of some 14 to 15 months.

Drilling times would depend on the thoroughness of the design and preparation and the availability of the right equipment. Crew competence would be also important as well as overall project management and engineering skills. In the UK, heath, safety and environmental programme requirements can slow down operations if an onerous regime is implemented compared to those carried elsewhere in Europe and in particular outside Western Europe, including North America, but with good systems, training, sufficient personnel to cope with the requirements and an automated rig, these time pressures could be minimised.

Ground conditions and the fact that the hole sizes are outside the normal envelope create more uncertainty in time estimation. The process of drilling and disposing of drilling waste material must be well rehearsed such that no one element is critical in the process. All efforts should be to achieve a high drilling percentage in rig time distribution. Typically, what is often called '*on bottom time*', ie that time spent actually drilling a new hole is 30% to 45% for normal onshore drilling, the higher end more applicable to the use of PDC bits in soft formations which have longer lives than roller cone bits. In the case of drilling in crystalline rock, the percentage would be at the lower end at about 30%.

Non productive time could be minimised by good planning both on a daily basis and by detailed project planning to minimise any delays and optimise the performance of the equipment and personnel.

Crew availability is difficult to predict some years ahead, although the current general shortage of technical personnel may get worse in future years as the supply of suitable qualified and experienced personnel may exceed the demand. Deep borehole disposal would be a major project, therefore dedicated crews could be developed providing that pay rates were above the industry norm. The key would be to find a core team of experienced personnel who would be prepared to stay with the project supplemented by the right calibre personnel from other industries. The use of a modern automated rig with mechanical pipe handling would make the project attractive to the more experienced and qualified end of the labour market.

Lead times for the manufacturing or adaptation and commission of drilling rigs and associated equipment and the permanent materials such as casing for example are probably about 24 months at the moment. This is from the time that tenders are awarded.

Prior to this, the planning, design and procurement programmes could take a further year assuming that by the time this process commences, all the research, conceptual engineering, characterisation studies, site selection and borehole design have been completed and reported.

9 WASTE DEPLOYMENT ENGINEERING ISSUES

In the case of waste disposal in the deployment zone, a continuous casing would be envisaged, but the top part could be cut and recovered after the waste had been deployed to leave a large diameter hole in the seal zone similar to a liner arrangement and therefore access to the outer larger diameter casing to cut sections to expose the rock for seal construction.

Liners introduce a stepped hole profile, but the problems associated with these steps could be overcome with a relatively simple design of an entry guide as mentioned in Section 7.5.

The concept for waste deployment investigated previously was to lower each package or canister on drill pipe [Juhlin *et al* 1989]. This would be the most positive approach. Release from the drill pipe at the desired depth would necessitate the design of a fast-release connection that should be possible using existing low torque connection designs currently used in the oilfield for fishing tools with some form of torque restraint or actuated mechanism. These ‘safety joints’ are common in the deep drilling industry and provide an easy ‘back off’ or release mechanism to be included in the part of the tool for assured back-off and, if necessary, reconnection. Harrison suggested another standard oilfield arrangement known as the ‘J-slot’, which is in effect a bayonet arrangement than when rotated backwards releases the tool [Harrison 2002]. This device also needs some form of torque restraint to effect a back off and is risky in that premature back off can occur. For this particular case some engineering design would be necessary to ensure a guaranteed back-off or release mechanism to allow the canister to be deployed exactly as required.

Reference has been made above to the use of coiled tubing strings and this would also present a positive means of lowering and releasing waste elements and would have advantages of speed and the potential for a signalling system using a wireline incorporated in the tubing (see Section 5.14 above). CT may have significant application for this type of programme as it offers not only a means of deploying waste packages, but also in the introduction of grouts, high density shot, and other materials into the borehole at an accurate elevation coupled with rapid deployment and withdrawal. It would also provide a signalling and power transmission cable through an integral cable for a release mechanism.

In the case of canisters or packages that could be designed to suit the deployment process, the top design could incorporate a long ‘fishing neck’ and safety joint with ports or jet nozzles below the safety joint to facilitate the displacement of material in any retrieval, process. If the waste was not to be retrieved, this feature would still be valuable in the remote possibility that a problem arises. However, in this case, it has been assumed that the waste would not have to be retrieved at some later date. This would be an important decision. If the waste would need to be retrieved post placement, this would introduce additional problems and limitations.

The materials for these specialist placement devices should be corrosion resistant. The likelihood that each canister may settle to sit on top of the lower canister dictates that any design should ideally incorporate a nesting capability and the canisters should be centralised. This add on could be a simple arrangement at the top and bottom of the fuel rod assembly or canister and should be capable of being engineered.

The canister or deployment system design would need to address the self weight of the waste assembly as deploying canisters one on top of the next would create high axial loads. Vertical loads would be likely to be serious in the disposal of very dense spent fuels. Loads could be mitigated at the deployment stage through the use of supporting grouts or fillers or load bearing mechanical bridge plugs placed above groups of canisters to act as a load bearing platform for the next canister group. The solutions to the support of the actual waste packages are related to the waste packaging and disposal designers and not strictly a drilling issue, but the process would need to be practicable in the context of deep drilling and completion technology.

The status of the borehole at the time of deployment is important to consider. A decision would need to be made about whether or not solid casing with or without a sealant behind could be used. If solid casing was used and the annulus seal was not important in the deployment zone accepting the eventual deterioration and disintegration of the casing, then the operation would be simple. If a sealant or filler of some type behind the casing were necessary, then this would be feasible as discussed in Section 7.8 above, but more difficult and of course time consuming. The ideal scenario would be a perfectly smooth borehole with no potential for material entering the borehole to impede the waste deployment. This could only be achieved if a casing was run to the total depth of the borehole into which the waste was to be placed. For solid casing, this would be assured. For perforated or high voids ratio casing, the voids would need to be such as to prevent the ingress of rock fragments or other material. Problems could arise in weathered zones where small rock fragments, some sand-sized, could enter the borehole through the voids. This could be alleviated to a degree by careful positioning of short solid sections across troublesome zones identified from some form of borehole logging or reconciliation with drilling data.

The borehole during the disposal process could be filled with any fluid that suits from water to any form of inhibited fluid or clay based material to preserve the material in the casing and canister for as long as possible. If a more robust barrier was necessary, a deployment mud of say high density bentonite placed with an extrusion device at each stage of deployment would again not be that difficult to engineer. High density mud or shot would make the retrieval of waste difficult.

Stage barriers could be created with pre-compacted bentonite blocks placed in a ‘dispenser’ and surrounded by high density liquid bentonite supported on the bridge plugs. The pre-compacted bentonite would eventually hydrate and create a positive pressure on the system which if coupled with a perforated or high voids ratio technical liner through the waste deployment zone would allow the seal to be generated both in the annulus and between waste packages itself with time. In crystalline rock, the perforated casings should be more than adequate to prevent the ingress of fine material if the voids in the casing were positioned across the lengths of intact or competent rock and not across any weathered joints. Post drilling breakout would be supported by the casing.

Whilst operations in deep boreholes always present a risk of failure, with a continuous and effectively lined borehole and appropriate designed tools, surface handling equipment and procedures, the probability of successful deployment of canisters would be very high.

The waste types present a number of sizes of packages or canister sizes and types for disposal. In a recent paper by Gibb, disposal options for spent fuel and fissile material are modelled for three versions of deep borehole disposal [Gibb *et al* 2007]. The waste types considered are:

- Two variants of low-temperature, very deep disposal (LTVDD).
- High temperature very deep disposal (HTVDD).

These are shown diagrammatically in Figure 9.1.

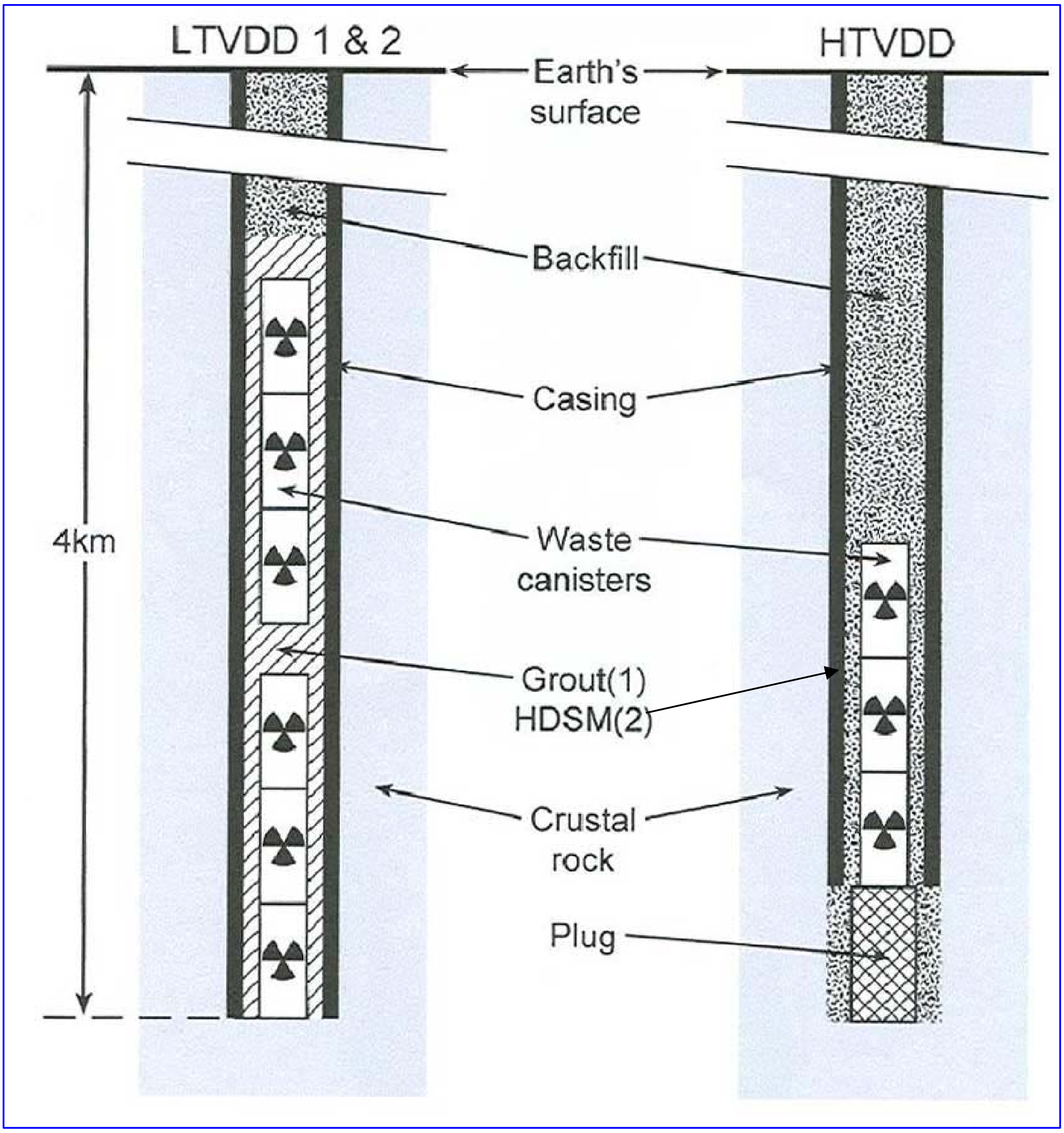


Figure 9.1 : Waste disposal concepts (after Gibb)

Gibb proposes that in the first case, low temperature waste could be packaged in steel containers. High temperature waste would require special containers such as ceramic. Reference is made for the low temperature cases to the use of cementitious grouts (Grout (1)) for filling the void space between the casing and rock wall through perforations in the casing and between the casing and the waste. This method allows for the cementitious 'grout' to set hard before deploying the next string of canisters so minimising the risk of distortion of the canisters due to the weight of the canister string.

For the high temperature cases, the use of fillers comprising a high density support matrix (HDSM (2)) to surround the canisters and fill the void spaces is proposed. Such an expedient would provide a slightly less than neutral density so eliminating the problem of self weight of the canisters.

The type of grout to be considered for the support and sealing in the low temperature case would need some further study as in general cementation of casing in deep wells for both the petroleum and geothermal industries is very unreliable and poorly executed for a whole raft of reasons. This would not acceptable for a waste disposal concept in its present form as the results cannot be assured. The use of lead shot or similar in the high temperature case has attractions and may provide the solution needed particularly for cases where the final temperature rises to above the melting point of the seal material to effect a complete filling of any voids and form an effective seal.

Canister or waste package deployment would need to be associated with a strict and precise means of monitoring the depth of deployment and inventory recording. Depths could be measured by surface drilling rig instrumentation verified by gamma markers located in the surface casing to calibrate or check the depth at the points as the waste was deployed. To avoid the potential for any gamma radiation from the deployed waste packages to interfere with a signal, such gamma markers would have to be located some distance above the waste deployment zone. These markers could be detected with a gamma tool incorporated in the deployment assembly and the depth calibrated for each run. The use of coiled tubing for waste deployment would have advantages in this respect. The data recovery system at the surface would need to be designed and use could be made of drill pipe telemetry or mud pulse telemetry if drill pipe was used, the later only possible if circulation whilst deploying canisters was allowed. The use of electromagnetic telemetry may also be considered as mentioned in Section 5.11 above. The use of CT incorporating signalling and data transmission conductors could easily provide the necessary data transmission facility for this requirement.

If a process could be designed to deploy the waste packages and canister effectively, the running of each canister or package could be achieved in say three to four days with drill pipe allowing time for the installation, depth control and the placement of any intermediate seals and/or support bridge plugs referred to earlier. With coiled tubing this would be faster. In earlier studies for SKB [Juhlin *et al* 1989], a deployment of waste at the rate of 200 m stack height per month was suggested and this seems to be a reasonable yardstick at this stage. This means that to fill a 2 km length borehole (4 km to 2 km), it would take some 10 months to complete plus the time taken to construct the upper seals in the column from 2 km up to the depth of any subsurface abutment seal arrangement at say 500 m.

With finessing of systems and procedures and perhaps the use of coiled tubing as against drill pipe, this time for the waste deployment process could be significantly reduced. There is always a learning curve and for a multi-borehole programme, if the design was robust, the times required would reduce after the first few boreholes.

Overall, at this stage, it is estimated that drilling and waste deployment would take about two years per borehole. It may be possible to complete the overall process in one year if the borehole dimension was kept as small as possible.

10 FINAL BOREHOLE SEALING

Section 7.8 above discusses the need for cementation or sealing behind the casing above the deployment zone for well control purposes during the drilling process and to provide as good a sealing of the annulus and surrounding rock as possible. This section primarily relates to the final sealing process after the waste had been deployed which may modify or augment that cementation or sealing undertaken during the drilling phase to isolate the deployed waste from the biosphere. Clearly the requirements for cementing casing during the drilling phase would be markedly different to the requirements for post closure sealing.

In the deployment zone, there is a question to answer as to whether or not any material in the casing-rock annulus would required at all. This is a debate that needs to be addressed by others as well as the drilling specialists. The concept put forward by Gibb requires some form of cementitious grout in the low temperature case or the use of lead or other shot in the high temperature case [Gibb *et al* 2007].

Above the waste deployment zone (ie above 2 km or even 3 km), a ‘main seal’ could be constructed by removing sections of the casing and creating high density bentonite or other purpose designed sealants at intervals to provide a cascade of 10 m to 20 m high seals which coupled with a stage collar approach would allow the systematic injection of sealant between the barrier blocks at intervals throughout the column. This would need some detailed research. This is in addition to the general cementation or sealing behind the casing carried out during the drilling process mentioned above.

Gibb suggests the use of a high density support matrix which could be a Pb based alloy deployed as fine shot to fill the void between the containers and the casing and the casing and the annulus [Gibb *et al* 2007]. The actual detail would need to be the subject of a separate study, but there would also need to be a dialogue between the drilling interests and the disposal and sealing interests as the operations would have to be practical with the deep drilling and completion technology that is available or could be engineered

An abutment would be required from about 500 m to 250 m constructed of say concrete and asphalt and from 250 m to surface with concrete to create a permanent seal to the disposal borehole system. This would be a mining operation and the ‘shaft’ could be pre-constructed prior to the drilling the remainder of the hole to eliminate the need to drill a large diameter surface hole. The casings could then be cut off and anchored as necessary to the rock wall once the drilling had been completed.

The drilling or deployment rig could be moved away from the borehole once the waste had been deployed. The mining operation could be supported by a simple shaft head arrangement for man riding and lowering materials.

11 COST ESTIMATES

The costs that would be associated with waste emplacement have not been considered as part of this report.

Cost estimates for borehole construction can only be a rough estimation at this stage. Costs would also depend on the eventual borehole size and design that was implemented. This involves the geological setting and how many casing strings would have to be installed and other factors.

The cost of new rigs and equipment is largely influenced by the price of steel and the demand for drilling rigs and engineering resources. Rental day rates for drilling rigs, associated equipment, supporting services and consumables such as bits, drill string components and tools are also controlled by demand. The current high activity in the oil and gas market has inflated prices for equipment, tools and personnel to the highest level in history. This has had an effect on day rates for rigs and equipment and charges for service personnel at the present time, but could vary significantly both up and down in the future.

The other aspect to consider is that any equipment must satisfy current EU regulations and the interpretation of those regulations in the UK. This means that standard American, Chinese or Russia rigs, for example, cannot be used. Designs of rigs built in Europe for use in Europe are different and the specification of equipment, structural calculations, electrical codes and items, etc. are all to a higher specification that is allowed under the American Petroleum Institute (API) standards and codes of practice that govern the global market elsewhere particularly in North America. US manufacturers by and large will not currently build rigs for Europe as there is a high worldwide demand elsewhere and the cost and complexity of conforming to the CE marking and other regulatory requirements is high for standard proven equipment designs. Europe is in effect trying to create a restricted market. There are limited rig constructors in Europe, but the costs of drilling rigs and equipment manufactured in Europe is higher than similar equipment from North America and significantly more than equipment from China for example. Eventually, ISO standards for drilling equipment may be agreed which would provide a wider choice of manufacturer.

Assuming that a deep borehole disposal concept was limited to borehole sizes that are considered feasible, ie the 300 mm and 500 mm clear hole diameter cases, and hence rig sizes are quantifiable at the top end of the current oilfield type, then there are some data from which a capital cost and hence amortisation can be calculated and an indication of rental rates which gives a broad framework in which to estimate daily costs. Using these data, the cost of the borehole construction per year including an allowance for the rig and associated equipment, crews, supervision, casing, tools, bits, fuel and daily consumables would be about £20 to £25 million. So to drill a large diameter borehole, a budget of about £25 million to say £35 million would be appropriate at this stage. This does not include the site development costs and any additional technical and scientific personnel, overheads, etc that may be required over and above the requirements for drilling implementation. Costs may be reduced if a workable and robust design could be evolved and for a multi-borehole programme, reductions of 25% to even 50% should be achievable in the longer term.

For the smallest case, ie a diameter of 300 mm, the costs would be more like £15 million. The recent Basel-1 well drilled to 5 km with a final diameter of 251 mm and completed in 2007 cost £13 million which gives some credibility to these rough estimates.

These preliminary estimates of costs only relate to borehole construction. Equipment and factors relating to the deployment of waste including handling, shielding, etc are outside the scope of this report.

These preliminary estimates include what would be considered a reasonable allowance for drilling problems during the construction of a borehole or what can be described as 'trouble time', More serious issues such abandonment due to hole stability problems of casing becoming stuck and non retrievable are considered possible, but low risk, but if this should occur, then costs may be increased depending on what action was taken to try and recover the situation or whether or not the borehole had to be abandoned and sealed. The worst case scenario would be that a well was drilled to final depth then collapses or the inability to install casing results in the loss of a borehole, so the downside is the full cost except what can be recovered in terms of casing material.

In budgeting, the loss of one well in 25 may be a reasonable provision.

The MIT report discussed drilling costs of deep geothermal wells [MIT 2007]. For 5000 m deep geothermal wells based on 2004 costs, the researchers estimate the well cost to be $US 8 million. However, the report acknowledges the paucity of data and the cost data is often incomplete and expenses allocated elsewhere which distorts the figures. Outrun costs overall are usually more than these estimates from modelling and, in trying to present a realistic cost structure in this report for NDA, a conservative approach has been taken. However, the comment in the MIT report about significant reductions with time is also relevant and given the right approach and a proven design, there are significant cost saving opportunities.

Looking at individual well records in the report, a 5.6 km deep granite well in New Hampshire cost $US 15, 570k over 154 days of drilling. Note also that drilling costs worldwide have increased significantly since 2004 and in Europe are at least 50% more expensive in 2007 than in 2004. Also, the yardstick for costs of drilling in Europe as against North America is that drilling costs a pound for every dollar.

Therefore, using the MIT data and accounting for escalation since 2004, the cost estimate from the MIT model for a 5 km well in Europe would be about £12 million. This is similar to the actual cost of the well in Basel which included some problems of installing casing in the upper section and some cementing problems. So the estimates are of the right order.

Another recent data point is a geothermal well in Germany near Munich which took 235 days to drill 3.87 km with a final diameter of 222 mm. The overall cost for this borehole was approximately £14 million. There were some technical problems in the well mainly attributed to the casing design and thermal effects as the bottom hole temperature was higher than predicted. The well took about twice as long as it should have done so a true cost of such a well should have been about £7 million to £8 million which is consistent with the £ for $ yardstick when compared with the MIT report model. These data are from personal knowledge of the author and not published.

It is relevant to point out that whilst the smallest diameter being considered in this report is close to the deep large diameter wells considered for geothermal purposes in the MIT report and to the Basel-1 well, once the diameter increases to the 500 mm and 750 mm case, the drilling tools, methods and practices have to change from the traditional oilfield approach which means that a linear extrapolation of costs is unrealistic. Hence significant increases in the preliminary estimates of costs above are not likely.

For the future, drilling costs are not likely to continue to rise at the same rate as has been experienced in the last two years. This unusual recent history is a result amongst other factors of historical over capacity in the market after the slump in the early 1980s with many rigs being scrapped in the last few years as they reached the end of their useful life coupled with the significant rise in demand for oil and gas and the political uncertainty created by events in the Middle East, South America and Africa. Another factor has been the significant increase in steel and equipment prices caused by high demand in the Chinese market which has again distorted long term trends.

The consolidation in the industry which was a feature of the period of low demand firstly in the service sector, then in the manufacturing sector and finally the rig sector has been arrested and more companies are now designing and manufacturing rigs and equipment which suggests that prices for equipment will not escalate at the same rates as over the last two years. Noteworthy is that there are some strong rig design and manufacturing companies in Europe and the standards set by Europe may force the North American manufacturers, who hitherto have been dominant in the business, to follow, although there is no sign of this happening at the moment. The Chinese manufacturers are starting to penetrate the market, but their quality leaves a lot to be desired in certain products, but in the next few years they too will improve their standards and quality and provide a stabilising influence on the global market.

12 RISK ISSUES

The principle risks associated with deep borehole disposal relate to the construction of the borehole, and with appropriate design the risks associated with waste emplacement should be insignificant.

Given that the caveats and limitations of the drilling, casing and the drilling related sealing process described above are taken into account, including the installation of casings or liners, it is considered that a deep borehole disposal design that is practicable could be developed. This is despite the fact that a deep large diameter borehole for this application would extend the current experience and technology outside the current envelope of experience and technology. Such a challenging project would introduce more risks than would be normal for a deep drilling project within current boundaries of experience.

The problems associated with implementing such a system can be summarised as follows:

12.1 Drilling

- Surface drilling rig or associated equipment failure. This would be likely to be within 1% to 5% of the rig operating time.

- Drill string and assembly failure. There would always be a risk, but with rigorous preventative inspection, assuming routine drilling, this would be likely to be rare and one occurrence per borehole may be a reasonable allowance, but even this is pessimistic. In most cases a failure could be relatively easily rectified by carrying out a fishing programme to latch on to the lost part of the drill string and if necessary wash mover any tools that are in the hole and which become jammed by fine grained material settling around the string. The time spent would depend on the severity of the case and in larger diameter boreholes the problem would be greater. The time lost could be anything from a day for a simple fishing trip in relatively small diameter borehole and up to say a week or more for the larger hole cases.

- Borehole instability would be perhaps the biggest risk. In sedimentary rocks this would be likely to be higher than in crystalline rocks as a result of weak or mechanically unstable formations such as weakly cemented rock or sloughing clays for example. However, in crystalline rocks there would still the risk of instability as a result of stress conditions resulting in breakout from the wall of the borehole. Breakout would be manifested by pieces of rock coming loose from the borehole wall as a result of stress effects when the natural support was removed. This could create serious problems of hole fill due to debris on the bottom of the hole or on the top of tools and the jamming of drilling assemblies. Sometimes these fragments can be broken up with the drilling assemblies. In the worst case, this could result in stuck pipe or drilling assemblies which could not be released necessitating a major fishing operation and even the possibility of abandonment of the borehole. These risks would need to be considered as part of the site characterisation phase of the project.

- Casing installation could be risky if the borehole was potentially unstable and creates a situation whereby the casing could not be run to the planned depth. Also a tortuous hole and sometimes differential sticking (borehole, fluid pressure greater than the formation pore pressure) can cause smooth casing (ie no centralisers) or drilling assemblies to be pulled to one side of the borehole which is difficult to move due to the high suction forces. The remedies include trying to extract the casing, clean the borehole, and start again or circulate the annulus between the casing and the borehole with lower density fluid. It must be appreciated that the loads involved running casing are extremely high and any attempt to pull the casing back with the rig or an independent casing jacking system may fail. This also applies to the potential to continuously move or 'work' casing up and down during installation to prevent sticking.

- Cementation or sealing around casing annuli is the weakest area of this concept as the supporting industries cannot deliver a quality solution. The integrity of the rock, annular cementation and casing bond and the predictability of the quality of the cement placed in the annulus is the most difficult aspect of any deep borehole to achieve. In practice simply because of the limited placement methods available for such long sections of a vertical or near vertical column. This whole issue needs very thorough review and possibly a research and development programme to identify an acceptable engineering method of annular filling.

12.2 Waste deployment

Risks in drilling the boreholes could be engineered to be acceptable and some failures allowed. When it comes to the actual disposal or deployment of the waste elements, failure could not be contemplated and the engineering and procedures would therefore need to be designed to be as near assured as was possible if not guaranteed.

A permanent casing throughout the full depth of the borehole for waste deployment, would significantly reduce, if not virtually eliminate the risk of failure, and provide the platform for effectively an assured deployment.

Open hole solutions could not give this comfort and indeed would introduce serious risks which are considered unacceptable. Retrieval of a waste canister, if it was prevented from reaching the desired depth or becomes struck in an unlined borehole would create a major problem which may be unsolvable and therefore would need to be eliminated.

The use of a permanent casing throughout the waste deployment zone is a much debated issue, but from a practicality point of view, it would be the only solution. Moreover, certain DBD concepts advocate that the casing in the deployment zone need not or should not be permanent and recovered *after the* deployment of the waste material was complete. In some cases this is seen as an advantage. The SKB study also concluded that some form of casing in the deployment zone was necessary [Juhlin *et al* 1989].

The reality of this situation is that to withdraw casing over any length of borehole at this depth and in these sizes is simply unrealistic and another solution would need to be found if this was an essential element of the deep borehole disposal concept.

One theoretical option would be to remove lengths of casing by milling, prior to the next package to be disposed, immediately above already emplaced waste. This would introduce a risk of wall instability and material falling into the borehole on top of existing waste. Such an approach would necessitate the use of drilling tools in the borehole and fluid circulation to the surface above already emplaced waste with the attendant risk of accidental contact by a drilling assembly, which is considered to be highly undesirable.

Waste deployment should be an entirely separate operation from drilling.

13 FORESEEABLE FUTURE DEVELOPMENTS

Whilst it is very important to base any design concept for deep borehole disposal on proven engineering and achievable adaptations or extension of existing technology, it is also reasonable to examine some new development that may have a significant bearing on the feasibility of this method of waste disposal, for the future. To do such an exercise thoroughly would take time and a need to talk to industry and research specialists over a wide range of subjects, so these comments are based on known views about new methods and equipment.

A recent comprehensive report by an MIT lead study group on the potential of geothermal energy within the United States is one of the first studies of its kind in 30 years [MIT 2007]. The report contains some interesting contributions on emerging technologies. The emphasis in this report for geothermal exploitation is somewhat different to the case for waste disposal, but at the same time has some similarities. The primary focus for geothermal drilling is to reduce drilling costs and in particular for wells drilled to 4 km and deeper.

The report considers the adaptation of oil and gas well drilling technologies to geothermal applications and what are referred to as 'revolutionary technologies' not yet available commercially.

Regarding the adaptation of existing technology, the emphasis in the MIT report is on the interest in casing and cementing and particularly in expandable tubular casings, low clearance well casing designs, casing while drilling, multilaterals (fanned arrays) and the improvement in rates of penetration.

The following developments may have an application in the deep borehole disposal concept. These partially reflect ideas highlighted in the MIT report and also the work of others as well as the author's opinion.

13.1 Expandable tubular casing

Casing and cementing costs are high for deep wells due to the number of casing strings required and the volume of cement. The use of expandable casing is therefore attractive particularly as the casing is generally required for well bore stability and not for pressure control. In the case of geothermal, thermal expansion remains a problem and the weaker expandable casing has still to be proven in geothermal applications.

Similarly, there is a demand for an increase in the range of sizes available of expandable tubulars. The process was originally developed by Shell and allows the plastic deformation of the tubular casing using an under-reamer behind the lead bit which when withdrawn increases the casing diameter. This is shown diagrammatically in Figure 7.2 in Section 7.5.

There are other developments on expandable casing being considered for welded pipe and for diameters up to 1066 mm diameter [Worrall 2007]. These ideas are from the same base team ex Shell that developed the first expandable casing systems which are now available worldwide in the smaller hole sizes. These systems could provide a 'round pipe' in an elliptical hole common in drilling in stressed rock at depth. If this technology could be developed, it would minimise the well borehole diameters and avoid the necessity to start in very large sizes.

A further development is the use of expandable screens primarily intended for reservoir production zones particularly where ‘sanding’ is a problem in producing wells. Such screen type profiles in an expandable tube may be appropriate with some design changes for a high void ratio casing for the deployment zone.

13.2 Under-reamers

High quality under-reamers for hard and abrasive formations are required for the geothermal applications. Failures of the under-reamer arms are commonplace. Under-reamers are tools that can cut a hole to a larger size than the main borehole by expanding cutter arms that move outwards when the fluid through the tool is pressurised. These have limited application to deep borehole disposal.

The oil industry has started to use what are called bi-centre bits and PDC type under-reamer cutters. The bi-centre bit cuts a large diameter hole underneath the casing by an eccentric action. Bi-centre bits are now used to allow smaller diameter casing string suite to be used so reducing the overall profile of a deep borehole and hence the cost of casing. Again bi-centre bits have limited application for deep borehole disposal.

PDC bits and cutters have not been proven in geothermal or crystalline environments and hence the MIT report calls for more robust tools.

13.3 Drilling with casing

This method is starting to become more popular in the oil and gas industry. It is an extension of the old duplex system commonly used in the geotechnical process industry. Although the oil industry refers to it as a ‘new technology’, what is new is that the specialist equipment has been developed to use this approach in normal oilfield sizes. Cementing with this approach still requires further development.

13.4 Multi-laterals

This is of interest to the geothermal industry, but as reported above, is not at a stage yet or in the size range that is relevant to deep borehole disposal.

13.5 Novel drilling technologies

This section of the MIT report covers the more exotic and esoteric drilling technologies that are not really applicable to the deep borehole disposal case. These are focussed on reducing drilling costs in the means of destructively drilling the rock to access the geothermal reservoir. The ideas include:

- Projectile drilling consisting of projecting steel balls at high velocity using pressurised water to fracture and remove the rock.

- Spallation drilling uses high temperature flames to rapidly heat the rock surface causing it to fracture or ‘spall’. This has been tested in granites in New Hampshire for example using ignited diesel fuel and is not particularly new. Quarrymen use this method to cut large blocks of granite as the heat disintegrates part of the crystal structure particular in medium and course grained rock.

- Laser drilling uses the same mechanism to remove rock, but relies on pulses of laser to heat the rock surface.

- Chemical drilling involves the use of strong acids to break down the rock and has the potential to be used in conjunction with conventional drilling techniques.

None of these techniques is close to commercial application and some if not most cannot be considered a viable development for the application of deep radioactive waste disposal in the foreseeable future. However, at this juncture it is right to list them as they may have an application if developed further in the future.

13.6 Downhole thrusters

Another idea which has technical merit, but also technical challenges, is the use of a downhole thruster to provide the necessary force on the bit for large diameter holes particularly related to drilling in crystalline rock. Typically, the bit force needs to be 90 kg/mm diameter (5000 lb/in diameter) on the cutters to crush the rock. Applying this sort of load requires large numbers of doughnut type collars in the borehole, all which adds to risk. Worrall [Worrall 2007] together with the author have considered the use of the tunnelling machine approach for this application whereby the forward force of the cutter head is provided by hydraulic thrusters anchored to the side of the tunnel. If the same principle could be used for vertical drilling, then this would allow the sort of loads to be applied to the bit that is required for large diameter drilling which would otherwise be difficult to achieve.

This type of approach is worthy of further consideration and research into the feasibility would be required. Informal discussions have been held with Herrenknecht, the major German tunnelling machine manufacturer who build full face machines up to 15 m diameter so are not short of experience in this field. As Herrenknecht has an interest in vertical drilling as well as tunnelling, they would be a candidate for some further work on this issue.

13.7 Downhole pump for reverse circulation

To avoid the need for a dual string for reverse circulation, there have been some ideas to develop a combined lift pump system. This is also an area that would have serious benefits if such a system could be engineered as it would make the drilling of large diameter holes much easier.

14 RESEARCH AND DEVELOPMENT REQUIREMENTS

The status of the technology for each hole diameter scenario is summarised in the table presented in Appendix A.

If it was planned to develop the deep borehole concept for implementation the following elements of a deep borehole disposal scheme would require further study and in some case research and development:

1 Hole stability review from stress and geological data for each prospective site including where possible new stress determinations. Translation of data assessment into a recommendation for the drilling process such as the choice of drilling fluid.

2 A more detailed review of a possible deep borehole design including the depths of stages and diameters if a target site(s) was identified.

3 Study of available drilling rig designs and potential for heavier units including the consideration of features specially required for this application with costing and lead time assessment.

4 Study of waste deployment rig equipment that may be separate from the borehole drilling rig and equipment.

5 A review of the use of coiled tubing unit to deploy waste and provide inhole services including communication and data transmission.

6 A study of the technologies available for drill pipe, mud pulse telemetry and electromagnetic telemetry for data communications.

7 A review of the latest air drilling and air assist drilling and the use of dual fluid systems using state-of-the art downhole hammers (DTH) possibly with some field trials as an alternative to fluid flush drilling at depth in crystalline rocks.

8 Development of a downhole pump for reverse circulation drilling with a single string rather than a concentric dual string.

9 Design of drilling assemblies to meet the programme requirements based on a preferred borehole design and drilling method.

10 Investigation into vertical ‘thrusters’ to apply high loads to bits for large diameter drilling.

11 Review of fishing tools for large diameter boreholes.

12 Further review of the latest large diameter shaft drilling experience and practice.

13 Further review of the latest deep, large diameter, drilling for oil, gas and geothermal applications.

14 The design of suitable large diameter drilling bits for drilling in crystalline basement rocks.

15 The selection or design of drill string(s) to cater for the specific requirements of this application for both normal and reverse circulation procedures including the surface handling arrangements for all tubulars and associated assemblies.

16 Conceptual design of casing strings including connection design, applicability of welded connections and centralisation. This could be extended to a full design study for a preferred case with full stress analysis including any thermal considerations.

17 Detailed calculation of casing weights and a review of handling and installation procedures for the conceptual design in Item 16 above.

18 Review of cementing possibilities, fillers, the use of placement tubes on the outside of large diameter casings, stage collars and the surface equipment. This is perhaps the most important issue and the weakest element relating to the concept of disposal in deep boreholes.

19 Research into the use of expandable liners and whether such systems could be developed for the large diameters involved and would be appropriate to this application.

20 Research into methods and materials of cementation and/or annular filling in the waste deployment zone.

21 Research into the development of waste containers to allow them to be deployed in a smaller diameter borehole to depth.

22 Research into methods and equipment to cut sections of casing in the seal zone above the waste disposal zone to allow barrier seals to be placed as discussed in Section 7.8.

23 Development of a placement method for high density clay based mud (eg bentonite) if a deployment fluid was required in the deployment zone.

24 Research into acceptable borehole fluids for deployment of waste if a deployment mud was not necessary.

25 Research into other methods of sealing of the borehole within the deployment zone and the placement of the sealant.

26 Design of the top sealing abutment and consideration of whether this construction should be partly completed in a mined shaft prior to drilling.

27 Generation of an accurate costing model.

15 CONCLUSIONS

This limited study has revisited old ideas and experiences and some new ideas and approaches in relation to the practicability of adopting the deep borehole concept for the disposal of radioactive waste. The key outcome of the study is that deep borehole disposal is a valid option, under certain circumstances, although a large amount of detailed borehole development work would be required to develop the concept into something meaningful. The prizes for developing a robust design for such an endeavour may be a solution to waste disposal for certain wastes that is cost effective and technically acceptable.

The following conclusions can be drawn from this review:

1 Drilling deep boreholes at the large sizes considered relevant for radioactive waste disposal would be a serious challenge.

2 The key constraint that would apply to construction appears to be installation of casing and sealing the annulus effectively.

3 The smallest diameter option (300 mm) considered to 4 km or 5 km would be close to a world record in terms of the depth and diameter relationship, which highlights the tremendous challenge of this concept. Other than the superdeep KTB well [KTB 1996], there are no other cases of drilling to this depth and diameter combination.

4 A borehole of 300 mm finished diameter to 4 km or even 5 km in appropriate geologies using oilfield equipment and systems is achievable now albeit challenging as it is only a modest departure from the experience so far in the deep drilling industry.

5 A borehole with a finished diameter of 500 mm to 4 km is considered practicable in appropriate geological conditions, but would require more investigation and the development of tools and systems.

6 A 750 mm finished borehole diameter is considered difficult to implement to 4 km, but it may be possible to a lesser depth of say 3 km with appropriate development effort and suitable geology.

7 The possibility of drilling a 1000 mm clear diameter borehole to 4 km is considered impractical at the present time and should not be contemplated as it is considered a step too far.

8 Only vertical boreholes should be considered as part of the NDA programme of monitoring international al R&D at this stage, as this would minimise the risks associated with large casing installation in large diameter boreholes and in the waste deployment process.

9 The use of multiple legs to a single main shaft or borehole in a ‘fanned array’ is considered impractical in the diameters required and introduces risks which at this stage are not acceptable. There may be possibilities for this approach at some time in the future.

10 The ideal geological scenario would be a relative easy to drill, yet stable sedimentary cover to say 1800 m ideally with only one casing string other than an initial shaft or starter hole with a 2200 m section of crystalline rock to a final depth of 4 km ideally with a large grain size to facilitate drilling (as against a fine grained strong rock).

11 Large holes in crystalline rock are very unusual and so drill bit technology and the associated tools and rig requirements would need some significant development.

12 Whilst a permanent casing or liner through the waste deployment zone is considered essential to ensure access for waste disposal and provide the necessary comfort of success that such a scheme would require, nevertheless, a liner or casing may cause difficulty in creating a completely filled annulus and hence difficulty in ensuring a tight near field around the waste. No other scenario can 'guarantee' waste would be deployed satisfactorily.

13 Whilst the liner concept would introduce a diameter change at the liner hanger (see Section 7.5), nevertheless a suitably engineered entry guide could be designed and installed to provide assured deployment of the waste packages

14 Research would be necessary into the development of a slotted or perforated casing for the deployment zone that satisfies both the borehole support requirement and the proposed need to grout or fill the waste-casing and casing-rock annuli with some form of filler. The concept of a high void ratio casing has been mentioned. Such a casing would be feasible to manufacture and could be designed to be strong enough to support the borehole wall, providing that the borehole over this sector was in relatively competent rock. In essence, such a casing or liner is simply to provide a mechanical support to the rock to stop pieces falling out which are able to do so in an unlined borehole. There is a question of void size and the proportion of voids across the profile. This would be a matter for investigation together with the manufacturing issues and whether or not expandable casing could accommodate such a feature.

15 The debate about whether or not a steel or similar string of casing could be installed without any annulus filing would need to be addressed by others. If the answer was that it was not necessary, then a centralised casing through the waste deployment zone would give a virtually guaranteed 'vessel' in which to deploy waste in a controlled and predictable manner. If the answer was that in a lined borehole in the disposal zone the annulus must be cemented or sealed in some way, then this would introduce the need for a perforated casing to allow sealing material to pass through as cementation or sealing with solid casing is considered unreliable.

16 If an unlined borehole was required in the disposal zone, then the concept is considered to be of high risk of failure.

17 Also the approach whereby casing was withdrawn after waste deployment is not considered possible.

18 In respect of the drilling technology, waste should be disposed of in as small a diameter elements as possible to limit the hole size required, but this would require a larger land area for a repository.

19 Waste canister or waste element groups could be supported at intervals in the deployment zone either with mechanical bridge plugs or by lead shot plugs placed as proposed by Gibb [Gibb 2005, Gibb 2007] to support the initial weight of the column of waste at the time of deployment by transferring the load to the surrounding casing. This would most likely be necessary as the load bearing strength of the canister would be limited and could fail under excess load from the

waste packages placed above even though the canisters would be laterally supported by the annular filling media (e.g. lead shot).

20 The upper section of the borehole could be sealed in stages after having first removed the completion casing which extends into the deployment zone to expose the upper casing string and then by cutting windows in the upper casing. A multi-barrier system could be formed to seal off the annulus and drilling disturbed zone at intervals along the borehole. This is an area which would require detailed research.

21 A seal abutment could be formed by mining to about 500 m. This operation could be carried out before drilling to eliminate the need for one stage of large diameter drilling and provide the necessary facilities to form an under reamed or undercut concrete and asphalt abutment by mining methods.

22 The drilling and deployment of waste in the smallest diameter (300 mm) borehole scenario would probably take about two years, but with time and experience and a robust design, the time could be reduced to 18 months or even 12 months.

23 Costs to drill a 4 km deep disposal borehole with a 300 mm clear diameter at final depth would be about £15 million and about £20 to 25 million for a 500 mm diameter borehole. This excludes the waste deployment process. Reductions in time and hence cost for a multi-borehole programme by 25% (after five holes) to 50% (after 10 holes) should be possible.

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17 GLOSSARY

Annular velocity	The velocity of return fluid in the drill string-casing or drill string rock annulus during normal circulation drilling.
AGR	Advance Gas Cooled Reactor.
Balanced drilling	When the density of the borehole fluid is equivalent to the natural pore pressure.
Blow out	An uncontrollable eruption of fluid from a borehole usually caused when gas expands and migrates to the surface and can result in a surface fire if burning gas is ignited.
Casing	A permanent or temporary tubular lining, usually of steel, installed in a borehole which may or may not be cemented in place.
Coiled tubing (CT)	A continuous length of steel tubing that is coiled on a large diameter reel and is used for accessing deep boreholes from a variety of drilling and other related operations.
CoRWM	Committee on Radioactive Waste Management.
DBD	Deep Borehole Disposal.
DCDMA	Diamond Core Drillers Manufacturers Association (USA)
Differential sticking	A phenomenon that occurs when the borehole fluid has a lower density that the natural pore pressure in the formation particular in high porosity rock whereby a drill string or casing can be ‘sucked’ against the side of the borehole and is difficult to release.

Downhole drilling device	A downhole positive displacement motor or turbine that is used to rotate the bit at the bottom of the drill sting and is powered by the pressurised mud stream which is pumped down the drill sting when drilling a borehole with normal circulation.
Down-the-hole hammer (DTH)	A percussion device that operates through air pressure and creates an impact action on the attached bit to crush the formation and thereby advance a borehole.
Electromagnetic telemetry	A system for data transmission via low frequency electromagnetic waves which are detected by a ground antenna at the surface.
Expandable casing	A cold working process for borehole tubulars in the borehole whereby an expansion cone or mandrel is drawn through the tube to deform the steel casing tube to expand the diameter and hence result in a closer fit to the borehole wall profile than is possible with a standard casing tube.
Fishing	The process for recovering lost components of the drill string and other debris in a borehole using special fishing tools.
Flashing	The change of state from water or brine to steam within a borehole as the liquid rapidly vaporises as the pressure reduces close to the surface.
Fracture pressure	The pressure at which breakdown of the rock can be initiated such that rock will ‘fracture’ or ‘split’ by either the formation of new fractures in intact rock or by opening up existing sealed fractures in the rock.
Geological bias	The tendency to influence the trajectory of a borehole by the orientation of jointing systems, cleavage, folding and stress anisotropy.

Geopressurised formations	A formation that contains fluid which occurs in nature at a pressure higher than the natural hydrostatic gradient such as high pressure water, brine or gas.
High void ratio casing	A casing usually of steel that has a number of perforations which are larger and hence cover more surface area of the tube than a normally accepted perforated casing or screen.
HTVDD	High Temperature Very Deep Disposal.
J-slot	A device like a bayonet fitting that allow downhole tools to be released by counter rotation.
Kick	A term used to describe the presence in a borehole of a geopressurised fluid which if not controlled could result in a blow out.
Liner	A partial casing that can be installed from the bottom of an existing casing string to the new depth of the borehole and is secured with a liner hanger. Liners are used to reduce casing weight and cost (see Section 7.5).
Liner hanger	The device that supports and locks a liner in place in an existing casing string (see Section 7.5).
Logging-whilst-drilling (LWD)	The transmission of data from sensors in the drilling assembly to provide information in the formations being drilled.
Lost circulation	A term used to describe the loss of drilling fluid in a borehole due to highly porous formations.
LTVDD	Low Temperature Very Deep Disposal.
Measurement–whilst-drilling (MWD)	The transmission of data from sensors in the drilling assembly to provide information principally relating to the trajectory (eg azimuth and inclination) and other data that assists in the control of the drilling.
Metric tonne	2200 lb.

Mud pulse telemetry	The terms used to transmit data through pulses in the stream of drilling mud which are interpreted at the surface to give quasi real time information to the drilling crew.
Multi-lateral	A term to describe the drilling of a well which has several branches in the lower part to access a target formation. Multi-laterals are generally used for drain holes in oil reservoirs. The technology uses a splitter device at a predetermined depth to allow access to the various branches which are drilled by directional drilling.
NDA	Nuclear Decommissioning Authority.
Normal circulation	A term used to describe the circulation of drilling fluid through the drill string and the bit and return up the drill string-casing or drill string-rock annulus.
Overbalanced drilling	Drilling when the density of the borehole fluid is greater than the natural pore pressure.
Overpull	A term used to identify the hoisting load that is required over and above the buoyed weight of the drilling assembly to overcome friction and other effects.
Packed hole assembly	A drilling assembly that incorporates a number of blade or roller stabilisers and heavy drill collars to provide a stiff column above the bit to help maintain the hole inclination (vertical or inclined).
Pendulum assembly	A heavy assembly that by gravitational forces maintains hole verticality.
Pore pressure	The pore pressure is the pre-existing pressure in pores or fractures that occurs in nature.
PWR	Pressurised Water Reactor

Reverse circulation	A term used to describe the circulation of drilling fluid down the drill string –casing and drill-string-rock annuls which return up the drill string and is opposite to normal circulation.
ROP	Rate Of Penetration.
Rotary table	The equipment which transmits torque to a drill string at the surface by means of a hexagonal or square kelly which is attached to the top of the drill string.
Sidetrack	A term that describes the process of drilling a new branch to a borehole by exiting the side of the borehole using a whipstock or downhole drilling assembly.
Stage collar	A ported collar that can be inserted in a casing string to access the casing annulus to allow the injection of fluid such as cement into the annular space when the system is pressurised.
Stress breakout	The local failure of a formation which exhibits high anisotropy in the principal stresses, usually horizontal, which creates irregular or oval shaped boreholes.
Top abutment seal	A terms used to describe the final cap of a waste disposal borehole which is suggested to be emplaced at 250 m to 500 m depth.
Tortuosity	The irregularities in a borehole trajectory cased by spiral effects during drilling or rapid changes in the radius of curvature such that a straight or uniform borehole trajectory is not achieved. This can cause problems in installing stiff casings strings as the effective diameter is less than the drilled diameter.
Tube-à-manchette	A sleeved port system in a double packer assembly that allows fluids and grouts to be injected under pressure at different intervals in a borehole.

Underbalanced drilling	Drilling where the density of the borehole fluid is less than the natural pore pressure.
Whipstock	A long, curved, taper shaped wedge made of steel that is deployed and oriented just above the blockage or purposely placed bridge in a borehole to allow the next drilling run to deflect into a new trajectory through the side of the borehole. In cased holes, the whipstock is usually integrated with a casing mill to cut the window through the casing to allow the drilling to proceed.
WOB	Weight On Bit
WVP	Waste Vitrication Plant.

APPENDIX A

TECHNOLOGY STATUS SUMMARY

KEY

Available	*Readily available from supporting industries*
Adaptable	*Available with some bespoke adaptation for this application*
Research	*Using existing knowledge and materials can be achieved with some detailed design and engineering and possibly trials for a modest investment.*
Impractical	*With current technology and experience, considered impractical at least for now.*

DEEP HOLE DISPOSAL: TECHNOLOGY STATUS SUMMARY

4000 m DEEP WITH 300 mm DIAMETER IN THE DISPOSAL ZONE

Element	*Available*	*Adaptable*	*Research*	*Impractical*	*Comments*
Surface location			x		Site selection
Surface borehole facilities	x				Civil engineering
Geology			x		Site selection to optimise conditions
Surface drilling equipment		x			Upgrade existing rig designs
Tubular handling systems		x	x		Upgrade existing equipment or designs
Hole sizes and depths		x			Slightly larger than past experience
Drill string	x				6-5/8 in strings are available.
Drilling assemblies	x				Use existing designs as a basis
Drilling method (liquid flush)	x				Use existing processes as a basis
Drilling method (air flush)			x		Needs some design for this special case (if applicable)
Drilling bits	x				Use existing oilfield designs as a basis
Drilling fluid systems	x				Use existing fluids technology as a basis
Solids control	x				Range of equipment available
Verticality control	x				Available for this size of hole
Borehole surveying		x			Use existing technology adapted for the larger hole sizes
Coring		x			If necessary, but would need to be limited in diameter
Wireline logging		x			If necessary, but not good quality in large size holes
Testing		x			If necessary with some adaptation.
Well control	x				Use existing technology as a basis or pilot hole
Casing stress analysis	x				Software and specialists available
Primary casing		x			Follows from stress analysis
Cementation			x		Needs research as to the best options as large sizes
Casing in deployment zone			x		From stress analysis and waste deployment concept
Deployment fluid (mud)		x			Material research and acceptance
Annulus grout or filler			x		From waste deployment concept
Waste deployment			x		Development of the process from waste disposal concept
Grout or filler placement			x		Development of the process from waste disposal concept
Coiled tubing		*x*			Needs detailed review of possible applications

Element	*Available*	*Adaptable*	*Research*	*Impractical*	*Comments*
Data communication		x			Mud pulse and drill string telepathy or wireline systems
Bridge plugs		x			Larger than normal oilfield sizes
Window cutting for seals		x			Larger size than normal
Upper sealing material			x		Material research and acceptance
Sealing material placement			x		Needs detailed work
Top sealing abutment			x		Key issue needing detailed work and concept development
Monitoring		x			Scope to be determined and scheme developed
Costing		x			Model needed
Timetable	x				Standard software, but timings need detailed study

DEEP HOLE DISPOSAL : TECHNOLOGY STATUS SUMMARY

4000 m DEEP WITH 500 mm DIAMETER IN THE DISPOSAL ZONE

Element	*Available*	*Adaptable*	*Research*	*Impractical*	*Comments*
Surface location			x		Site selection
Surface borehole facilities	x				Civil engineering
Geology			x		Site selection to optimise conditions
Surface drilling equipment		x			Upgrade existing rig designs with some research into equipment for the large sizes
Tubular handling systems		x			Use existing equipment or designs
Hole sizes and depths		x			Much larger than past experience
Drill string			x		Special strings may be required
Drilling assemblies			x		Use existing designs as a basis
Drilling method (liquid flush)			x		Use existing processes as a basis
Drilling method (air flush)				x	Not practical in these large hole sizes
Drilling bits			x		Use existing oilfield and shaft drilling designs as a basis
Drilling fluid systems			x		Use existing fluids technology as a basis
Solids control		x			Range of equipment available
Verticality control		x			Available, but in small sizes (may need pilot hole)
Borehole surveying		x			Use existing technology adapted for the larger hole sizes
Coring		x			If necessary, but would need to be limited in diameter (;pilot hole)
Wireline logging		x			If necessary, but other than calliper, in pilot hole
Testing		x			If necessary with some adaptation
Well control		x			Use existing technology as a basis or pilot hole
Casing stress analysis	x				Software and specialists available
Primary casing		x			Follows from stress analysis
Cementation			x		Needs research into the best options as large sizes outside normal experience
Casing in deployment zone			x		Follows from stress analysis
Deployment fluid (mud)		x			Material research and acceptance
Annulus grout or filler			x		From waste deployment concept
Waste deployment			x		Development of the process from waste deployment concept
Grout or filler placement			x		Development of the process from waste deployment concept
Coiled tubing		*x*			Needs detailed review of possible applications

Element	*Available*	*Adaptable*	*Research*	*Impractical*	*Comments*
Data communication			x	x	Mud pulse and drill string telepathy or wireline systems
Bridge plugs				x	Larger than normal oilfield sizes
Window cutting for seals				x	Larger size than normal
Upper sealing material				x	Material research and acceptance
Sealing material placement				x	Needs detailed work
Top sealing abutment				x	Key issue needing detailed work and concept development
Monitoring				x	Scope to be determined and scheme developed
Costing		x			Model needed
Timetable	x				Standard software, but timings need detailed study

DEEP HOLE DISPOSAL : TECHNOLOGY STATUS SUMMARY

4000 m DEEP WITH 750 mm DIAMETER IN THE DISPOSAL ZONE

Element	*Available*	*Adaptable*	*Research*	*Impractical*	*Comments*
Surface location			x		Site selection
Surface borehole facilities	x				Civil engineering
Geology			x		Site selection to optimise conditions
Surface drilling equipment			x		Use existing rig design concepts with some research for larger holes
Tubular handling systems			x		Use existing equipment or designs as a basis
Hole sizes and depths			x		Very much larger than experience
Drill string			x		Special strings would be required
Drilling assemblies			x		Use existing designs as a basis
Drilling method (liquid flush)			x		Use existing processes as a basis
Drilling method (air flush)				x	Not practical in these large hole sizes
Drilling bits			x		Use existing shaft drilling designs as a basis
Drilling fluid systems			x		Use existing fluids technology as a basis
Solids control		x			Range of equipment available
Verticality control		x			Available, but in small sizes (would need pilot hole)
Borehole surveying			x		Use existing technology adapted for the larger hole sizes
Coring		x			If necessary, but would have to be carried out in pilot hole
Wireline logging		x			If necessary, but other than calliper, in pilot hole
Testing		x			If necessary with some adaptation
Well control			x		Use existing technology as a basis or pilot hole
Casing stress analysis	x				Software and specialists available
Primary casing			x		Follows from stress analysis
Cementation			x		Needs research into the best options as large sizes at this depth well outside experience
Casing in deployment zone			x		Follows from stress analysis
Deployment fluid (mud)		x			Material research and acceptance
Annulus grout or filler			x		From waste deployment concept
Waste deployment					Development of the process from waste deployment concept
Grout or filler placement					Development of the process from waste deployment concept

Element	*Available*	*Adaptable*	*Research*	*Impractical*	*Comments*
Coiled tubing		*x*			Needs detailed review of possible applications
Data communication			x		Mud pulse and drill string telepathy or wireline systems
Bridge plugs			x		Much larger than normal oilfield sizes
Window cutting for seals			x		Much larger size than normal
Upper sealing material			x		Material research and acceptance
Sealing material placement			x		Needs detailed work
Top sealing abutment			x		Key issue needing detailed work and concept development
Monitoring			x		Scope to be determined and scheme developed
Costing		x			Model needed
Timetable	x				Standard software, but timings need detailed study

DEEP HOLE DISPOSAL : TECHNOLOGY STATUS SUMMARY

4000 m DEEP WITH 1000 mm DIAMETER IN THE DISPOSAL ZONE

Element	*Available*	*Adaptable*	*Research*	*Impractical*	*Comments*
Surface location			x		Site selection
Surface borehole facilities	x				Civil engineering
Geology			x		Site selection to optimise conditions
Surface drilling equipment			x		Upgrade existing rig designs with some research for large holes
Tubular handling systems			x		Use existing equipment or designs
Hole sizes and depths				x	Much larger than experience and considered a step too far
Drill string			x		Special strings would be required
Drilling assemblies			x		Use existing designs as a basis for research
Drilling method (liquid flush)			x		Use existing processes as a basis
Drilling method (air flush)				x	Not practical in these large hole sizes
Drilling bits					Use existing shaft designs as a basis
Drilling fluid systems			x		Use existing fluids technology as a basis
Solids control		x			Range of equipment available
Verticality control		x			Available, but in small sizes (would need pilot hole)
Borehole surveying			x		Use existing technology adapted for the larger hole sizes
Coring		x			If necessary, but would have to be carried t in pilot hole
Wireline logging			x		If necessary, but other than calliper, in pilot hole
Testing			x		If necessary with some adaptation
Well control			x		Use existing technology as a basis or pilot hole
Casing stress analysis	x				Software and specialists available
Primary casing				x	Follows from stress analysis
Cementation				x	Needs research, but depths and diameters suggest impractical
Casing in deployment zone				x	Follows from stress analysis
Deployment fluid (mud)			x		Material research and acceptance
Annulus grout or filler			x		From waste disposal concept
Waste deployment			x		Development of the process from waste deployment concept
Grout or filler placement			x		Development of the process from waste deployment concept

Element	*Available*	*Adaptable*	*Research*	*Impractical*	*Comments*
Coiled tubing			*x*		Needs detailed review of possible applications
Data communication			x		Mud pulse and drill string telepathy or wireline systems
Bridge plugs				x	Larger than normal oilfield sizes
Window cutting for seals				x	Larger size than normal
Upper sealing material			x		Material research and acceptance
Sealing material placement			x		Needs detailed work
Top sealing abutment			x		Key issue needing detailed work and concept development
Monitoring			x		Scope to be determined and scheme developed
Costing		x			Model needed
Timetable	x				Standard software, but timings need detailed study