DBHD ist das Werk eines Künstlers – welche Voraussetzungen es brauchte.

Nur ein Künstler, der sich seiner immer abrufbaren originären Kreativität im vollen Umfang bewusst ist, konnte etwas so perfektes, Neues wie DBHD entwickeln. - Deshalb ist und bleibt DBHD für BGE und BFE immer unerreichbar.

Es liegt in der Natur des Künstlers keine Kopie zu machen, sondern es von Grund auf neu zu denken, neu zu erfinden. Dafür braucht es eine geistige Unabhängigkeit, die Frechheit Neues zu denken, und die Lust an der Qual.

Der schöpferische Akt brauchte die Annäherung, das Spiel, das Ausprobieren, die Irrwege, Fehler, die Niederlagen, die Neuanfänge, die radikalen Wenden und die Neugierde, das Hartnäckig sein, die echte Passion, und den Mut die gefundene Form zu akzeptieren. Immer wieder zu prüfen und zu akzeptieren.

„Es brauchte auch die Notwendigkeit und auch die Grenzen unserer Zeit“. In einem Raum unbegrenzter Möglichkeiten gäbe es keinen bestmöglichen Plan. Das Entwerfen ist die geschulte, und hundertfach geübte Form der Kreativität.

Kunst kommt von Können. Man muss sich vorher ein Sortiment an Fähigkeiten erwerben, bevor man es wagen kann „einen epochalen Entwurf“ dieser Dimension anzugehen ! Und auch ein Künstler hat eine Schulbildung, und ein höhere Handelsschule Abi gab Einblick darin, dass wir alles in Euro und Cent bewerten.

Eine handwerkliche Ausbildung heißt es selbst wirklich mal getan und gesehen zu haben. Das Material und seine Eigenschaften. Die Grenzen und Möglichkeiten Dinge auf Mass zu trennen und zu fügen. Etwas herzustellen das eine Funktion erfüllt, und etwas das tot-kalt, aber immer und immer wieder nützlich ist.

Eine Metall- Meisterschule verschafft einem mehr Horizont. Ganze Felder der tradierten Handwerkskunst des Bauens zu erkennen. - Die Fähigkeit technisch zu zeichnen, zu rechnen und zu schreiben und zu sprechen. Mit den Einheiten auf gutem Fuss zu stehen, und die Bandbreite des handwerklich, industriellen Denkens zu erfassen und in neuen Aufgabenfeldern neu anwenden zu können.

Einige Semester Maschinenbau, einige Semester Kunst. Tatsächlich kam dann im Architektur-Studium der Künstler dem Ingenieur sehr nahe. Seitdem liegen die beiden in einem immer wieder fruchtbaren Streit. Entwerfen muss man an Beispielaufgaben immer und immer wieder üben. Technik braucht Fakten, und ein Ingenieur sammelt Fakten und wertet diese aus. Beide befassen sich immer und immer wieder mit den Materialien. - Ihren Fähigkeiten und Ihren Grenzen.

Die Zeit als Fernmelde-Soldat und die Zeit als Website-Autor war sicherlich auch von Bedeutung um eine Kommunikation in die Welt hinaus halbwegs sicher zu ermöglichen. – Millionen von Lesern ww waren bisher live dabei !

Die Erziehung zu Fleiss, Ehrlichkeit und Hartnäckigkeit spielte sicherlich eine grosse Rolle. - Auch die Möglichkeiten eines Elternhauses, das Sprachreisen bzw. fremdsprachlichen Zusatzunterricht ermöglicht hat. – Auch das eigene Selbstverständnis zwischen Unternehmern, Ärzten und Lehrern aufzuleben.

Wesentlich bleibt aber der Aspekt des Künstlers. - Eine unabhängige Geisteshaltung, die der eigenen geschulten originären Kreativität auch mal traut und sich mutig auf den Weg begibt, auch wenn man am Anfang nur wenig davon sehen kann. Eine passionierte Gangart die auch ein Scheitern akzeptiert und wenige Tage oder Wochen später immer noch am Problem kaut, um dann zu unvermuteter Zeit einige Schritte zurückzugehen, und von dort aus einen viel besseren Weg findet. Aus der Leidenschaft die Kraft ziehen die Irrwege abzuarbeiten, und immer wieder weiterzumachen und dabei nur das Wesentliche als gesetzt mitzunehmen. Es immer wieder zu neu zu lesen, zu recherchieren und zu filtrieren um das Wesentliche zu identifizieren und zum EL zu formen.

DBHD ist das Lebenswerk eines Künstlers der sich viele Fähigkeiten erwerben musste, um sich einer schwierigen Aufgabe stellen zu können, und bei deren Erarbeitung nicht die Leichtigkeit den Entwerfens, aber auch nicht die ernsthaftigkeit des Themas aus den Augen zu verlieren. Schmerzhafter Prozess ...

Es liegt nun ein Werk vor, das geschmiedet ist aus allen Bereichen der Kunst, der Technik, des Wissens, der Wissenschaft, der Bodenständigkeit, aber auch der „originären Kreativität“. Es ist eine Architektur entstanden die das Problem einer Lösung zuführt, die machbar ist, die an die Grenzen geht, die neue Wege beschreitet die mit tradierten Mittel möglich sind. Ein Entwurf der sich vor der Übertreibung hütet, aber alle Möglichkeiten maximal nutzt, um effizienter und genialer und seriöser zu sein. Das war nicht ganz einfach, weil die Aufgabe eine so mönströse Dimension aus Berg, Geologie, Atommüll, Angst, Politik, Metallen aller Art, Physik, Chemie, Mechanik und vielen weiteren technologischen Herausforderungen enthielt. – Ich hoffe sie wissen dieses Lebenswerk zu würdigen. Es zeigt sich, das ich nur für die Lösung dieser einen Aufgabe geschaffen wurde.

Mit freundlichen Grüssen Version 0.0.3 / Aug. 2019
Volker Goebel
Dipl.-Ing.
Endlager-Fachplaner ww

Wir erinnern uns an all die Ansätze die gescheitert sind weil etwas fehlte :

Institut für Endlager-Planung der Universität Clausthal – Dr. Röhlig

Institut für Endlagerung bei der GRS – Dr. Fischer-Appelt

Abteilung Endlagerforschung bei der GRS – Dr. Mönig

DBE – erst Gorleben dann gar nichts mehr – Bollingfehr

DBE Tec – immer wieder nur gar nichts – Dr. Berlepsch

ENTRIA – es mal zusammen versuchen – wieder nichts

KIT – es dort auch zusammen versuchen – auch nichts

DAEF – es BRD weit zusammen versuchen – wieder nichts

IGD-TP – es international zusammen versuchen – und wieder NICHTS

Alle diese Leute und all diese Ansätze waren zu ein-dimensional und alle zusammen konnten doch immer noch zu viel wenig und haben immer nur Bruchstücke vorgelegt aber nie eine Lösung ...

„Man muss es auch zeichnen" – die techn. Zeichnung schafft eine Verbindlichkeit – man muss „echte originäre Kreativität" mit einem umfänglichen Wissen, und erlernten multidisziplinären Fähigkeiten zusammenbringen. Man braucht auch den Mut zu Lücke, die dann Andere füllten – man braucht den Mut mit Ungewissheiten durch Eingrenzung umzugehen. Ein Physiker macht noch keine Planung. Dafür braucht es den Künstler der sich mit dem Ingenieur streitet und den Wissenschaftlern, und den Behörden, und der Politik gut zuhört. Alle Gebäude dieser Welt wurden von Architekten geplant. Endlager ist ein Gebäude – ein Zugangs-Bauwerk. Ihr könnt ja alle daran mitarbeiten. Aber erst mal brauchte es eine Struktur dafür ! Also, seid jetzt nicht beleidigt – bringt Euch ein – der Weg ist lang.

DBHD
1.4.2
International
DBHD Materialien
0.00 m
1 bar
578 m. casing bc. of GWL
-300 m
+65 bar =
6,5 MPa
-600 m
+129 bar
12,9 MPa
300 m.
-900 m
+194 bar
19,4 MPa
0.00 m
Biosphere
-300 m
+9°C
-600 m
+18°C
-900 m
+27°C
1.106 Meter Sediments
Sediments
Heat Conductivity
Sediment Rock app.
2 bis 3 W/mxK
Groundwater
possible
Max. depth
of new
Ice Age scarfs
250 Mio. years old
250 Closure
-1.200 m
+259 bar
25,9 MPa
-1.500 m
+324 bar
32,4 MPa
750 m storage area
-1.800 m
+388 bar
38.8 MPa
-2.100m
+453 bar
45.3 MPa
100
-1.200 m
+36°C
-1.500 m
+45°C
-1.800 m
+54°C
-2.100m
+63°C
1.100 Meter rocksalt layer
Rocksalt
Concrete
Pellets
258 Mio. years old
volcanic crust of the earth
-2.400 m
+518 bar
51.8 MPa
-2.700 m
+583 bar
58.3 MPa
-2.400 m
+72°C
-2.700 m
+81°C
Volcanic
crust of the earth
Heat Conductivity
rocks app.
2 bis 3 W/mxK
Density app.
2.200 bis 2.500
Kg / m³
DBHD 1.4.2 International
mid size pellet with 2.590 m3 concrete
Pellet Diameter = 18.00 Meters
Storage Area DBHD : D = 18 Meter / SBM Drill is D = 12 Meter
DBHD 1.4.2 International
mid size pellet with 2.590 m3 concrete
Pellet Diameter 18.00 Meters
DBHD 1.4 Thermodynamische
Berechnung von Dr. G. Herres
Grenztemperatur 265°C
Grenztemperatur, Ausdehnung,
Gelände-Hebung - für DBHD 1.4
capacity 27.500 tons net spent fuel
DBHD_1.4.2_International_nucl_rep

4

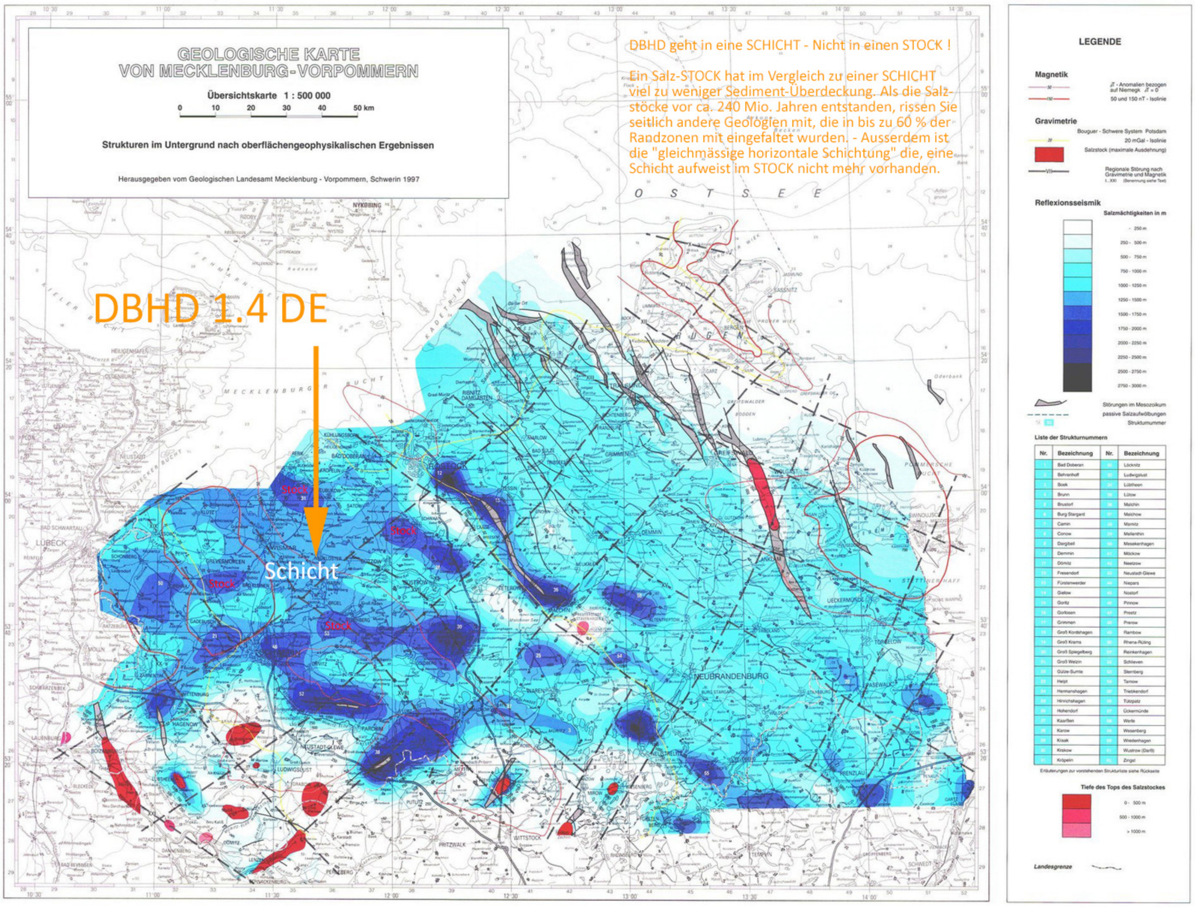
	A	B	C	D	E	F	G	H
1			Version 0.2.6			http://www.ing-goebel.de		
2		**Calculation 6x DBHD 1.4.2 nuclear repository International**						
3		Last edit: 11. August 2019 / Dipl.-Ing. Volker Goebel CH, DE / Nuclear Repository Planner ww						
4		**Capacity : 2.047 HLW Containers Germany / plus 577 HLW Containers from Switzerland**						
5		**Repository-Storage-Depth : from -1.350 Meters down to -2.100 Meters**						
6		Based on : Draft-Planning from 2014 - 2019 actually in Version **1.4.2 with Time Table**						
7								
8								
9		**Type of invest**	**Amount**	**Offer / Quote**	**Factor**	**Total**	**Comment**	**dwg**
10				or hint from :				
11		Repository Plans	2014-2019 (5,5 yrs)	Ing. Goebel + Team	375.000 €	2.062.500 €	Planning DBHD	yes
12		Probe-Drillings	12 x	Prof. Dr. M. Reich	8.500.000 €	102.000.000 €	Cores > -2.300 m	
13		8x Land Purchase	6,6 km2	from local owners		66.000.000 €	6 x 110.000 m2	yes
14		Shaft-Boring-Ma.	2 x SBM	Herrenknecht AG	60.000.000 €	120.000.000 €	2 yrs. delivery time	yes
15		External streets	40 km	make-over		12.000.000 €	new / enhance	
16		DB Rail Connection	3 x	only last meters		18.000.000 €	3 of 8 locations	
17		E-powerconnection	6 x	local supplier		25.000.000 €	50 kV med. voltage	
18		Water-connection	6 x	incl. water		18.000.000 €	10 bar with DN 200	
19		Internal Logistics		anticipation		30.000.000 €	6 building sites	yes
20		Drill platform core	6 x	43.000 m3	1.000 €	258.000.000 €	floors and walls	yes
21		Mat. storage ring	6 x	70.000 m3	900 €	378.000.000 €	floors and walls	yes
22		Conveyor Belts	3 x			60.000.000 €	diverse types	
23		Heavy load trucks				9.000.000 €	MB Dump trucks	
24		Compensationes	20.000 Shares DE	direct local people	30.000 €	600.000.000 €	payment not bribe	yes
25		Compensationes	5.667 Shares CH	direct local people	30.000 €	170.000.000 €	payment not bribe	yes
26		Planning Offices	Scientific expertise	many disciplines		123.000.000 €	over 12 years	
27		Approval Fees		many agencies		50.000.000 €	to Gov. Agencies	
28		Startfound. SBM	6 x	Thyssen Schachtbau	3.000.000 €	18.000.000 €	temp. Structures	
29		Shaft Drills D=12 m	6 x	Thyssen Schachtbau	31.500.000 €	189.000.000 €	autom. Maschine	
30		Spray-concr.-wall	9,3 m2 x 1.350 m	12.555 m3 x 6	600 €/m3	45.200.000 €	steel-fibre-amored	yes
31		Shaft completition	3 sets	Siemag Tecberg	30.000.000 €	90.000.000 €	Vent., Transport	
32		Air-Conditioning	6 x	Siemag Tecberg	7.000.000 €	42.000.000 €	cold dry air IN	
33		Flow-Ice + Piping	6 x	Siemag Tecberg	8.000.000 €	48.000.000 €	50 Liters / Sec.	
34		Cable-Drum-Houses	6 x	140.000 m3 S.T.	1.000 €	840.000.000 €	Drum-Diam.=14 m	
35		Work-Over Rigs	3 x	Steelbuilders	3.200.000 €	9.600.000 €	with return pulley	
36		Dyneema Ropes	10 x	Gleistein DE	3.900.000	39.000.000 €	D=80 mm 2.120 m	
37		Transition Cone	6 x	concrete constr.	880.000 €	5.300.000 €	12 m. to 18 m.	
38		Hole-opening	6 x	to Diam. = 18 m.	4.800.000 €	28.800.000 €	with chain-saws	
39		Staff 60 years	50 Man&Woman	4 h. shifts down t.		356.250.000 €	Work & Safety	
40		Lead Castor Casting	2.624 Containers	GNS or DBHD	89.000 €/unit	233.536.000 €	for ever undercritical	
41		Rocksalt-Salt-Sale	6 x 255.000 m3	rough quality	50 €/m3	-76.500.000 €	Asse/M./Gorleben	K+S
42		Concrete-Pellets	464 Pellets	2.590 m2 x 464 x 6	70 €/m3	504.739.200 €	Quality-Concrete	yes
43		Sand/fine gravel	464 Layers 1,5 m	382 m3 x 464 x 6	50 €/m3	159.000.000 €	D = max. 3 mm	
44		Magnetit powder	464 Portions	70 m3 x 464 x 6	680 €/m3	132.518.400 €	Rio Tinto, Billiton	
45		Closure works	6 x	own Salt grain		60.000.000 €	Salt + M. Pressure	
46		building back	6 x			12.000.000 €	farmland again	
47		Unforseeables	2%			95.550.122 €	not BER airport	
48		**Total**	**August 2019**	**Version 26**		**4.873.056.222 €**		
49								
50								
51		plus HLW containers, plus rail-transports, plus law-cases				**4,9 Mrd. EUR**		
52								
53								
54								

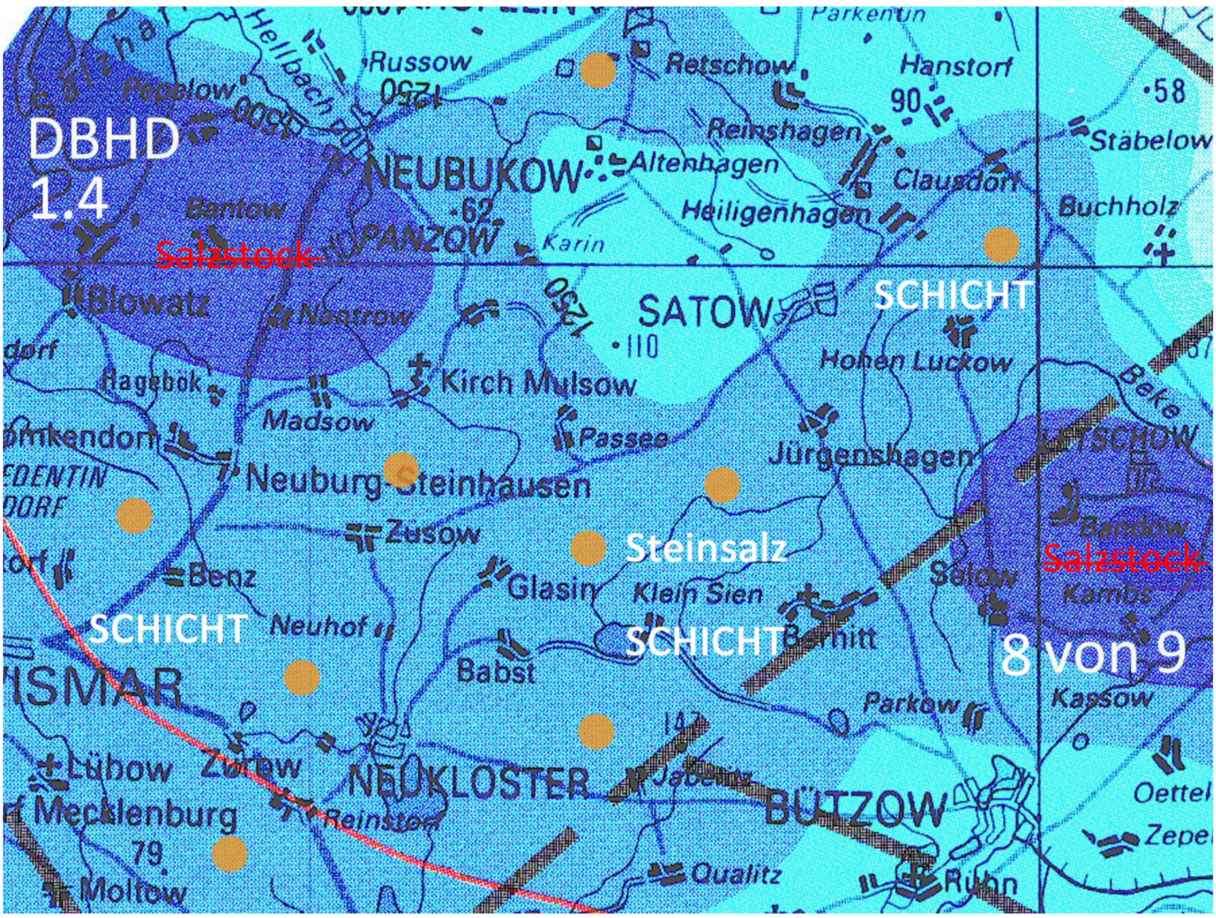
DBHD 1.4.2

International

capacity 27.500 tons net spent fuel

EN_010_Calculation_DBHD_1.4.2_International_nuclear_repository_Invest.xlsx


GEOLOGISCHE KARTE
VON MECKLENBURG-VORPOMMERN
Übersichtskarte 1 : 500 000
Strukturen im Untergrund nach oberflächengeophysikalischen Ergebnissen
Herausgegeben vom Geologischen Landesamt Mecklenburg - Vorpommern, Schwerin 1997
DBHD geht in eine SCHICHT - Nicht in einen STOCK !
Ein Salz-STOCK hat im Vergleich zu einer SCHICHT viel zu weniger Sediment-Überdeckung. Als die Salz-stöcke vor ca. 240 Mio. Jahren entstanden, rissen Sie seitlich andere Geologien mit, die in bis zu 60 % der Randzonen mit eingefaltet wurden. - Ausserdem ist die "gleichmässige horizontale Schichtung" die, eine Schicht aufweist im STOCK nicht mehr vorhanden.
O S T S E E
DBHD 1.4 DE
Schicht
LEGENDE
Magnetik
Gravimetrie
Reflexionsseismik


DBHD
1.4
Salzstock
SCHICHT
Steinsalz
SCHICHT
SCHICHT
Salzstock
8 von 9
NEUBUKOW
SATOW
WISMAR
NEUKLOSTER
BÜTZOW

SANDIA REPORT

SAND2009-4401
Unlimited Release
Printed August 2009

Deep Borehole Disposal of High-Level Radioactive Waste

Patrick V. Brady, Bill W. Arnold, Geoff A. Freeze, Peter N. Swift, Stephen J. Bauer, Joseph L. Kanney, Robert P. Rechard, Joshua S. Stein

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Sandia is a multiprogram laboratory operated by Sandia Corporation,
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National Nuclear Security Administration under Contract DE-AC04-94AL85000.

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Abstract

Preliminary evaluation of deep borehole disposal of high-level radioactive waste and spent nuclear fuel indicates the potential for excellent long-term safety performance at costs competitive with mined repositories. Significant fluid flow through basement rock is prevented, in part, by low permeabilities, poorly connected transport pathways, and overburden self-sealing. Deep fluids also resist vertical movement because they are density stratified. Thermal hydrologic calculations estimate the thermal pulse from emplaced waste to be small (less than 20 ^{o}C at 10 meters from the borehole, for less than a few hundred years), and to result in maximum total vertical fluid movement of ~100 m. Reducing conditions will sharply limit solubilities of most dose-critical radionuclides at depth, and high ionic strengths of deep fluids will prevent colloidal transport.

For the bounding analysis of this report, waste is envisioned to be emplaced as fuel assemblies stacked inside drill casing that are lowered, and emplaced using off-the-shelf oilfield and geothermal drilling techniques, into the lower 1-2 km portion of a vertical borehole ~ 45 cm in diameter and 3-5 km deep, followed by borehole sealing.

Deep borehole disposal of radioactive waste in the United States would require modifications to the Nuclear Waste Policy Act and to applicable regulatory standards for long-term performance set by the US Environmental Protection Agency (40 CFR part 191) and US Nuclear Regulatory Commission (10 CFR part 60). The performance analysis described here is based on the assumption that long-term standards for deep borehole disposal would be identical in the key regards to those prescribed for existing repositories (40 CFR part 197 and 10 CFR part 63).

CONTENTS

FIGURES

TABLES

NOMENCLATURE

BTC	Buttress threaded casing
BWR	Boiling water reactor
CSNF	Commercial spent nuclear fuel
DB	Deep boreholes
DB-PA	Deep borehole performance assessment
DSNF	Defense spent nuclear fuel
EIS	Environmental impact statement
EPA	Environmental Protection Agency
FEP	Features, events, and processes
HLW	High-level waste
HLWG	High-level waste glass
ID	Inner diameter
MTHM	Metric tons of heavy metal
NEPA	National Environmental Policy Act (1970)
NRC	Nuclear Regulatory Commission
NWPA	Nuclear Waste Policy Act (1984, 1987)
ppf	pounds per foot
OD	Outer diameter
PA	Performance assessment
PWR	Pressurized water reactor
RMEI	Reasonably maximally exposed individual
SKB	Svensk Kärnbränslehantering AB (Swedish Nuclear Fuel and Waste Management Co.)
SNF	Spent nuclear fuel
TRU	Transuranic (waste)

1. INTRODUCTION

The purpose of this report is to document an evaluation and analysis of several factors (technical, regulatory, safety and performance) concerning the potential for a deep borehole disposal program, particularly with regard to the US, but also relevant to any agency or institution considering the potential for a borehole disposal program.

In 1957 the US National Academy of Sciences Committee on Waste Disposal considered both deep borehole disposal of radioactive waste (in liquid form) and mined storage of radioactive waste in a positive light (National Academy of Sciences 1957). The intervening half-century has seen high-level waste (HLW) and spent nuclear fuel (SNF) disposal efforts in the US and other nations focus primarily on mined repositories, yet over the same time, the potential technical and cost advantages of deep borehole disposal have become more apparent. Radioactive waste emplaced in solid form (spent fuel or glass) at the bottom of deep (3-5 km) boreholes in crystalline basement rocks – typically granites (see schematic in Figure 1) - with off-the-shelf oilfield technology would be more effectively isolated from the biosphere than waste emplaced in shallower, mined repositories. The physical transport of radionuclides away from HLW and SNF at multi-kilometer depths would be limited by: low water content, low porosity and low permeability of crystalline basement rock, high overburden pressures that contribute to the sealing of transport pathways; and the presence of convectively stable saline fluids. Deep borehole disposal of radioactive waste has the added advantage of not producing as large a "thermal footprint" as a mined geologic repository, because boreholes placed more than ~200 m apart are unlikely to thermally affect one another.

DOE estimates that 109,300 metric tons heavy metal (MTHM) of high-level waste and spent nuclear fuel – primarily commercial spent nuclear fuel (CSNF), but also DOE spent nuclear fuel (DSNF), and high-level waste glass (HLWG) – will need to be disposed of in the US (the projected US HLW and SNF inventory is summarized in Appendix A).

Deep borehole disposal, characterization and excavation costs should scale linearly with waste inventory: small inventories require fewer boreholes; large inventories require more boreholes. Not needing a specially engineered waste package would also lower overall borehole disposal costs. Both aspects might make borehole disposal attractive for smaller national nuclear power efforts (having an inventory of 10,000 MTHM or less). In the US, the 70,000 MTHM of waste currently proposed for Yucca Mountain could be accommodated in about 600 deep boreholes (assuming each deep borehole had a 2 km long waste disposal zone that contained approximately 400 vertically stacked fuel assemblies). The remainder of the projected inventory of 109,300 MTHM could be fit into an additional 350 or so boreholes.

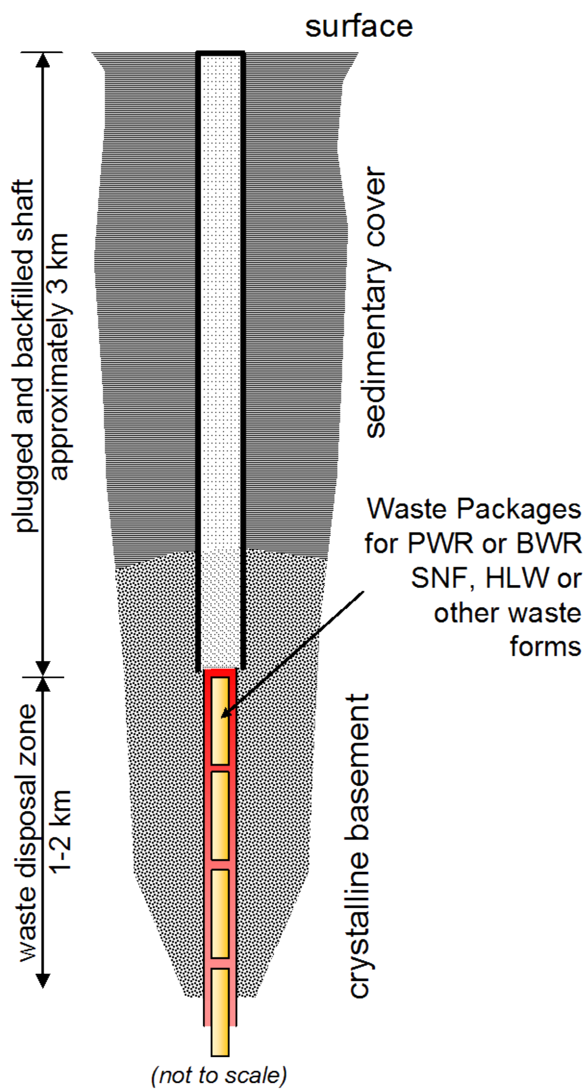


Figure 1. Deep Borehole Disposal Schematic.

Because crystalline basement rocks are relatively common at 2-5 km depth (See Figure 2; also see O'Brien et al. 1979; Heiken et al. 1996), the US waste disposal burden might be shared by shipping waste to regional borehole disposal facilities. If located near existing waste inventories and production, shipping would be minimized. A disposal length of ~2km, and holes spaced 0.2km apart suggests the total projected US inventory could be disposed in several borehole fields totaling ~30 square kilometers.

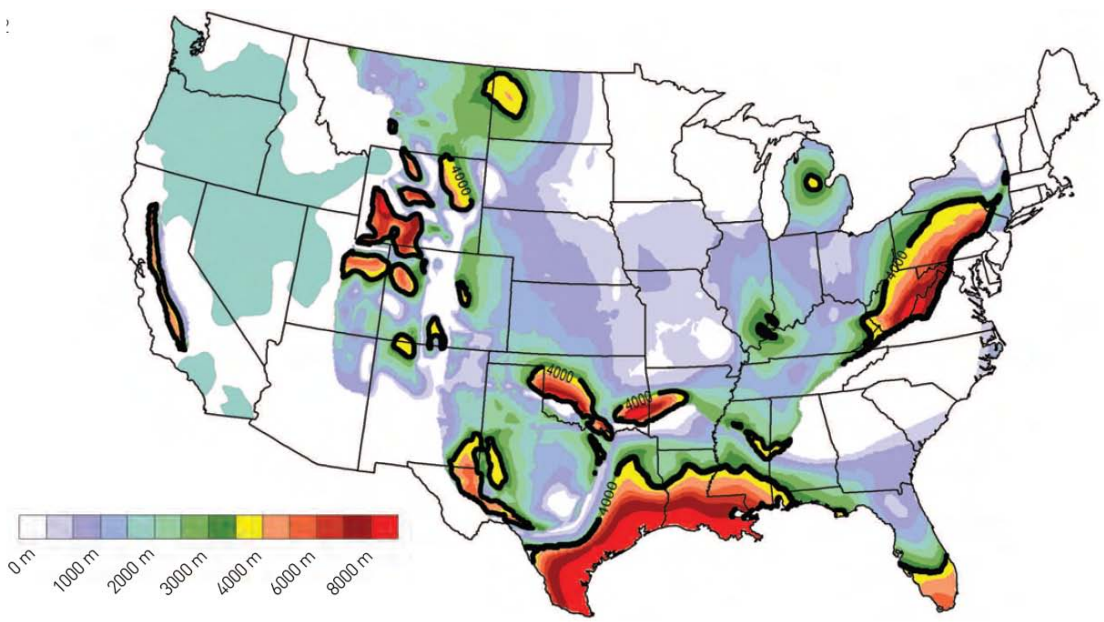


Figure 2. Sediment Thickness Map of the US (MIT, 2006).

Petroleum drilling costs have decreased to the point where boreholes are now routinely drilled to multi-kilometer depths. Research boreholes in Russia and Germany have been drilled to 8-12 km. The drilling costs for 950 deep boreholes to dispose of the entire 109,300 MTHM inventory, assuming a cost of $20 million per borehole (see Section 3.1), would be ~ $19 billion. Very rough estimates of other costs are $10 billion for associated site characterization, performance assessment analysis, and license application, $20 billion for disposal operations, monitoring, and decommissioning, $12 billion for ancillary program activities, and $10 billion for transportation, resulting in a total life-cycle cost for a hypothetical deep borehole disposal program of $71 billion (in 2007 dollars). Although there are significant uncertainties in the cost estimates for deep borehole disposal presented here, the estimated total life-cycle cost may be significantly lower than the estimated total cost of Yucca Mountain. Note in particular the lower construction/operation and transportation outlays that borehole disposal would allow.

This document outlines a technical and performance assessment analysis of deep borehole disposal of US HLW and SNF. Section 2 examines how federal regulations might be applied to deep borehole disposal. Section 3 outlines the technical basis for deep borehole disposal and the engineering obstacles that must be overcome. Sections 4 and 5 consider potential release scenarios and present a preliminary performance assessment of the deep borehole disposal safety case. Section 6 concludes with a summary and recommendations of future work.

2. ASSUMPTIONS ABOUT A REGULATORY FRAMEWORK

The current regulatory and legal framework for radioactive waste management is centered on mined geologic repositories, and was not intended to be applied to the long-term performance of deep borehole disposal systems. The Nuclear Waste Policy Act (NWPA) restricts consideration of geologic repositories in the United States to a single site, Yucca Mountain in Nevada, and EPA and NRC regulations (40 CFR part 197 and 10 CFR part 63, respectively) have been written specific for that site. Implementation of a deep borehole disposal system would, therefore, at a minimum, require amendment of the Nuclear Waste Policy Act. In principle, existing regulations from the 1980s that predate the selection of Yucca Mountain (i.e., 40 CFR part 191 and 10 CFR part 60) could be applied to borehole disposal systems without modification. However, these early regulations are inconsistent with recommendations provided to the EPA in 1995 by the National Research Council of the National Academies of Science and Engineering at the request of Congress, which called for system-level performance metrics based on annual risk, and may therefore be viewed as inadequate.

In order to evaluate the system performance of a deep borehole disposal concept, it it necessary to adopt or develop a regulatory standard by which the performance can be measured. For the purposes of this preliminary analysis, the NWPA is assumed to be amended to allow consideration of sites other than Yucca Mountain and alternative disposal concepts, and new regulations are assumed to be promulgated that are similar in key regards to the current Yucca Mountain regulations, consistent with the EPA's interpretation of the National Academies' recommendations as promulgated in 40 CFR part 197. Thus, the primary overall performance measure of interest is mean annual dose to a hypothetical individual, with limits set at 0.15 mSv/yr for 10,000 years following disposal and for 1 mSv/yr for the period between 10,000 years and 1 million years. Other details of the regulatory framework, including screening criteria for potentially relevant features, events, and processes, as described in Section 4, are also assumed to be unchanged from those stated in 40 CFR part 197 and 10 CFR part 63, with the exception of human intrusion scenarios, for which new regulatory requirements would need to be developed. Four assumptions warrant further explanation.

First, for simplicity in modeling, all characteristics of the hypothetically exposed individual are assumed to be identical to those of the "reasonably maximally exposed individual" defined in 40 CFR part 197: these characteristics are appropriate for humans living in arid regions similar to Yucca Mountain, but may need to be reconsidered for disposal sites in other regions. The assumption should in no way be interpreted as indicating a preference in this analysis for one geographic region over another: the assumption was made solely to allow the use of existing information regarding biosphere pathway analyses. As shown later in this report (see Section 5), this assumption has little or no impact on overall estimates of performance.

Second, the exposed individual is assumed for the purposes of this analysis to live directly above the waste, rather than 18 kilometers away from the repository, as specified in 40 CFR part 197. This assumption focuses the analysis on the isolation provided by the deep geologic setting, and avoids speculation about site-specific aspects of geology closer to the land surface.

Third, requirements in both the NWPA and the EPA and NRC regulations specific to the retrievability of waste are assumed to be modified to reflect the more permanent disposal nature of a deep borehole disposal system. Although retrievability would be maintained during emplacement operations, waste may not be fully recoverable once the borehole has been sealed, and deep borehole systems may not be the best choice if permanent and irreversible disposal is not intended. Consistent with this observation, it should be noted that although the analysis presented in this report treats the direct disposal of SNF as a bounding performance case, deep borehole disposal systems may be particularly appropriate for other waste forms, including reprocessing wastes.

Fourth, this analysis considers only a single disposal borehole. Actual disposal systems would likely contain an array of multiple boreholes, and it may be appropriate therefore to scale performance estimates upward for larger numbers of boreholes. Individual boreholes in a disposal array are assumed to be placed sufficiently far apart, however, that interactions among the holes will be insignificant and it would be conservative to assume that any single individual human could be exposed to the sum of the releases from all boreholes in a repository.

A feature of deep borehole disposal concepts is the potential for multiple implementations where several disposal fields (borehole arrays) could be developed, each serving a given region, and each expected to encounter similar conditions at depth. The hydrogeologic and hydrochemical conditions common to deep granitic basement rock are thought to be advantageous to borehole disposal system performance. As shown in Figure 2, many regions within the US have granitic rocks at an appropriate depth and therefore many viable sites for borehole disposal are conceivable. In this regard, future regulatory frameworks developed for deep borehole disposal may best be served by establishing generic criteria (analogous to 10 CFR 60) rather than attempt to create multiple site-specific standards.

Lastly, although the analysis presented here is for SNF as a bounding performance case, it should be recognized that borehole disposal systems may be particularly appropriate for other waste forms (e.g., spent sealed sources), and, thus, new regulations could reflect the generic factors which favor borehole disposal system performance, as well as acknowledge particular waste form characteristics (e.g., low heat production, low radionuclide concentration, etc).

3. TECHNICAL BASIS AND CHARACTERIZATION

Deep emplacement of HLW and SNF in crystalline basement rocks underlying sedimentary strata is expected to provide effective long-term (> 1 million years) isolation of radionuclides from the biosphere due to the following thermal, hydrologic, chemical, and mechanical characteristics of the borehole and the surrounding rock at depths of several kilometers:

- **Long transport pathways** - Potential transport pathways to the biosphere are long and would therefore involve extensive radioactive decay, dilution, formation of radionuclide-bearing phases, and retardation, given the impediments to vertical migration of radionuclides from several kilometers depth.
- **Slow fluid movement** - Fluid movement at > 4 km depth is inhibited by low porosities (< 1%), very low permeabilities (10^{-16} to 10^{-20} m^2), and the presence of convectively-stable, high ionic strength brines (≥ 150 g/L) (See Table 1) in the rock. The permeabilities of deep crystalline rock are roughly 10 orders of magnitude less than those of gravel aquifers. The porosities of deep crystalline rock are 10 to 40 times less. Deep crystalline rocks typically have low water content. Minimal hydrologic flow is thought to occur, primarily through discontinuous fractures. Fluid movement up boreholes will likewise be limited by low permeabilities in the filled borehole and/or disturbed rock annulus which are expected to range from 10^{-13} m^2 for fractured rock to 10^{-16} m^2 for packed sediments, to 10^{-18} m^2 for clay or bentonite (Freeze and Cherry, 1979; Table 2.2).
- **Insufficient upward ambient driving pressure** – Basement rocks do not typically contain pressurized aquifers or other flow features that would produce significant upward flow gradients under ambient conditions. Therefore, the most significant driving force for fluid flow and radionuclide migration away from a deep borehole is likely to be minor thermal pressurization from decay heat.
- **Chemical conditions limit radionuclide release and transport** – Reducing conditions are likely to prevail at depth which will maintain fuel and most radionuclides at very low solubilities. High ionic strength brines will limit the formation and movement of radionuclide-bearing colloids. Finally, sorption of many radionuclides onto the crystalline rock and/or borehole fill material will retard transport.
- **Mechanical stability** – Crystalline rocks such as granites are particularly attractive for borehole emplacement because of their large size, relatively homogeneous nature, low permeability and porosity, and high mechanical strength (to resist borehole deformation). In addition, high overburden pressures contribute to sealing of some of the fractures that provide transport pathways.

Table 1. Typical Deep Borehole Characteristics (Juhlin and Sandstedt 1989).

Borehole	Maximum depth of water circulation (m)	Minimum depth to high salinity water (m)	Permeability below 1000 m (m^2)
USA-10	900	1800	10^{-18}
FRG-2	500	3500	Not Reported
SWT-1	1050	1326	$10^{-16} – 10^{-20}$
URS-1	800	1200	10^{-19}
SWE-1	1200	>6000	10^{-16} -10^{-17}

To support the performance assessment analysis of Section 5, an underlying technical basis must be selected for, at a minimum, the physical design, the predicted thermal effects, and the near-field chemical characteristics. Section 3.1 lays out a deep borehole design. Section 3.2 describes the thermal effects from decay heat on the hydrologic behavior of the borehole. Section 3.3 outlines the chemical characteristics of the borehole and the surrounding rock.

3.1. Deep Borehole Design

As noted in Section 1, the projected US waste inventory of 109,300 MTHM would require several hundred deep boreholes for disposal, assuming no reprocessing or other mechnical consolidation of SNF. The analysis in this section focuses on the design, drilling, and performance of a single borehole.

3.1.1. Waste Canisters

Emplacing intact spent fuel assemblages, without pre-consolidation, is one of the simplest approaches to borehole disposal (Hoag 2006), and is the one considered here. CSNF assemblages come in two types: those used in pressurized water reactors (PWRs) and those used in boiling water reactors (BWRs). Nearly all (98%) of US BWR assemblies are 4476 mm long and 139 mm wide, or smaller. Most (80%) of PWR assemblies are 214 mm wide and 4059 mm long (See Table 2), or smaller (DIANE Publishing Company 1995).

Table 2. Reference PWR and BWR Fuel Assembly Dimensions and Masses.

	Height (mm)	Width (mm)	Mass (kg)
PWR	4059	214	666
BWR	4476	139	297
	(feet/inches)	**(inches)**	
PWR	13’ 3”	8.4	
BWR	14’ 7”	5.5	

Source: Dimensions are from Table 28 of (DIANE Publishing Company 1995). Masses are from Section 7.2.2 of (Juhlin and Sandstedt 1989).

The transverse (i.e., diagonal width) dimension of a PWR assembly is 11.9" (302 mm); that of a BWR assembly is 7.8" (198 mm). A canister made of standard oilfield casing 5 m tall and having an inner diameter of 12-1/2" (318 mm) and an outside diameter of 13-3/8" (340 mm) could therefore hold one PWR assembly (Hoag 2006) or, with considerable extra space, one BWR assembly. End-caps would be welded on after assemblies had been inserted into the canisters. The disposal canister must be strong enough to prevent releases and exposure through the waste emplacement phase, including recovery operations for canisters that are stuck or damaged during emplacement. To maintain early physical stability, the inner void spaces would be filled with powdered bentonite. The canister is expected to possess no other intrinsically waste-isolating characteristics.

3.1.2. Boreholes

It is anticipated that boreholes will be on the order of 5 km (~16,400 ft) deep. A 1-2 km long waste disposal zone (the lower portion of the borehole) might conceivably hold 200-400 canisters. The canisters could be emplaced one at a time or as part of a canister string – a grouping of 10 or 20 canisters.

The in situ stress of the basement rock at depth will be assessed to determine deep borehole compatibility with the stress condition. The large boreholes will need to remain stable during the construction phase until the casing is cemented in, the waste canisters are emplaced, and the boreholes are plugged/backfilled. Also, horizontal stresses in the borehole region will increase after waste emplacement due to thermal expansion of the rock caused by heat from radioactive decay of the emplaced waste. These anticipated stresses will be evaluated as part of the borehole design.

The design concept for deep borehole disposal is such that a borehole will accommodate a 13-3/8" (340 mm) OD canister. The depths for each borehole section are approximate and are presented as examples of the design which may vary depending on the specific site geology. However, the disposal concept is keyed to deep placement of waste at depths of 3-5 km (~10,000-16,400 ft).

From the surface down the design is as follows (Figure 3):

1. 48" (1219 mm) Conductor hole with 40" (1016 mm) conductor pipe to 50 ft (~15 m) depth
2. 36" (914 mm) Surface Hole with 30" (762 mm) 310 ppf X-56 Line Pipe to 500 ft (~150 m)
3. 26" (660 mm) Intermediate Hole with 20" (508 mm) 169 ppf N-80 BTC Seamless to 5,000 ft (~1,500 m)
4. 17 ½" (445 mm) Bottom Hole with 16" (406 mm) casing to 17,000 ft (~5,200 m) (cemented from 5000 ft to total depth, upper 5000 ft removed after canister placement and sealing).

The cement in the waste disposal zone will be engineered to accommodate thermally induced stresses during the emplacement time and chemical requirements for appropriately longer time periods.

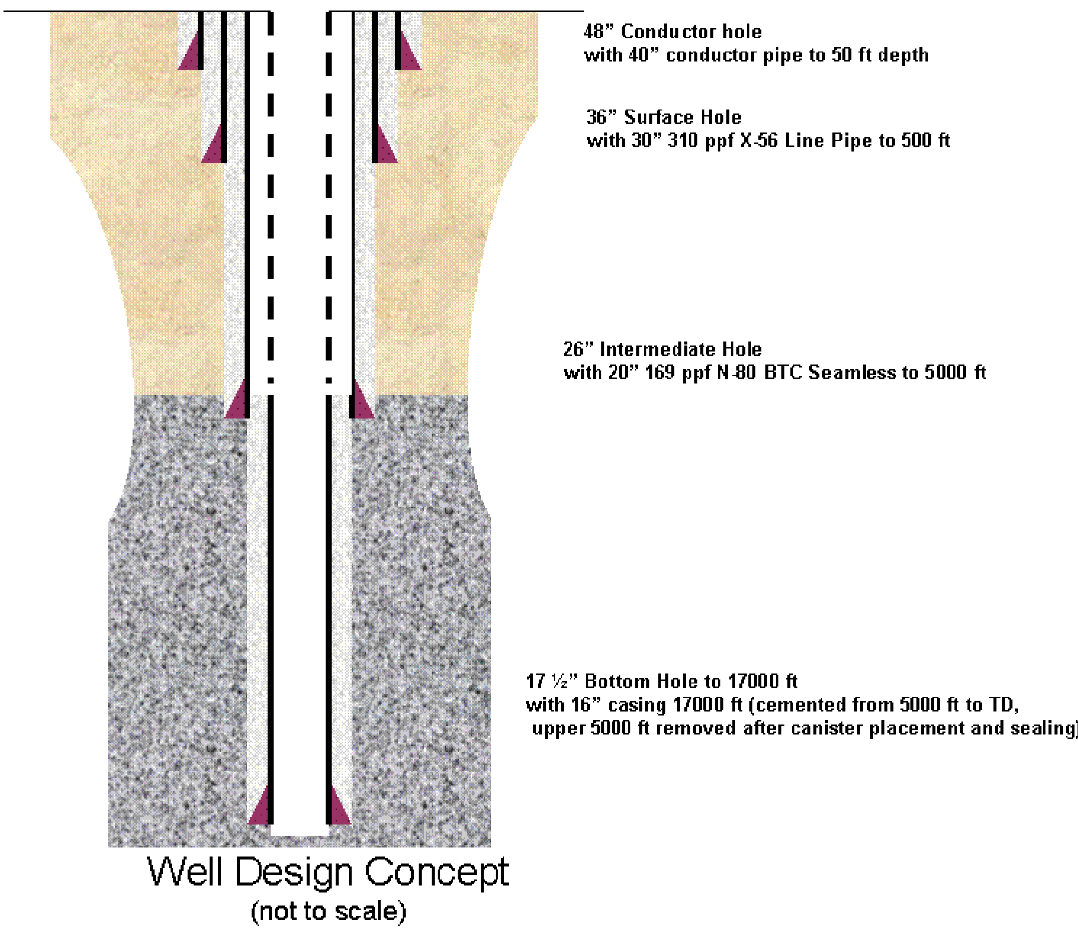


Figure 3. Deep Borehole Drilling Design Concept.

3.1.3. Seals

The borehole seal system is designed to limit entry of water and migration of contaminants through the borehole after it is decommissioned. The key features of the seal system design are that it exhibits excellent durability and performance and is constructible using existing technology. The design approach applies redundancy to functional elements and specifies multiple, common, low-permeability materials to reduce uncertainty in performance.

In the waste disposal zone itself, bentonite will be used as a buffer/seal material because of its low permeability, high sorption capacity, self-sealing characteristics, and durability. The canister strings will be surrounded by "deployment mud" comprised of bentonite-water slurry.

Canister strings will be separated by an approximately 1 m interval of compacted bentonite. Compacted bentonite will also be used at the top of the waste disposal zone, above the canister strings.

Mechanical barriers (bridge plug, packer, etc.) in the casing at the top of the waste disposal zone could be used to isolate the wellbore. However, the elastomeric materials typically used as part of their sealing element will degrade over time and there may be operational difficulties in running (or retrieving) the plugs. Therefore this option is not considered to be desirable or highly feasible.

The upper 1,500 m (5,000 ft) of the emplacement borehole casing will be removed after canister placement and sealing. A borehole seal system extending from the top of the waste disposal zone to the surface will be deployed to further isolate the emplaced wastes from the accessible environment. This borehole seal system will use a combination of bentonite, asphalt and concrete. The main seal will consist of compacted bentonite packs placed in a bentonite-water slurry (deployment mud). If the intermediate 20” casing is left in the borehole, this casing can be milled out at appropriate intervals to allow free movement of the sealing medium from the hole to the annulus and surrounding rock.

A top seal will consist of asphalt from 500 m to 250 m, with a concrete plug extending from 250 m to the surface. Seal materials are discussed below.

Compacted Clay

Compacted clays are commonly proposed as primary sealing materials for nuclear waste repositories and have been extensively investigated against rigorous performance requirements (e.g., Van Geet 2007). Advantages of clays for sealing purposes include: low permeability, demonstrated longevity in many types of natural environments, deformability, sorptive capacity, and demonstrated successful utilization in practice for a variety of sealing purposes. Compacted clay as a borehole sealing component functions as a barrier to water flow and radionuclide movement and possibly to gas flow.

The exact specification for compacted clays used in borehole sealing will depend upon site-specific details such as water chemistry, but an extensive experimental data base exists for the permeability of a variety of bentonite clays under a variety of conditions. Bentonite clay, a highly plastic swelling clay material (Mitchell 1993) is chosen here because of its positive sealing characteristics. Compacted bentonitic clay can generate swelling pressure and wetted swelling clay will seal fractures as it expands into available space and will ensure conformance between the clay seal component and the borehole walls.

Bentonitic clays have been widely used in field and laboratory experiments concerned with radioactive waste disposal. Verification of engineering properties such as density, moisture content, permeability, or strength of compacted clay seals can be determined by direct and indirect measurement during construction.

Asphalt

Asphalt is used to prevent water migration down the borehole. Asphalt is a strong cement, readily adhesive, highly waterproof, and durable. Furthermore, it is a plastic substance that is readily mixed with mineral aggregates. A range of viscosity is achievable for asphalt mixtures. It is highly resistant to most acids, salts, and alkalis. Asphalt has existed for tens of thousands of years as natural seeps. Longevity studies specific to DOE's Hanford site have utilized asphalt artifacts buried in ancient ceremonies to assess long-term stability (Wing and Gee 1994). Asphalt used as a seal component deep in the borehole will encounter a benign environment, devoid of ultraviolet light or an oxidizing atmosphere. For these reasons, it is believed that asphalt components will possess their design characteristics for an extended period of time. For example, studies conducted for WIPP indicate that the permeability of a massive asphalt column is expected to have an upper limit of 1×10^{-18} m^2 for an extensive period of time (DOE 1996).

Construction of the seal components containing asphalt can be accomplished using a slickline process where low-viscosity heated material is effectively pumped into the borehole. Sufficient construction practice and laboratory testing information is available to assure performance of the asphalt component. Laboratory validation tests to optimize viscosity may be desirable before final installation specifications are prepared.

Concrete

Concrete has low permeability and is widely used for hydraulic applications. The exact concrete composition will depend upon site-specific geology and water chemistry, but performance can be established through analogous industrial applications and in laboratory and field testing. For example, laboratory and field testing have shown that the Salado Mass Concrete used in the WIPP will remain structurally sound and possess very low permeability (between 2×10^{-21} and 1×10^{-17} m^2) for long periods (DOE 1996). Standard ASTM specifications exist for both green and hydrated concrete properties. Quality control and a history of successful use in both civil construction and mining applications will assure proper placement and performance.

3.1.4. Cost and Schedule

The deep disposal borehole design presented above is similar to the geothermal well design analyzed by Polsky et al. (2008) in well diameter, depth, and lithology. Therefore, the geothermal well construction cost and schedule analysis (combinations of labor, equipment, and materials) from Polsky et al. (2008) can be used to estimate costs and schedule for a deep disposal borehole. In 2008 dollars, a 5 km (~16,400 ft) deep well will cost about $20 million and take about 110 days to construct (Figure 4). Thus base costs for ~1000 boreholes (to accommodate the total projected US inventory) would be ~$20B, not including emplacement operations, licensing, etc. Assuming emplacement and sealing could be accomplished in ~100 additional days, and with 10 separate disposal fields of ~100 holes each (covering ~3 square kilometers or 1-2 square miles), then ~50 years would be needed to emplace the total projected US inventory.

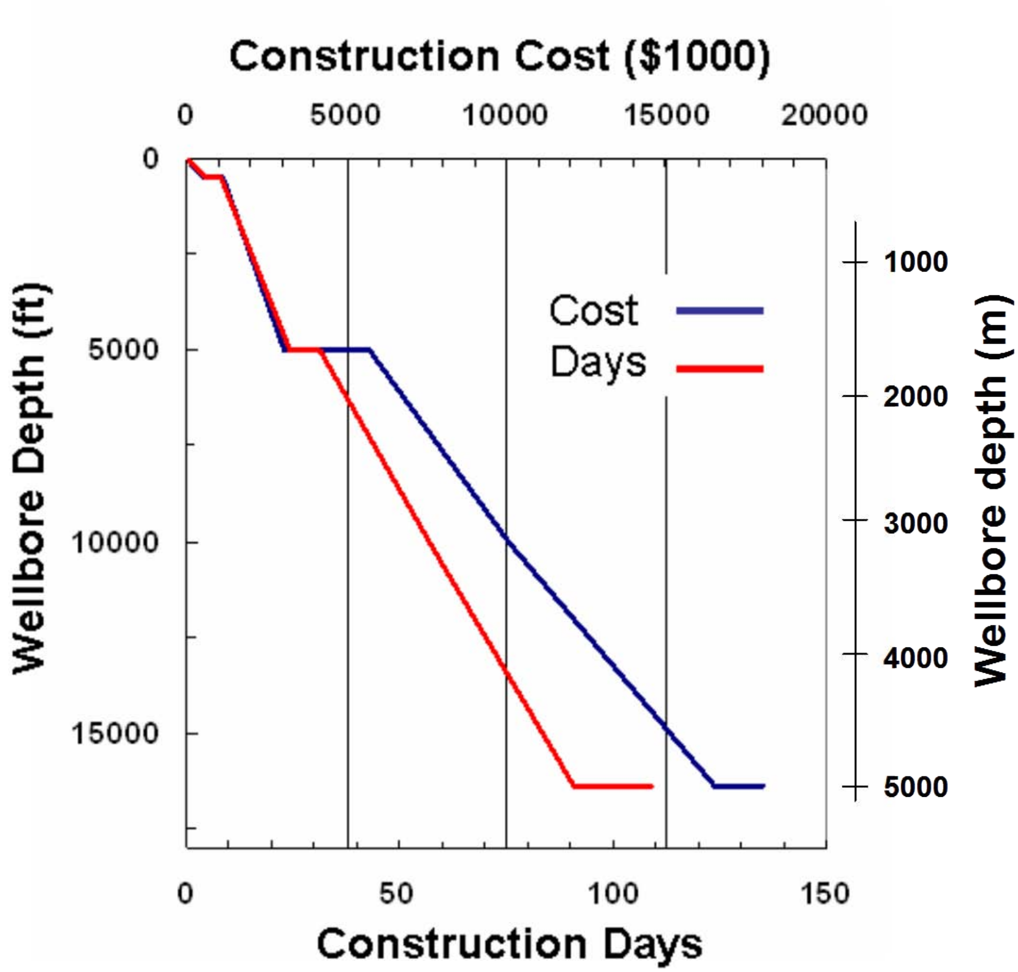


Figure 4. Deep Borehole Drilling Design Schedule and Cost.

3.2. Thermal Effects on Hydrologic Environment

Thermal conditions in deep boreholes have been considered in detail recent years by Gibb and co-workers (e.g., Gibb, McTaggart et al. 2008). The most significant driving force for fluid flow and radionuclide migration away from a deep borehole is likely to be due to thermal pressurization from decay heat. An analysis of these effects on the hydrologic behavior of the deep borehole is presented here.

3.2.1. Heat Conduction

Temperatures within the borehole and the host rock were simulated using a horizontal, two-dimensional model of thermal conduction implemented with the FEHM software code (Zyvoloski, Robinson et al. 1997). The model domain is 2,000 m square, centered on the borehole, with an unstructured grid of progressively higher resolution near the waste canister. The thermal conduction model was constructed using the design basis concepts and dimensions from Hoag (2006), with a borehole diameter of about 50 cm and assuming a depth of 4 km.

Constant temperature boundary conditions of 110 ^{o}C are assigned at the lateral boundaries of the model, which are sufficiently distant from the borehole to minimize impacts on the temperature simulations near the borehole. The geothermal gradient is assumed to be 25 ^{o}C/km and the average near surface temperature is assumed to be 10 ^{o}C. The model uses the heat output curves for a single average pressurized water reactor (PWR) fuel assembly that has been aged for 25 years, as used for the Yucca Mountain performance assessment modeling (Sandia National Laboratories 2008). Representative values of thermal conductivity for granite (3.0 W/ m ^{o}K), thermal conductivity of bentonite grout (0.8 W/ m ^{o}K), bulk density of granite (2750 kg/m^{3}), specific heat of granite (790 J/kg ^{o}K), and porosity of granite (0.01) are used in the thermal conduction model.

Figure 5 shows the temperature histories for the waste package wall, borehole wall, and several distances from the centerline of the borehole simulated in the vicinity of a borehole containing stacked individual spent fuel assemblies. The model did not attempt to simulate the temperatures within the waste canister. Temperature increases in the vicinity of the borehole are not large, do not persist for long periods of time, and drop off rapidly with distance from the borehole. Temperatures at the borehole wall peak at about 30 ^{o}C higher than the ambient temperature of the host rock within ten years of waste emplacement. Temperature increases would be significantly higher for fuel assemblies that have not been aged as long or if the thermal conductivity of the granite were significantly lower than the assumed value (3.0 W/ m ^{o}K).

Simulated temperature increases near the waste emplacement borehole from the thermal conduction model are significantly lower than those calculated in a previous study by ONWI (Woodward-Clyde Consultants 1983), which showed simulated peak temperature increases at the borehole wall of 150 ^{o}C to 200 ^{o}C. However, the ONWI (Woodward-Clyde Consultants 1983) modeling considered reprocessed high-level waste (HLW) that had been aged only 10 years and which had a higher initial heat output of 2,600 W/canister compared to 580 W/canister of the older spent nuclear fuel considered here.

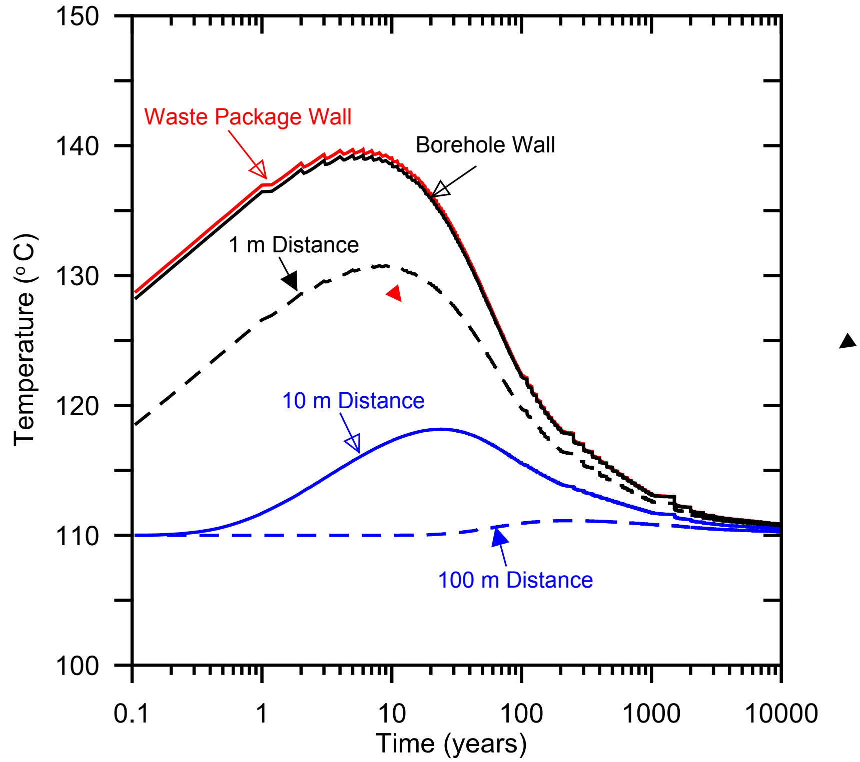


Figure 5. Temperature as a Function of Time and Distance from the Borehole for PWR Spent Fuel Assembly Disposal

A similar analysis of thermal conduction was performed for borehole disposal of vitrified HLW from the reprocessing of spent nuclear fuel. This model uses the same model domain and parameter values as those described above. The heat output curves are for the current vitrified waste produced by reprocessing of commercial spent nuclear fuel in France (Andra 2005). For this analysis it is assumed that the waste is aged for 10 years before disposal and that the vitrified waste fills the waste canister with an inside diameter of 318 mm.

The resulting temperature histories for varying distances from the centerline of the disposal borehole are shown in Figure 6. The simulated temperature increases are significantly higher for the disposal of HLW than those for disposal of spent fuel assemblies, with the temperature increasing by about 125 °C at the borehole wall at the time of peak temperature. Temperatures decline more rapidly for the disposal of HLW because the heat output from the reprocessing waste is dominated by the relatively short-lived fission products ^{90}Sr and ^{137}Cs. It should be noted that the thermal impacts of HLW disposal could easily be controlled by reducing the diameter of the waste canisters or by reducing the concentrations of fission products in the waste glass. Reducing the diameter of the waste canister by a factor of two would reduce the thermal output per meter of borehole and the peak increase in temperatures by about a factor of four.

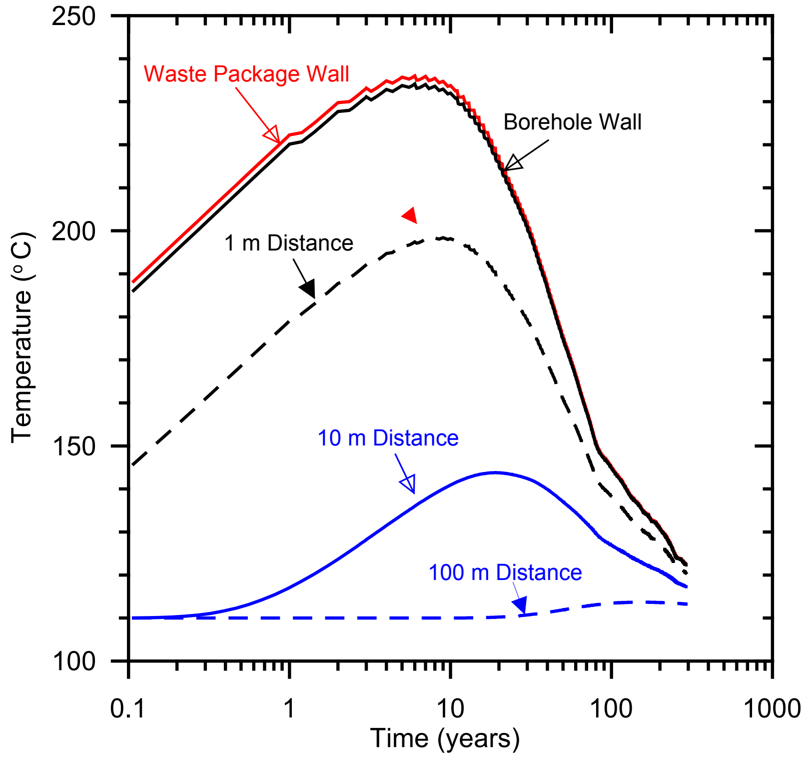


Figure 6. Temperature as a Function of Time and Distance from the Borehole for Disposal of Vitrified HLW from Reprocessing.

3.2.2. Thermally Driven Hydrologic Flow

The heat generated from the waste emplaced in the borehole will cause fluid temperatures and pressures to rise in the vicinity of the waste. The elevated pressure will drive fluid away from the heated zone. The path of least resistance will be up the sealed borehole and adjacent disturbed host rock, where permeabilities are likely to be higher than that of the undisturbed bedrock. To assess potential transport, vertical fluid flow rates were estimated using a vertical, radial, two-dimensional model of coupled heat and fluid flow implemented with the FEHM software code (Zyvoloski, Robinson et al. 1997).

The model domain is a cylinder with a radius of 100 m and height of 4,000 m (Figure 7). Constant temperature boundary conditions of 60 °C for the top (depth = 2 km) of the domain and 160 °C for the bottom (depth = 6 km). The sides were held at a constant temperature consistent with the assumed geothermal gradient.

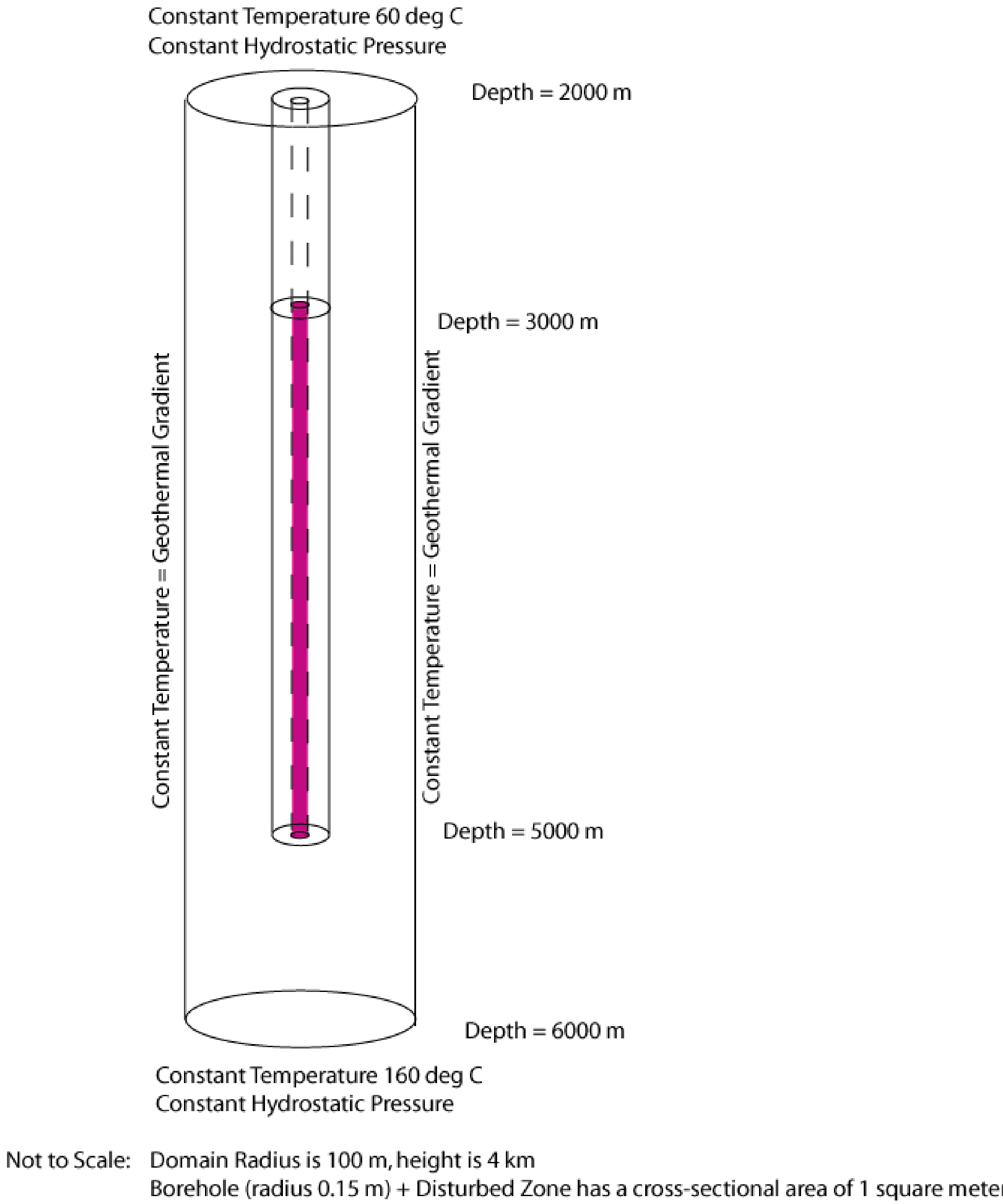


Figure 7. Model Domain for Coupled Heat and Fluid Flow Simulation to Estimate Vertical Fluid Velocities in the Heated Borehole. The waste disposal zone (the waste filled-borehole region that generates heat) is shown in pink.

The simulation was initiated with hydrostatic conditions in equilibrium with the geothermal gradient. Flow was allowed through the top and bottom boundaries by fixing the flowing pressure at the boundaries to the initial hydrostatic pressures. The domain is divided into four materials: undisturbed bedrock, disturbed bedrock, sealed borehole (above the waste disposal zone) and waste-filled borehole (the 2,000-m waste disposal zone). The flow path for fluids to be transported toward the surface is conceptualized to be in the combined sealed borehole and disturbed zone surrounding the borehole. The cross sectional area of this combined zone is assumed to be 1 m^2. Properties assigned to these materials are listed in Table 3 and are consistent with the properties used in the thermal-conduction model described in the previous section. Properties assigned to bedrock are representative of typical granite. The sealed borehole (radius = 0.15 m in this calculation) is characterized as being sealed with bentonite. The waste filled borehole is assigned a high thermal conductivity, typical of steel, a low porosity, and a permeability equal to the disturbed bedrock. The waste filled borehole material (i.e., the waste disposal zone) is modeled as a time-dependent heat source, consistent with the source used in the thermal-conduction model for typical PWR fuel assemblies that have been aged 25 years and subsequently stacked one on top of another 2,000 m deep. Disposal of reprocessing HLW with a higher heat output could have a larger impact on thermally-driven flow than analyzed for PWR here.

Table 3. Material Properties for Borehole Flow Model.

Property	Bedrock	[a]Disturbed Bedrock	Sealed Borehole	Waste-Filled Borehole
Permeability [m^2]	10^{-19}	10^{-16}	10^{-16}	10^{-16}
Density [kg/m^3]	2,750	2,750	2,750	2,750
Specific heat [MJ/kg-°K]	790	790	760	760
Thermal Conductivity [W/m-°K]	3.0	3.0	0.8	46.0
Porosity	0.01	0.01	0.35	0.0001

[a]Assumes presence of grout/backfill.

The model was used to simulate flow conditions for 100,000 years, although no significant flow occurred after 10,000 years. Figure 8, shows the vertical fluid specific discharge as a function of time for two locations in the borehole: (1) a depth of 3,000 m corresponding to the top of the waste disposal zone, and (2) a depth of 2,000 m corresponding to the top of the model domain.

The results demonstrate that upward fluid velocities at the top of the waste disposal zone occur immediately upon the addition of heat to the system. Flow at the top of the model domain is delayed slightly and is of lower magnitude than at the top of the waste disposal zone. This result is expected since the vertical head gradient decreases with distance away from the heat source and, also, a fraction of the flow will be oriented horizontally into the bedrock, thus decreasing the vertical flow with distance up the borehole. Flow increases quickly and then gradually decreases as the radioactive heat source decays with time.

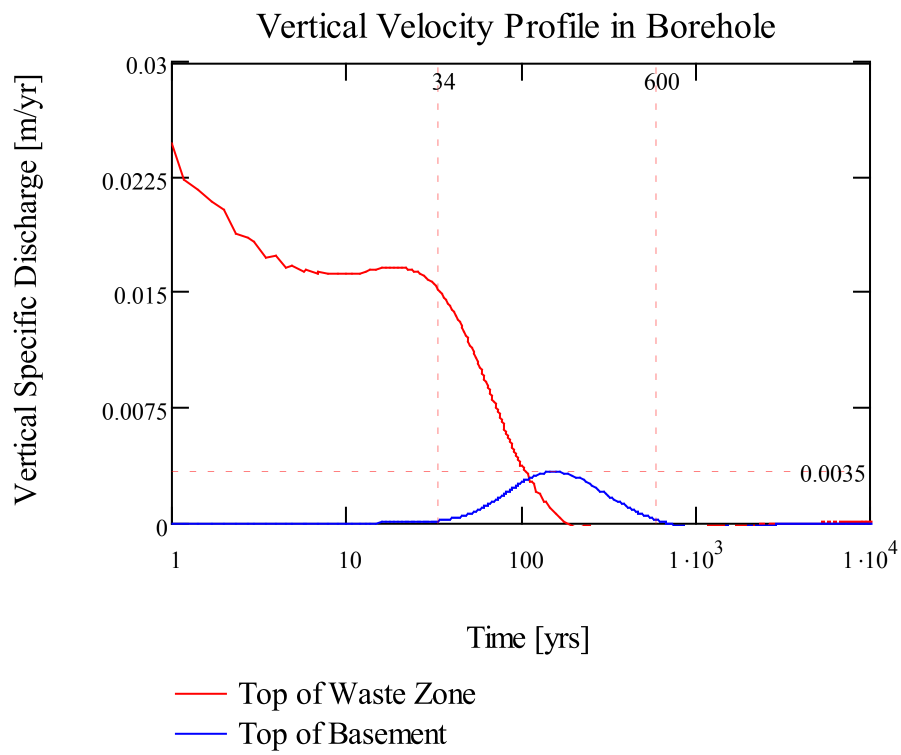


Figure 8. Vertical Specific Discharge at Two Locations as a Function of Time (Log Axis).

Hydrologic pore velocity is equal to specific discharge divided by porosity. Pore velocity is equivalent to the transport velocity for an unretarded radionuclide. Since the flow path above the waste zone is comprised of an inner sealed borehole of radius 0.15 m and a porosity of 0.35 and the outer ring-shaped disturbed zone of radius $1/\sqrt{\pi}$ = 0.564 m and a porosity of 0.01, the area weighted average porosity of the flow path is 0.034. Thus the maximum pore velocity at the top of the waste zone is 0.662 m/yr, but upward flow in this area only occurs for the first approximately 180 years. Maximum pore velocity at the top of the basement domain peaks at 0.103 m/yr at about 150 years. Upward flow will occur from approximately 34 to 600 years.

The model results shown in Figure 8 indicate that upward fluid flow in the heated borehole only persists for a relatively short period of time (<1,000 yrs) after emplacement. Fluid movement is primarily caused by the local elevated pressures due to thermal expansion of the pore water. As the heat generation decreases, the temperature of the waste decreases and the fluid begins to contract, lowering pressure. Buoyancy forces are not significant in this system because heat flow is primarily conductive rather than advective. The permeability of the sealed borehole would have to be significantly higher and there would have to be a source of water connected to the borehole by a high-permeability conduit in order for buoyancy-driven flow (i.e., a chimney effect) to be an important factor. Because the actual pore water density will likely increase with depth due to salinity stratification, this simulation probably represents an upper bound on the fluid flow rates.

Figure 9 displays the temperature histories as a function of horizontal distance away from the borehole at the depth in the middle of the waste disposal zone (at ~4 km depth). Note that the modeled temperatures are very similar to those calculated with the thermal model (see Figure 5). The main difference is the assumption that the temperatures at 100 m remain constant in the flow model. This assumption is not expected to significantly affect the flow rates up the borehole.

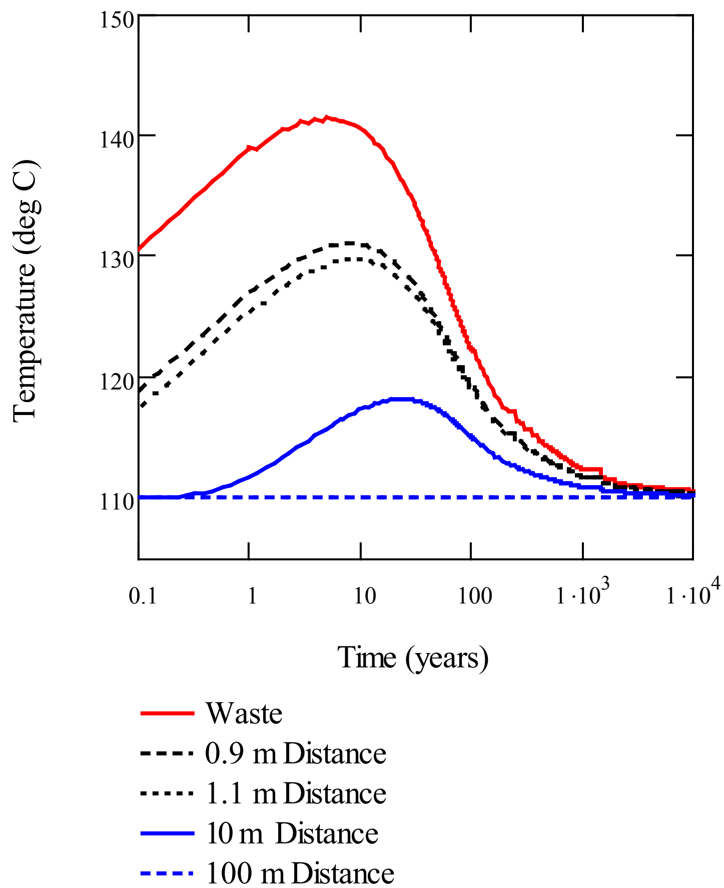
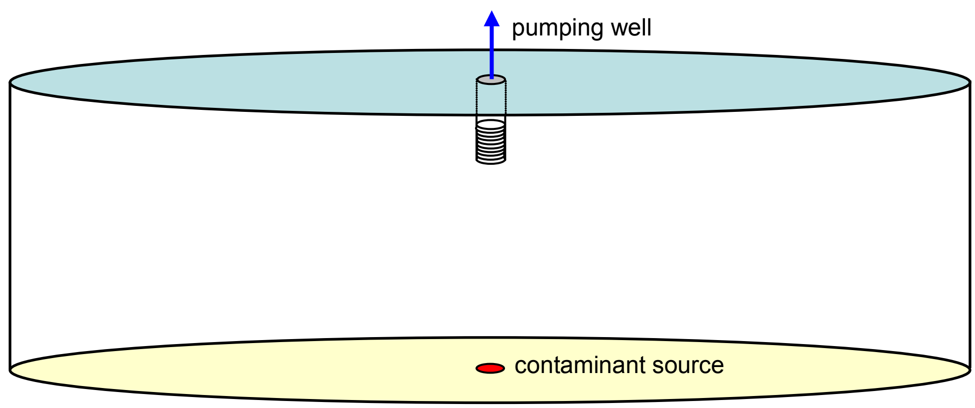


Figure 9. Temperature Histories for Locations at a Depth in the Middle of the Waste Zone at Several Horizontal Distances from the Center of the Waste–Filled Borehole.

3.2.3. Groundwater Pumping and Dilution Above the Borehole Disposal System

If there is significant migration of radionuclides from the deep borehole, the most likely and highest-impact mechanism by which radionuclides could be released to the biosphere from the disposal system is groundwater pumping. The analysis of thermally driven flow in Section 3.2.1 simulated the potential hydrologic movement to a location 1,000 m above the waste disposal zone. Release to the biosphere requires the transport of radionuclides an additional 2,000 m to the land surface in the borehole disposal system described in this study.

A simplified, but conservative, model of groundwater pumping and radionuclide transport is constructed to simulate the transport time between a release point 1,000 m above the waste and a hypothetical pumping well located near the disposal borehole. The model also simulates the amount of dilution associated with capturing radionuclide mass in the pumping well. The conceptual model is shown diagrammatically in Figure 10. The model domain is cylindrical with a radius of 10,000 m and a depth of 2,000 m. Specified-pressure boundary conditions corresponding to hydrostatic conditions are applied on the sides and bottom of the model domain, with a no-flow boundary condition at the upper surface. A continuous contaminant source with approximately 1 m^2 area is specified on the bottom boundary directly beneath the pumping well. A specified volumetric flow rate of 0.0035 m^3/year at the contaminant source corresponds to the maximum flow rate in the borehole simulated by the thermal-hydrologic model (Figure 8). The pumping well has a screened interval between 100 m and 200 m depth from which a specified volumetric flow rate is withdrawn.



Not to Scale: Model domain has a radius of 10 km and depth of 2 km.
Contaminant source has a cross-sectional area of approximately 1 m^2.

Figure 10. Model Domain for Groundwater Pumping and Radionuclide Transport.

The numerical model is implemented with the FEHM software code using a two-dimensional radial representation in which the grid resolution is finer near the axis of the well and the vertical grid spacing is 5 m. The horizontal permeability is 10^{-13} m^2 and the vertical permeability is 10^{-14} m^2 for a horizontal/vertical anisotropy ratio of 10. The permeability of the disposal borehole plus disturbed zone between the contaminant source and the pumping well is a factor of 10 higher than the surrounding rock. The porosity is assumed to be 0.01, which is appropriate for fractured bedrock, but is very low for most clastic sedimentary rocks. The aquifer compressibility is assigned a representative value of 10^{-4} MPa^{-1}. Two pumping cases are simulated for differing capacity wells, one as a water supply for 25 people and one supplying water to 1000 people. Pumping rates are calculated using the average domestic water consumption in the U.S. of 86.5 gal/day/person (Van der Leeden et al. 1990).

The groundwater pumping and radionuclide transport model is generic in nature and consequently is constructed with simplifying assumptions barring site-specific information. There are several aspects of this simplified groundwater pumping model that tend to underestimate the transport time between the contaminant source and the pumping well, and underestimate the amount of dilution of radionuclide concentrations:

- No recharge is applied to the upper boundary of the model. In areas where there is substantial precipitation much of the groundwater captured by the pumping well would come from local recharge.
- No ambient horizontal shallow groundwater flow is included in the model. The capture zone for a pumping well located in a regional horizontal groundwater flow field extends to a finite depth. The radionuclide source at 2,000 m depth would be below the capture zone of the pumping well for even moderate horizontal flow.
- The permeability of the system does not decrease with depth in the model. Average permeability typically decreases by orders of magnitude over the depth range of 2,000 m in fractured bedrock, significantly reducing the fraction of deep fluids that would be captured in the pumping well.
- The vertical anisotropy in permeability is a factor of 10 in the model. The vertical anisotropy in groundwater flow systems is often much greater than 10, particularly in sedimentary strata with shale aquitards. Higher values of vertical anisotropy significantly reduce the fraction of deep fluids that would be captured in the pumping well.
- The value of porosity used in the model is representative of fractured bedrock. The value of porosity would be much higher for most porous sedimentary rocks. The low value of porosity used in the model would tend to underestimate the transport time between the contaminant source and the pumping well.
- The volumetric inflow rate of contaminated fluid at the base of the model is held constant at the maximum rate simulated by the coupled heat and hydrologic flow model in Section 3.2.2. The contaminant inflow into the upper 2 km of the system would stop before 1,000 years based on the results shown in Figure 8.
- Simulations are conducted only for a non-sorbing, non-decaying species. The transport time between the contaminant source and the pumping well would be much greater for sorbing radionuclides.

Thus, the results noted here are considered conservative and perhaps bounding. The simulated radionuclide breakthrough curves at the pumping well for the two pumping cases are shown in Figure 11. The contamination arrives at the higher capacity pumping well for 1,000 people in significant quantities after several thousand years and at the pumping well for 25 people after more than 200,000 years of continuous pumping. The model results in Figure 11 show that although the contaminants arrive at the higher capacity well sooner, the maximum relative concentration is much lower than for the lower pumping rate because of the greater dilution in the larger volume of well water. The maximum relative concentrations in the pumping wells indicate dilution factors of 3.16×10^7 and 8.19×10^5 for the higher capacity pumping case and the lower capacity pumping case, respectively. Overall, the pumping well model indicates significant delays in the transport of radionuclides to the pumping well and large dilution factors relative to the radionuclide concentrations in the disposal borehole driven upward by thermal expansion of fluids near the disposal zone. In addition, the pumping well model significantly underestimates radionuclide transport times and the amount of dilution in radionuclide concentrations, as described above.

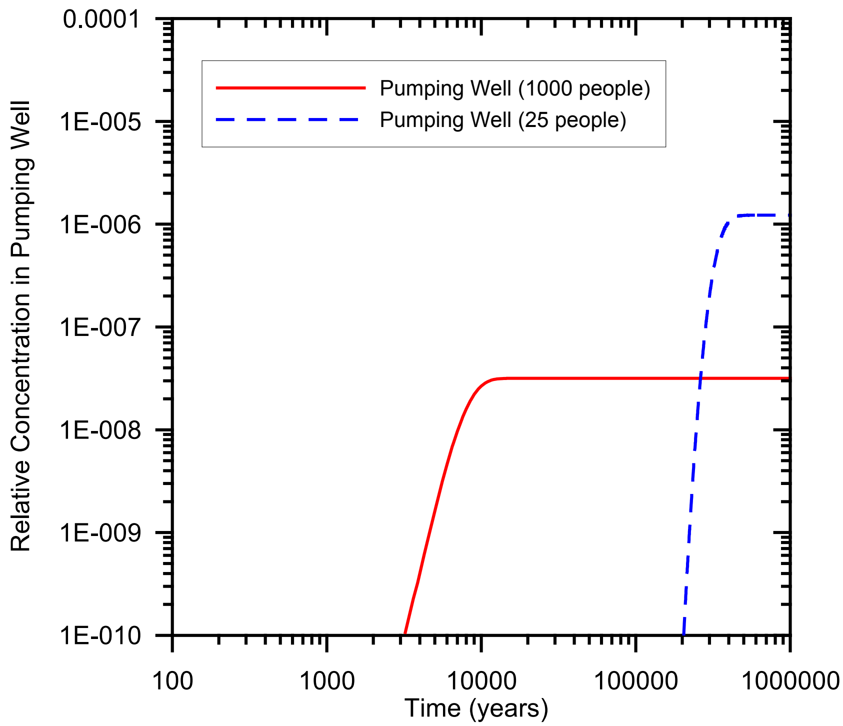


Figure 11. Simulated Breakthrough Curves for Two Groundwater Pumping Scenarios (Unit concentration at source).

In summary, even in the unlikely event of a water supply well located directly above the disposal borehole, significant delays in time and large amounts of dilution would occur during the capture of contaminants from the deep disposal system. Both of these factors would greatly reduce the potential radiological dose to hypothetical human receptors using that water supply.

3.3. Chemical Environment

The geochemical behavior (solubility, sorption, colloidal behavior, etc.) of the projected waste inventory in the deep borehole environment sets limits on the stability of the uranium spent fuel matrix and on radionuclide transport to the biosphere. Radionuclide solubilities and sorption coefficients are therefore important input parameters for performance assessment calculations (Section 5). The US inventory of high-level radioactive waste and spent nuclear fuel used for the purposes of this analysis is 109,300 metric tons (DOE Office of Public Affairs, August 5, 2008) which includes the 70,000 MTHM considered for disposal at Yucca Mountain in addition to waste to be generated in the future. The inventory and the important isotopes are discussed in greater detail in Appendix A.

Fluids recovered from deep boreholes tend to be rich in sodium, calcium, and chloride. Lesser amounts of sulfate and carbonate are likely to be present. For the purposes of estimating radionuclide solubilities, a reasonable salinity is ~ 2-3 M/L, pHs are 8-9 and the system E_H is ~ -300 mV (Anderson 2004). As discussed in Section 3.2, geothermal gradients are such that the temperatures at the bottom of the deep boreholes are expected to be above 100 ^oC. Oxygen tends to be scavenged, and the low redox state anchored, by the presence of reduced Fe and Mn in the basement rocks.

Additional geochemically appealing features of deep boreholes are that the elevated temperatures of deep boreholes should stabilize the less soluble crystalline forms of radioelement oxide minerals, while high temperatures and high salinities will both favor the less soluble anhydrous forms of the oxide phases. Note though that the relatively high temperatures and salinities of deep fluids should accelerate the corrosion of steel pipes, fuel assemblies, and the waste itself. The scarcity of oxygen might slow the oxidation of spent fuel.

3.3.1. Radionuclide Solubilities

Given the conditions outlined above, bounding estimates can be made of the dissolved levels of radionuclides likely to be present once basement fluids come into contact with spent fuel assemblages. Table 4 identifies likely solubility-limiting phases and provides estimates of dissolved radioelement concentrations at depth. Because of the uncertainty associated with estimating thermodynamic constants and the activity coefficients of aqueous species in high temperature, high ionic strength brines, the numbers in Table 4 are probably only accurate to within an order of magnitude.

The relatively low solubility of UO_2 under deep borehole conditions will favor stabilization of spent fuel rods. When contacted by water, fuel rods will have diminished thermodynamic drive to dissolve, thus slowing the matrix release of actinides and fission products. Yet even if fuel rods were to instantly dissolve to the thermodynamically stable actinide oxides, the solubilities of isotopes of Am, Ac, Cm, Np, Pa, Pu, Tc, and Th are lower than that of uranium – sometimes several orders of magnitude lower – suggesting that aqueous releases of these radionuclides will be small. Some species (e.g., ^{99}Tc) have solubility limits that are below drinking water limits.

It is less clear whether iodine, radium, and strontium will form solubility-limiting solids. If deep fluids contain appreciable sulfate, $SrSO_4$ and $RaSO_4$ might form to limit dissolved Sr and Ra levels. Dissolved carbonate might also lead to the formation of $SrCO_3$. Radioiodine is a fission product that should become reduced to iodide given sufficient electron donors in the borehole domain. Unless iodide forms insoluble metal iodides, radioidide levels in solution adjacent to the fuel will probably be set by the available inventory. Pending closer examination of sulfate, carbonate, and heavy metal contents of borehole fluids, no limiting concentrations are set for I, Sr, and Ra.

Table 4. Radionuclide Solubilities in Deep Boreholes at T = 200°C, pH 8.5, E_H = -300 mV, 2M NaCl solution.

Radioelement	Solubility-limiting phase	[a]Dissolved concentration (moles/L)	Notes
Am	Am_2O_3	1×10^{-9}	$AmOH(CO_3)$ would control Am solubilities if carbonate present.
Ac	Ac_2O_3	1×10^{-9}	Am solubility is used as proxy for chemically similar Ac.
C	*	*	No solubility limiting phase
Cm	Cm_2O_3	1×10^{-9}	Am solubility is used as proxy for chemically similar Cm.
Cs	*	*	No solubility limiting phase
I	Metal iodides ?	*	See discussion
Np	NpO_2	1.1×10^{-18}	
Pa	PaO_2	1.1×10^{-18}	Np solubility is used as proxy for chemically similar Pa.
Pu	PuO_2	9.1×10^{-12}	
Ra	$RaSO_4$	*	See discussion
Sr	$SrCO_3$, $SrSO_4$?	*	See discussion
Tc	TcO_2	4.3×10^{-38}	
Th	ThO_2	6.0×10^{-15}	
U	UO_2	1.0×10^{-8}	

[a]Calculated using the PHREEQC code version 2.12.03 and the thermo.com.V8.R6.230 database from Lawrence Livermore National Laboratories, except for the 25°C TcO_2 solubility product and enthalpy, which came from the R5 version of the Yucca Mountain Project thermodynamic database.

3.3.2. Radionuclide Sorption

Radionuclide sorption has rarely been measured at temperatures much greater than 25 °C. Nevertheless, there is sufficient experimental data to suggest that most radionuclides released from the bottoms of deep boreholes will adsorb to basement rocks, to overlying sediments, and to the bentonite used to seal the borehole. Table 5 provides a compilation of representative distribution coefficients, k_ds. A radioelement k_d (mL/g) is the ratio of radioelement sorbed on a material (moles/g) to the amount of radioelement remaining in solution (moles/mL). Distribution coefficients tend to lump together multiple equilibrium and kinetic reactions, are specific to the conditions under which they were measured (e.g., pH, ionic strength, temperature, fluid-to-rock ratio, among others) and, therefore provide only a rough predictor of the potential for contaminant retardation (McKinley and Scholtis 1993; Bethke and Brady 2000). Nevertheless, k_ds are useful in examining boundary level controls over radioelement transport. Elements with k_ds of 0 (for example, iodine) won't sorb and will therefore move at the velocity of the fluids that carry them. Elements with k_d's of 10 or more will move at less than 1% of the velocity of deep fluids. Table 5 emphasizes that sorption will sharply limit the transport of most radionuclides from deep boreholes. The two exceptions are isotopes of iodine and carbon – ^{129}I and ^{14}C.

Table 5. [a]Deep Borehole k_ds (ml/g).

Element	$k_{d\ basement}$	$k_{d\ sediment}$	$k_{d\ bentonite}$
Am, [b]Ac, [b]Cm	50-5000	100-100,000	300-29,400
C	0-6	0-2000	5
Cs	50-400	10-10,000	120-1000
Np, [b]Pa	10-5000	10-1000	30-1000
Pu	10-5000	300-100,000	150-16,800
[c]Ra	4-30	5-3000	50-3000
Sr	4-30	5-3000	50-3000
[d]Tc	0-250	0-1000	0-250
Th	30-5000	800-60,000	63-23,500
U	4-5000	20-1700	90-1000
I	0-1	0-100	0-13

[a]All values are from the review of McKinley and Scholtis (1993). Values less than one were rounded down to zero.
[b]k_ds for Ac and Cm are set equal to those of chemically similar Am. l_ds for Pa are set equal to those of chemically similar Np.
[c]k_ds for Ra were set equal to those of somewhat chemically similar Sr.
[d]Tc k_ds under reducing borehole conditions will likely be much greater than the zero values listed here which were measured under more oxidizing conditions.

4. SCENARIO ANALYSIS

The selection of scenarios for analysis in the deep borehole disposal performance assessment is based on the assumption that regulatory requirements for deep borehole disposal will be essentially the same as those currently extant in 10 CFR 63. Specifically, the performance measure of interest is assumed to be the mean annual dose to a hypothetical member of the public (the "reasonably maximally exposed individual" of 40 CFR 197.21) who lives in the accessible environment near the disposal site. Consistent with approach taken in 40 CFR 197, it is assumed that the mean annual dose shall include probability-weighted consequences of releases due to all significant features, events, and processes (FEPs), and shall account for uncertainty associated with those FEPs. As described in Section 4.1, a FEP screening approach similar to that taken for both Yucca Mountain and WIPP is adopted to identify the significant FEPs that should be included in the quantitative performance assessment. Section 4.2 describes how those FEPs that are identified as being significant to performance are combined into the scenarios analyzed in Section 5.

4.1. Identification of Relevant Features, Events, and Processes

Various programs in the US and other nations have compiled exhaustive lists of FEPs for mined geologic disposal that should be evaluated for potential relevance to deep borehole disposal of radioactive wastes. Depending on subjective decisions about how to partition the essentially infinite number of possible future occurrences, these lists can range from a relatively small number of broadly defined FEPs to a very large number of more narrowly defined FEPs. In practice, lists that aggregate phenomena at relatively coarse levels have proven to be suitable for evaluation in regulatory settings in the US (e.g., WIPP Compliance Certification Application [DOE 1996, DOE 2004], Yucca Mountain License Application [DOE 2008b, Sandia National Laboratories 2008b]).

Once potentially relevant FEPs for deep borehole disposal have been identified, they must be evaluated against screening criteria provided in US regulations. Specifically, EPA regulations for Yucca Mountain state that FEPs that have an annual probability of occurrence less than one chance in 100,000,000 in the first 10,000 years after closure may be excluded from the analysis. Features, events, and processes that have higher probabilities, but do not significantly change the results of long-term performance assessments, may also be omitted from the analysis (40 CFR 197.36(a)(1)). In addition, some potentially relevant FEPs are screened from further consideration because they are inconsistent with specific aspects of the regulatory requirements. For example, existing regulations for WIPP and Yucca Mountain indicate that performance assessments should not include consequences of deliberate human acts of sabotage or disruption in the far future. For this analysis it is assumed that all regulatory requirements relevant to FEP analyses for Yucca Mountain apply equally to deep borehole disposal.

The FEP list from the Yucca Mountain license application (see Appendix B, Table B-1) was adopted as a reasonable starting point for evaluation. Each of the 374 FEPs on this list has been considered (screened) for potential relevance to deep borehole disposal; FEPs that may be unique to deep borehole disposal have been considered and compared to the list to identify existing

FEPs that capture the processes of interest and concern for boreholes. No new FEPs were identified in this process, confirming that, although the Yucca Mountain list was specifically tailored for a mined repository, it remains a useful starting point for this preliminary analysis.

In evaluating Yucca Mountain FEPs for the deep borehole disposal performance assessment, the following assumptions are made that go beyond the basic assumption that regulatory criteria are the same as those stated in 40 CFR part 197.

- Biosphere exposure is assumed to occur via a contaminated groundwater well immediately adjacent to the borehole. There is therefore no release pathway of interest in the unsaturated zone (UZ). All relevant biosphere pathways associated with contaminated well water (e.g., irrigation, crops, livestock, drinking, etc.) are included.
- No credit is taken for the waste package or waste form as flow barriers. Therefore, all FEPs related to the performance of waste package and waste form as flow and transport barriers are excluded from the analysis.
- Chemical effects of the waste package and waste form are of interest and must be evaluated further.
- The "Drift" is the portion of the borehole that contains waste (i.e., the waste disposal zone).
- The engineered barrier system (EBS) includes seals and drifts, but the effective contribution comes from the borehole seals.
- Backfill, to the extent that it is used, is the material that is emplaced in the waste disposal zone of the borehole surrounding waste canisters.
- There are two release pathways of primary interest: transport through the EBS (seals), and transport through the saturated zone (SZ) in the surrounding rock
- Naval and DOE spent fuels (called out specifically in the YM analysis) are omitted from this analysis.
- Retrievability of waste, which is required to be feasible under current regulations, is assumed to be excluded as a position of policy.

Tables B-1 and B-2 in Appendix B summarize the screening decisions for each FEP (whether a FEP is likely to need to be included in or excluded from a full performance assessment for deep borehole disposal) and also includes a qualitative estimate of the level of effort likely to be required to provide a robust basis for the screening of the FEP. For excluded FEPs, 1 means the technical or regulatory basis is readily available and all that is needed is documentation; 2 means new technical work likely is needed, and 3 indicates a potentially significant amount of work is needed. For included FEPs, 1 indicates that this is a normal part of modeling, 2 indicates that this is a significant aspect of the modeling, and 3 indicates possible modeling challenges. Notes entered in this column provide clarification about how the FEP may need to be considered for deep borehole disposal.

Section 4.3 provides additional support for the decision to exclude criticality, molecular diffusion, and thermal hydrofracturing from the performance assessment.

4.2. Scenario Selection

Consideration of the FEPs that have a preliminary screening of “included” in Table 9 shows that radionuclides emplaced in deep boreholes might reach the biosphere along one, or a combination, of three principal paths: 1) up the borehole (includes accidental release during emplacement); 2) along the annulus of disturbed rock; and/or 3) radially out through groundwater. These pathways are described below as three scenarios chosen for analysis in a preliminary performance assessment. A more complete screening of the FEPs may identify additional scenarios of interest, and may also show that some aspects of the chosen scenarios do not need further analysis.

Scenario 1: Transport in the borehole. *Hydrologic flow up the borehole transports radionuclides to a shallow aquifer from which they are pumped to the biosphere* – This scenario requires sufficiently high permeability within the borehole and a sustained upward gradient in hydrologic potential for it to occur. Vertical permeability within the borehole in the waste disposal zone may be relatively high, given the presumably rapid degradation of the disposal canisters stacked within the borehole. Vertical permeability within the borehole above the level of waste emplacement will be engineered to be very low and would require failure of the borehole grout and seals (or bypassing of such seals) to permit significant fluid flow up the borehole. An upward gradient in hydrologic potential within the borehole could result from: a) ambient hydrologic conditions, b) thermal pressurization of fluid within the waste disposal zone from waste heat, c) buoyancy of heated fluid within the waste disposal zone, or d) thermo-chemical reactions that release water and/or gases within the waste disposal zone.

Scenario 2: Transport in disturbed rock around the borehole. *Hydrologic flow up the annulus of disturbed rock surrounding the borehole transports radionuclides to a shallow aquifer from which they are pumped to the biosphere* – This scenario requires sufficiently high permeability in the rock surrounding the borehole and a sustained upward gradient in hydrologic potential for it to occur. Vertical permeability within disturbed rock in the waste disposal zone and in the overlying rock may be relatively high if the annular space is not effectively grouted during borehole construction and/or abandonment. Vertical permeability in the crystalline rock immediately outside the heated volume near the waste disposal zone could be increased because thermo-mechanical effects would reduce the vertical mechanical stress. An upward gradient in hydrologic potential within the annulus of the borehole could result from: a) ambient hydrologic conditions, b) thermal pressurization of fluids within the waste disposal zone from waste heat, c) buoyancy of heated fluids within the waste disposal zone, or d) thermo-chemical reactions that release water and/or gases within the waste disposal zone.

Scenario 3: Transport in surrounding rock away from the borehole. *Hydrologic flow up through the crystalline basement and sedimentary cover transports radionuclides to a shallow aquifer from which they are pumped to the biosphere* – This scenario requires sufficiently high permeability within fracture zones and/or faults in the crystalline basement and sedimentary cover and a sustained upward gradient in hydrologic potential for it to occur. Given the low vertical permeability of the crystalline basement rocks and the stratified sedimentary cover, a through-going feature such as an interconnected group of fracture zones or faults would be required to conduct significant quantities of fluid to a shallow aquifer.

4.3. Justification for Exclusion of Selected Features, Events, and Processes

4.3.1. Exclusion of Criticality from Deep Borehole Disposal

The possibility of a self-sustained nuclear chain reaction event (critical event or "criticality") has always been a consideration of geologic disposal, similar to any facility that handles fissile material. As early as 1974, the criticality scenario class was identified as a potential event in the Waste Isolation Pilot Plant (WIPP) in southern New Mexico, a repository for transuranic (TRU) waste which opened in 1999 (Rechard, Sanchez et al. 2001). Because of the potential interest, a preliminary discussion is provided concerning the credibility of a down-hole criticality with respect to inclusion or exclusion from a formal, site-specific performance assessment for SNF. HLW and other radioactive waste such as small spent sealed sources would present a much lower potential for criticality.

During transportation to the site and during repository operations when humans are present, stringent administrative and physical measures would be in place to prevent criticality. These standard operational aspects are not discussed here. Rather, this discussion focuses on the low probability of criticality after deep borehole disposal in two general locations: in the waste canister (Section 4.3.1.1); and outside the waste canister in the near or far field (Section 4.3.1.1). The focus here is on direct disposal of spent fuel assemblies rather than HLW which has most of the fissile mass removed.

4.3.1.1. Low Probability of Criticality in a Single Waste Canister

As noted in Section 4.1, a FEP can be excluded if (a) the annual probability of occurrence is less than one chance in 10^{-8} (i.e., low probability), or (b) its omission does not significantly change the results of long-term performance assessments (i.e., low consequence). New regulations applicable to deep borehole disposal (see Section 2) would likely retain this concept.

Fissile material cannot become critical after disposal unless several conditions are met. Specifically, several features must be present, and events and especially geologic processes must act to alter the waste canister and its contents for a critical event to occur inside the canister. However, physical constraints limit the possibility of criticality inside the waste canister.

To elaborate, because of the small diameter of a deep borehole, the number of CSNF assemblies that can be placed in a canister is limited. This criticality analysis assumes one PWR assembly is placed in a canister. One PWR assembly cannot become critical even when fully flooded. For low enriched uranium, the heterogeneous lumping of the uranium in an assembly is the most reactive configuration. Hence, any re-arrangement to a more homogeneous configuration lowers the reactivity. Based on 383 kg of uranium in a reference PWR (derived from Table 7), the amount of fissile ^{235}U would vary between 3% (11.5 kg) for older fuel, 5% (19 kg) for fuel currently in use, and perhaps a maximum of 10% (38 kg) for fuel sometime in the future. Yet, homogeneous mixtures of rock with high silica content (~75%wt silica), typically require >350 kg, >65 kg, or >30 kg of fissile ^{235}U, respectively, ignoring the presence of any neutron absorbing elements such fission products, actinides, or purposely placed boron or gadolinium (Figure 9 from Rechard, Sanchez et al. 2003). Hence, only a homogeneous mixture of future fresh fuel at 10% enrichment could be critical in a single canister. In reality fission products and actinides would also be present in spent fuel, which would lower reactivity, hence, even future CSNF at an initial 10% enrichment would not be critical. More importantly, the diameter of the canister or borehole is not sufficient to prevent excess loss of neutrons within the fissile material as discussed in Section 4.3.1.2 for criticality outside the waste canister.

For DOE SNF, the packaging scheme could limit the fissile ^{235}U roughly to those amounts listed above (i.e., <350 kg for DOE SNF with <3% enrichment, <65 kg for DOE SNF with <5% enrichment, and <30 kg for DOE SNF with any other enrichment.

4.3.1.2. Low Probability of Criticality Outside the Waste Canisters

Because of the physical constraint on the amount of fissile mass in a canister, criticality is not credible inside the canister. Criticality directly outside the canister also has physical constraints. Specifically, the minimum diameter of a homogeneous critical sphere is greater than the 0.445 m (17.5 in.) diameter borehole at depth (Figure 3). For example, the minimum diameter for a critical sphere at 10% enrichment and a 20 kg/m^3 concentration at the minimum mass of 30 kg is 0.71 m; More realistic depositional concentrations of 5 kg/m^3 (concentrations found in high grade ores ~2300 ppm) result in a minimum diameter of 1.1 m. Ideal planar configurations must also be at least 0.5 m thick, as corroborated by the natural reactors at Oklo that were about 1 m thick (Rechard et al. 2001; Section 3.5). Hence, criticality is not credible in the confines of the borehole at depths where disposal occurs.

If a critical event is to occur outside the package, geologic processes must transport fissile material from several packages into the host rock or to depositional zones away from the disposal area and then assemble the fissile material into a critical configuration. These geologic processes are the same as must be invoked to remove fission products and actinides from the waste and transport them to the biosphere.

As discussed in Section 3.3, the chemical environment in a deep borehole greatly limits the mobility of radionuclides, in general, and fissile material, in particular. There is no likely mechanism to oxidize the uranium to the more mobile species (i.e., U^{+6}); hence, the solubility of uranium (U^{+4}) in the anoxic environment of the borehole is 10^{-8} mole/L (2.38×10^{-6} kg/m^3) (Table 4). As noted above, the concentration, either as a liquid or solid, must reach ~5 kg/m^3 (~2300 ppm) to go critical (6 orders of magnitude higher concentration). More importantly, enough mass must be released from the borehole waste disposal zone. As noted below in Section 5, uranium is not transported out of the waste disposal zone. At the upward velocities from thermal effects that might occur in the initial 200 years after disposal, it would take 9 billion years to deplete the uranium in a single waste canister (383 kg). In one million years, about 0.04 kg would be depleted using the thermal upward velocity in the initial 200 years. If a disposal borehole had 450 canisters, the maximum release from the disposal zone would only be about 19 kg, of which at most 10% would be fissile. A release of 1.9 kg of fissile ^{235}U is much less than the 30 kg necessary to become critical. Hence, criticality in the far field is not credible.

4.3.2. Exclusion of Molecular Diffusion from Deep Borehole Disposal

Chemical diffusion of radionuclides through the host rock matrix and borehole seals will result in the migration of contaminant mass, even in the absence of fluid flow. The potential impact of diffusion on radionuclide containment is evaluated here using an analytical solution for one-dimensional diffusive transport through a porous medium, assuming a constant radionuclide concentration in the waste disposal zone. The solution is for a non-sorbing species without radioactive decay, according to the following equation (Crank 1956):

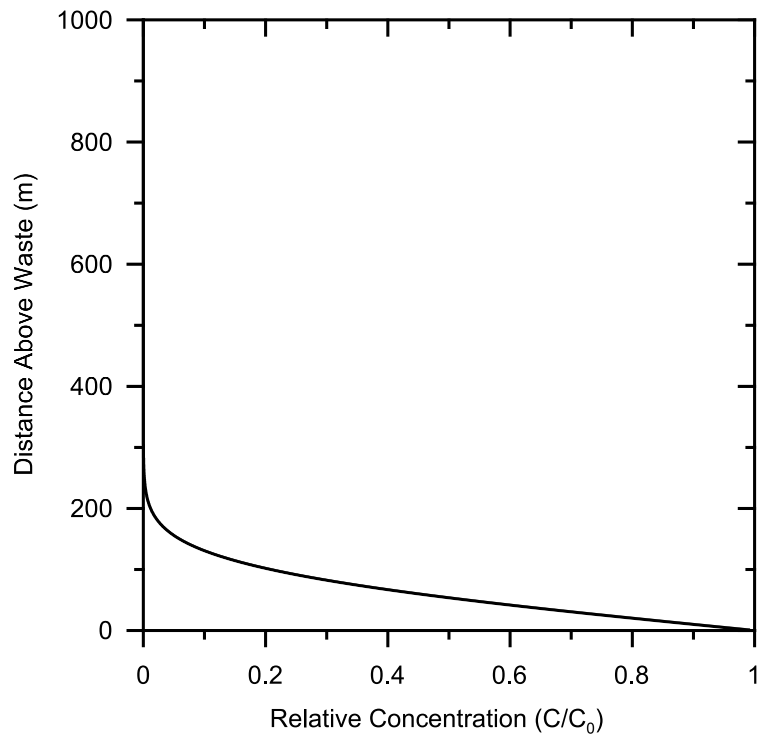
$$\frac{C}{C_0} = erfc\left[\frac{z}{2\sqrt{D_{eff}t}}\right] \qquad \text{(Eq. 4-1)}$$

where C is the radionuclide concentration, C_0 is the radionuclide concentration in the waste zone, *erfc* is the complementary error function, z is the distance above the waste, D_{eff} is the effective diffusion coefficient, and t is time.

The vertical concentration profile above the waste from this solution is plotted in Figure 12 at 1,000,000 years after waste emplacement, assuming an effective diffusion coefficient of 1×10^{-10} m^2/s. Migration of radionuclide mass via diffusion has occurred to a vertical distance of about 200 m above the waste in this time.

The concentrations shown in Figure 12 are overestimated with regard to the geometry of the system. Diffusion from the top of the waste disposal zone would have a radial component as well as a vertical component, reducing the migration rate in the vertical direction. Radionuclides that sorb on the rock matrix and borehole sealing material would be significantly retarded during diffusive migration. In addition, radioactive decay for radionuclides with half lives less than the time frame of the calculation would decrease concentrations. The value of the effective diffusion coefficient (1×10^{-10} m^2/s) used in the analysis is relatively high for granite, but is approximately representative of the elevated temperature conditions in the deep borehole disposal system.

Overall, diffusion in crystalline host rock and borehole seals is a slow process for the migration of radionuclide contamination, even on geologic time scales. Given the depth of deep borehole disposal system, diffusion can be excluded as a significant process from further consideration in performance assessment analyses.



Note: Assuming constant concentration of C_0 at the waste and effective diffusion coefficient of 1 x 10^{-10} m^2/s.

Figure 12. Concentration Profile for a Non-sorbing Species from Diffusion at 1,000,000 Years After Waste Emplacement.

4.3.3. Exclusion of Thermal Hydrofracturing from Deep Borehole Disposal

Permeability of the host rock near the borehole potentially could be enhanced by hydrofracturing resulting from the thermal expansion of fluid. This might increase the permeability in the host rock around the sealed borehole and provide a pathway for upward vertical hydrologic flow and radionuclide migration toward the surface.

This potential process was evaluated using a modified version of the two-dimensional heat conduction model in which heat and fluid flow were coupled. The model was run assuming a permeability of 1.0 x 10^{-20} m^2 for the granite, which is a very low permeability, near the lower end of the range for unfractured crystalline rocks and shales. Low permeability tends to maximize the fluid pressures in the system during heating.

The simulated fluid pressures as a function of time for varying distances from the waste container are shown in Figure 13. The peak pressures occur near the borehole in the time frame of a few days after emplacement and borehole sealing. Note that the ambient (hydrostatic) fluid pressure in the model is 39.2 MPa. For hydrofracturing to occur, the fluid pressure would have to exceed the ambient stress in the host rock. Horizontal stress is generally lower than vertical stress, so the induced fractures would be vertical and preferentially oriented in the direction of the maximum horizontal stress. Based on a compilation of data on horizontal stress in the crust, the average horizontal stress increases with depth by a factor of about 24 MPa/km (Japan Nuclear Cycle Development Institute 2000) – the lithostatic gradient. Using this estimate, the average horizontal stress at 4 km depth would be about 96 MPa. The hydrothermal modeling results suggest that comparable fluid pressures would not be achieved and that no hydrofracturing would occur by this process.

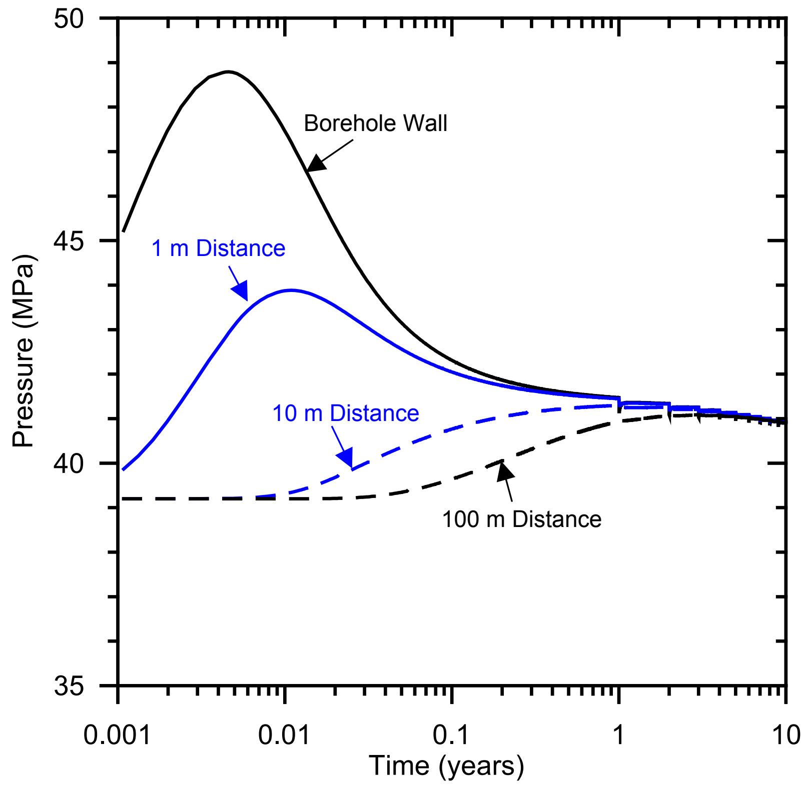


Figure 13. Fluid Pressure Histories for Locations at a Depth in the Middle of the Waste Zone at Several Horizontal Distances from the Center of the Waste–Filled Borehole.

5. PERFORMANCE ASSESSMENT

Based on the scenario analysis described in Section 4, a preliminary deep borehole performance assessment (DB-PA) was performed for a simplified and conservative representation of combined radionuclide releases from Scenarios 1 and 2 from Section 4.2. The conceptual model is as follows:

- 400 PWR assemblies (~150 MTHM) vertically stacked down the length of the waste disposal zone (~ 2 km).
- Initial radionuclide inventory consistent with Appendix A (CSNF/PWR aged to year 2117). Effects of ingrowth accounted for in a bounding fashion.
- Dissolved concentrations in the waste disposal zone limited by thermal-chemical conditions (see Table 4).
- Thermally driven hydrologic flow from the top of the waste disposal zone upward through 1000 m of a bentonite sealed borehole with a specific discharge of 0.017 m/yr for 200 years (see Figure 8).
- Radionuclide transport up the borehole calculated using a 1-dimensional analytical solution to the advection-dispersion equation (see Equation 5-1 below).
- Pumping of borehole water (from the location 1000 m above the top of the waste disposal zone) to the surface (biosphere) via a withdrawal well. No credit is taken for sorption or decay along the saturated zone transport pathway from the borehole to the withdrawal well.
- A dilution factor of 3.16×10^7 (see Section 3.2.3) is applied to account for the fact that the borehole water would mix with water in an existing aquifer before it would be captured by the withdrawal well (assumed to supply 1,000 people).
- A transport time of 8,000 years (see Figure 11) is applied to account for the time taken for the bulk of the dissolved radionuclide mass to be captured by the withdrawal well (at a constant pumping rate necessary to supply 1,000 people).
- Doses to a hypothetical person living near the withdrawal well are based on biosphere dose conversion factors (BDCFs) consistent with the lifestyle of the Yucca Mountain reasonably maximally exposed individual (RMEI), as specified by the EPA in 40 CFR 197.

The conceptual model was implemented numerically in a Microsoft Excel spreadsheet. Equation 5-1 gives the analytical solution for dissolved radionuclide concentration in the sealed borehole, C (in mg/L), as a function of time, t, and distance, x, from the source that is used in the numerical model. It is based on the Ogata-Banks solution for 1-dimensional advection-dispersion from a continuous source with retardation (sorption as described by kds in Table 5) and radioactive decay (Domenico and Schwartz 1990, Equation 17.10).

$$C(x,t) = (C_o / 2) * \exp\{[x / 2\alpha_x][1 - (1 + 4\lambda\alpha_x / v_c)^{1/2}]\} \\ * \operatorname{erfc}\{[x - v_c t (1 + 4\lambda\alpha_x / v_c)^{1/2}] / [2 (\alpha_x v_c t)^{1/2}]\} \quad \text{(Eq. 5-1)}$$

where:

$$v_c = v / R_f \quad \text{(Eq. 5-2)}$$

$$R_f = 1 + (\rho_b k_d) / n \quad \text{(Eq. 5-3)}$$

and:

C_o	=	initial source concentration (mg/L)
v_c	=	dissolved radionuclide velocity (m/yr)
v	=	hydrologic pore velocity (m/yr)
R_f	=	retardation factor
k_d	=	distribution coefficient (L/g)
n	=	porosity of sealed borehole
ρ_b	=	bulk density of sealed borehole (kg/m^3)
α_x	=	longitudinal dispersivity (m)
λ	=	decay constant (yr^{-1})

In addition to the continuous source solution described by Equation 5-1, the DB-PA model also contains an instantaneous source solution. However, for the base-case DB-PA conditions the instantaneous source solution was not required.

Radionuclide transport up the borehole from the source (waste disposal) zone occurs for 200 years, corresponding to the duration of the thermally driven flow in Figure 8. Subsequent to the the thermal period, ambient conditions are not expected to provide any upward gradient, and upward radionuclide transport was assumed to cease.

The source concentration at the top of the waste disposal zone was determined by (a) calculating a maximum potential concentration based on dissolving the entire initial mass inventory in a PWR into the void volume (i.e., the potential volume of water) of a waste canister, and (b) selecting the lower of the maximum potential concentration and the solubility limits (see Table 4) as the source concentration.

Sealed borehole properties representative of bentonite (permeability of 1×10^{-16} m^2, porosity of 0.034, and bulk density of 1200 kg/ m^3) in conjunction with the thermally driven driving pressure produced a hydrologic pore velocity of 0.502 m/yr and a corresponding 1000 m borehole travel time (for an unretarded radionuclide) of 1991.3 years. Because the period of thermally driven flow (200 years) is short relative to the hydrologic travel time up the sealed borehole (1991.3 yrs), the only radionuclide with a non-zero concentration 1000 m above the waste disposal zone in the sealed borehole is ^{129}I, which is the only radionuclide that has no retardation. The non-zero ^{129}I concentration (which is only 5.3×10^{-8} mg/L) represents the leading edge of the dispersive transport front. However, the center of mass never reaches the top of the 1000 m sealed section of the borehole because there is no further movement after 200 years.

Accounting for the 8,000-year travel time for the radionuclides to reach the withdrawal well, results in a peak dose to the RMEI at 8,200 years. The DB-PA calculated results (dose to the RMEI) for all radionuclides at 8,200 years are shown in Table 6. The total dose to the RMEI at 8,200 years is 1.4×10^{-10} mrem/yr. The only contributor to the dose is ^{129}I.

These DB-PA results are based on several bounding and conservative assumptions, such as: all waste is assumed to instantly degrade and dissolve inside the waste canisters; all waste is assumed to be PWR assemblies; no credit is taken for sorption or decay along the saturated zone transport pathway from the sealed borehole to the withdrawal well. Thus, as a first approximation, more refined performance assessments may indicate lower doses, or later peak doses, or both, than established here.

Other scenarios, with larger or longer flows, higher permeabilities, and different source configurations, would require refinements to the conceptual model.

Table 6. Total Peak Dose (mrem/yr) to RMEI and Travel Distance Resulting From 200 Years of Thermally Driven Transport

Radionuclide	Center of Mass Travel Distance From Source at 200 yrs (m)	Concentration in Borehole 1000 m above Source at 200 yrs (mg/L)	Dose to RMEI at 8,200 yrs (mrem/yr)
Actinium Series			
^{243}Am	0.00	0.00	0.00
^{239}Pu	0.00	0.00	0.00
^{235}U	0.01	0.00	0.00
^{231}Pa	0.03	0.00	0.00
^{227}Ac	0.00	0.00	0.00
Uranium Series			
^{242}Pu	0.00	0.00	0.00
^{238}U	0.01	0.00	0.00
^{238}Pu	0.00	0.00	0.00
^{234}U	0.01	0.00	0.00
^{230}Th	0.00	0.00	0.00
^{226}Ra	0.01	0.00	0.00
Neptunium Series			
^{245}Cm	0.00	0.00	0.00
^{241}Pu	0.00	0.00	0.00
^{241}Am	0.00	0.00	0.00
^{237}Np	0.03	0.00	0.00
^{233}U	0.01	0.00	0.00
$^{229\text{Th}}$	0.00	0.00	0.00
Thorium Series			
^{240}Pu	0.00	0.00	0.00
^{236}U	0.01	0.00	0.00
^{232}Th	0.00	0.00	0.00
^{228}Ra	0.01	0.00	0.00
^{232}U	0.01	0.00	0.00
Fission Products			
^{14}C	0.57	0.00	0.00
^{90}Sr	0.01	0.00	0.00
^{99}Tc	0.14	0.00	0.00
^{129}I	100.44	5.32×10^{-8}	1.42×10^{-10}
^{135}Cs	0.01	0.00	0.00
^{137}Cs	0.01	0.00	0.00
Ingrowth (from all RNs)		0.00	0.00
TOTAL DOSE			**1.42×10^{-10}**

6. SUMMARY AND CONCLUSIONS

6.1. Preliminary Results

Thermal, hydrologic, and geochemical calculations suggest that radionuclides in spent fuel emplaced in deep boreholes will experience little physical reason to leave the borehole/near borehole domain. The vast majority of radionuclides, and the fuel itself, will be thermodynamically stable and will therefore resist dissolution into borehole fluids, or movement into and through the adjacent rocks. Thermal-hydrologic calculations indicate that, except for an early window extending from the time of emplacement to ~ 150 years post-emplacement (in the borehole), and ~ 600 years (to the top of the basement), there will be no vertical fluid flow to transport radionuclides towards the surface. Vertical transport velocities in the early flow window will be between 0.1 (basement) and 0.7 (borehole) m/yr. This means that total vertical fluid movement in, and adjacent to, deep borehole disposal zones should not exceed roughly 100 meters. In the absence of advection, chemical diffusion cannot move radionuclides from boreholes through discontinuous, stagnant, and density-stratified waters over distances much greater than about 200 meters in the 1,000,000 years needed for the vast bulk of the radioactivity to decay away. Simplified and conservative performance assessment calculations indicate that radiological dose to a human receptor via the groundwater pathway would be limited to a single radionuclide (^{129}I) and would be negligibly small, ~10 order of magnitude below current criteria.

6.2. Recommendations for Additional Work

A more complete technical analysis of the deep borehole option requires a comprehensive evaluation of potentially relevant features, events, and processes, beginning with the preliminary list identified in Appendix B and expanding that list as appropriate. More detailed analyses should be performed to confirm that FEPs that have been excluded from this preliminary analysis do not significantly impact long-term performance. Future performance assessment modeling should consider all relevant release scenarios and pathways based on FEP analyses, rather than focusing on the single pathway considered in this report. FEP analyses and future iterations of performance assessment modeling will provide guidance regarding where resources should be focused to build confidence in the understanding of borehole disposal systems.

Three specific areas for future research are noted here, based on preliminary analyses:

1. The coupled thermal-hydrologic-chemical-mechanical behavior of the borehole and disturbed region during the thermal pulse, and in the presence of density-stratified waters, should be modeled more accurately.

2. Additional consideration should be focused on the design and long-term performance of deep seals. Calculated releases might be lowered even further from the already low values predicted above by development and deployment of sorbents that sorb/sequester ^{129}I in the borehole, or in the seals. Layered bismuth hydroxide compounds have shown great promise for limiting ^{129}I transport to the biosphere (Krumhansl et al., 2006). The performance of bismuth compounds must be verified

(and possibly optimized) under the temperature-salinity conditions that will prevail in deep boreholes.

3. Modeling of both the detailed thermal-hydrologic-chemical-mechanical behavior and the full-system performance of multi-borehole arrays should be undertaken, consistent with an assumption that a regional borehole disposal facility could entail an array of 10-100 individual boreholes. Such investigations could elaborate on the potential for cross-hole effects, help determine minimum inter-holes distances, etc. In order to establish a better sense of the potential performance variability that might be expected in multiple implementations of borehole disposal fields, individual preliminary performance assessments should be performed for several specific regions. Specific regions could be identified based on the availability of pre-existing geohydrologic data for depths of ~ 3 - 5 kilometers.

In addition to the technical issues related to the post-closure performance of the deep borehole disposal system described above, several other topics that are beyond the scope of this report should be examined in further detail:

1. A more comprehensive and detailed cost analysis would provide a firmer basis for quantitative comparisons with other disposal system options;

2. A detailed description of the changes to legal and regulatory requirements for implementation of deep borehole disposal would provide policymakers with a roadmap for necessary actions (specifically, consideration might be given to developing a risk-based standard); and

3. Detailed analyses of engineering systems and operational practices for waste emplacement are needed to demonstrate the viability of the deep borehole disposal concept. Also, the advantages of applying deep borehole disposal in countries possessing smaller and/or non-fuel waste inventories should be explored further.

It is recommended that ultimately a full-scale pilot project be undertaken, perhaps with surrogate waste, in order to fully explore the viability of a borehole disposal concept. The scientific and engineering advances gained from a single pilot project, and the applicability to subsequent borehole disposal implementations, are in contrast to site-specific mined repositories and their unique site characterization demands with relatively little transferable knowledge to subsequent repositories. Given the potential for standardizing the borehole design, and thus the ready extension to multiple borehole facilities, a single pilot project could provide significant gains on the scientific and engineering issues needing to be resolved, enable the development of international standards, and accelerate the evaluation of the viability of deep borehole disposal of spent nuclear fuel and high-level radioactive waste.

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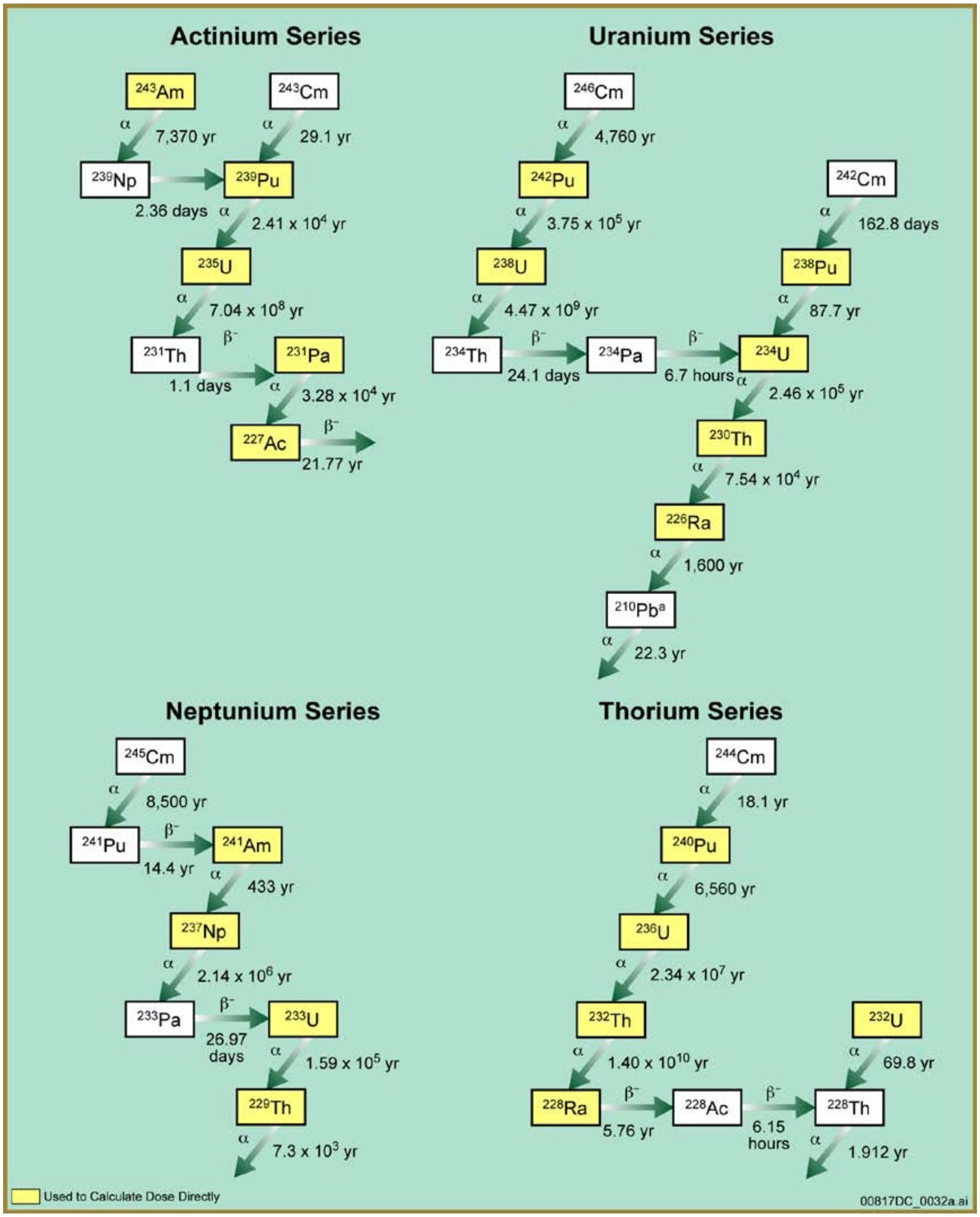
APPENDIX A: U.S. HLW AND SNF INVENTORY

Evaluation of the deep borehole disposal concept in this report is based on estimates of current and projected future quantities of high-level radioactive waste and spent nuclear fuel in the U.S. In 2007, DOE estimated that 109,300 metric tons heavy metal (MTHM) of high-level waste and spent nuclear fuel in the U.S. will ultimately need to be stored (DOE Office of Public Affairs, August 5, 2008). This inventory consists of 70,000 MTHM that is included in the Yucca Mountain license application, with the remainder that will need to be disposed of from future production. The inventory includes commercial spent nuclear fuel (CSNF), DOE spent nuclear fuel (DSNF), and high-level waste glass (HLWG). The inventory consists of actinide elements in several radionuclide decay chains (Figure 14) along with a number of fission products.

The 70,000 MTHM Yucca Mountain inventory is predominantly (about 70%) CSNF, which in turn consists of spent fuel assemblies from pressurized water reactors (PWRs) and boiling water reactors (BWRs). A representative inventory, showing the important actinide elements from Figure 14 and the important fission products, for a single Yucca Mountain waste package is provided in Table 7. The 31-radionuclide inventory is shown for an initial time (either 2030 or 2067 depending on waste type) and aged to a common year, 2117, about 100 years from the present. Note that this table actually represents two different types of waste packages: a CSNF waste package that contains the CSNF inventory (a single CSNF waste package would contain either 21 PWR assemblies or 44 BWR assemblies); and a codisposal waste package that combines the DSNF and HLWG inventory. Also, note that the inventories in Table 7 do not include any Mixed Oxide (MOX) fuel or Lanthanide Borosilicate (LaBS) waste.

For the purposes of discussing and characterizing the waste for deep borehole disposal, the relative radionuclide inventories for CSNF shown in Table 7 are considered representative of the entire US HLW and SNF inventory. The other waste streams (DSNF and HLWG) contains similar relative radionuclide inventories (Table 7) as the CSNF waste stream.

By weight, CSNF is about 97% ^{238}U, with contributions of 0.3-0.8% from ^{235}U, ^{236}U, ^{239}Pu, and ^{240}Pu. All other radionuclides contribute less than 0.1%. Figure 15 shows the relative contributions of the 31 radionuclides by activity (in curies), which is a more direct indicator of their potential effect on dose. Note that Figure 15 includes all waste (not just CSNF), but the relative contributions are likely to be the same. The change in importance of the various radionuclides over time is indicative of the effects decay and ingrowth. The same information is tabulated in Table 8, which also shows the decline in total activity over time.



Source: Figure 6.3.7-4 of (Sandia National Laboratories 2008).

[a] A series of short-lived daughters between ^{226}Ra and ^{210}Pb are not shown. Also, ^{210}Pb is not used to calculate dose directly, but its biosphere dose conversion factor is included with that of ^{226}Ra.

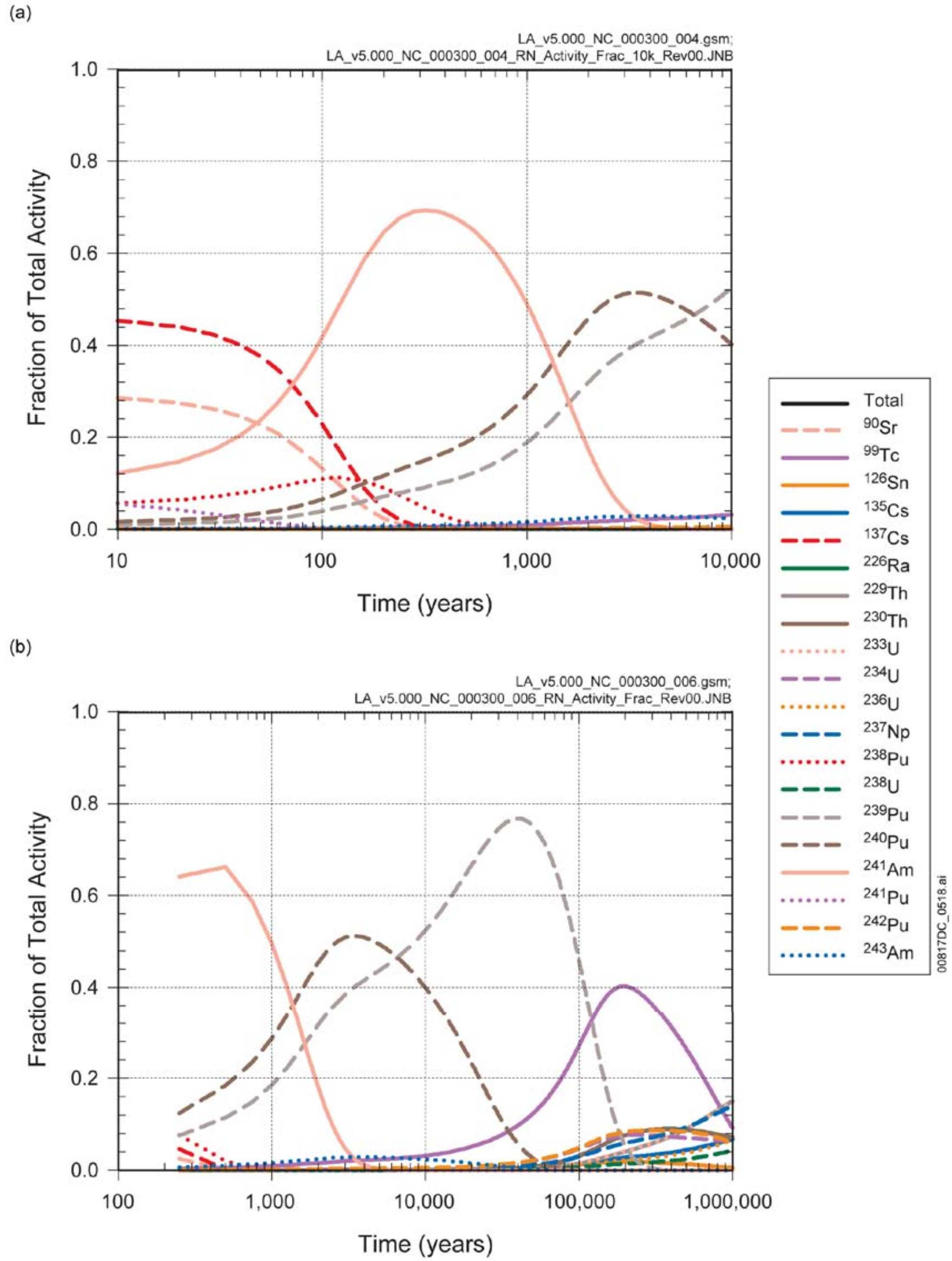
[b] Value listed under each radionuclide is the approximate decay half-life for the radionuclide.

Figure 14. Decay Chains of the Actinide Elements.

Table 7. Yucca Mountain Nuclear Waste Inventory per Waste Package by Radionuclide.

	Waste Package Inventory (g/pkg)					
Radionuclide	**CSNF at 2067**	**CSNF after 50 Years**	**DSNF at 2030**	**DSNF after 87 Years**	**HLWG at 2030**	**HLWG after 87 Years**
^{227}Ac	2.47E-06	6.27E-06	1.22E-03	1.39E-03	1.91E-04	9.47E-04
^{241}Am	8.18E+03	9.84E+03	2.18E+02	2.15E+02	3.75E+01	3.37E+01
^{243}Am	1.24E+03	1.23E+03	6.73E+00	6.68E+00	5.75E-01	5.70E-01
^{14}C	1.35E+00	1.34E+00	1.81E+00	1.79E+00	0.00E+00	0.00E+00
^{36}Cl	3.23E+00	3.23E+00	4.23E+00	4.23E+00	0.00E+00	0.00E+00
^{245}Cm	1.75E+01	1.74E+01	9.25E-02	9.18E-02	5.43E-02	5.39E-02
^{135}Cs	4.36E+03	4.36E+03	9.74E+01	9.74E+01	1.27E+02	1.27E+02
^{137}Cs	5.90E+03	1.86E+03	9.72E+01	1.31E+01	3.02E+02	4.07E+01
^{129}I	1.73E+03	1.73E+03	3.56E+01	3.56E+01	7.27E+01	7.27E+01
^{237}Np	4.57E+03	5.32E+03	8.14E+01	1.12E+02	9.95E+01	1.04E+02
^{231}Pa	9.17E-03	1.22E-02	2.14E+00	2.14E+00	1.53E+00	1.53E+00
^{238}Pu	1.52E+03	1.02E+03	1.25E+01	6.28E+00	3.91E+01	1.96E+01
^{239}Pu	4.32E+04	4.31E+04	2.21E+03	2.20E+03	5.58E+02	5.57E+02
^{240}Pu	2.05E+04	2.04E+04	4.35E+02	4.31E+02	4.61E+01	4.57E+01
^{241}Pu	2.66E+03	2.40E+02	2.92E+01	4.49E-01	1.22E+00	1.89E-02
^{242}Pu	5.28E+03	5.28E+03	3.02E+01	3.02E+01	3.89E+00	3.89E+00
^{226}Ra	0.00E+00	1.29E-04	4.57E-05	1.80E-04	2.42E-05	2.68E-05
^{228}Ra	0.00E+00	1.90E-11	1.51E-05	8.77E-06	6.00E-06	1.20E-05
^{79}Se	4.19E+01	4.19E+01	6.82E+00	6.82E+00	7.01E+00	7.01E+00
^{126}Sn	4.63E+02	4.63E+02	9.40E+00	9.40E+00	1.70E+01	1.70E+01
^{90}Sr	2.49E+03	7.46E+02	5.22E+01	6.43E+00	1.74E+02	2.14E+01
^{99}Tc	7.55E+03	7.55E+03	1.58E+02	1.58E+02	1.01E+03	1.01E+03
^{229}Th	0.00E+00	2.07E-05	3.24E-01	5.22E-01	3.30E-03	1.05E-02
^{230}Th	1.52E-01	4.32E-01	1.18E-01	2.33E-01	8.12E-04	9.02E-03
^{232}Th	0.00E+00	5.63E-02	2.17E+04	2.17E+04	2.98E+04	2.98E+04
^{232}U	1.02E-02	6.20E-03	1.28E+00	5.39E-01	4.08E-04	1.72E-04
^{233}U	5.76E-02	1.37E-01	5.38E+02	5.38E+02	1.94E+01	1.94E+01
^{234}U	1.75E+03	2.24E+03	4.73E+02	4.79E+02	2.33E+01	4.24E+01
^{235}U	6.26E+04	6.27E+04	2.51E+04	2.51E+04	1.41E+03	1.41E+03
^{236}U	3.84E+04	3.85E+04	1.25E+03	1.25E+03	5.99E+01	6.03E+01
^{238}U	7.82E+06	7.82E+06	6.84E+05	6.84E+05	2.37E+05	2.37E+05

Source: Sandia National Laboratories 2008a; Table 6.3.7-4a



Source:Sandia National Laboratories 2008a, Figure 8.3-2.

Figure 15. Mean Radionuclide Contributions to the Total Yucca Mountain Nuclear Waste Inventory as a Function of Time for (a) 10,000 Years and (b) 1,000,000 Years After 2117.

Table 8. Decay of Total Yucca Mountain Nuclear Waste Inventory as a Function of Time and Dominant Contributors to Total Curie Inventory.

Time After Closure, 2117 (yrs)	Percent of Total Initial Curie Inventory	Major Contributors to Total Inventory at Time after Closure
0	100.00	^{137}Cs (46%), ^{90}Sr (29%), ^{241}Am (10%)
10	81.2	^{137}Cs (45%), ^{90}Sr (28%), ^{241}Am (12%)
100	20.75	^{241}Am (41%), ^{137}Cs (22 %), ^{90}Sr (13%), ^{238}Pu (11%))
1,000	4.20	^{241}Am (48%), ^{240}Pu (29%), ^{239}Pu (19%)
10,000	1.18	^{239}Pu-239 (52%), ^{240}Pu (40%)
100,000	0.10	^{239}Pu-239 (46%), ^{99}Tc-99 (27%)
500,000	0.03	^{99}Tc-99 (26%), ^{229}Th-229 (9%), ^{230}Th (9%), ^{226}Ra-226 (9%), ^{233}U (9%), ^{237}Np-237 (9%), ^{242}Pu (8%), ^{234}U-234 (7%)
1,000,000	0.02	^{233}U-233 (15%), ^{229}Th (15%), ^{237}Np-237 (14%), ^{99}Tc-99 (9%), ^{230}Th (7%), ^{226}Ra-226 (7%), ^{135}Cs (7%), ^{236}U-236 (6%), ^{242}Pu (6%)

Source: Table 8.3-1 of (Sandia National Laboratories 2008)

At early time (the first few hundred years after emplacement) the radionuclides with the highest activity are all short-lived (half-lives less than 500 years): ^{137}Cs, ^{90}Sr, ^{241}Am, and ^{238}Pu. From about 100 years to 1,500 years after emplacement, ^{241}Am is the largest contributor to the total activity. Subsequent to that, moderate half-life radionuclides become more important. ^{240}Pu (half-life of 6,560 years) is the largest contributor to total activity from about 1,500 years to 7,000 years after emplacement, then ^{239}Pu (half-life of 24,100 years) becomes the largest contributor until about 100,000 years after emplacement. At very long times (greater than 100,000 years after emplacement), the following long-lived radionuclides become most important to total activity: ^{99}Tc, ^{242}Pu, ^{237}Np, ^{234}U, ^{230}Th, ^{226}Ra, ^{233}U, ^{229}Th, ^{135}Cs, and ^{236}U.

Table 8 shows that the total activity (in curies) of the inventory decays to about 20% of the initial activity after 100 years, to about 4% after 1,000 years, and to about 1% of the initial activity after 10,000 years. Roughly 1000 years is required before the total radioactivity in CSNF would decay to the background level of a 0.2% U ore body. The radiation in un-processed spent fuel requires roughly 10,000 years to decay to the background levels of an ore body (Langmuir 1996).

APPENDIX B: COMPARISON OF DEEP BOREHOLE DISPOSAL AND YMP FEPS

Table B-1. Yucca Mountain Project Features, Events, and Processes List and Screening Decisions Listed by FEP Number. (based on: Sandia National Laboratories 2008b, Table 7.1). A "?" denotes a lower level of confidence in the preliminary analysis.

FEP Number	*FEP Name*	*YMP Screening Decision*	*Likely DBD Decision*	*Estimated DBD Level of Effort*
0.1.02.00.0A	*Timescales of Concern*	*Included*	*Include*	*1*
0.1.03.00.0A	*Spatial Domain of Concern*	*Included*	*Include*	*1*
0.1.09.00.0A	*Regulatory Requirements and Exclusions*	*Included*	*Include*	*3 Regulations and laws will need to be revised*
0.1.10.00.0A	*Model and Data Issues*	*Included*	*Include*	*1*
1.1.01.01.0A	*Open Site Investigation Boreholes*	*Excluded*	*Exclude*	*1*
1.1.01.01.0B	*Influx Through Holes Drilled in Drift Wall or Crown*	*Excluded*	*Exclude (NA)*	*1*
1.1.02.00.0A	*Chemical Effects of Excavation and Construction in EBS*	*Excluded*	*Exclude*	*2*
1.1.02.00.0B	*Mechanical Effects of Excavation and Construction in EBS*	*Excluded*	*Include*	*2*
1.1.02.01.0A	*Site Flooding (During Construction and Operation)*	*Excluded*	*Exclude*	*1*
1.1.02.02.0A	*Preclosure Ventilation*	*Included*	*Exclude (NA)*	*1*
1.1.02.03.0A	*Undesirable Materials Left*	*Excluded*	*Exclude (NA)*	*2*
1.1.03.01.0A	*Error in Waste Emplacement*	*Excluded*	*Exclude*	*3 Need to consider the emplacement that may get stuck halfway down. Also need to consider canisters that are crushed by overlying canisters*
1.1.03.01.0B	*Error in Backfill Emplacement*	*Excluded*	*Include?*	*Maybe be difficult to ensure that backfill is emplaced uniformly, may be simplest to include FEP and take no credit for backfill1*
1.1.04.01.0A	*Incomplete Closure*	*Excluded*	*Exclude*	*2*
1.1.05.00.0A	*Records and Markers for the Repository*	*Excluded*	*Exclude (regulatory)*	*1*
1.1.07.00.0A	*Repository Design*	*Included*	*Include*	*1*
1.1.08.00.0A	*Inadequate Quality Control and Deviations from Design*	*Excluded*	*Exclude (regulatory or low consequence)*	*1*

FEP Number	*FEP Name*	*YMP Screening Decision*	*Likely DBD Decision*	*Estimated DBD Level of Effort*
1.1.09.00.0A	*Schedule and Planning*	*Excluded*	*Exclude*	*1*
1.1.10.00.0A	*Administrative Control of the Repository Site*	*Excluded*	*Exclude*	*1*
1.1.11.00.0A	*Monitoring of the Repository*	*Excluded*	*Exclude*	*1*
1.1.12.01.0A	*Accidents and Unplanned Events During Construction and Operation*	*Excluded*	*Exclude*	*1*
1.1.13.00.0A	*Retrievability*	*Included*	*Exclude (policy)*	*2*
1.2.01.01.0A	*Tectonic Activity - Large Scale*	*Excluded*	*Exclude*	*1*
1.2.02.01.0A	*Fractures*	*Included*	*Include*	*2*
1.2.02.02.0A	*Faults*	*Included*	*Include*	*2*
1.2.02.03.0A	*Fault Displacement Damages EBS Components*	*Included*	*Include?*	*2 Note—if no credit is taken for WP and WF components, all EBS FEPs are simplified to the consideration of the borehole seals*
1.2.03.02.0A	*Seismic Ground Motion Damages EBS Components*	*Included*	*Exclude*	*2*
1.2.03.02.0B	*Seismic-Induced Rockfall Damages EBS Components*	*Excluded*	*Exclude (NA)*	*1*
1.2.03.02.0C	*Seismic-Induced Drift Collapse Damages EBS Components*	*Included*	*Exclude (NA)*	*1*
1.2.03.02.0D	*Seismic-Induced Drift Collapse Alters In-Drift Thermohydrology*	*Included*	*Exclude (NA)*	*1*
1.2.03.02.0E	*Seismic-Induced Drift Collapse Alters In-Drift Chemistry*	*Excluded*	*Exclude (NA)*	*1*
1.2.03.03.0A	*Seismicity Associated With Igneous Activity*	*Included*	*Exclude*	*1*
1.2.04.02.0A	*Igneous Activity Changes Rock Properties*	*Excluded*	*Exclude*	*2 Need to evaluate potential for igneous activity at each site (should generically be low), also need to determine if repository heat can contribute to rock melting*
1.2.04.03.0A	*Igneous Intrusion Into Repository*	*Included*	*Exclude*	*2*
1.2.04.04.0A	*Igneous Intrusion Interacts With EBS Components*	*Included*	*Exclude*	*2*
1.2.04.04.0B	*Chemical Effects of Magma and Magmatic Volatiles*	*Included*	*Exclude*	*2 Volatiles may impact transport*
1.2.04.05.0A	*Magma Or Pyroclastic Base Surge Transports Waste*	*Excluded*	*Exclude (NA)*	*1*
1.2.04.06.0A	*Eruptive Conduit to Surface Intersects Repository*	*Included*	*Exclude*	*2*
1.2.04.07.0A	*Ashfall*	*Included*	*Exclude*	*1*
1.2.04.07.0B	*Ash Redistribution in Groundwater*	*Excluded*	*Exclude*	*1*

FEP Number	*FEP Name*	*YMP Screening Decision*	*Likely DBD Decision*	*Estimated DBD Level of Effort*
1.2.04.07.0C	*Ash Redistribution Via Soil and Sediment Transport*	*Included*	*Exclude*	*1*
1.2.05.00.0A	*Metamorphism*	*Excluded*	*Exclude*	*2* *Repository heat may create metamorphic conditions*
1.2.06.00.0A	*Hydrothermal Activity*	*Excluded*	*Exclude*	*3* *Repository heat may create local hydrothermal activity*
1.2.07.01.0A	*Erosion/Denudation*	*Excluded*	*Exclude*	*1*
1.2.07.02.0A	*Deposition*	*Excluded*	*Exclude*	*1*
1.2.08.00.0A	*Diagenesis*	*Excluded*	*Exclude*	*2*
1.2.09.00.0A	*Salt Diapirism and Dissolution*	*Excluded*	*Exclude*	*1*
1.2.09.01.0A	*Diapirism*	*Excluded*	*Exclude*	*2* *Need to demonstrate that repository heat will not generate local diapirism*
1.2.09.02.0A	*Large-Scale Dissolution*	*Excluded*	*Exclude*	*1*
1.2.10.01.0A	*Hydrologic Response to Seismic Activity*	*Excluded*	*Exclude*	*1*
1.2.10.02.0A	*Hydrologic Response to Igneous Activity*	*Excluded*	*Exclude*	*2*
1.3.01.00.0A	*Climate Change*	*Included*	*Exclude*	*1*
1.3.04.00.0A	*Periglacial Effects*	*Excluded*	*Include*	*1*
1.3.05.00.0A	*Glacial and Ice Sheet Effect*	*Excluded*	*Include*	*2* *Need to consider fluid pressure effects of future ice sheet loading*
1.3.07.01.0A	*Water Table Decline*	*Excluded*	*Exclude*	*1*
1.3.07.02.0A	*Water Table Rise Affects SZ*	*Included*	*Exclude*	*1*
1.3.07.02.0B	*Water Table Rise Affects UZ*	*Included*	*Exclude*	*1* *All UZ FEPs are simplified*
1.4.01.00.0A	*Human Influences on Climate*	*Excluded*	*Exclude*	*1*
1.4.01.01.0A	*Climate Modification Increases Recharge*	*Included*	*Exclude*	*1*
1.4.01.02.0A	*Greenhouse Gas Effects*	*Excluded*	*Exclude*	*1*
1.4.01.03.0A	*Acid Rain*	*Excluded*	*Exclude*	*1*
1.4.01.04.0A	*Ozone Layer Failure*	*Excluded*	*Exclude*	*1*
1.4.02.01.0A	*Deliberate Human Intrusion*	*Excluded*	*Exclude*	*1*
1.4.02.02.0A	*Inadvertent Human Intrusion*	*Included*	*Exclude*	*1 (requires regulatory change)*
1.4.02.03.0A	*Igneous Event Precedes Human Intrusion*	*Excluded*	*Exclude*	*1*
1.4.02.04.0A	*Seismic Event Precedes Human Intrusion*	*Excluded*	*Exclude*	*1*
1.4.03.00.0A	*Unintrusive Site Investigation*	*Excluded*	*Exclude*	*1*
1.4.04.00.0A	*Drilling Activities (Human Intrusion)*	*Included*	*Exclude*	*1*
1.4.04.01.0A	*Effects of Drilling Intrusion*	*Included*	*Exclude*	*1*
1.4.05.00.0A	*Mining and Other Underground Activities*	*Excluded*	*Exclude*	*1*

FEP Number	*FEP Name*	*YMP Screening Decision*	*Likely DBD Decision*	*Estimated DBD Level of Effort*
	(Human Intrusion)			*Includes natural resource issues*
1.4.06.01.0A	*Altered Soil Or Surface Water Chemistry*	*Excluded*	*Exclude*	*1*
1.4.07.01.0A	*Water Management Activities*	*Included*	*Exclude*	*1*
1.4.07.02.0A	*Wells*	*Included*	*Exclude*	*1*
1.4.07.03.0A	*Recycling of Accumulated Radionuclides from Soils to Groundwater*	*Excluded*	*Exclude*	*1*
1.4.08.00.0A	*Social and Institutional Developments*	*Excluded*	*Exclude*	*1*
1.4.09.00.0A	*Technological Developments*	*Excluded*	*Exclude*	*1*
1.4.11.00.0A	*Explosions and Crashes (Human Activities)*	*Excluded*	*Exclude*	*1*
1.5.01.01.0A	*Meteorite Impact*	*Excluded*	*Exclude*	*1*
1.5.01.02.0A	*Extraterrestrial Events*	*Excluded*	*Exclude*	*1*
1.5.02.00.0A	*Species Evolution*	*Excluded*	*Exclude*	*1*
1.5.03.01.0A	*Changes in the Earth's Magnetic Field*	*Excluded*	*Exclude*	*1*
1.5.03.02.0A	*Earth Tides*	*Excluded*	*Exclude*	*1*
2.1.01.01.0A	*Waste Inventory*	*Included*	*Include*	*1*
2.1.01.02.0A	*Interactions Between Co-Located Waste*	*Excluded*	*Exclude*	*1*
2.1.01.02.0B	*Interactions Between Co-Disposed Waste*	*Included*	*Exclude*	*1*
2.1.01.03.0A	*Heterogeneity of Waste Inventory*	*Included*	*Include*	*1*
2.1.01.04.0A	*Repository-Scale Spatial Heterogeneity of Emplaced Waste*	*Included*	*Include*	*1*
2.1.02.01.0A	*DSNF Degradation (Alteration, Dissolution, and Radionuclide Release)*	*Included*	*Exclude*	*1*
2.1.02.02.0A	*CSNF Degradation (Alteration, Dissolution, and Radionuclide Release)*	*Included*	*Exclude*	*1* *Assume no credit for CSNF waste form*
2.1.02.03.0A	*HLW Glass Degradation (Alteration, Dissolution, and Radionuclide Release)*	*Included*	*Exclude*	*1* *Assume no credit for HLW waste form?*
2.1.02.04.0A	*Alpha Recoil Enhances Dissolution*	*Excluded*	*Exclude*	*1*
2.1.02.05.0A	*HLW Glass Cracking*	*Included*	*Exclude*	*1*
2.1.02.06.0A	*HLW Glass Recrystallization*	*Excluded*	*Exclude*	*1*
2.1.02.07.0A	*Radionuclide Release from Gap and Grain Boundaries*	*Included*	*Exclude*	*1*
2.1.02.08.0A	*Pyrophoricity from DSNF*	*Excluded*	*Exclude*	*1*
2.1.02.09.0A	*Chemical Effects of Void Space in Waste Package*	*Included*	*Exclude*	*1*
2.1.02.10.0A	*Organic/Cellulosic Materials in Waste*	*Excluded*	*Exclude*	*1*
2.1.02.11.0A	*Degradation of Cladding from Waterlogged Rods*	*Excluded*	*Exclude*	*1*
2.1.02.12.0A	*Degradation of Cladding Prior to Disposal*	*Included*	*Exclude*	*1*
2.1.02.13.0A	*General Corrosion of Cladding*	*Excluded*	*Exclude*	*1*
2.1.02.14.0A	*Microbially Influenced Corrosion (MIC) of Cladding*	*Excluded*	*Include*	*1*
2.1.02.15.0A	*Localized (Radiolysis Enhanced) Corrosion of Cladding*	*Excluded*	*Exclude*	*1*
2.1.02.16.0A	*Localized (Pitting) Corrosion of Cladding*	*Excluded*	*Exclude*	*1*
2.1.02.17.0A	*Localized (Crevice) Corrosion of Cladding*	*Excluded*	*Exclude*	*1*
2.1.02.18.0A	*Enhanced Corrosion of Cladding from*	*Excluded*	*Exclude*	*1*

FEP Number	FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort
	Dissolved Silica			
2.1.02.19.0A	*Creep Rupture of Cladding*	*Excluded*	*Exclude*	*1*
2.1.02.20.0A	*Internal Pressurization of Cladding*	*Excluded*	*Exclude*	*1*
2.1.02.21.0A	*Stress Corrosion Cracking (SCC) of Cladding*	*Excluded*	*Exclude*	*1*
2.1.02.22.0A	*Hydride Cracking of Cladding*	*Excluded*	*Exclude*	*1*
2.1.02.23.0A	*Cladding Unzipping*	*Included*	*Exclude*	*1*
2.1.02.24.0A	*Mechanical Impact on Cladding*	*Excluded*	*Exclude*	*1*
2.1.02.25.0A	*DSNF Cladding*	*Excluded*	*Exclude*	*1*
2.1.02.25.0B	*Naval SNf Cladding*	*Included*	*Exclude*	*1* *Exclude Naval SNF from analysis completely*
2.1.02.26.0A	*Diffusion-Controlled Cavity Growth in Cladding*	*Excluded*	*Exclude*	*1*
2.1.02.27.0A	*Localized (Fluoride Enhanced) Corrosion of Cladding*	*Excluded*	*Exclude*	*1*
2.1.02.28.0A	*Grouping of DSNF Waste Types Into Categories*	*Included*	*Exclude*	*1*
2.1.02.29.0A	*Flammable Gas Generation from DSNF*	*Excluded*	*Exclude*	*1*
2.1.03.01.0A	*General Corrosion of Waste Packages*	*Included*	*Exclude*	*1* *Assume no flow barrier credit for WP*
2.1.03.01.0B	*General Corrosion of Drip Shields*	*Included*	*Exclude (NA)*	*1*
2.1.03.02.0A	*Stress Corrosion Cracking (SCC) of Waste Packages*	*Included*	*Exclude*	*1*
2.1.03.02.0B	*Stress Corrosion Cracking (SCC) of Drip Shields*	*Excluded*	*Exclude (NA)*	*1*
2.1.03.03.0A	*Localized Corrosion of Waste Packages*	*Included*	*Exclude*	*1*
2.1.03.03.0B	*Localized Corrosion of Drip Shields*	*Excluded*	*Exclude*	*1*
2.1.03.04.0A	*Hydride Cracking of Waste Packages*	*Excluded*	*Exclude*	*1*
2.1.03.04.0B	*Hydride Cracking of Drip Shields*	*Excluded*	*Exclude (NA)*	*1*
2.1.03.05.0A	*Microbially Influenced Corrosion (MIC) of Waste Packages*	*Included*	*Exclude*	*1*
2.1.03.05.0B	*Microbially Influenced Corrosion (MIC) of Drip Shields*	*Excluded*	*Exclude*	*1*
2.1.03.06.0A	*Internal Corrosion of Waste Packages Prior to Breach*	*Excluded*	*Exclude*	*1*
2.1.03.07.0A	*Mechanical Impact on Waste Package*	*Excluded*	*Exclude*	*1* *This FEP includes all damage to WPs after emplacement*
2.1.03.07.0B	*Mechanical Impact on Drip Shield*	*Excluded*	*Exclude (NA)*	*1*
2.1.03.08.0A	*Early Failure of Waste Packages*	*Included*	*Exclude*	*1*
2.1.03.08.0B	*Early Failure of Drip Shields*	*Included*	*Exclude (NA)*	*1*
2.1.03.09.0A	*Copper Corrosion in EBS*	*Excluded*	*Exclude*	*1*
2.1.03.10.0A	*Advection of Liquids and Solids Through Cracks in the Waste Package*	*Excluded*	*Exclude*	*1*
2.1.03.10.0B	*Advection of Liquids and Solids Through Cracks in the Drip Shield*	*Excluded*	*Exclude (NA)*	*1*
2.1.03.11.0A	*Physical Form of Waste Package and Drip*	*Included*	*Include*	*1*

FEP Number	FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort
	Shield			
2.1.04.01.0A	*Flow in the Backfill*	*Excluded*	*Include*	*1 Include FEPs that degrade backfill by assuming no credit due to difficulty in ensuring full emplacement*
2.1.04.02.0A	*Chemical Properties and Evolution of Backfill*	*Excluded*	*Include*	*1*
2.1.04.03.0A	*Erosion or Dissolution of Backfill*	*Excluded*	*Include*	*1*
2.1.04.04.0A	*Thermal-Mechanical Effects of Backfill*	*Excluded*	*Include*	*1*
2.1.04.05.0A	*Thermal-Mechanical Properties and Evolution of Backfill*	*Excluded*	*Include*	*1*
2.1.04.09.0A	*Radionuclide Transport in Backfill*	*Excluded*	*Exclude*	*1 Exclude beneficial transport effects of backfill because of difficulty in ensuring full emplacement*
2.1.05.01.0A	*Flow Through Seals (Access Ramps and Ventilation Shafts)*	*Excluded*	*Include*	*3*
2.1.05.02.0A	*Radionuclide Transport Through Seals*	*Excluded*	*Include*	*3*
2.1.05.03.0A	*Degradation of Seals*	*Excluded*	*Include*	*3*
2.1.06.01.0A	*Chemical Effects of Rock Reinforcement and Cementitious Materials in EBS*	*Excluded*	*Include (Seals are EBS, so one entire release pathway to RMEI is in EBS)*	*3*
2.1.06.02.0A	*Mechanical Effects of Rock Reinforcement Materials in EBS*	*Excluded*	*Include*	*3 What happens to borehole seal as casing degrades?*
2.1.06.04.0A	*Flow Through Rock Reinforcement Materials in EBS*	*Excluded*	*Exclude*	*1*
2.1.06.05.0A	*Mechanical Degradation of Emplacement Pallet*	*Excluded*	*Exclude (NA)*	*1*
2.1.06.05.0B	*Mechanical Degradation of Invert*	*Excluded*	*Exclude (NA)*	*1*
2.1.06.05.0C	*Chemical Degradation of Emplacement Pallet*	*Included*	*Exclude (NA)*	*1*
2.1.06.05.0D	*Chemical Degradation of Invert*	*Excluded*	*Exclude (NA)*	*1*
2.1.06.06.0A	*Effects of Drip Shield on Flow*	*Included*	*Exclude (NA)*	*1*
2.1.06.06.0B	*Oxygen Embrittlement of Drip Shields*	*Excluded*	*Exclude (NA)*	*1*
2.1.06.07.0A	*Chemical Effects at EBS Component Interfaces*	*Excluded*	*Include?*	*2*
2.1.06.07.0B	*Mechanical Effects at EBS Component Interfaces*	*Excluded*	*Include*	*3*
2.1.07.01.0A	*Rockfall*	*Excluded*	*Exclude*	*1*
2.1.07.02.0A	*Drift Collapse*	*Excluded*	*Exclude*	*1 If drift = borehole,*

FEP Number	*FEP Name*	*YMP Screening Decision*	*Likely DBD Decision*	*Estimated DBD Level of Effort*
				then this is a potentially significant operational FEP
2.1.07.04.0A	*Hydrostatic Pressure on Waste Package*	*Excluded*	*Include*	*2*
2.1.07.04.0B	*Hydrostatic Pressure on Drip Shield*	*Excluded*	*Exclude (NA)*	*1*
2.1.07.05.0A	*Creep of Metallic Materials in the Waste Package*	*Excluded*	*Exclude*	*1*
2.1.07.05.0B	*Creep of Metallic Materials in the Drip Shield*	*Excluded*	*Exclude (NA)*	*1*
2.1.07.06.0A	*Floor Buckling*	*Excluded*	*Exclude*	*1*
2.1.08.01.0A	*Water Influx at the Repository*	*Included*	*Include*	*1*
2.1.08.01.0B	*Effects of Rapid Influx into the Repository*	*Excluded*	*Exclude*	*1*
2.1.08.02.0A	*Enhanced Influx at the Repository*	*Included*	*Exclude*	*1*
2.1.08.03.0A	*Repository Dry-Out Due to Waste Heat*	*Included*	*Include*	*1*
2.1.08.04.0A	*Condensation Forms on Roofs of Drifts (Drift-Scale Cold Traps)*	*Included*	*Exclude*	*1*
2.1.08.04.0B	*Condensation Forms at Repository Edges (Repository-Scale Cold Traps)*	*Included*	*Exclude*	*1*
2.1.08.05.0A	*Flow Through Invert*	*Included*	*Exclude (NA)*	*1*
2.1.08.06.0A	*Capillary Effects (Wicking) in EBS*	*Included*	*Exclude*	*1*
2.1.08.07.0A	*Unsaturated Flow in the EBS*	*Included*	*Exclude*	*1*
2.1.08.09.0A	*Saturated Flow in the EBS*	*Excluded*	*Include*	*3*
2.1.08.11.0A	*Repository Resaturation Due to Waste Cooling*	*Included*	*Include*	*1*
2.1.08.12.0A	*Induced Hydrologic Changes in Invert*	*Excluded*	*Exclude (NA)*	*1*
2.1.08.14.0A	*Condensation on Underside of Drip Shield*	*Excluded*	*Exclude (NA)*	*1*
2.1.08.15.0A	*Consolidation of EBS Components*	*Excluded*	*Include*	*3*
2.1.09.01.0A	*Chemical Characteristics of Water in Drifts*	*Included*	*Include*	*3*
2.1.09.01.0B	*Chemical Characteristics of Water in Waste Package*	*Included*	*Include*	*3*
2.1.09.02.0A	*Chemical Interaction With Corrosion Products*	*Included*	*Include*	*3*
2.1.09.03.0A	*Volume Increase of Corrosion Products Impacts Cladding*	*Excluded*	*Exclude*	*1*
2.1.09.03.0B	*Volume Increase of Corrosion Products Impacts Waste Package*	*Excluded*	*Exclude*	*1*
2.1.09.03.0C	*Volume Increase of Corrosion Products Impacts Other EBS Components*	*Excluded*	*Exclude*	*1*
2.1.09.04.0A	*Radionuclide Solubility, Solubility Limits, and Speciation in the Waste Form and EBS*	*Included*	*Include*	*3*
2.1.09.05.0A	*Sorption of Dissolved Radionuclides in EBS*	*Included*	*Include*	*3*
2.1.09.06.0A	*Reduction-Oxidation Potential in Waste Package*	*Included*	*Include*	*1*
2.1.09.06.0B	*Reduction-Oxidation Potential in Drifts*	*Included*	*Include*	*1*
2.1.09.07.0A	*Reaction Kinetics in Waste Package*	*Included*	*Exclude*	*2*
2.1.09.07.0B	*Reaction Kinetics in Drifts*	*Included*	*Exclude*	*2*
2.1.09.08.0A	*Diffusion of Dissolved Radionuclides in EBS*	*Included*	*Include*	*3*
2.1.09.08.0B	*Advection of Dissolved Radionuclides in EBS*	*Included*	*Include*	*3*
2.1.09.09.0A	*Electrochemical Effects in EBS*	*Excluded*	*Exclude*	*1*
2.1.09.10.0A	*Secondary Phase Effects on Dissolved*	*Excluded*	*Include*	*2*

FEP Number	FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort
	Radionuclide Concentrations			
2.1.09.11.0A	Chemical Effects of Waste-Rock Contact	Excluded	Include	2
2.1.09.12.0A	Rind (Chemically Altered Zone) Forms in the Near-Field	Excluded	Exclude	2
2.1.09.13.0A	Complexation in EBS	Excluded	Exclude	2
2.1.09.15.0A	Formation of True (Intrinsic) Colloids in EBS	Excluded	Exclude	1
2.1.09.16.0A	Formation of Pseudo-Colloids (Natural) in EBS	Included	Exclude	1
2.1.09.17.0A	Formation of Pseudo-Colloids (Corrosion Product) in EBS	Included	Exclude	1
2.1.09.18.0A	Formation of Microbial Colloids in EBS	Excluded	Exclude	1
2.1.09.19.0A	Sorption of Colloids in EBS	Excluded	Exclude	1
2.1.09.19.0B	Advection of Colloids in EBS	Included	Exclude	1
2.1.09.20.0A	Filtration of Colloids in EBS	Excluded	Exclude	1
2.1.09.21.0A	Transport of Particles Larger Than Colloids in EBS	Excluded	Exclude	1
2.1.09.21.0B	Transport of Particles Larger Than Colloids in the SZ	Excluded	Exclude	1
2.1.09.21.0C	Transport of Particles Larger Than Colloids in the UZ	Excluded	Exclude	1
2.1.09.22.0A	Sorption of Colloids at Air-Water Interface	Excluded	Exclude	1
2.1.09.23.0A	Stability of Colloids in EBS	Included	Include	3
2.1.09.24.0A	Diffusion of Colloids in EBS	Included	Include	3
2.1.09.25.0A	Formation of Colloids (Waste-Form) By Co-Precipitation in EBS	Included	Include	?
2.1.09.26.0A	Gravitational Settling of Colloids in EBS	Excluded	Exclude	1
2.1.09.27.0A	Coupled Effects on Radionuclide Transport in EBS	Excluded	Include	2
2.1.09.28.0A	Localized Corrosion on Waste Package Outer Surface Due to Deliquescence	Excluded	Exclude	1
2.1.09.28.0B	Localized Corrosion on Drip Shield Surfaces Due to Deliquescence	Excluded	Exclude (NA)	1
2.1.10.01.0A	Microbial Activity in EBS	Excluded	Include	2
2.1.11.01.0A	Heat Generation in EBS	Included	Include	3
2.1.11.02.0A	Non-Uniform Heat Distribution in EBS	Included	Include	3
2.1.11.03.0A	Exothermic Reactions in the EBS	Excluded	Exclude	1
2.1.11.05.0A	Thermal Expansion/Stress of in-Package EBS Components	Excluded	Exclude	1
2.1.11.06.0A	Thermal Sensitization of Waste Packages	Excluded	Exclude	1
2.1.11.06.0B	Thermal Sensitization of Drip Shields	Excluded	Exclude	1
2.1.11.07.0A	Thermal Expansion/Stress of in-Drift EBS Components	Excluded	Include	3 This may be where thermal-mechanical effects on the seals is captured
2.1.11.08.0A	Thermal Effects on Chemistry and Microbial Activity in the EBS	Included	Include	3
2.1.11.09.0A	Thermal Effects on Flow in the EBS	Included	Include	3
2.1.11.09.0B	Thermally-Driven Flow (Convection) in Waste Packages	Excluded	Exclude	1
2.1.11.09.0C	Thermally Driven Flow (Convection) in Drifts	Included	Include	3

FEP Number	*FEP Name*	*YMP Screening Decision*	*Likely DBD Decision*	*Estimated DBD Level of Effort*
				Drifts = boreholes with waste
2.1.11.10.0A	*Thermal Effects on Transport in EBS*	*Excluded*	*Include*	*3*
2.1.12.01.0A	*Gas Generation (Repository Pressurization)*	*Excluded*	*Exclude*	*3 Need to consider gas pressure effects on seals*
2.1.12.02.0A	*Gas Generation (He) from Waste Form Decay*	*Excluded*	*Exclude*	*3*
2.1.12.03.0A	*Gas Generation (H_2) from Waste Package Corrosion*	*Excluded*	*Exclude*	*3*
2.1.12.04.0A	*Gas Generation (CO_2, CH_4, H_2S) from Microbial Degradation*	*Excluded*	*Include*	*2*
2.1.12.06.0A	*Gas Transport in EBS*	*Excluded*	*Exclude*	*2*
2.1.12.07.0A	*Effects of Radioactive Gases in EBS*	*Excluded*	*Exclude*	*1*
2.1.12.08.0A	*Gas Explosions in EBS*	*Excluded*	*Exclude*	*1*
2.1.13.01.0A	*Radiolysis*	*Excluded*	*Exclude*	*3*
2.1.13.02.0A	*Radiation Damage in EBS*	*Excluded*	*Exclude*	*1*
2.1.13.03.0A	*Radiological Mutation of Microbes*	*Excluded*	*Include*	*1*
2.1.14.15.0A	*In-Package Criticality (Intact Configuration)*	*Excluded*	*Exclude*	*3*
2.1.14.16.0A	*In-Package Criticality (Degraded Configurations)*	*Excluded*	*Exclude*	*3 Criticality exclusion on Prob. of geometry? Consequence is low, but hard to quantify because of thermal effects*
2.1.14.17.0A	*Near-Field Criticality*	*Excluded*	*Exclude*	*2*
2.1.14.18.0A	*In-Package Criticality Resulting from a Seismic Event (Intact Configuration)*	*Excluded*	*Exclude*	*1*
2.1.14.19.0A	*In-Package Criticality Resulting from a Seismic Event (Degraded Configurations)*	*Excluded*	*Exclude*	*1*
2.1.14.20.0A	*Near-Field Criticality Resulting from a Seismic Event*	*Excluded*	*Exclude*	*1*
2.1.14.21.0A	*In-Package Criticality Resulting from Rockfall (Intact Configuration)*	*Excluded*	*Exclude*	*1*
2.1.14.22.0A	*In-Package Criticality Resulting from Rockfall (Degraded Configurations)*	*Excluded*	*Exclude*	*1*
2.1.14.23.0A	*Near-Field Criticality Resulting from Rockfall*	*Excluded*	*Exclude*	*1*
2.1.14.24.0A	*In-Package Criticality Resulting from an Igneous Event (Intact Configuration)*	*Excluded*	*Exclude*	*2*
2.1.14.25.0A	*In-Package Criticality Resulting from an Igneous Event (Degraded Configurations)*	*Excluded*	*Exclude*	*2*
2.1.14.26.0A	*Near-Field Criticality Resulting from an Igneous Event*	*Excluded*	*Exclude*	*1*
2.2.01.01.0A	*Mechanical Effects of Excavation and Construction in the Near-Field*	*Included*	*Include*	*3 High K pathways around borehole*
2.2.01.01.0B	*Chemical Effects of Excavation and Construction in the Near-Field*	*Excluded*	*Include*	*2 Altered rock properties near*

FEP Number	FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort
				borehole
2.2.01.02.0A	Thermally-Induced Stress Changes in the Near-Field	Excluded	Include	3
2.2.01.02.0B	Chemical Changes in the Near-Field from Backfill	Excluded	Exclude	1
2.2.01.03.0A	Changes In Fluid Saturations in the Excavation Disturbed Zone	Excluded	Exclude	1
2.2.01.04.0A	Radionuclide Solubility in the Excavation Disturbed Zone	Excluded	Include	2
2.2.01.05.0A	Radionuclide Transport in the Excavation Disturbed Zone	Excluded	Include	3
2.2.03.01.0A	Stratigraphy	Included	Include	1
2.2.03.02.0A	Rock Properties of Host Rock and Other Units	Included	Include	1
2.2.06.01.0A	Seismic Activity Changes Porosity and Permeability of Rock	Excluded	Exclude	1
2.2.06.02.0A	Seismic Activity Changes Porosity and Permeability of Faults	Excluded	Exclude	1
2.2.06.02.0B	Seismic Activity Changes Porosity and Permeability of Fractures	Excluded	Exclude	1
2.2.06.03.0A	Seismic Activity Alters Perched Water Zones	Excluded	Exclude	1
2.2.06.04.0A	Effects of Subsidence	Excluded	Exclude	1
2.2.06.05.0A	Salt Creep	Excluded	Exclude	1
2.2.07.01.0A	Locally Saturated Flow at Bedrock/Alluvium Contact	Excluded	Exclude	1
2.2.07.02.0A	Unsaturated Groundwater Flow in the Geosphere	Included	Exclude	1
2.2.07.03.0A	Capillary Rise in the UZ	Included	Exclude	1
2.2.07.04.0A	Focusing of Unsaturated Flow (Fingers, Weeps)	Included	Exclude	1
2.2.07.05.0A	Flow in the UZ from Episodic Infiltration	Excluded	Exclude	1
2.2.07.06.0A	Episodic Or Pulse Release from Repository	Excluded	Exclude	1
2.2.07.06.0B	Long-Term Release of Radionuclides from The Repository	Included	Include	2
2.2.07.07.0A	Perched Water Develops	Included	Exclude	1
2.2.07.08.0A	Fracture Flow in the UZ	Included	Exclude	1
2.2.07.09.0A	Matrix Imbibition in the UZ	Included	Exclude	1
2.2.07.10.0A	Condensation Zone Forms Around Drifts	Included	Exclude	1
2.2.07.11.0A	Resaturation of Geosphere Dry-Out Zone	Included	Include	1
2.2.07.12.0A	Saturated Groundwater Flow in the Geosphere	Included	Include	3 This is one of two release pathways (EBS transport through seals is the other)
2.2.07.13.0A	Water-Conducting Features in the SZ	Included	Included	3
2.2.07.14.0A	Chemically-Induced Density Effects on Groundwater Flow	Excluded	Exclude	1
2.2.07.15.0A	Advection and Dispersion in the SZ	Included	Include	3
2.2.07.15.0B	Advection and Dispersion in the UZ	Included	Exclude	1
2.2.07.16.0A	Dilution of Radionuclides in Groundwater	Included	Include	1

FEP Number	FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort
2.2.07.17.0A	*Diffusion in the SZ*	*Included*	*Include*	*3*
2.2.07.18.0A	*Film Flow into the Repository*	*Included*	*Exclude*	*1*
2.2.07.19.0A	*Lateral Flow from Solitario Canyon Fault Enters Drifts*	*Included*	*Exclude (NA)*	*1*
2.2.07.20.0A	*Flow Diversion Around Repository Drifts*	*Included*	*Exclude*	*1*
2.2.07.21.0A	*Drift Shadow Forms Below Repository*	*Excluded*	*Exclude*	*1*
2.2.08.01.0A	*Chemical Characteristics of Groundwater in the SZ*	*Included*	*Include*	*1*
2.2.08.01.0B	*Chemical Characteristics of Groundwater in the UZ*	*Included*	*Exclude*	*1*
2.2.08.03.0A	*Geochemical Interactions and Evolution in the SZ*	*Excluded*	*Include*	*2*
2.2.08.03.0B	*Geochemical Interactions and Evolution in the UZ*	*Excluded*	*Exclude*	*1*
2.2.08.04.0A	*Re-Dissolution of Precipitates Directs More Corrosive Fluids to Waste Packages*	*Excluded*	*Exclude*	*1*
2.2.08.05.0A	*Diffusion in the UZ*	*Excluded*	*Exclude*	*1*
2.2.08.06.0A	*Complexation in the SZ*	*Included*	*Include?*	*?*
2.2.08.06.0B	*Complexation in the UZ*	*Included*	*Exclude*	*1*
2.2.08.07.0A	*Radionuclide Solubility Limits in the SZ*	*Excluded*	*Include*	*2*
2.2.08.07.0B	*Radionuclide Solubility Limits in the UZ*	*Excluded*	*Exclude*	*1*
2.2.08.07.0C	*Radionuclide Solubility Limits in the Biosphere*	*Excluded*	*Exclude*	*1*
2.2.08.08.0A	*Matrix Diffusion in the SZ*	*Included*	*Include*	*3*
2.2.08.08.0B	*Matrix Diffusion in the UZ*	*Included*	*Exclude*	*1*
2.2.08.09.0A	*Sorption in the SZ*	*Included*	*Include*	*3*
2.2.08.09.0B	*Sorption in the UZ*	*Included*	*Exclude*	*1*
2.2.08.10.0A	*Colloidal Transport in the SZ*	*Included*	*Include*	*3*
2.2.08.10.0B	*Colloidal Transport in the UZ*	*Included*	*Exclude*	*1*
2.2.08.11.0A	*Groundwater Discharge to Surface Within The Reference Biosphere*	*Excluded*	*Exclude*	*1*
2.2.08.12.0A	*Chemistry of Water Flowing into the Drift*	*Included*	*Include*	*2*
2.2.08.12.0B	*Chemistry of Water Flowing into the Waste Package*	*Included*	*Include*	*2*
2.2.09.01.0A	*Microbial Activity in the SZ*	*Excluded*	*Include*	*2*
2.2.09.01.0B	*Microbial Activity in the UZ*	*Excluded*	*Include*	*1*
2.2.10.01.0A	*Repository-Induced Thermal Effects on Flow in the UZ*	*Excluded*	*Exclude*	*1*
2.2.10.02.0A	*Thermal Convection Cell Develops in SZ*	*Excluded*	*Exclude ??*	*3*
2.2.10.03.0A	*Natural Geothermal Effects on Flow in the SZ*	*Included*	*Include*	*2*
2.2.10.03.0B	*Natural Geothermal Effects on Flow in the UZ*	*Included*	*Exclude*	*1*
2.2.10.04.0A	*Thermo-Mechanical Stresses Alter Characteristics of Fractures Near Repository*	*Excluded*	*Exclude ??*	*3*
2.2.10.04.0B	*Thermo-Mechanical Stresses Alter Characteristics of Faults Near Repository*	*Excluded*	*Exclude ??*	*3*
2.2.10.05.0A	*Thermo-Mechanical Stresses Alter Characteristics of Rocks Above and Below The Repository*	*Excluded*	*Exclude ??*	*3*
2.2.10.06.0A	*Thermo-Chemical Alteration in the UZ (Solubility, Speciation, Phase Changes,*	*Excluded*	*Exclude*	*1*

FEP Number	FEP Name	YMP Screening Decision	Likely DBD Decision	Estimated DBD Level of Effort
	Precipitation/Dissolution)			
2.2.10.07.0A	*Thermo-Chemical Alteration of the Calico Hills Unit*	*Excluded*	*Exclude (NA)*	*1*
2.2.10.08.0A	*Thermo-Chemical Alteration in the SZ (Solubility, Speciation, Phase Changes, Precipitation/Dissolution)*	*Excluded*	*Exclude ??*	*3*
2.2.10.09.0A	*Thermo-Chemical Alteration of the Topopah Spring Basal Vitrophyre*	*Excluded*	*Exclude (NA)*	*1*
2.2.10.10.0A	*Two-Phase Buoyant Flow/Heat Pipes*	*Included*	*Exclude*	*1*
2.2.10.11.0A	*Natural Air Flow in the UZ*	*Excluded*	*Exclude*	*1*
2.2.10.12.0A	*Geosphere Dry-Out Due to Waste Heat*	*Included*	*Include*	*1*
2.2.10.13.0A	*Repository-Induced Thermal Effects on Flow in the SZ*	*Excluded*	*Include ??*	*3*
2.2.10.14.0A	*Mineralogic Dehydration Reactions*	*Excluded*	*Exclude ??*	*3*
2.2.11.01.0A	*Gas Effects in the SZ*	*Excluded*	*Exclude*	*2*
2.2.11.02.0A	*Gas Effects in the UZ*	*Excluded*	*Exclude*	*1*
2.2.11.03.0A	*Gas Transport in Geosphere*	*Excluded*	*Exclude*	*1*
2.2.12.00.0A	*Undetected Features in the UZ*	*Excluded*	*Exclude*	*1*
2.2.12.00.0B	*Undetected Features in the SZ*	*Included*	*Include*	*1*
2.2.14.09.0A	*Far-Field Criticality*	*Excluded*	*Exclude*	*1*
2.2.14.10.0A	*Far-Field Criticality Resulting from a Seismic Event*	*Excluded*	*Exclude*	*1*
2.2.14.11.0A	*Far-Field Criticality Resulting from Rockfall*	*Excluded*	*Exclude*	*1*
2.2.14.12.0A	*Far-Field Criticality Resulting from an Igneous Event*	*Excluded*	*Exclude*	*1*
2.3.01.00.0A	*Topography and Morphology*	*Included*	*Exclude*	*1*
2.3.02.01.0A	*Soil Type*	*Included*	*Include*	*1 (Biosphere model inputs are all "included" assuming well water and farming)*
2.3.02.02.0A	*Radionuclide Accumulation in Soils*	*Included*	*Include*	*1*
2.3.02.03.0A	*Soil and Sediment Transport in the Biosphere*	*Included*	*Exclude*	*1*
2.3.04.01.0A	*Surface Water Transport and Mixing*	*Included*	*Exclude*	*1*
2.3.06.00.0A	*Marine Features*	*Excluded*	*Exclude*	*1*
2.3.09.01.0A	*Animal Burrowing/Intrusion*	*Excluded*	*Exclude*	*1*
2.3.11.01.0A	*Precipitation*	*Included*	*Exclude*	*1*
2.3.11.02.0A	*Surface Runoff and Evapotranspiration*	*Included*	*Exclude*	*1*
2.3.11.03.0A	*Infiltration and Recharge*	*Included*	*Exclude*	*1*
2.3.11.04.0A	*Groundwater Discharge to Surface Outside The Reference Biosphere*	*Excluded*	*Exclude*	*1*
2.3.13.01.0A	*Biosphere Characteristics*	*Included*	*Include*	*1 Assume well pumps from SZ at location of borehole*
2.3.13.02.0A	*Radionuclide Alteration During Biosphere Transport*	*Included*	*Include*	*1*
2.3.13.03.0A	*Effects of Repository Heat on The Biosphere*	*Excluded*	*Exclude*	*1*
2.3.13.04.0A	*Radionuclide Release Outside The Reference Biosphere*	*Excluded*	*Exclude*	*1*
2.4.01.00.0A	*Human Characteristics (Physiology,*	*Included*	*Include*	*1*

FEP Number	***FEP Name***	***YMP Screening Decision***	***Likely DBD Decision***	***Estimated DBD Level of Effort***
	Metabolism)			
2.4.04.01.0A	*Human Lifestyle*	*Included*	*Include*	*1*
2.4.07.00.0A	*Dwellings*	*Included*	*Include*	*1*
2.4.08.00.0A	*Wild and Natural Land and Water Use*	*Included*	*Include*	*1*
2.4.09.01.0A	*Implementation of New Agricultural Practices Or Land Use*	*Excluded*	*Exclude*	*1*
2.4.09.01.0B	*Agricultural Land Use and Irrigation*	*Included*	*Include*	*1*
2.4.09.02.0A	*Animal Farms and Fisheries*	*Included*	*Include*	*1*
2.4.10.00.0A	*Urban and Industrial Land and Water Use*	*Included*	*Include*	*1*
3.1.01.01.0A	*Radioactive Decay and Ingrowth*	*Included*	*Include*	*1*
3.2.07.01.0A	*Isotopic Dilution*	*Excluded*	*Exclude*	*1*
3.2.10.00.0A	*Atmospheric Transport of Contaminants*	*Included*	*Exclude*	*1*
3.3.01.00.0A	*Contaminated Drinking Water, Foodstuffs and Drugs*	*Included*	*Include*	*1*
3.3.02.01.0A	*Plant Uptake*	*Included*	*Include*	*1*
3.3.02.02.0A	*Animal Uptake*	*Included*	*Include*	*1*
3.3.02.03.0A	*Fish Uptake*	*Included*	*Include*	*1*
3.3.03.01.0A	*Contaminated Non-Food Products and Exposure*	*Included*	*Include*	*1*
3.3.04.01.0A	*Ingestion*	*Included*	*Include*	*1*
3.3.04.02.0A	*Inhalation*	*Included*	*Include*	*1*
3.3.04.03.0A	*External Exposure*	*Included*	*Include*	*1*
3.3.05.01.0A	*Radiation Doses*	*Included*	*Include*	*1*
3.3.06.00.0A	*Radiological Toxicity and Effects*	*Excluded*	*Exclude*	*1*
3.3.06.01.0A	*Repository Excavation*	*Excluded*	*Exclude*	*1*
3.3.06.02.0A	*Sensitization to Radiation*	*Excluded*	*Exclude*	*1*
3.3.07.00.0A	*Non-Radiological Toxicity and Effects*	*Excluded*	*Exclude*	*1*
3.3.08.00.0A	*Radon and Radon Decay Product Exposure*	*Included*	*Include*	*1*

CSNF = commercial SNF, DSNF = DOE-owned SNF, EBS = Engineered Barrier System, HLW = high-level waste, MIC = microbially influenced corrosion, SNF = spent nuclear fuel, SSC = stress corrosion cracking, SZ = saturated zone, UZ = unsaturated zone.

Table B-2. High Priority Borehole FEPs – Excluded FEPs That Need New Technical Work and Included FEPs That Require Significant Modeling or Possible Model Changes.

FEP Number	*FEP Name*	*Likely DBD Decision*	*Estimated DB Level of Effort*
0.1.09.00.0A	*Regulatory Requirements and Exclusions*	*Include*	*3 Regulations and laws will need to be revised*
1.1.02.00.0A	*Chemical Effects of Excavation and Construction in EBS*	*Exclude*	*2*
1.1.02.00.0B	*Mechanical Effects of Excavation and Construction in EBS*	*Include*	*2*
1.1.02.03.0A	*Undesirable Materials Left*	*Exclude (NA)*	*2*
1.1.03.01.0A	*Error in Waste Emplacement*	*Exclude*	*3 Need to consider the emplacement that gets stuck halfway down. Also need to consider canisters that are crushed by overlying canisters*
1.1.04.01.0A	*Incomplete Closure*	*Exclude*	*2*
1.1.13.00.0A	*Retrievability*	*Exclude (policy)*	*2*
1.2.02.01.0A	*Fractures*	*Include*	*2*
1.2.02.02.0A	*Faults*	*Include*	*2*
1.2.02.03.0A	*Fault Displacement Damages EBS Components*	*Include?*	*2 Note—if no credit is taken for WP and WF components, all EBS FEPs are simplified to the consideration of the borehole seals*
1.2.03.02.0A	*Seismic Ground Motion Damages EBS Components*	*Exclude*	*2*
1.2.04.02.0A	*Igneous Activity Changes Rock Properties*	*Exclude*	*2 Need to evaluate potential for igneous activity at each site (should generically be low), also need to determine if repository heat can contribute to rock melting*
1.2.04.03.0A	*Igneous Intrusion Into Repository*	*Exclude*	*2*
1.2.04.04.0A	*Igneous Intrusion Interacts With EBS Components*	*Exclude*	*2*
1.2.04.04.0B	*Chemical Effects of Magma and Magmatic Volatiles*	*Exclude*	*2 Volatiles may impact transport*

FEP Number	*FEP Name*	*Likely DBD Decision*	*Estimated DB Level of Effort*
1.2.04.06.0A	*Eruptive Conduit to Surface Intersects Repository*	*Exclude*	*2*
1.2.05.00.0A	*Metamorphism*	*Exclude*	*2 Repository heat may create metamorphic conditions*
1.2.06.00.0A	*Hydrothermal Activity*	*Exclude*	*3 Repository heat may creat local hydrothermal activity*
1.2.08.00.0A	*Diagenesis*	*Exclude*	*2*
1.2.09.01.0A	*Diapirism*	*Exclude*	*2 Need to demonstrate that repository heat will not generate local diapirism*
1.2.10.02.0A	*Hydrologic Response to Igneous Activity*	*Exclude*	*2*
1.3.07.02.0B	*Water Table Rise Affects UZ*	*Exclude*	*1 All UZ FEPs are simplified*
1.4.02.02.0A	*Inadvertent Human Intrusion*	*Exclude*	*1 (requires regulatory change)*
2.1.02.02.0A	*CSNF Degradation (Alteration, Dissolution, and Radionuclide Release)*	*Exclude*	*1 Assume no credit for CSNF waste form*
2.1.02.03.0A	*HLW Glass Degradation (Alteration, Dissolution, and Radionuclide Release)*	*Exclude*	*1 Assume no credit for HLW waste form*
2.1.05.01.0A	*Flow Through Seals (Access Ramps and Ventilation Shafts)*	*Include*	*3*
2.1.05.02.0A	*Radionuclide Transport Through Seals*	*Include*	*3*
2.1.05.03.0A	*Degradation of Seals*	*Include*	*3*
2.1.06.01.0A	*Chemical Effects of Rock Reinforcement and Cementitious Materials in EBS*	*Include (Seals are EBS, so one entire release pathway to RMEI is in EBS)*	*3*
2.1.06.02.0A	*Mechanical Effects of Rock Reinforcement Materials in EBS*	*Include*	*3 What happens to borehole seal as casing degrades?*
2.1.06.07.0A	*Chemical Effects at EBS Component Interfaces*	*Include?*	*2*
2.1.06.07.0B	*Mechanical Effects at EBS Component Interfaces*	*Exclude?*	*3*
2.1.07.02.0A	*Drift Collapse*	*Exclude*	*1*

FEP Number	FEP Name	Likely DBD Decision	Estimated DB Level of Effort
			If drift = borehole, then this is a major operational FEP
2.1.07.04.0A	*Hydrostatic Pressure on Waste Package*	*Include*	*2*
2.1.08.09.0A	*Saturated Flow in the EBS*	*Include*	*3*
2.1.08.15.0A	*Consolidation of EBS Components*	*Include*	*3*
2.1.09.01.0A	*Chemical Characteristics of Water in Drifts*	*Include*	*3*
2.1.09.01.0B	*Chemical Characteristics of Water in Waste Package*	*Include*	*3*
2.1.09.02.0A	*Chemical Interaction With Corrosion Products*	*Include*	*3*
2.1.09.04.0A	*Radionuclide Solubility, Solubility Limits, and Speciation in the Waste Form and EBS*	*Include*	*3*
2.1.09.05.0A	*Sorption of Dissolved Radionuclides in EBS*	*Include*	*3*
2.1.09.07.0A	*Reaction Kinetics in Waste Package*	*Exclude*	*2*
2.1.09.07.0B	*Reaction Kinetics in Drifts*	*Exclude*	*2*
2.1.09.08.0A	*Diffusion of Dissolved Radionuclides in EBS*	*Include*	*3*
2.1.09.08.0B	*Advection of Dissolved Radionuclides in EBS*	*Include*	*3*
2.1.09.10.0A	*Secondary Phase Effects on Dissolved Radionuclide Concentrations*	*Include*	*2*
2.1.09.11.0A	*Chemical Effects of Waste-Rock Contact*	*Include*	*2*
2.1.09.12.0A	*Rind (Chemically Altered Zone) Forms in the Near-Field*	*Exclude*	*2*
2.1.09.13.0A	*Complexation in EBS*	*Exclude*	*2*
2.1.09.15.0A	*Formation of True (Intrinsic) Colloids in EBS*	*?*	*?*
2.1.09.16.0A	*Formation of Pseudo-Colloids (Natural) in EBS*	*?*	*?*
2.1.09.17.0A	*Formation of Pseudo-Colloids (Corrosion Product) in EBS*	*?*	*?*
2.1.09.18.0A	*Formation of Microbial Colloids in EBS*	*?*	*?*
2.1.09.19.0A	*Sorption of Colloids in EBS*	*Include?*	*2*
2.1.09.19.0B	*Advection of Colloids in EBS*	*Include?*	*2*
2.1.09.20.0A	*Filtration of Colloids in EBS*	*Include?*	*2*
2.1.09.23.0A	*Stability of Colloids in EBS*	*Include*	*3*
2.1.09.24.0A	*Diffusion of Colloids in EBS*	*Include*	*3*
2.1.09.25.0A	*Formation of Colloids (Waste-Form) By Co-Precipitation in EBS*	*Include*	*?*
2.1.09.26.0A	*Gravitational Settling of Colloids in EBS*	*?*	*?*
2.1.09.27.0A	*Coupled Effects on Radionuclide Transport in EBS*	*?*	*?*
2.1.10.01.0A	*Microbial Activity in EBS*	*Include*	*2*
2.1.11.01.0A	*Heat Generation in EBS*	*Include*	*3*
2.1.11.02.0A	*Non-Uniform Heat Distribution in EBS*	*Include*	*3*
2.1.11.07.0A	*Thermal Expansion/Stress of in-Drift EBS Components*	*Include*	*3 This may be where thermal-mechanical effects on the seals is captured*
2.1.11.08.0A	*Thermal Effects on Chemistry and Microbial Activity in the EBS*	*Include*	*3*
2.1.11.09.0A	*Thermal Effects on Flow in the EBS*	*Include*	*3*
2.1.11.09.0C	*Thermally Driven Flow (Convection) in Drifts*	*Include*	*3*

FEP Number	*FEP Name*	*Likely DBD Decision*	*Estimated DB Level of Effort*
			Drifts = boreholes with waste
2.1.11.10.0A	*Thermal Effects on Transport in EBS*	*Include*	*3*
2.1.12.01.0A	*Gas Generation (Repository Pressurization)*	*Exclude*	*3* *Need to consider gas pressure effects on seals*
2.1.12.02.0A	*Gas Generation (He) from Waste Form Decay*	*Exclude*	*3*
2.1.12.03.0A	*Gas Generation (H_2) from Waste Package Corrosion*	*Exclude*	*3*
2.1.12.04.0A	*Gas Generation (CO_2, CH_4, H_2S) from Microbial Degradation*	*Include*	*2*
2.1.12.06.0A	*Gas Transport in EBS*	*Exclude*	*2*
2.1.13.01.0A	*Radiolysis*	*Exclude*	*3*
2.1.14.15.0A	*In-Package Criticality (Intact Configuration)*	*Exclude*	*3*
2.1.14.16.0A	*In-Package Criticality (Degraded Configurations)*	*Exclude*	*3* *Criticality exclusion on Prob. of geometry? Consequence is low, but hard to quantify because of thermal effects.*
2.1.14.17.0A	*Near-Field Criticality*	*Exclude*	*2*
2.1.14.24.0A	*In-Package Criticality Resulting from an Igneous Event (Intact Configuration)*	*Exclude*	*2*
2.1.14.25.0A	*In-Package Criticality Resulting from an Igneous Event (Degraded Configurations)*	*Exclude*	*2*
2.2.01.01.0A	*Mechanical Effects of Excavation and Construction in the Near-Field*	*Include*	*3* *High K pathways around borehole*
2.2.01.01.0B	*Chemical Effects of Excavation and Construction in the Near-Field*	*Include*	*2* *Altered rock properties near borehole*
2.2.01.02.0A	*Thermally-Induced Stress Changes in the Near-Field*	*Include*	*3*
2.2.01.04.0A	*Radionuclide Solubility in the Excavation Disturbed Zone*	*Include*	*2*
2.2.01.05.0A	*Radionuclide Transport in the Excavation Disturbed Zone*	*Include*	*3*
2.2.07.06.0B	*Long-Term Release of Radionuclides from The Repository*	*Include*	*2*
2.2.07.12.0A	*Saturated Groundwater Flow in the Geosphere*	*Include*	*3* *This is one of two release pathways (EBS transport through seals is the other)*
2.2.07.13.0A	*Water-Conducting Features in the SZ*	*Included*	*3*
2.2.07.15.0A	*Advection and Dispersion in the SZ*	*Include*	*3*
2.2.07.17.0A	*Diffusion in the SZ*	*Include*	*3*

FEP Number	*FEP Name*	*Likely DBD Decision*	*Estimated DB Level of Effort*
2.2.08.03.0A	*Geochemical Interactions and Evolution in the SZ*	*Include*	*2*
2.2.08.06.0A	*Complexation in the SZ*	*Include?*	*?*
2.2.08.07.0A	*Radionuclide Solubility Limits in the SZ*	*Include*	*2*
2.2.08.08.0A	*Matrix Diffusion in the SZ*	*Include*	*3*
2.2.08.09.0A	*Sorption in the SZ*	*Include*	*3*
2.2.08.10.0A	*Colloidal Transport in the SZ*	*Include*	*3*
2.2.08.12.0A	*Chemistry of Water Flowing into the Drift*	*Include*	*2*
2.2.08.12.0B	*Chemistry of Water Flowing into the Waste Package*	*Include*	*2*
2.2.09.01.0A	*Microbial Activity in the SZ*	*Include*	*2*
2.2.10.02.0A	*Thermal Convection Cell Develops in SZ*	*Exclude ??*	*3*
2.2.10.03.0A	*Natural Geothermal Effects on Flow in the SZ*	*Include*	*2*
2.2.10.04.0A	*Thermo-Mechanical Stresses Alter Characteristics of Fractures Near Repository*	*Exclude ??*	*3*
2.2.10.04.0B	*Thermo-Mechanical Stresses Alter Characteristics of Faults Near Repository*	*Exclude ??*	*3*
2.2.10.05.0A	*Thermo-Mechanical Stresses Alter Characteristics of Rocks Above and Below The Repository*	*Exclude ??*	*3*
2.2.10.08.0A	*Thermo-Chemical Alteration in the SZ (Solubility, Speciation, Phase Changes, Precipitation/Dissolution)*	*Exclude ??*	*3*
2.2.10.13.0A	*Repository-Induced Thermal Effects on Flow in the SZ*	*Include ??*	*3*
2.2.10.14.0A	*Mineralogic Dehydration Reactions*	*Exclude ??*	*3*
2.2.11.01.0A	*Gas Effects in the SZ*	*Exclude*	*2*
2.3.02.01.0A	*Soil Type*	*Include*	*1 (Biosphere model inputs are all "included" assuming well water and farming)*
2.3.13.01.0A	*Biosphere Characteristics*	*Include*	*1 Assume well pumps from SZ at location of borehole*

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Energy

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ice | proceedings

Proceedings of the Institution of Civil Engineers

http://dx.doi.org/10.1680/ener.13.00016
Paper 1300016
Received 12/10/2013 Accepted 18/02/2014
Keywords: energy/nuclear power/waste management & disposal

Deep borehole disposal of nuclear waste: engineering challenges

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In recent years, geological disposal of radioactive waste has focused on placement of high- and intermediate-level wastes in mined underground caverns at depths of 500–800 m. Notwithstanding the billions of dollars spent to date on this approach, the difficulty of finding suitable sites and demonstrating to the public and regulators that a robust safety case can be developed has frustrated attempts to implement disposal programmes in several countries, and no disposal facility for spent nuclear fuel exists anywhere. The concept of deep borehole disposal was first considered in the 1950s, but was rejected as it was believed to be beyond existing drilling capabilities. Improvements in drilling and associated technologies and advances in sealing methods have prompted a re-examination of this option for the disposal of high-level radioactive wastes, including spent fuel and plutonium. Since the 1950s, studies of deep boreholes have involved minimal investment. However, deep borehole disposal offers a potentially safer, more secure, cost-effective and environmentally sound solution for the long-term management of high-level radioactive waste than mined repositories. Potentially it could accommodate most of the world's spent fuel inventory. This paper discusses the concept, the status of existing supporting equipment and technologies and the challenges that remain.

1. Introduction

Since the 1940s, radioactive wastes have been accumulating in many countries at ever increasing rates. Despite the hazards and risks posed by such materials, no facility yet exists anywhere in the world for the disposal of spent nuclear fuel and other high-level wastes (HLW). With the ever increasing demand for energy and the world focussing on low carbon sources, it is clear that nuclear power must play a significant part for the foreseeable future, especially as the scarcity of cheap fossil fuels and environmental concerns threaten the sustainability of economies. However, it is inconceivable that this could happen without a solution to the problem of how to dispose of spent nuclear fuel and other HLW and acceptable radioactive waste disposal remains a pressing and critical issue for mankind.

Disposal in deep boreholes was considered over 50 years ago (NAS, 1957), but was rejected in favour of mined and engineered repositories at depths of only a few hundred metres largely because, at the time, the technology for drilling large enough diameter holes to depths of a few kilometres did not exist. After nearly 60 years of research and development (R&D) programmes spread across many countries and costing billions of dollars, mined repositories are still not without their problems and an operating facility is still some decades away, with the Finnish repository at Onkalo likely to be the first. This dilemma is highlighted by the recent cancellation of the Yucca Mountain repository in the USA and the challenges to Svensk Kärnbränslehantering's (SKB) application for a spent fuel repository at Forsmark in Sweden, together with the failure to progress a geological disposal facility in West Cumbria in the UK.

Advances in deep drilling technology over the past 20–30 years have led to the reconsideration of deep borehole disposal (DBD), notably in the USA (Brady *et al.*, 2009; MIT, 2003; Woodward-Clyde Consultants, 1983), in Sweden (Juhlin and Sandstedt, 1989; Juhlin *et al.*, 1998) and in the UK (Beswick,

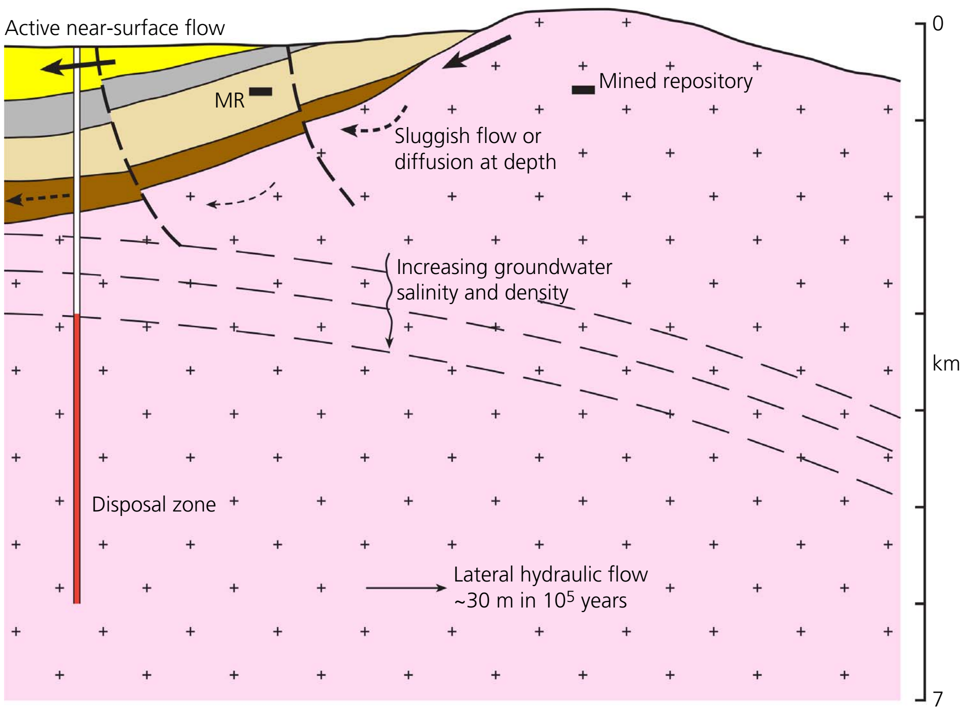

Figure 1. Schematic diagram of the deep borehole disposal concept (not to scale). Modified after Chapman and Gibb (2003)

2008; Chapman and Gibb, 2003; Gibb, 1999, 2000; Nirex, 2004) and it is now emerging as a realistic alternative to mined repositories for spent nuclear fuel, reprocessing waste and plutonium. This is particularly so in the USA where the Department of Energy, following the recommendations of a presidential Blue Ribbon Commission, has initiated a programme, led by Sandia National Laboratories, to investigate DBD with the objective of taking it to a full-scale demonstration with non-active waste.

While DBD has the potential to offer a safer, more secure, cost-effective and environmentally sound disposal route that could possibly be implemented earlier than mined repositories, a number of technical challenges remain (e.g. NWTRB, 2013). This paper considers these and discusses how they are being, or could be, addressed.

2. Background

The DBD concept (Figure 1) involves sinking large-diameter cased boreholes 4–6 km into the granitic basement of the continental crust and deploying packages of radioactive waste in the lower reaches of the hole before sealing it above, or at the top of, the disposal zone and backfilling the rest of the borehole. With a geological barrier an order of magnitude deeper than mined repositories, it makes use of the very low bulk hydraulic conductivities ($<\sim 10^{-11}$ m/s) usually found at such depths, even in fractured rocks. It also capitalises on the likelihood that any fluids in the rocks at these depths will be saline brines (Moller *et al.*, 1997; Stober and Bucher, 1999, 2004) out of physical and chemical contact with the near-surface circulating groundwaters, which rarely extend below 1 or 2 km. This isolation is due to a density stratification (Arnold *et al.*, 2013; Bucher and Stober, 2000) that has often been stable for many millions of years (Fehn and Snyder, 2005) and is likely to remain so far into the future, unaffected by climate changes, sea-level rises, glaciations and even earthquakes. This density stratification, combined with low lateral flow rates and almost non-existent vertical flow, ensures that any radionuclides that eventually escape from the waste packages and disposal zone will go effectively nowhere in the 1 Ma or so required for most HLWs to become radiologically harmless, and certainly not back up to the biosphere.

Compared to mined repositories as a route for the long-term management of HLWs, DBD offers many potential advantages in addition to the greater isolation and safety described above (Chapman and Gibb, 2003; Gibb *et al.*, 2008b; MIT, 2003). At a few tens of millions of dollars per borehole, a DBD programme is likely to be significantly more cost effective than a mined repository, estimates for which range from hundreds of millions to tens of billions of dollars. Furthermore, the nature of a mined repository requires that high 'up-front' costs are incurred before any waste is emplaced and substantial operating costs follow, possibly for hundreds of years. By contrast, DBD is effectively a 'pay as you go' scheme that allows a small disposal programme to be expanded as required or a large one to be terminated at any point (and for whatever reason) without any significant further cost.

It should be much easier to find a geologically suitable site for DBD than for a mined repository because much of the continental crust is underlain at appropriate depths by granitic basement with low hydraulic conductivities. In contrast to the detailed site characterisation of a large volume of rock required for a mined repository, for DBD it is only necessary to identify a modest, relatively homogeneous, volume of a suitable rock at appropriate depths with low bulk hydraulic conductivities and low differential stress regimes in an area with a density stratified saline hydrogeology. The planning and construction of a mined repository for nuclear wastes takes many decades (e.g. the current timescale for a UK repository is to open in around 2040 and take its first HLW or spent fuel by 2075). As a 4 km-deep borehole with a useable diameter of approximately 0·5 m could be drilled in under a year (Beswick, 2008) and filled and sealed in another 2 or 3 years, the first DBD could be completed less than 5 years after a successful demonstration of the concept, identification of a site and granting of regulatory approval. Site identification, with its socioeconomic–political aspects, is the most likely cause of delay, but the greater depth of burial, safety and availability of technically suitable sites for DBD could facilitate public and political acceptance.

One of the major problems associated with mined repositories relates to the transport of wastes. A serious political, economic and technical difficulty faced by the cancelled US federal repository at Yucca Mountain was the need to transport spent fuel from all over the continental USA to Nevada through many non-nuclear states by means of an incomplete transport infrastructure. By contrast, DBD could reduce or even eliminate the transport issue through its potential for dispersed disposal. The footprint of an individual borehole is tiny and even for a multi-borehole array it is quite small. Heat flow modelling of DBD of quite high heat-generating wastes (Gibb *et al.*, 2012) has shown that boreholes need be only a few tens of metres apart. Consequently, a DBD programme could involve many small sites with only one or a few boreholes each, even extending to individual nuclear power plants disposing of their own wastes on or near site. All that is needed is suitable geology nearby.

Disposal of high heat-generating wastes, such as high burn-up spent nuclear fuel, creates problems for mined repositories, necessitating increased spacing of the disposal vaults/tunnels and, because of limitations imposed by engineered barrier materials, can require protracted post-reactor cooling before disposal – in some cases for up to 100 years and more (NDA, 2009). By contrast, DBD is relatively insensitive to both the composition of the waste (as long as it is solid) and its heat output (Gibb *et al.*, 2012) thus allowing relatively early disposal of heat-generating wastes without any increase in the volume of host rock required.

The environmental impact of DBD is considerably less than a mined repository. Irrespective of the number of boreholes at any one site, they would probably be drilled and filled one (or at the most two) at any one time. Consequently, the surface facilities and disruption would be small compared with the construction and operation of a repository. More importantly, they would be transient. Once a borehole is sealed and the rig removed the environmental impact of a backfilled borehole is effectively zero, so the environmental disruption from any one hole is likely to last for less than 2 or 3 years. Contrast this with mined repositories, which would take decades to construct and could remain open and operational for many decades or even hundreds of years if new-build spent nuclear fuel is to be accommodated.

The March 2011 accident at Fukushima in Japan was a timely reminder of the need for all nuclear installations to be able to withstand both the direct and indirect effects of tectonic events. While the near-field (engineered barrier) containment of a mined repository could be designed to survive small earthquakes, the only safeguard against major seismic events is to avoid faults that could be reactivated and site the repository well away from fault zones that could host a magnitude 6+ event. DBD, on the other hand, is inherently secure against even high-magnitude tectonic events because seismic shaking and shear waves would have little effect on the density stratification of saline fluids in the host rock. Consequently, while these might damage the integrity of the containers, disrupt the near-field barriers in the borehole and fracture the surrounding host rock, they would not destroy the isolation of the fluids into which the radionuclides might subsequently be leached.

The main perceived disadvantage of DBD is the near irretrievability of the wastes. Until the borehole is sealed the waste packages could be recovered almost as easily as they can be emplaced, but if individual packages are sealed in or once the hole itself is sealed above the disposal zone, recovery of the packages becomes very difficult and expensive. In countries where retrievability of the wastes beyond the point of closure of the repository (or borehole) is a legal or regulatory requirement DBD is not really an option. Against this, there are some potential wastes for which security is paramount; for example, fissile materials such as highly enriched uranium and plutonium. As covert recovery of packages from a DBD would not be possible given the scale of any such operation, the security offered by this form of disposal is unbeatable, making it the ideal way of putting such materials beyond illegal use and as a safeguard against nuclear weapons proliferation (Gibb *et al.*, 2008b; Halsey *et al.*, 1995; Von Hippel *et al.*, 2012).

Many different variants of the basic DBD concept have been proposed (e.g. Brady *et al.*, 2009; Gibb, 2000; Gibb *et al.*, 2008a, 2012; Hoag, 2006; Juhlin and Sandstedt, 1989; Woodward-Clyde Consultants, 1983) involving different depths and sizes of borehole and a variety of waste container geometries, materials and contents. Essentially, these fall into two main categories that can be referred to as 'high temperature' and 'low temperature' very deep disposal, or DBD (Gibb, 2010; Gibb *et al.*, 2008a). In the former the temperatures generated by radioactive decay of the wastes are high enough to induce partial melting of the host rock around the waste packages (>~700°C). In the latter, temperatures in and around the borehole are well below those required to melt the host rock and are usually below approximately 250°C. For a variety of reasons, including the nature of existing spent nuclear fuel and HLW inventories, current investigations, R&D and interest are focussed on the low-temperature variants.

3. Waste packages

Largely because of the volumes involved, DBD has really only been proposed for spent nuclear fuel, vitrified reprocessing wastes and fissile materials. With the possible exception of plutonium (Gibb *et al.*, 2008a) the waste form is invariably enclosed in a cylindrical metal container, usually mild or stainless steel, to form the waste package. Among the most fundamental parameters for any DBD are the dimensions of the package, its weight and the heat output of its contents. The diameter of the package; that is, the outside diameter (OD) of the container effectively determines the size of the borehole required throughout the disposal zone and hence should be the primary influence on the borehole design. In this section the parameters of some waste packages likely to be required for DBD of spent nuclear fuel, reprocessing HLW and plutonium are considered.

3.1 Spent nuclear fuel

The fuel for nuclear reactors comes in a wide variety of compositions, physical forms, shapes and sizes. For the most common type of fission reactor, the light water reactor (LWR), the fuel element or assembly consists basically of a number of long, thin cylindrical fuel rods held in place within a square metal frame by various grids, spacers and springs (Figure 2). After irradiation in the reactor the fuel rods are highly radioactive, but the other metal components of the assembly are much less so

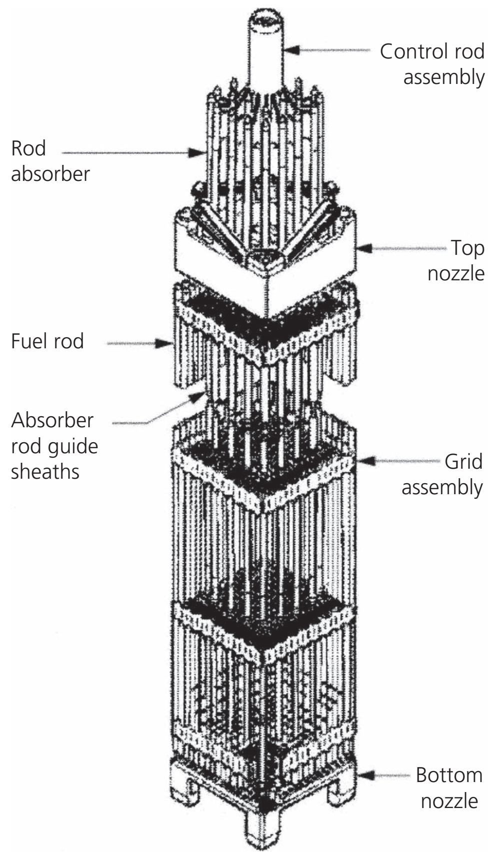

Figure 2. Typical pressurised water reactor fuel assembly (Westinghouse AP 1000 reactor) (from NDA, 2009)

and would be classed as only intermediate-level waste and need not follow the same disposal route as the fuel itself.

During operation of the reactor, rods can occasionally become damaged and need to be removed or replaced. The assembly is designed so this can be done by remote operation in the reactor fuel pond when the assembly is out of the reactor. The exact procedure varies with the reactor type and assembly design, but this creates a mechanism whereby the spent fuel rods could be separated from the rest of the assembly for storage and/or disposal. This is known as fuel rod consolidation. Perhaps counterintuitively, consolidation lowers even further any risk of criticality in a DBD by reducing the volume within the container that could eventually fill with water (to moderate the reaction).

3.1.1 Disposal of complete LWR assemblies

There are two main types of LWR in operation worldwide – boiling water reactors (BWR) and pressurised water reactors (PWR). A typical fuel assembly for a BWR is 0·139 m square and 4·42 m high, contains around 74 fuel rods and weighs about 300 kg. A cylindrical container to take a single BWR assembly would require an internal diameter (ID) of 0·198 m and internal height of 4·43 m.

For DBD the containers must be sufficiently robust to withstand any damage that might occur during emplacement, an external hydrostatic pressure that could eventually exceed 150 MPa and load stresses from overlying waste packages without losing its integrity, ideally until long after the borehole is sealed. Clearly, the container cannot be expected to withstand the load stresses imposed by the whole (>1 km long) stack of potentially very heavy waste packages and some form of additional support (see Section 7) would be required. For a stainless steel container with a welded lid preliminary calculations suggest that a wall thickness of approximately 2 cm would be needed, giving an OD of 0·238 m, but a detailed analysis of the stresses involved is required as part of the container design R&D. Also, to minimise any risk of collapse under the external pressures, the voids within the container must be filled. The more complete the filling of the voids the greater the reduction in any risk of post-disposal criticality by minimising the space available for the influx of water when eventually the integrity of the container is breached. Materials suggested for filling range from graphite or silica sand (Sapiie and Driscoll, 2009) through bentonite to molten lead (Gibb *et al.*, 2008b, 2012). While molten lead guarantees complete filling of the voids, provides a barrier to the escape of radionuclides, affords radiation protection and has the additional benefit of disposing of irradiated lead from the nuclear industry, it adds significantly to the weight of the package. Depending on the infill, a 0·238 m OD container with one BWR assembly would weigh between 800 and 1900 kg.

A typical PWR fuel assembly (Figure 2) is 0·215 m square and 4·795 m high, contains approximately 264 fuel rods and weighs about 700 kg. The container for a single assembly would require an ID of 0·32 m and an internal height of 4·81 m. Depending on the infill, such a package with an OD of 0·36 m would weigh between 1400 and 5000 kg.

Some DBD schemes have sought to accommodate the disposal of multiple complete fuel assemblies, notably three BWR assemblies (Sapiie and Driscoll, 2009) and four BWR assemblies (Juhlin and Sandstedt, 1989). Three BWR assemblies could be fitted into a container with an ID of 0·365 m (OD of 0·405 m) and inside height of 4·43 m (external height of 4·47 m). Such waste packages would weigh between 2000 and 5650 kg, depending on infill and could be approaching the upper limits of possible borehole diameter. The SKB concept for four BWR assemblies was subsequently deemed to require a borehole diameter in excess of 0·8 m (Harrison, 2000) and is probably outside the envelope of what could be achieved at this stage without significant technological development (Beswick, 2008).

Direct disposal of complete assemblies is likely to be favoured by waste owners as it avoids dismantling of the assemblies in the fuel ponds with its additional costs and a slight extra risk of radiation exposure to the workforce. The downside is that it is very wasteful of borehole disposal space and significantly increases the cost of DBD compared to the disposal of consolidated fuel rods.

3.1.2 Disposal of consolidated fuel rods

Fuel rod consolidation aims to dispose of as much spent fuel as possible in each container. Containers for the disposal of fuel rods would not need to be quite as high as those for complete assemblies. For example, PWR fuel rods are only 4·58 m long so the container need be only 4·6 m high compared to 4·81 m (internal). However, if containers already existed for the disposal of complete assemblies it would make sense to use these for the fuel rods as well. Taking a single PWR assembly container with an ID of 0·32 m (OD of 0·36 m), the maximum theoretical number of PWR fuel rods it could hold would be 1029. However, given that the rods would have to be inserted remotely into the containers, maximum packing densities are unlikely to be achievable in practice and a more realistic figure is likely to be around 80% or 825 rods (Gibb *et al.*, 2012), equivalent to just over three PWR assemblies. Again, the voids between the rods would have to be filled and, depending on the material used, a 0·36 m OD steel container with 825 PWR fuel rods would weigh between 3200 and 4300 kg.

Containers capable of taking three BWR assemblies (ID of 0·365 m, OD of 0·405 m) could hold up to 1338 PWR rods with a practical number around 1071 or the equivalent of four PWR assemblies. Such waste packages would weigh between 4000 and 5400 kg depending on infill.

3.2 Vitrified reprocessing HLW

Reprocessing of spent nuclear fuel with vitrification of the waste products has taken place in some countries, notably France, the UK, the USA and Russia. The vitrified HLW produced at Sellafield (UK) and La Hague (France) is packaged in cylindrical stainless steel containers 0·43 m OD and 1·35 m high with a wall thickness of 0·005 m, each containing 380–390 kg of vitrified waste. It has been suggested that these packages could be suitable for DBD without overpacks, but with such thin walls it may be debatable whether they could withstand the stresses involved. In designing a DBD for these wastes it would be prudent to allow for an overpack with a wall thickness of at least 1 cm, giving a package OD of 0·45 m and overall height of 1·37 m.

The reprocessing waste produced at Hanford (USA) is in much larger packages with a diameter of 0·61 m and a height of

4·57 m. It seems unlikely that DBD could accommodate such packages, at least until larger holes can be drilled.

3.3 Plutonium

Plutonium is a strategic material and to date no country has declared it as waste, although a case can be made on security and non-proliferation grounds for disposal (Von Hippel *et al.*, 2012). Plutonium can be burned in LWRs as mixed oxide fuel (MOX) and some countries (e.g. France) already do so while others such as the UK, which has the world's largest stockpile of civil plutonium, the USA and Russia have indicated an intention to do so. The spent MOX fuel would then be disposed of like other spent LWR fuels, and Gibb *et al.* (2012) have demonstrated that DBD would be well suited to MOX disposal.

Direct disposal schemes for plutonium usually involve its immobilisation in some form of ceramic (Ewing, 1999), low specification MOX (i.e. MOX not intended for use in a reactor) or recrystallised rock (Gibb *et al.*, 2008a). However, it can also be put into small packages inserted into larger containers of spent fuel or HLW – the so-called 'can-in-can' method (Kuehn *et al.*, 1997). As no plutonium has yet been packaged for disposal, there are few constraints on the size of any containers used, although criticality issues could favour quite small packages. Given the relatively small volumes involved, the best strategy for DBD of plutonium would undoubtedly be small-diameter packages requiring only modest borehole diameters, thus enabling greater disposal zone depths than for spent fuel or HLW if desired.

3.4 Container ODs

It is clear from the above that for the DBD of spent nuclear fuel borehole sizes and designs need to be capable of accommodating packages with an OD of at least 0·36 m (one PWR assembly) and ideally 0·405 m (three BWR assemblies). If already packaged vitrified reprocessing wastes (other than Hanford packages) are to be disposed of, a package with an OD of 0·45 m needs to be accommodated. Consequently, throughout the remainder of this paper the assumption is made that the target diameter for the boreholes should be 0·61 m (24 in) or 0·66 m (26 in). These are the two standard diameters that could take the size of casing needed for a 0·45 m package with adequate and preferable clearances, respectively.

4. Deep borehole construction

Over the 50 years since DBD was first considered, there has been continuous and comprehensive development in all aspects of deep borehole construction driven by the demands of the oil and gas industry to find new resources, geothermal development requirements and also for deep and very deep geoscientific boreholes. Since reviews in the 1980s (e.g. Juhlin and Sandstedt (1989) and more recently Beswick (2008)) improvements in drilling technology and equipment and a better understanding of geomechanics in deep stressed rock have continued. Beswick (2008) gives some examples of drilling achievements up to that time.

Consideration of drilling for DBD to date has been based on desk studies drawing experience from the traditional deep drilling industries, such as the hydrocarbon, the geothermal energy and the mining industries, and from geoscience projects with the conclusions largely influenced by what has been achieved to date and translating it into a possible scenario for DBD. This understandable, but conservative, approach has not considered what could be achieved if there was a need to drill larger diameter boreholes to depth.

In future considerations of DBD as an option for certain wastes, the borehole size should be governed by the sizes of waste packages required to optimise the potential application of DBD. From the discussion above (Sections 3.1 to 3.4) it would appear that a 0·445 m (17·5 in) diameter clear hole (i.e. inside casing) size would accommodate a large proportion of the spent nuclear fuel inventory and a 0·50 m (19·7 in) clear hole could take all but the largest reprocessing waste packages. A 0·445 m clear hole is a convenient size as it corresponds to a standard size for deep drilling equipment used in the oil industry, but necessitates a nominal hole diameter of not less than 0·610 m to accommodate the size of steel casing that would need to be installed through the disposal zone. This is not a size that has been drilled to date at the 4000–5000 m depth in any of the supporting drilling industries, and larger diameters would be necessary in the upper parts of the borehole to provide support by casing the borehole in stages, the depths of which are governed by the geology.

In a report to the UK Nuclear Decommissioning Authority, Beswick (2008), presented a historical summary of depth against diameters in graphical form and, based on previous experience, concluded that a 0·30 m hole size and even a 0·50 m hole size were probably achievable extensions of hole diameter at 4000 m. Noteworthy is that significant 'big hole' experience was gained from drilling for military purposes. The US government drilled 550 large-diameter boreholes to depths of 1000 m or more with diameters from 1·22 to 3·66 m and opened some to 6·4 m diameter for nuclear munitions testing. Similar programmes were also undertaken in large-diameter boreholes in the former USSR, China and by the French in the Pacific Islands (Beswick, 2008; FAS, 2007).

The idea of drilling a 0·61 or 0·66 m diameter borehole to a depth of between 4000 and 5000 m, while challenging, is certainly not out of the question. Thirty years ago in 1983 and 1984, a 3810 m deep hole was drilled and a string of 0·508 m (20 in) casing installed in the 0·66 m diameter hole to a depth of 3800 m in Louisiana, with an internal drift diameter of 0·462 m (Pejac and Fontenot, 1988). This paper summarises the casing design processes and quality assurance for deep large-diameter strings and is as relevant today as it was then. At the time, this was an impressive achievement and highlights the fact that the DBD concept requires only a modest advance on what was achieved almost 30 years ago.

In recent years, the focus of deep drilling has been on 'long reach', horizontal drilling and deep ocean drilling, and not so much on large-diameter wells to great depths. Development in drilling technology is driven by demand. For example, in the early 1980s, less than 1% of all drilling in the USA was carried out using down-hole drilling motors rather than surface rotation of the drill string (Beswick and Forrest, 1982). A conservative approach at that time would never have contemplated the massive changes that have occurred in directional drilling equipment and practices using these down-hole devices enabling long reach wells in the oil industry to reach lengths of more than 12 km, with horizontal sections of over 11 km on Sakhalin Island, Russia (Exxon Neftegas, 2013). The shale gas revolution in the USA with over 25 000 or more wells drilled each year, together with other shale gas developments worldwide, routinely drills lateral sections up to 1500 m long, a practice that would not have been thought possible 10 years ago. These examples highlight how those who pioneer new applications outside the conventional envelope of current practice can achieve results that conservative minds would not contemplate. DBD is at this stage and needs some bold thinking and investment to explore this option fully for radioactive waste.

Compared with the billions of dollars spent worldwide in the pursuit of relatively shallow mined repositories, investment in DBD to date has been minimal. Therefore, it is not reasonable to dismiss the scenario that, in favourable geology, a deep vertical borehole can be drilled to between 4000 and 5000 m with a final hole diameter of 0·61 m or more and with a clear cased hole diameter of 0·445 m or over. To advance the DBD concept a full-scale trial borehole that would prove feasibility, is essential. The trial borehole would also enable development of the drilling equipment and practices, testing of the deployment methods with dummy waste canisters and investigation of sealing options. Individual elements of the processes involved could also be tested in shallow boreholes, for example, in a quarry, such that the outcomes could be verified by inspection after exposure by excavation.

Demonstrating the concept of DBD would be a major project requiring heavy equipment (Figure 3), comprehensive borehole design work, equipment engineering and planning with meticulous attention to detail, but it offers huge rewards in the form of a safe, feasible and economic option for nuclear waste disposal. Most of the elements for the design and construction of deep, large-diameter boreholes are already in place, but for those that are not, or require development or adaptation, each is a significant challenge in its own right. Some key aspects and the status of the related technologies are summarised below.

4.1 Geological setting

Much of the continental crust is underlain at suitable depths for DBD by granitic basement rocks. Experience over the past 40 years in geoscientific and geothermal energy boreholes provides considerable data on drilling in granitic basement rocks. While very different from the geological conditions generally encountered in the oil and gas industry, this allows a detailed design to be undertaken with confidence. From a drilling perspective, site selection ideally should avoid complex sedimentary sequences that necessitate several intermediate casing strings, but any sedimentary cover should be easy to drill and relatively stable. Selection should also provide a stable formation throughout the proposed disposal zone. Boreholes should be sited to avoid abnormally geopressurised zones, potential hydrocarbon provinces, mineral resources (as indicated by surface and known expressions of economic mineralisation), likely geothermal energy prospects (high geothermal gradients) and other sub-surface resources likely to attract

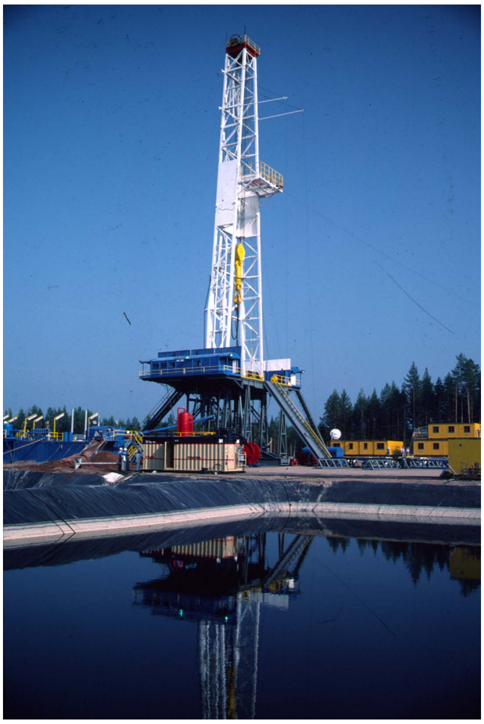

Figure 3. Heavy drilling rig suitable for deep borehole disposal

attention in the future and hence liable to intrusion. Regions where significant anisotropic horizontal stress differences occur should also be avoided.

4.2 Exploratory boreholes

Before the design and construction of any borehole or clusters of boreholes for DBD, a slim exploration borehole should be drilled to slightly beyond full depth to determine the geology, hydrogeology (especially hydraulic conductivities and hydrogeochemistries), pressure and stress conditions at the chosen location through mud logging, geophysical logging and other appropriate testing. Such a borehole poses no special challenges as several similar boreholes have been drilled successfully before and some much deeper than the planned depth of a DBD hole. Noteworthy, however, is the need to seal any exploratory borehole after completion of the evaluation programme in the same way that an actual DBD hole would be sealed, otherwise the borehole may provide a conduit for the eventual release of radionuclides to the biosphere.

4.3 Borehole design

First, a scheme for the intermediate and final casing depths and diameters must be determined. The exploration borehole would provide important data to assess the necessity for borehole wall support or the isolation of certain geological strata for a variety of reasons. One of the principal tasks is to design and analyse the stresses in the various casing strings for all loading conditions during the construction of the borehole, waste package deployment and sealing phases. The current practice for complex and exotic wells and those wells that experience stress cycling, such as for gas storage and engineered geothermal systems, is to adopt a design approach using a computer model developed over 25 years ago (Jellison and Klementich, 1990) and enhanced in recent years. This and other similar tools are technically robust tubular design and analysis models that consider all loading conditions of the casing and the von Mises equivalent stress-intensity criteria. Borehole design also addresses all aspects of the borehole construction including the drilling fluids programme and provides a road map for the execution of the drilling phase of the project.

Noteworthy is that the actual drilling, casing and cementing of the borehole, other than the verification of the integrity of the final casing string that would be installed to the bottom of the borehole is effectively ‘temporary work’ as against the waste package deployment and disposal zone seals (see Sections 5, 7 and 8), which are effectively the ‘permanent works’. During construction of the temporary works, and even to the point that the final casing is installed, the risk of problems and even failure inherent in deep drilling presents no danger and the borehole could be remediated or even abandoned at any time. The essential guarantee that has to be achieved in constructing the borehole is that once the final casing is in place, access throughout the borehole for waste deployment must be guaranteed. At this point the status of the ‘facility’ changes to a nuclear waste disposal facility.

4.4 Surface drilling and associated equipment

There is already in existence a small number of heavy land drilling rigs with the necessary capacity to construct a deep, large-diameter borehole for DBD (Figure 3). These have a lifting capacity of 1000–1200 t that would be adequate for the heaviest loads, which will be the casing loads during installation. All other supporting surface equipment is readily available.

In practice, if DBD were adopted as a method for the disposal of radioactive waste, it is envisaged that a purpose-designed rig would be constructed specifically for the drilling. Drilling rigs currently incorporate a high level of mechanisation and, to some degree, automation. The process of the development of more sophisticated and automated drilling rigs is a current issue in the oil and gas industry with increasing focus on safety by eliminating risks to personnel with various initiatives already in hand to develop a ‘drilling factory’ (Mazerov, 2011).

4.5 Hole advancement methods

Hole construction in these deep, large-diameter boreholes would require a blend of blind shaft drilling and oilfield drilling. For the upper large-diameter section, a reverse circulation approach is probably appropriate and this is the normal practice for shaft drilling. Combination roller bits or plate bits in various formats are available or can be manufactured for different geological formations. In the crystalline granitic basement, which would be drilled largely in 0·61 m (24 in) or 0·66 m (26 in) diameter, standard tungsten carbide insert bits are applicable with normal circulation, as used for most previous drilling in granite for geoscientific and geothermal energy applications. As well as rotary drilling, the use of hammer drills with drilling fluid circulation may be possible to increase the speed of drilling in the harder formations. Such devices are becoming available and can be engineered for hole sizes up to 0·66 m and even larger (M. McInnes, 2013, personal communication). The use of cluster configurations for the larger diameter hole sections may also be appropriate.

Extra-large drill pipe is already manufactured in 0·194 m (7·63 in) size and drill collars in 0·305 m (12 in) and 0·356 m (14 in) sizes for drilling the lowermost intervals. Oilfield drilling is normally carried out with 0·127 m (5 in) drill pipe and 0·15 m (6 in) to 0·24 m (9·5 in) drill collars. For the large diameters needed in the uppermost intervals of the borehole, the shaft drilling industry routinely utilises ‘donut’ drill collars with plate or multi-roller bits.

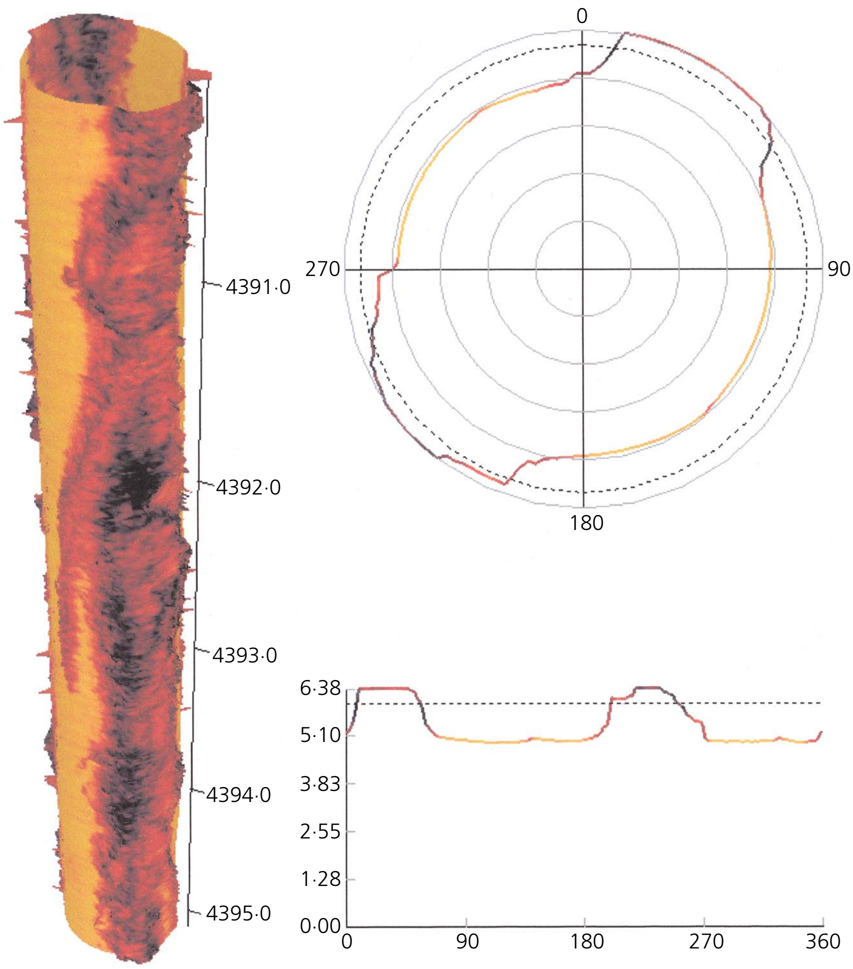

Figure 4. Illustration of stress breakout in deep boreholes (depth in metres, radius in inches) (from Beswick, 2008)

Progress rates for drilling in the basement are well understood. For example, the progress rate during drilling in the basement from 2400 to 5000 m in the Basel geothermal well drilled in 2006 (Häring *et al.*, 2008) was achieved at a rate almost identical to the prediction of approximately 40 m a day.

4.6 Deviation control

Drilling deep vertical boreholes necessitates careful control of verticality. Large-diameter holes, in particular, also require tortuosity to be minimal to allow stiff casing strings to be installed. An automated vertical drilling system was developed as part of the Kontinental Teifbohrprogram project in Germany, where a deep geoscientific borehole was drilled to a depth of 9001 m between 1990 and 1994. The vertical drilling system was used to 7500 m and controlled the verticality to within a departure of 12 m in 7500 m (Emmermann and Lauterjung, 1997; Engesar, 1996). These tools have since been further developed to become a robust workhorse for directional and vertical drilling in the oil industry (Ligrone *et al.*, 1996) and are available up to 0·66 m hole size.

Tortuosity can be overcome by drilling with stiff bottom hole assemblies and reaming to ensure that the hole is straight. Some advancement methods can create a spiral effect and this must be avoided by the application of the appropriate tools and drilling practices.

4.7 Geomechanics issues

Borehole stability is largely controlled by the in-situ stress regime arising from the tectonic history and the mechanical properties of the rock through which the borehole is drilled. Geomechanics considerations are now a mature element particularly in deep and exotic well design, and many models have been developed to investigate the effects (Cook *et al.*, 2007; Grandi *et al.*, 2002). Anisotropic horizontal stress differences lead to borehole breakout or elongation of the borehole shape. As an example, in the Basel geothermal well drilled to 5000 m (Beswick, 2008) the drilled diameter was 0·251 m, but the dimension on the long axis in parts was 0·430 m (Figure 4). However, even with an open hole section from 2400 to 5000 m, the well was relatively stable for some time. The borehole was suspended in 2008 and re-entered in 2010 when there was some restriction at 4673 m while trying to reach the bottom with coiled tubing (see Section 5.2.4) (M.O. Håring, 2013, personal communication). Breakout and hole elongation can in part be controlled by the properties of the drilling fluid, but nevertheless is a concern in all deep wells. In the case of DBD in which the proposed diameter is larger than is normally drilled at the depth of interest, the geomechanics issues need thorough investigation. Data from a slim exploration borehole in a potential location for DBD should provide the necessary information on the state of stress to allow a geomechanics model to be developed.

4.8 Casing

The borehole design will determine the borehole configuration and the appropriate sizes and properties with the depth of the nesting casing that needs to be installed to provide effective support. While any borehole design has to be related to geology and borehole stability factors, a typical scenario could be as shown in Table 1. This scenario is shown in Figure 5 overlain on some of the historical examples of actual depths and diameters achieved (Beswick, 2008).

The two uppermost casings would have welded connections as for shafts and water wells. The 0·762 m (30 in) casing could have screwed connections. This is a standard oilfield size and casing is readily available. The borehole must be cased to the bottom with no open hole to guarantee waste package deployment without any problems. The lowermost casing (0·508 m) would be perforated in the disposal zone to facilitate the waste package support and sealing programme (see Section 7). This casing is also readily available as a standard oilfield product and the string could be welded using the latest in-situ welding process (TubeFuse, 2013). This would also remove any risk of 'hang up' on upset casing connections during installation. Moreover, most casing failures occur at screwed connections and a welded string would remove this risk during the service life of the casing.

Depth: m	Hole diameter: m (in)	Casing OD: m (in)
Surface to 50	1·524 (60)	1·372 (54)
50 to 1000	1·220 (48)	1·016 (40)
1000 to 2500	0·914 (36)	0·762 (30)
2500 to 5000	0·610 or 0·660 (24 or 26)	0·508 (20)

Table 1. Typical borehole design and casing sizes for deep borehole disposal

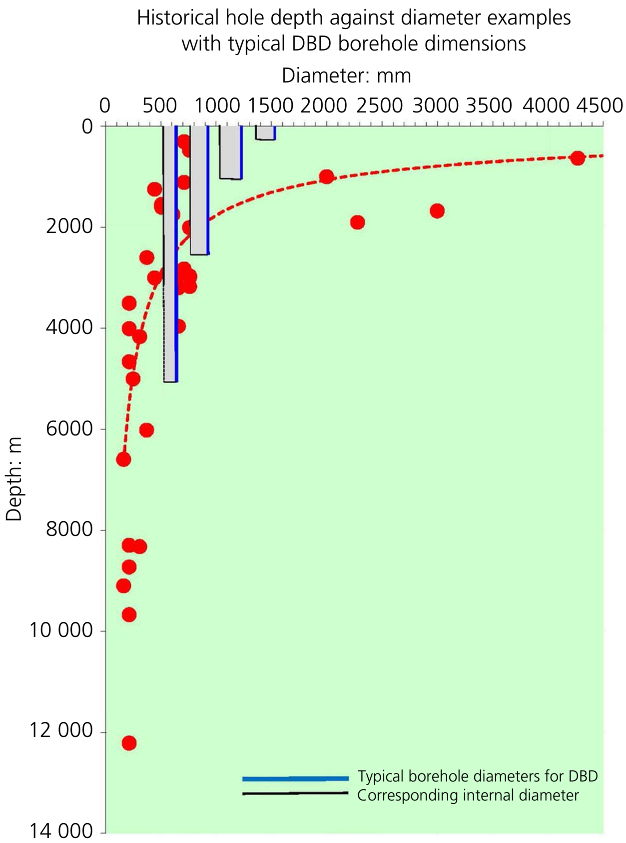

Figure 5. Depth against diameter for previous deep drilling projects with superimposed typical deep borehole disposal (DBD) borehole dimensions (after Beswick, 2008)

4.9 Cementing

Cementing of casing is necessary for casing stability and isolation of any intervals from a drilling perspective. Traditional oilfield cementing practices and verification do need some examination to determine where improvements can be made. An example of cementing a 3800 m string of 0·508 m casing was reported in a well in Louisiana in 1984 (Pejac and Fontenot, 1998). The proposed sealing process to isolate the disposal zone (see Section 8.2) will create containment within the host rock itself at depth. Once the waste has been emplaced, this sealing has to be implemented through windows cut in the 0·508 m casing to allow direct access to the host rock. However, window cutting in casing is a standard procedure in the oil industry.

4.10 R&D topics

While many of the elements of the borehole construction for a DBD solution to radioactive waste disposal are already available, there are some topics that need development, adaptation or further research (Beswick, 2008). The R&D programme should begin with a status review of the applicable technologies as some of the key topics have already advanced since the previous reviews through other initiatives. In particular, uncertainties remain in relation to the geomechanics in large-diameter boreholes at depth, casing design and installation in such large diameters, some large drilling tool design details and the sealing and cementing issues (see below).

Two related aspects crucial to the success of DBD are the development of sealing and support matrices (SSM) for the waste packages and a technology for sealing the borehole above the disposal zone in order to prevent it becoming a route for the escape of radionuclides to the biosphere (see Sections 7 and 8). Conventional materials and methods for sealing oil, gas and geothermal energy wells are unlikely to prove satisfactory for DBD of radioactive wastes and the associated long-term safety cases required. Consequently, research is required into both waste package SSMs and methods for sealing the borehole itself, and such programmes, in which the authors are involved, are underway at the University of Sheffield with the former funded by the Engineering and Physical Sciences Research Council.

5. Deployment strategies and methods

Strategies for waste package deployment will depend on many things, such as the number, weight and heat output of the packages, the emplacement mechanism employed and the capacity of the rig. The factors governing the rate at which the packages can be deployed in DBD however are

- the rate at which packages can be delivered to the site and readied for emplacement, and
- the time required to deliver the packages down-hole to the disposal zone, recover the delivery equipment and ready it for the next emplacement (i.e. the round trip time).

For various operational and economic reasons, DBD requires that the packages can be deployed at rates of the order of one per day. Most DBD concepts assume that waste packages would be deployed singly. However, it has been suggested that they could be deployed in small batches with physical and/or temporal separation between batches (Gibb *et al.*, 2008a) or even in 200 m-long strings of up to 40 packages (Arnold *et al.*, 2011). The deployment mechanism is usually taken to be lowering on the end of the drill pipe using the drilling rig or a lighter 'emplacement' rig. Potentially more efficient methods such as wireline and coiled tubing have been suggested (Beswick, 2008) and are discussed in Section 5.2.

5.1 Deployment rates

For practical reasons waste packages cannot be pushed down the borehole and must be lowered to the disposal zone under tension. There is therefore an upper limit to the speed at which they can be lowered equal to that at which they would free fall under the influence of gravity alone. This limiting velocity is also important in the context of the accidental release of a package during emplacement and the operational safety case.

The sinking of a cylindrical package in a fluid-filled borehole is complicated by the 'piston' or 'hydrodynamic braking' effect, which becomes increasingly more important as the clearance between the package and the casing decreases. Laboratory-scale experiments indicate that, while clearance is the dominant factor, there is also a relationship between the mass of the package and the limiting sinking velocity. The clearance between the waste package and the casing should be as small as possible to minimise the size and cost of the borehole if waste package diameter is the controlling factor or to maximise the amount of waste that can be disposed of if borehole diameter is a constraint. On the other hand, the clearance must be sufficient to eliminate any risk of jamming or damage to the container during the descent to the disposal zone. Clearances of 0·02 or 0·03 m have been suggested (Arnold *et al.*, 2011; Gibb *et al.*, 2012), but the optimum clearance needed to guarantee fail-safe package emplacement can only be ascertained by trials in a full-scale borehole.

Depending on their size, construction and contents, waste packages for the DBD of spent nuclear fuel are likely to weigh between 800 and 5650 kg (see Section 3.1) and preliminary calculations suggest the limiting sinking velocity in a DBD with a container OD to casing ID ratio of 0·85 (Arnold *et al.*, 2011; Gibb *et al.*, 2012) would be between 0·5 and 2·0 m/s. It is therefore likely to prove impossible to lower waste packages to the disposal zone of a 4–5 km deep borehole in under an hour. However, in practice the limiting factor on the time taken to reach the disposal zone will almost certainly be the emplacement mechanism.

5.2 Emplacement mechanisms

The emplacement of the waste packages, whether individually or in strings, must not be affected by any tortuosity in the borehole, but with the diameter, well construction and casing methods proposed, this should not be an issue. However, before any emplacement, the borehole would be checked thoroughly by running a calliper and/or a dummy waste package. Four main mechanisms could be considered

- free fall
- wireline
- drill pipe
- coiled tubing.

5.2.1 Free fall

'Free fall' should be considered only as a theoretical possibility for deployment, but it is important in the context of a waste package becoming detached from the equipment in other deployment methods. In the latter event the terminal velocities appear unlikely to result in any significant damage to robust steel containers. It is not an uncommon means of down-hole delivery in drilling operations and is the standard method when using wireline core barrels whereby the inner barrel is replaced by free fall to latch into the outer barrel on each sampling trip. Descent rates depend on a number of factors including the borehole fluid viscosity, package mass and the clearance (see Section 5.1). However, free fall allows no control on the emplacement and should not be employed for DBD of radioactive wastes.

5.2.2 Wireline

Wireline has the attraction of simplicity, but would limit the weight of the package and provides less control than using drill pipe or coiled tubing. It also carries an increased risk of 'hang ups' leading to recovery problems inappropriate for the disposal of radioactive wastes. There are two types of line – 'slick line' and 'wireline with electrical conductors'. The former is just a braided wire line in various sizes with depth control measured from the surface. A wireline with electrical conductors allows a release mechanism to be triggered and transmission of monitoring data, such as depth control by reference to fixed points in the casing string. All forms of wireline stretch much more under load than metal tube so depth control by reference to casing collars or markers recorded during installation is essential. Wireline winch systems can deliver up to 6000 m/h, but the actual package emplacement speed will depend on other factors such as the limiting velocity and is likely to be much less. Units are available with combined hydraulic cranes enabling a relatively small set-up over the borehole.

5.2.3 Drill pipe

The traditional means of working within a borehole, this requires a drilling or 'workover' rig and a relatively large site area. Drill pipe comes in 9·45 m or 12 m standard lengths and various diameters and steel strengths. Deployment is discontinuous in that each length of pipe has to be added or removed with each connection screwed in or out of the next. The rigs include various devices for making up, breaking out and torquing the drill pipe to the correct values. Deployment speed depends on the height of the rig and whether it is manual or automatic. Traditional 'triples' rigs lower or pull three lengths of 9·45 m drill pipe (i.e. ~28 m) at a time and rack the pipe stands back in the mast or derrick. The smaller 'doubles' variants pull two lengths of pipe (~19 m) and the rigs known as 'super-singles' handle one length of 12 m pipe. With conventional rigs this process requires a 'derrick hand' working high in the mast to rack the pipe back into finger boards designed to accommodate the size of pipe being used. However, modern rig designs, driven by health and safety concerns, have eliminated this practice through the use of robotics, with various types of pipe handling devices being available. Deployment speeds (or 'trip speeds') range from 500 to 600 m/h for automated systems to typically 1000 m/h in a cased hole with an experienced driller and derrick hand team, who must work efficiently together to enable such fast tripping. For DBD an automatic system would be preferable on safety grounds, and modern rigs are becoming increasingly sophisticated with the elimination of most of the manual operations. Using drill pipe the waste package release mechanism would have to be mechanical, which introduces some uncertainty, but a suitable system could be engineered. Depth control would be through the normal practice of surface measurement as the drill pipe is run.

5.2.4 Coiled tubing

The development of coiled tubing systems (Figure 6) has been rapid in recent years and they are now used for drilling, well intervention, logging and well completion operations, with a wide range of equipment available (Afghoul *et al.*, 2004; ICTA, 2005). New systems incorporate electrical conductors through the continuous tube allowing data transmission and commands for release mechanisms. The equipment is widely used in

Figure 6. Coiled tubing unit

different sizes and to depths well in excess of the 4–5 km proposed for DBD and with load capacities in excess of what would be necessary for waste package disposal. Deployment speeds could be 2000–3000 m/h with a waste package release mechanism triggered by means of conductors in the tubing and data acquisition possible through others. The surface set-up would be relatively small so reducing environmental disruption and significantly more cost effective than maintaining a drilling rig on site.

5.3 Emplacement times

The 'round trip' for waste packages, emplaced by whatever method, is not simply a matter of down-hole and return travel times (Schlumberger, 2013). It must also allow for surface operations – like attaching the package(s) – depth checks, package release and any other procedures that have to be undertaken in the disposal zone (see Section 7). Conservative estimates of the time required for a single emplacement trip using each of the three possible methods are

- wireline 8 h
- drill pipe 18 h
- coiled tube 8 h.

These times for wireline and coiled tube emplacement offer scope for improvement with practice, but at some increased risk, especially for the former in which fast running can lead to entanglements. Emplacement of very long and heavy strings of waste packages would probably necessitate the use of drill pipe, but the advantages of coiled tube could warrant reconsideration of this strategy towards individual emplacement or much smaller strings.

The basic equipment and systems for all three options are readily available, although some development of bespoke items such as waste package release mechanisms would be necessary. However, development costs would be minimal. In selecting the emplacement mechanism for the DBD of radioactive waste packages consideration needs to be given to the mechanisms and equipment that reduce to a minimum any risk of exposure to people at and around the site. Although every effort should be made to employ mechanisms that minimise the risk of accidental release of the packages this is, contrary to common misconception, not a serious problem. The terminal velocities reached in free fall of a waste package (see Section 5.1) are unlikely to result in any significant damage to a steel container. It is apparent from the above summary that the coiled tubing method would be the preferred option, with the additional benefit of being much more cost effective than the use of drill pipe necessitating a drilling or workover rig. Ideally, the waste disposal organisation would own a purpose-designed equipment package so the cost spread over a substantial disposal programme would be relatively low. However, for a demonstration borehole or pilot scheme, it would be preferable to utilise equipment readily available in the drilling industry.

6. Heat flow

Almost all the HLW appropriate for DBD generate significant amounts of decay heat, which, although transient on timescales of hundreds to thousands of years, add to the ambient temperatures at disposal zone depths. From various materials performance and engineering perspectives it is important to be able to predict the spatial and temporal distribution of temperature in and around the borehole and this is done by modelling heat flow for specific disposal scenarios. To a good approximation, the spatial and temporal distribution of temperature for a single borehole with emplaced waste can be treated as two separate problems in heat conduction and convection, with the former the dominant form of heat transfer. The solution from the conduction model can then be used as input to determine the extent of any convection.

The solution of the heat conduction equation of continuum mechanics is most easily obtained through the finite difference method (FDM), which transforms the partial differential equation into a sparse system of linear algebraic equations yielding solutions for the temperature at the nodes of a Eulerian grid, superimposed on the problem space. DBD heat flow research at the University of Sheffield utilises a dedicated heat conduction code, 'Granite' (Gibb *et al.*, 2008b, 2012; Travis *et al.*, 2012), which employs the FDM to model disposal of one or more containers in a single borehole. This code uses variable mesh spacing, with finer resolution in and near the borehole, and a coarser mesh in the far field. Components such as the casing, SSM (see Section 7), container material, container infill and waste are included in the model by assigning relevant material properties (density, specific heat and thermal conductivity) to the mesh points within the appropriate spatial regions. The temperature dependence of these properties is built in to the code.

The source term is an essential aspect of any heat flow model. In 'Granite' it is represented by those mesh points that lie within the waste region. In the case of DBD of consolidated fuel rods (see Section 3.1.2) the 'waste' consists of the fuel rods and their infill but only the central sections of the rods generate heat and this is accommodated in the model. A nuclear industry standard code, FISPIN (Burstall, 1979), is used to obtain decay curves for the particular spent nuclear fuel or waste. Where the 'waste' region is composite (e.g. comprising the fuel rods, their cladding and the infill) the thermal conductivity, density and specific heat of the composite material is estimated using models that treat the problem as thermal resistors in series and parallel arrangements. Another key feature of our FDM modelling is the inclusion of latent heat. Latent heat is less important in 'low temperature' DBD schemes than 'high temperature' versions, but it is significant for modelling rock welding scenarios (see Section 8.2 and Figure 7). In such cases, in which the heat melts the granite, subsequent cooling also needs to take account of the latent heat of crystallisation.

With an FDM code such as 'Granite', it is a straightforward task to determine temperature–time curves for any point in or around the borehole. These can be used to create peak temperature isotherm diagrams, which, in the context of 'high temperature' DBD or rock welding (see Section 8.2), can be combined with experimental data on granite to predict the size and shape of the melt zone around the waste containers or heater. This modelling also yields data on the times needed before the rock recrystallises and provides guidance on the minimum spacing required between boreholes for multiple borehole arrays and on deployment strategy, for example, waste package contents, batch sizes, emplacement intervals and so on.

Convection in the host rock fluid (groundwater) is treated as a fluid dynamics problem, decoupled from conduction, and solved to determine how far a particle might travel in the upward vertical direction as a result of convective flow in a thermal gradient. This gradient arises from the pre-existing geothermal gradient modified by the decaying heat profile from the stack of waste packages as determined by the conductive modelling. A simple model using a point source of heat permits an analytical solution and a conservative upper bound (Gibb *et al.*, 2008b). Preliminary calculations suggest that this method of potential radionuclide transport is both transient (lasting only a few hundred years) and of minor vertical extent (less than a few hundred metres) with the low hydraulic conductivities anticipated, and hence presents no real threat to containment in the context of DBD.

Heat flow issues are well understood and the modelling is sufficiently advanced to give confidence in the viability of the DBD concept, including the feasibility of sealing the borehole by rock welding. Further R&D in this area should focus on ever more detailed and specific disposal and sealing scenarios with concomitant refinement of the models and codes.

7. Sealing and support matrices

The long-term safety case of the DBD concept does not require the integrity of the containers to survive beyond the emplacement of the main borehole seals above the uppermost waste package (Arnold *et al.*, 2013; Gibb *et al.*, 2012) – at most a few years after emplacement of the packages is completed. However, it would benefit the post-operational safety case to prolong this containment far into the future by protecting the containers from saline groundwater for as long as possible. This could be achieved by inserting an impermeable material into the annulus between the container and the casing and, ideally, into the gaps between the casing and the rock. Depending on the material used, it could also serve as a barrier to the escape of any radionuclides that eventually leach out of the package by impeding fluid flow, sorption and so on.

While the primary function of the barrier material is to prevent the access of groundwater to the container and hence substantially delay corrosion, it has an important secondary function to support the waste packages physically. This will almost certainly be necessary to prevent buckling and other forms of load damage to the container caused by the overlying column of potentially very heavy waste packages. Steel containers could be designed with sufficient wall thickness to withstand these load stresses but at a cost and with a loss of disposal space. Using a support matrix with a high compressive strength would eliminate the need for this and/or the use of other means of reducing the load, such as bridge plugs at intervals up the disposal zone.

Several materials have been suggested for providing either the sealing or support functions for the waste packages, but the ideal is a dual-purpose SSM. Irrespective of the SSM used, a key factor is the need for the waste packages to be centred and aligned within the disposal zone casing. This is necessary to ensure a uniform thickness of seal around the package, and any eccentricity or misalignment would increase the likelihood of container buckling or other damage. Achieving centred alignment is a challenge that must be addressed by the emplacement technology R&D, but numerous solutions seem possible such as centring rollers or fins on the containers.

7.1 High-density matrices

A novel high-density support matrix (HDSM) was proposed by Gibb *et al.* (2008c) for wastes that generate temperatures greater than approximately 185°C in the annulus between the package and the borehole wall. Such temperatures are likely to be less than 150°C above the ambient value (80–130°C) at the disposal depths in continental crust. Suitable packages could contain large numbers of used fuel rods, high burn-up fuel, relatively young used fuel or any combination of these (Gibb *et al.*, 2012). Also suitable could be packages of vitrified reprocessing HLW with high waste loadings or that had not undergone several decades of cooling.

The HDSM is a lead-based alloy in the form of fine shot that is delivered down the drill pipe or deployment tube after the emplacement of each waste package, or small batch of packages. The heavy, free-flowing shot runs into all the spaces around the packages and, by means of weight-reducing perforations in the uncemented disposal zone casing, into any gaps between the casing and wall rock. Within a period of weeks to months (Gibb *et al.*, 2008c, 2012) the decay heat from the waste will cause the temperature to exceed the solidus of the alloy (~185℃), which melts to a dense liquid that fills any remaining voids between the containers and the borehole wall. Over a period of years to decades the heat output of the waste will decline and the alloy will re-solidify, effectively 'soldering' the packages into the borehole.

Although lead alloy HDSMs, which could have the added benefit of disposing of contaminated lead from the nuclear industry, work on a laboratory scale, they have yet to be tested in a full-scale borehole. This is something that could be done simply and economically using a shallow borehole, for example, in a quarry (see Section 4). For waste packages not capable of generating the moderate temperatures required for an alloy HDSM an alternative 'low temperature' SSM is needed. This could apply to a significant part of the inventory of older spent nuclear fuel, especially if fuel rod consolidation is not used.

7.2 Cementitious matrices

Many mined repository concepts, such as SKB's KBS-3, employ a layer of bentonite as the primary barrier around containers of spent nuclear fuel and some DBD concepts (e.g. Arnold *et al.*, 2011; Juhlin and Sandstedt, 1989) have suggested a similar material might be used to fill the annulus between the waste packages and casing. The successful use of swelling clays such as bentonite depends on inserting it dry and compacted into a confined space so subsequent hydration causes it to swell and create an impermeable barrier to groundwater. In a mined repository situation this is usually attempted by using shaped, pre-compacted blocks, but this is difficult and it would be virtually impossible to emplace dry bentonite around the waste packages at the bottom of a water-filled borehole. Consequently, if bentonite were to be used to surround and support the waste packages in DBD (e.g. Arnold *et al.*, 2011) it could only be as an uncompacted slurry. Moreover, there are issues about the temperature limit (~100℃) above which bentonite cannot be used.

Initially, it appears that the most promising material for any low-temperature SSM is some form of cement (Woodward-Clyde Consultants, 1983) because they are relatively inexpensive, can be pumped down-hole in their more fluid forms, remain soft long enough to be emplaced, have high compressive strengths when set and excellent radiation shielding properties (although the latter is of little benefit in DBD). Also, there is considerable experience of working with cementitious grouts in the drilling industry. In previous papers on DBD, Gibb *et al.* (2008a, 2008d) suggested that a cement grout was simply 'pumped down the borehole' through the drill pipe following the emplacement of the waste package(s). This assumes the cement would settle into the annulus between the container and casing and, ideally, into the gaps between the casing and rock before setting. However, emplacement of a cement SSM is a more complex engineering challenge, and cementing operations are some of the most difficult and uncertain procedures the drilling industry has to undertake, with frequent failures.

Before a cementitious SSM could be considered for use at the depths, pressures and temperatures of a DBD a number of specific challenges must be addressed. The research programme under way at the University of Sheffield (see Section 4.10) seeks to integrate borehole delivery engineering with a modelling and experimental study of cement formulations and their properties. The objective is to find or develop a suitable formulation and delivery method such that a cement-based SSM can be implemented successfully in the DBD of low heat-generating radioactive wastes. Preliminary studies indicate that the commercially available formulations used by the hydrocarbon and geothermal energy industries (mainly for cementing casing) and their emplacement methods are unlikely to deliver the 100% seal and zero failure rates required for DBD of nuclear wastes. Two principal approaches to the challenge imposed by these requirements are being investigated. In the first, the waste packages are emplaced singly or in batches of less than five followed by the cement, which has to find its way into all the necessary spaces before setting. In the second, delivery of the cement precedes emplacement of the waste package(s), which then has to sink completely into the cement before it sets. Both approaches have significant implications for the number of packages that could be emplaced at a time (i.e. the size of a batch) and for the key properties of the cement SSM, such as rheology, setting and thickening times, hardening and mechanical properties, geochemical reactivity and durability.

8. Borehole sealing

It is important that the borehole itself does not provide an easier route back to the surface for fluids or gasses carrying radionuclides than does the host geology, so it must be completely and permanently sealed above the topmost waste package. Hydrocarbon and geothermal energy wells are sealed in different places using a range of methods and materials, but emplacing these seals is not straightforward and there are engineering challenges in anchoring and/or sealing casing to the wall rock in such holes.

For DBD of radioactive wastes the contact between the seal and wall rock has to be good and would therefore require removal of the casing. Cutting the casing in or above the disposal zone and withdrawing it, as suggested by Gibb *et al.* (2012), is an engineering challenge and a simpler, more cost-effective alternative would be to cut or grind away several metres of the casing at the location(s) of the seal(s) to expose the wall rock. Irrespective of the sealing material used, the contact between it and the rock is a potential surface of weakness that could be exacerbated by longitudinal pressures in the borehole, tectonic stresses or chemical reactions between the seal and saline groundwaters at elevated temperatures and pressures. This could become a path of least resistance to any fluids seeking to flow up or down the borehole.

The presence of an excavation damage zone (EDZ) around the borehole is a significant complication. In hard rocks such as granite this may be restricted to a few tens of centimetres, but it would be almost impossible to get any sealing material, even in pressurised contact, to penetrate far enough into the micro-fractures of the EDZ to make it impermeable to fluid flow. A permeable EDZ is a potential by-pass of the borehole seals and must be blocked off or at least locally eliminated, possibly at intervals above the disposal zone.

8.1 Conventional methods

Sealing of boreholes in the oil and gas industry is commonplace and important, more so in recent years as well integrity has become such an important matter to the public minds and for operational reasons. Zone isolation and annular sealing is particularly important in high-pressure gas wells and gas storage wells.

To support these demands, the oil and gas industry has evolved a wide range of mechanical and cement-related devices and installation methods. New products appear on the market regularly including, in recent years, the ‘swell packer’ (Durongwattana *et al.*, 2012; Kennedy *et al.*, 2005) whereby an elastomer shell around a casing, for example, reacts with water or oil to form a swelling seal to block flow through an annulus. Other equipment such as casing packers can be inflated with cement to seal off an annulus and cement can be pumped under pressure through ports in the casing and ‘squeezed’ into the cavity, much like grouting with the tube-à-manchette system used for dam and tunnel grouting.

In most countries regulation requires that oil or gas wells from which extraction is finished are sealed to ensure that no hydrocarbons or other geopressurised fluids can reach the surface in the future. This is achieved by setting various mechanical and cement or cement-bentonite plugs and sometimes filling the whole well with a cementation compound in stages. Even in high-pressure gas scenarios, the possibility of gas leakage is remote after this sealing process has been completed. In the case of DBD any gas that might act as a carrier for radionuclides would be largely in solution at the disposal depths because of the pressure. If the solution migrated towards the surface up the borehole and the carrier gas exsolved, it would do so at relatively low pressures and could be blocked by the use of these methods, although they would require adaptation of the existing equipment and technology both for annuli between casing and wall rock and for the borehole itself.

There are, however, two aspects of DBD in which uncertainties must exist over the performance of these physical and mechanical methods for sealing the borehole above the waste packages. The first concerns the length of time for which their performance can be guaranteed and it seems unlikely that this could extend to the hundreds of thousands of years required for DBD. The second relates to the EDZ and the difficulties of eliminating it described above. Inflated packers would not affect the EDZ and cements and other grouts are unlikely to render it impermeable on the spatial or temporal scale needed. Consequently, while conventional seals may be adequate in the short term, the development of better and longer lived seals presents a R&D challenge.

8.2 Rock welding

To create a seal as strong as the host rock and eliminate the EDZ, Gibb *et al.* (2008b, 2008c, 2012) proposed that a short length of the borehole, from which the casing has been removed, be backfilled with finely crushed granitic host rock that is then partially melted, along with a significant thickness of the wall rock, by down-hole electrical heating. On cooling slowly the melt recrystallises to a holocrystalline rock virtually identical to (and continuous with) the host rock, thus eliminating the EDZ and sealing the borehole. This process is known as ‘rock welding’.

Rock welding could be repeated at intervals, as determined by the geological conditions and environment, above the topmost waste package with the borehole being backfilled between welds or sealed by more conventional methods as a form of additional insurance. Ideally, the borehole should be sealed within the upper part of the disposal zone to avoid the need to remove more than a single layer of casing and as short a distance as possible above the top waste package to maximise the geological barrier provided by DBD.

A rock welding R&D programme under way at the University of Sheffield consists of six integrated activities

- development of a baseline engineering concept
- heat flow modelling
- melting and recrystallisation of granitic rock
- design of down-hole heaters
- deployment engineering
- full-scale trials.

The baseline engineering concept involves backfilling the borehole for a few metres above the top waste package with crushed host rock then inserting a bridge plug, a simple cement

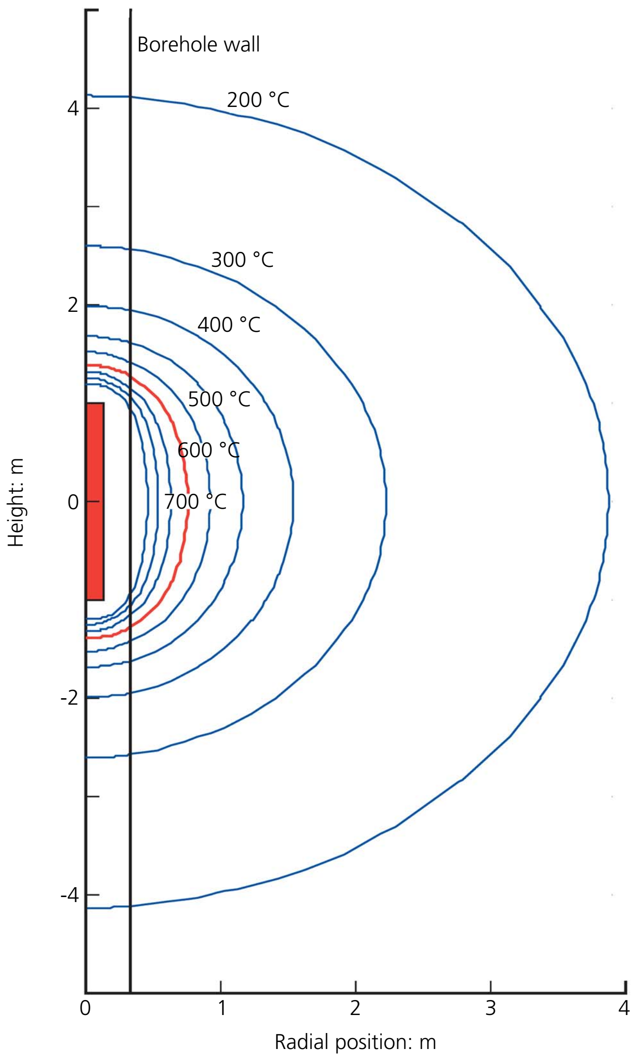

Figure 7. Peak temperatures generated during rock welding in and around a 0·66 m diameter borehole using a 2 m × 0·264 m diameter heater with a power input of 12 kW. Isotherms are at 100°C intervals with the 700°C isotherm (approximate granite solidus) as the thicker line

plug, or both. The disposal zone casing is then cut away for several metres above the plug to expose the wall rock and the hole is flushed with clean water. The hole is filled almost to the top of the exposed wall section with a dense slurry of crushed host rock and the solids are allowed to settle. A sacrificial electric heater, connected to the surface by a retrievable umbilical cord is then placed on top and allowed to settle a short distance into the slurry before more crushed host rock is added to backfill the hole for several metres above the heater. Finally, a pressure seal or packer, through which the umbilical cord passes, is set above the backfill. Power is supplied to the heater to partially melt the enclosing backfill and the host rock for an appropriate distance beyond the borehole wall. The viscous silicate melt flows into all the gaps accompanied by upward migration of the supercritical fluid phase and slight settling of the heater. After a predetermined period of weeks, the power is cut or reduced gradually so the melt recrystallises completely by the time it reaches its solidus temperature. This should take a matter of months.

Heat flow modelling (see Section 6) of various heating scenarios using purpose-designed software (Gibb *et al.*, 2008b, 2012; Travis *et al.*, 2012) predicts the three-dimensional distribution of temperature with time in and around the bore-hole. The results are combined with knowledge of the melting and crystallisation of granitic rock to ascertain the conditions required for the creation of rock welds of various shapes and sizes.

Attrill and Gibb (2003a, 2003b) showed that granite can be partially melted and recrystallised under attainable conditions and on practical timescales in the context of DBD. This experimental work was carried out at a pressure of 150 MPa (1500 bar), corresponding to ambient pressure 4 km down in continental crust, whereas the pressure at the top of the disposal zone in a water-filled borehole would only be around 30 MPa until the hole is sealed and pressure gradually recovers to ambient. However, refinement of the experimental work for lower pressures will not affect the phase relations significantly and is likely to revise temperatures upwards by only a few tens of degrees. Adequate partial melting of the granitic host rock for rock welding would require temperatures between 700 and 800°C and, under appropriate cooling conditions, the melt would be completely recrystallised on cooling to approximately 550°C. Once a site for DBD has been selected, further experimental work can refine the data for the actual host rock.

The outcomes of the heat flow modelling are used to inform the designs of the down-hole heater packages. A simple example is shown for a 0·66 m (26 in) diameter borehole (see Section 4.8) in Figure 7. The heater is 2 m long with a diameter of 0·264 m and a power density of 110 kW/m^3, corresponding to an input of 12 kW. It is assumed to be made of homogeneous material with a uniform heat generation, neither of which would be the case in practice, when more sophisticated designs would be used, but this is adequate to confirm that rock welding could be achieved with quite modest power inputs on a realistic timescale. Furthermore, temperatures down to approximately 500°C, while too low to melt the host rock, could anneal out any pre-existing microfractures, for example, in the EDZ. The shape and size of the weld can be controlled by varying the length and diameter of the heater, the power input and the distribution of heat output within the heater. The challenges currently being addressed for heater design are to

- ensure that the welds are large enough and have sufficient physical strength to seal the borehole and eliminate the EDZ
- avoid temperatures inside the heater being unacceptably high from the perspective of the materials used to construct it
- generate the temperatures necessary for melting the host rock to the required distance from the heater in suitably short times.

In the latter context it would not be cost effective or practical to have to continue supplying power for periods of many months or even years.

Suitable heaters can be developed to operate under the pressures, temperatures and the chemical environment of DBD, but some challenges, or at least developments, remain regarding down-hole deployment. Like the waste packages, the heater would have to be lowered down-hole and the best method would appear to be coiled tubing (see Section 5.2.4). It is already known that the necessary levels of power can be supplied to the depths involved by means of an umbilical cord. Similar or higher levels of power are supplied by this means to remotely operated submersible vehicles, which operate at greater depths and pressures than in a DBD. However, the engineering required to get the umbilical cord inside the coiled tube and through the pressure seal/packer above the rock weld zone has yet to be worked out in detail.

The eventual construction and testing of the heaters and the demonstration of successful rock welding require large, if not full, scale trials. However, provided the trial can be engineered to contain pressures around 30–40 MPa in the weld zone, it should prove possible to undertake this in a relatively shallow borehole, for example, in a quarry (see Sections 4 and 7.1), allowing easy access to the outcomes.

9. Conclusions

DBD offers an attractive alternative to relatively shallow mined repositories for many forms of HLW, including spent fuel, at substantially less cost per mass unit and with other significant advantages.

Even using current technology, albeit that the borehole diameters are larger than are normally required for other drilling applications, the gap between what can be achieved in deep drilling and the equipment and technology necessary to construct a borehole for DBD has narrowed to the point that a demonstration borehole should be seriously considered as soon as possible. Only then would the remaining issues be resolved and the viability of DBD as an option for the disposal of radioactive wastes be widely accepted.

Some technical challenges remain, mainly related to modification or upgrading of down-hole drilling and casing equipment and the crucial matter of borehole sealing, together with relatively minor details such as designing a waste package running and release tool and the surface shielding arrangements – the latter being well understood by the nuclear industry.

All the main surface equipment required is already available and proved. A concerted effort to address the remaining challenges is overdue. The costs of implementing a (non-active) full-scale, demonstration borehole are small compared with what has already been spent on other options.

The principal obstacle to the implementation of DBD is not really an engineering issue, but is the need for a comprehensive safety case (Chapman, 2013). The works of Brady *et al.* (2009) and Arnold *et al.* (2013) are a good start, and a successful borehole demonstration would confirm the engineering viability, but much remains to be done to gain regulatory approval for the disposal of radioactive wastes.

A successful demonstration should remove doubts about the viability of this potentially superior option, but further progress clearly requires acceptance of the concept and support by government and/or national waste management organisations as appears to be happening in the USA.

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Geschäftsstelle

Kommission
Lagerung hoch radioaktiver Abfallstoffe
gemäß § 3 Standortauswahlgesetz

Arbeitsgruppe 3
Entscheidungskriterien sowie Kriterien für Fehlerkorrekturen

Anhörung „Tiefe Bohrlöcher“ in der 9. Sitzung der Arbeitsgruppe 3 am 8. Juni 2015

Präsentation des Sachverständigen Andrew Orrell, International Atomic Energy Agency
„Final Disposal in Deep Boreholes Using Multiple Geologic Barriers: Digging Deeper For Safety”

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9. Juni 2015

Final Disposal in Deep Boreholes Using Multiple Geologic Barriers: Digging Deeper for Safety

Genesis of the US R&D Program for Deep Borehole Disposal

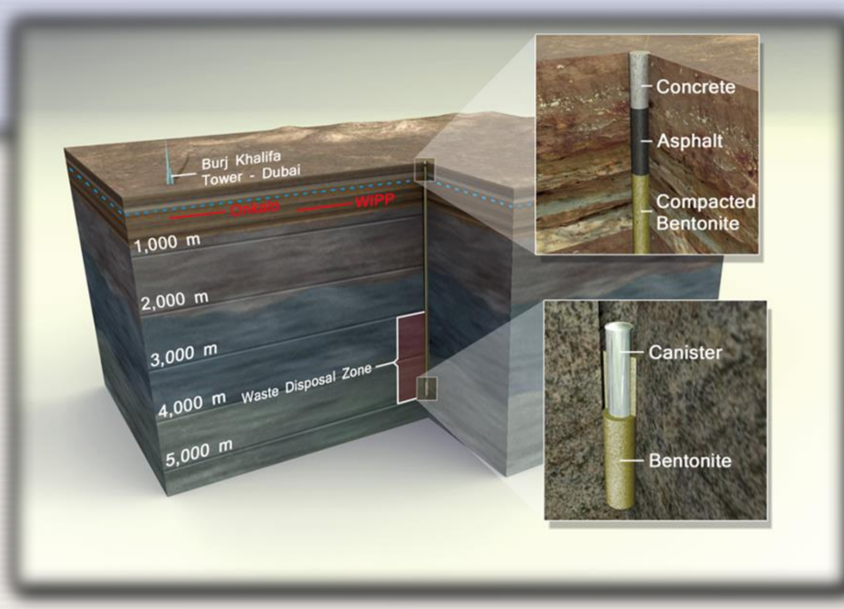
Andrew Orrell

International Expert-Workshop on June 5 and June 6, 2015

IAEA

International Atomic Energy Agency

Outline



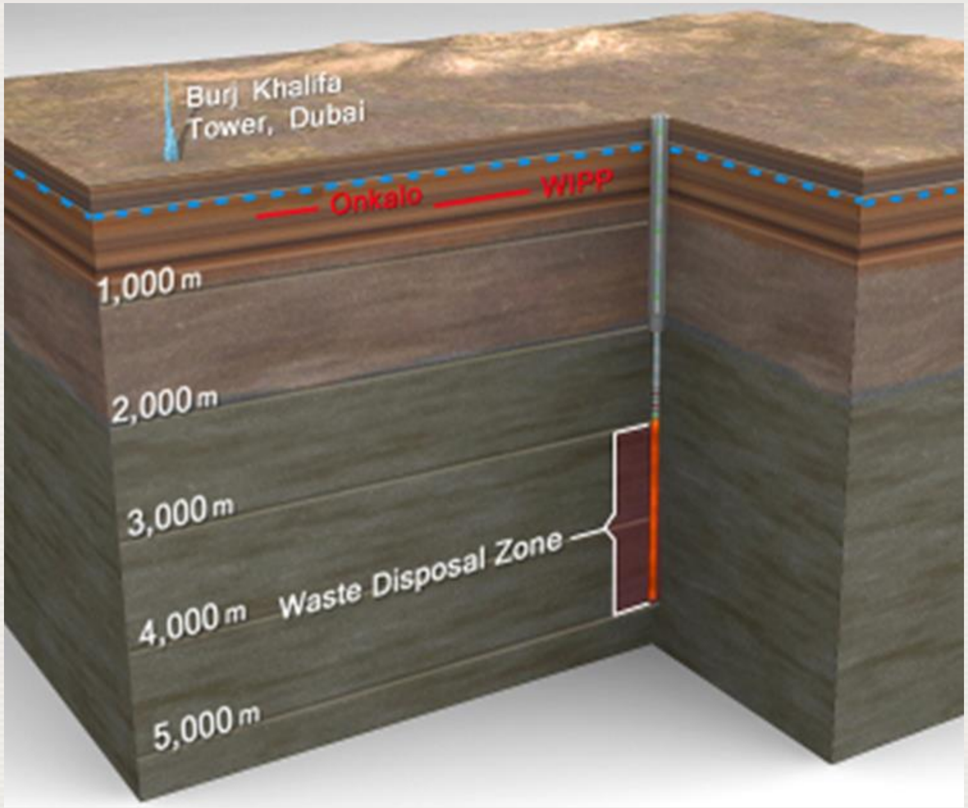
- Objective
- Concept
- History
- Recent U.S. Developments
  - Motivations for a Renewed Consideration
  - 2008-2013
- Final Thoughts

Objective

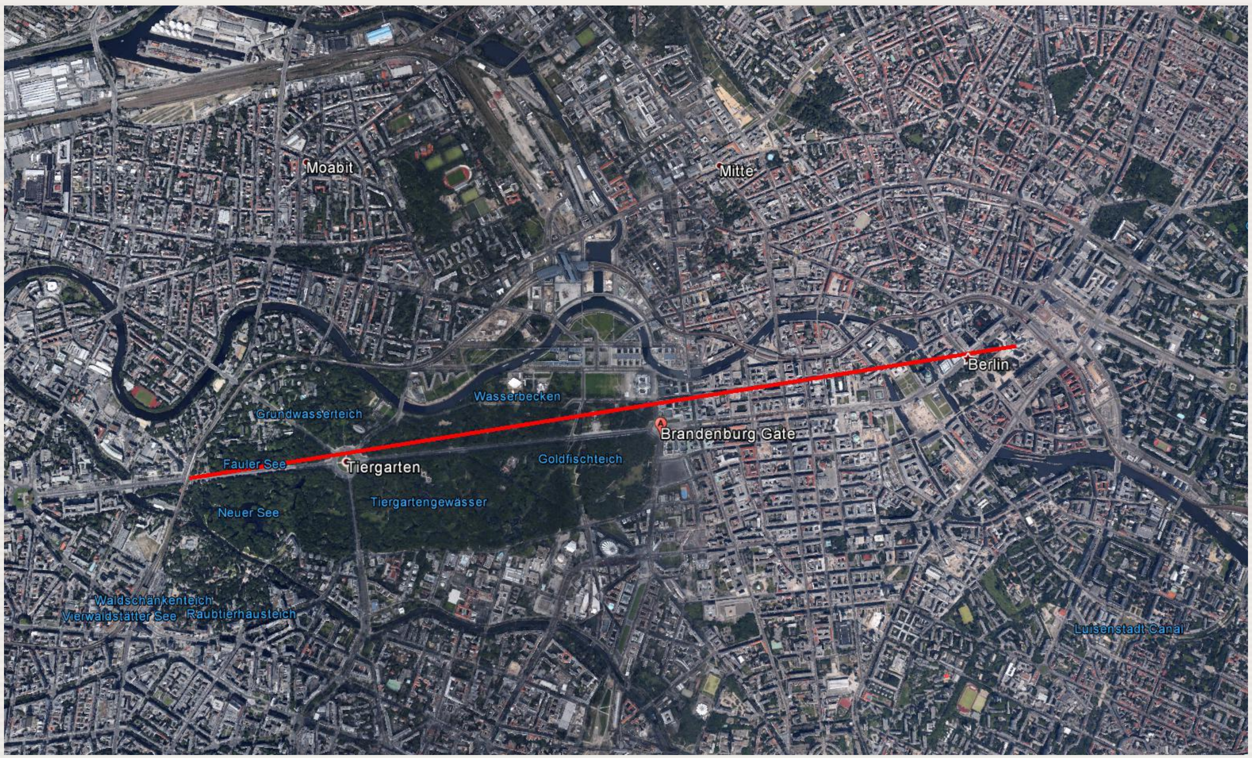
- To understand the context of what led to the current momentum to develop deep borehole disposal concept
- To accelerate and contribute to your own deliberations on whether to pursue

Deep Borehole Disposal Concept

- Disposal concept consists of drilling a borehole or array of boreholes into crystalline basement rock to about 5,000 m depth to ~45 cm diameter
  - Bottom hole diameter
    - 17 in. for bulk waste forms or SNF/HLW
    - 8.5 in. for smaller DOE-managed waste forms
- Borehole casing or liner assures unrestricted emplacement of waste canisters
- Waste would consist of spent nuclear fuel and/or high-level radioactive waste
- Approximately 400 waste canisters would be emplaced in the lower 2,000 m of the borehole
- Upper borehole would be sealed with compacted bentonite clay, cement plugs, and cemented backfill



5 Km Paths



368m

x 13.5 = 5 KM.

Tallest structure in Germany, Berliner Fernsehturm

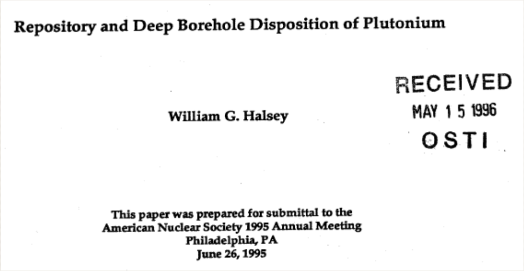
Asserted Benefits of Deep Borehole Disposal Concepts

- Crystalline basement rocks are relatively common at depths of 2 km to 5km
- Disposal could occur at multiple locations, reducing waste transportation costs and risks
  - Greater potential for site to site performance comparability, possibly avoiding 'best site' contentions, fostering equity and fairness issues.
- Low permeability and high salinity in the deep crystalline basement suggest extremely limited interaction with shallow groundwater resources; high confidence isolation
- Thermal loading issues are minimized
- Geochemically reducing conditions limit solubility and enhance the sorption of many radionuclides
- Retrievability is difficult, but not impossible
- Compatible with multiple waste forms and types (e.g. CANDU bundles, PWR w/ or w/o rod consolidation)
- The deep borehole disposal concept is modular, with construction and operational costs scaling approximately linearly with waste inventory
- Existing drilling technology permits construction of boreholes at a cost of about $20 million each
  - Low cost facilitates abandonment of emplacement-ready holes that fail to meet minimum criteria, limits 'make it work' perceptions
- Disposal capacity of ~950 boreholes would allow disposal of projected US SNF inventory
  - Dry Rod Consolidation (demonstrated at INL in the 80's and at present in Germany, Sweden) could reduce this by ~1/2, or possibly further reduce costs for smaller hole bottom diameter

Source: Brady, P.V., B.W. Arnold, G.A. Freeze, P.N. Swift, S.J. Bauer, J.L. Kanney, R.P. Rechard, J.S. Stein, 2009, *Deep Borehole Disposal of High-Level Radioactive Waste,* SAND2009-4401, Sandia National Laboratories, Albuquerque, NM, and
Technology and Policy Aspects of Deep Borehole Nuclear Waste Disposal, M. J. Driscoll, R. K. Lester, K. G. Jensen (MIT), B. W. Arnold, P. N. Swift, and P. V. Brady (SNL)

History of Deep Borehole Disposal

- **Deep borehole disposal of high-level waste (HLW) has been considered in the US since 1950s**
- **Deep borehole disposal of spent nuclear fuel and HLW has been studied in increasing detail periodically since the 1970s to the present (mostly in paper studies), usually in relation to various pressures**
  - **Disposal of surplus weapons Pu**
  - **Disposal of vitrified or cemented wastes**
  - **Disposal of fuel assemblies (with or without rod consolidation)**
  - **Melting of host rock to encapsulate waste**

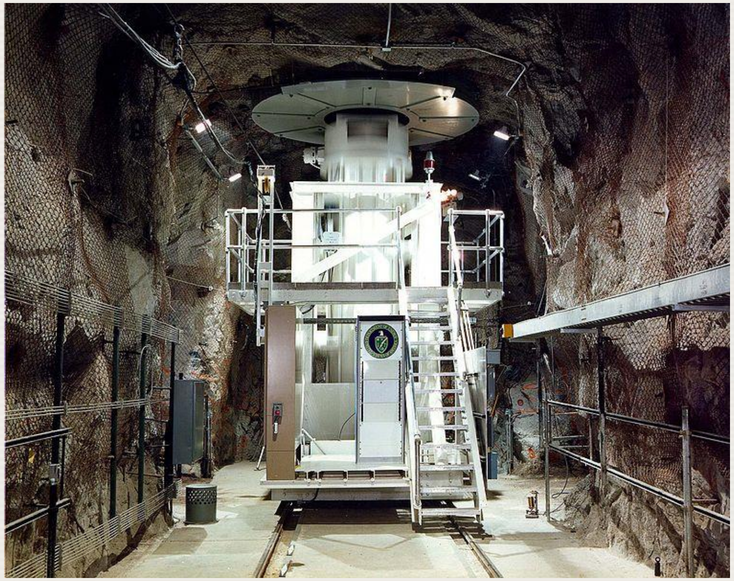

Repository and Deep Borehole Disposition of Plutonium

William G. Halsey

RECEIVED
MAY 1 5 1996
OSTI

This paper was prepared for submittal to the
American Nuclear Society 1995 Annual Meeting
Philadelphia, PA
June 26, 1995

- **Time was not ripe**
  - **Technological risks lower with u/g mining**
  - **Technical capability absent**
- **What has Changed?**
  - **Drilling technology capability has greatly increased**
  - **Experience with mined disposal repositories**
  - **New pressures for disposal**

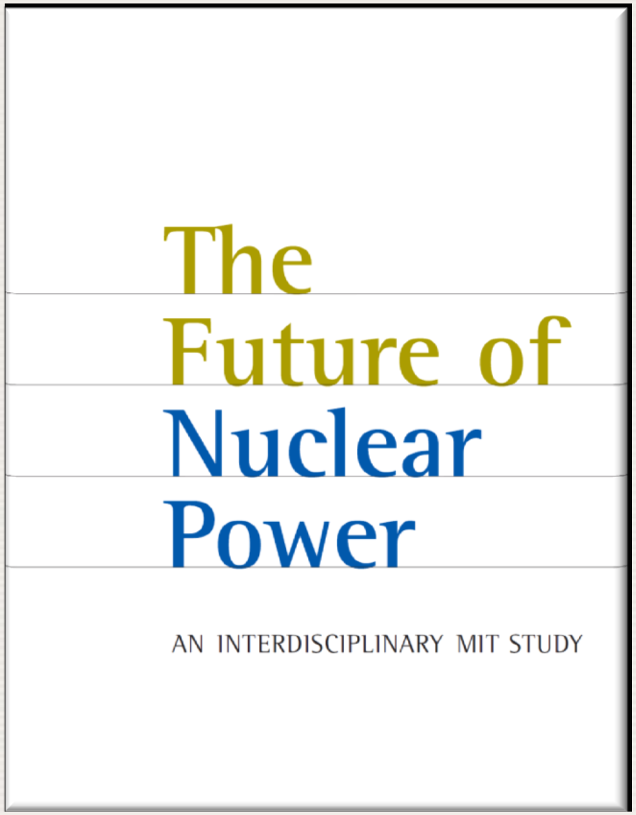


Recent U.S. Developments

MOTIVATIONS FOR A RENEWED CONSIDERATION

Deep Borehole Disposal

MIT July 2003



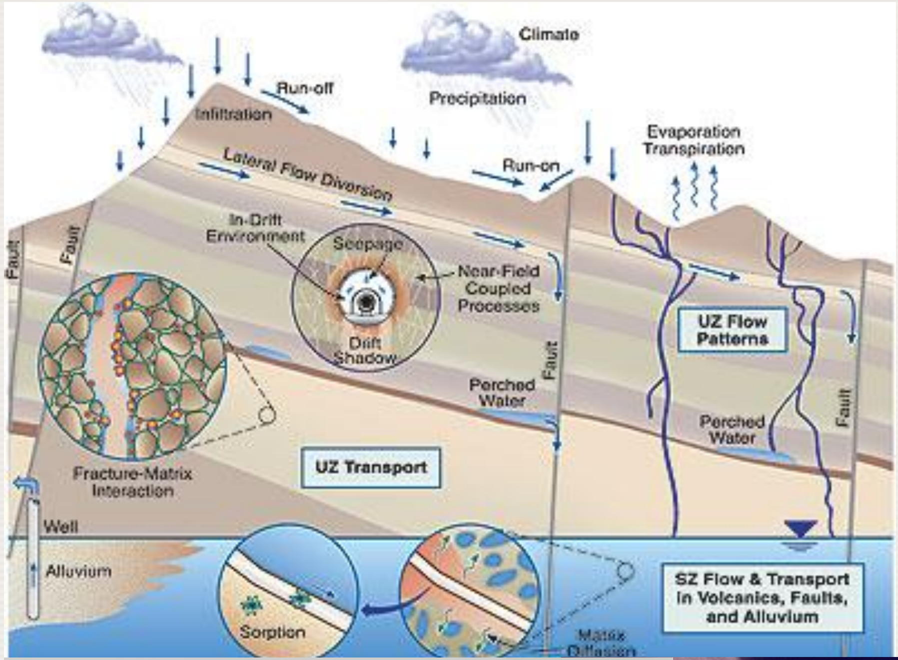
"We further conclude that waste management strategies in the once-through fuel cycle are potentially available that could yield long-term risk reductions at least as great as those claimed for waste partitioning and transmutation, with fewer short-term risks and lower development and deployment costs. *These include both incremental improvements to the current mainstream mined repositories approach and more far-reaching innovations such as deep borehole disposal*. "

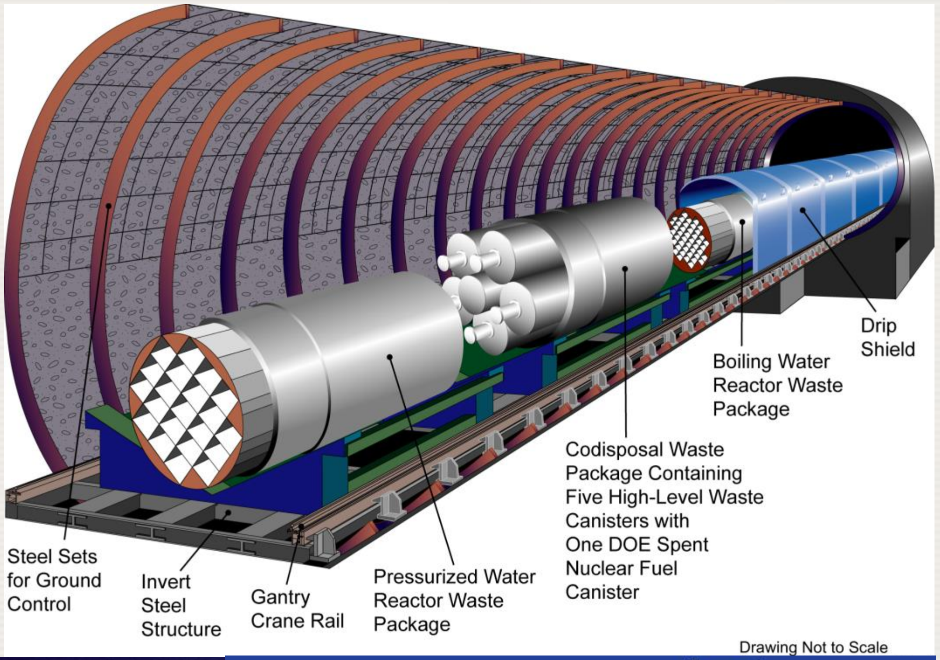
"More attention needs to be given to the characterization of waste forms and engineered barriers, followed by development and testing of engineered barrier systems. *We believe deep boreholes, as an alternative to mined repositories, should be aggressively pursued.* These issues are inherently of international interest in the growth scenario and should be pursed in such a context.

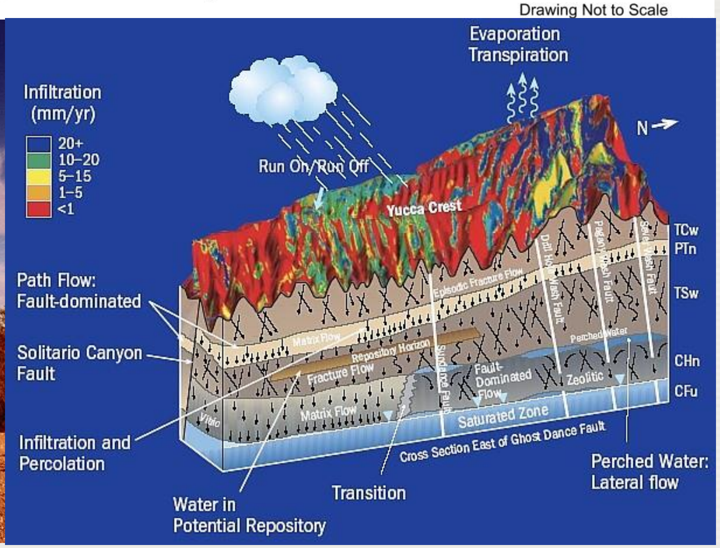
"A research program should be launched to determine the viability of geologic disposal in deep boreholes within a decade. " **(Listed as one of the principle recommendations on waste management – July 2003)**

Professors John Deutch and Ernest Moniz Chaired Effort to Identify Barriers and Solutions for Nuclear Option in Reducing Greenhouse Gases

Perspectives from a Mined Repository

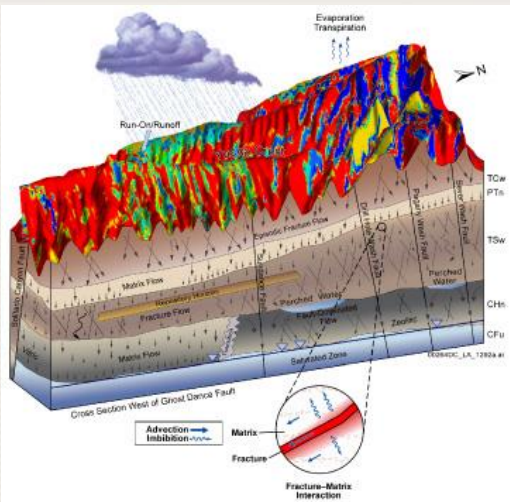


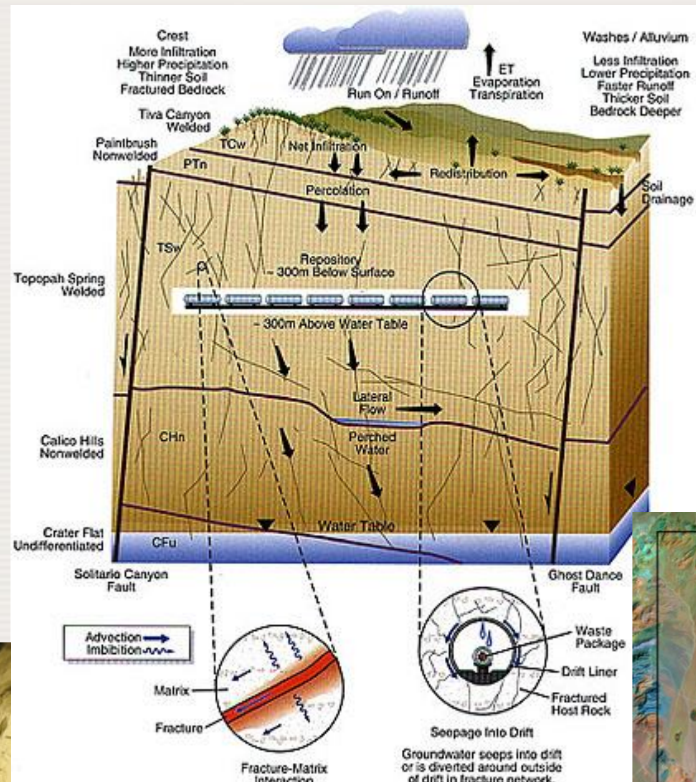


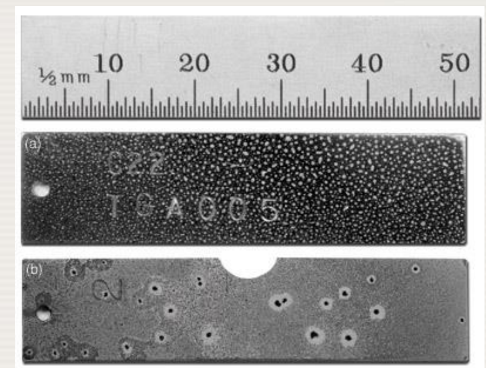


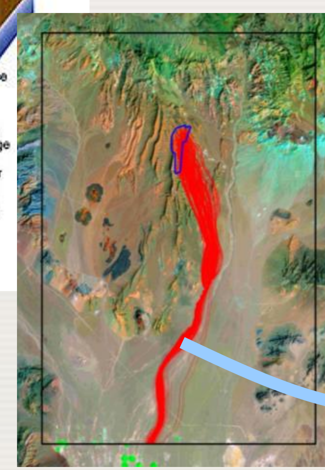
Mined Repositories

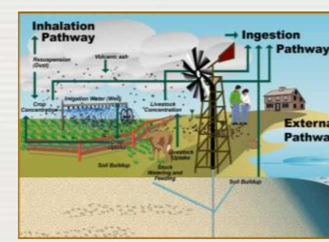
- Coupling between the surface and near-field disposal environment





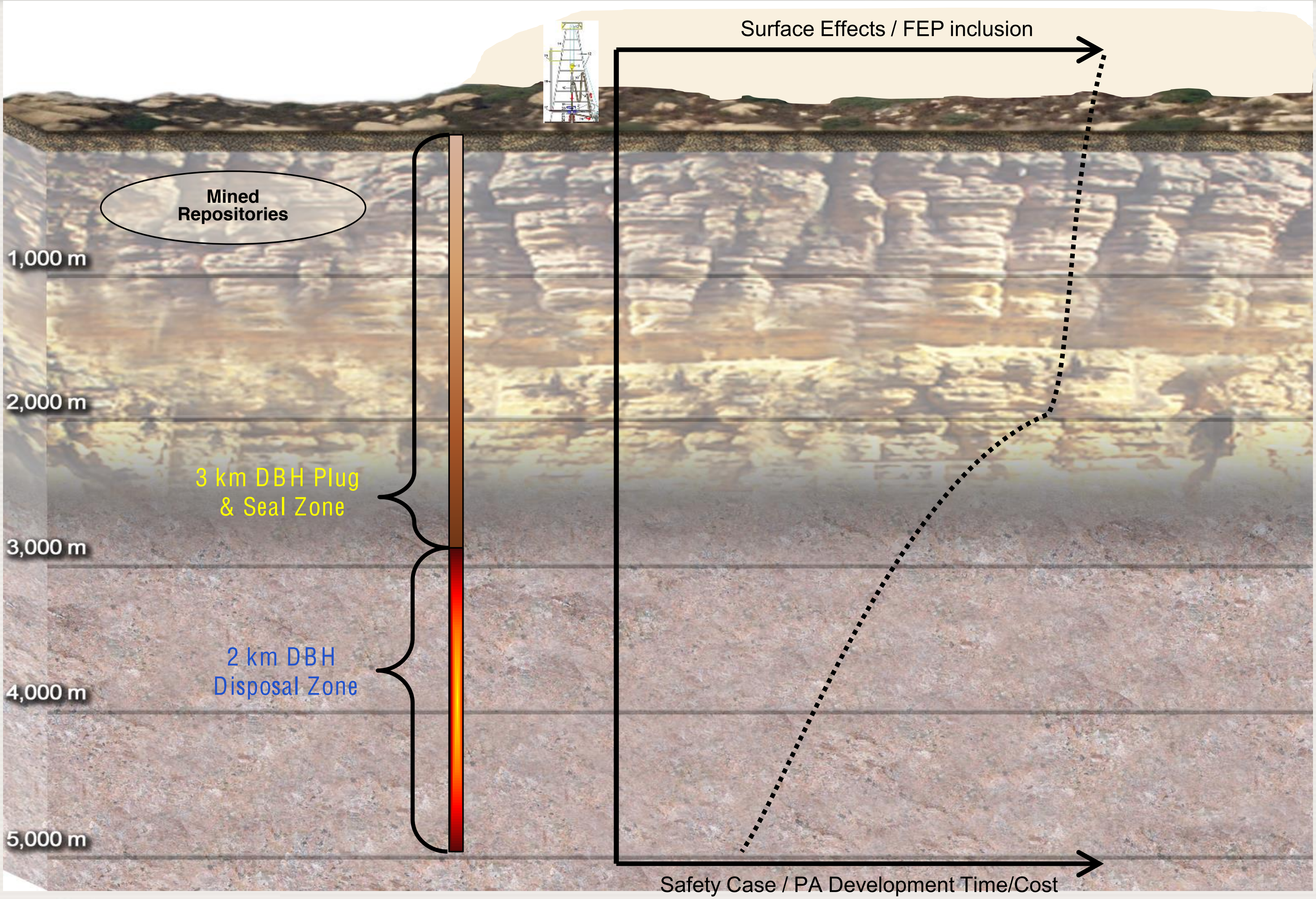






Deep Borehole Disposal Concept

Faster, Cheaper, Better Drivers



Performance Assessment
August 2009

SANDIA REPORT
SAND2009-4401
Unlimited Release
Printed August 2009

Deep Borehole Disposal of High-Level Radioactive Waste

Patrick V. Brady, Bill W. Arnold, Geoff A. Freeze, Peter N. Swift, Stephen J. Bauer, Joseph L. Kanney, Robert P. Rechard, Joshua S. Stein

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

Sandia National Laboratories

Preliminary analysis suggests excellent long-term performance

- Conservative estimate of deep borehole peak dose to a hypothetical human withdrawing groundwater above the disposal hole is
- 1.4 x 10-10 mrem/yr (1.4 x 10-12 mSv/yr)
- YMP standard is 15 mrem/yr (< 10,000 yrs) and 100 mrem/yr (peak dose to 1M yrs)

Source: Brady, P.V., B.W. Arnold, G.A. Freeze, P.N. Swift, S.J. Bauer, J.L. Kanney, R.P. Rechard, J.S. Stein, 2009, *Deep Borehole Disposal of High-Level Radioactive Waste,* SAND2009-4401, Sandia National Laboratories, Albuquerque, NM

Raising Visibility (2/2010)

NUCLEAR ENGINEERING INTERNATIONAL
FEBRUARY 2010
www.neimagazine.com

Into the deep

The lower reaches of a borehole drilled 5km (3mi) into the earth's crust represents an interesting alternative location for high-level radioactive waste compared to mined repositories at much lesser depths. The first deep borehole performance assessment and dose estimate has been carried out. By Bill W. Arnold, Peter N. Swift, Patrick V. Brady, S. Andrew Orrell, and Geoff A. Freeze

The potential technical and cost advantages of deep borehole disposal have become more apparent over time. Drilling technology for petroleum and geothermal production has improved, resulting in lower costs and greater reliability for the construction of deep boreholes. Deep borehole disposal, characterization and excavation costs should scale approximately linearly with waste inventory: small inventories require fewer boreholes; large inventories require more boreholes. Characterization of near-surface geology and hydrology required for deep borehole disposal should be less extensive and costly than for shallower mined repositories because of the greater isolation of waste in deep boreholes. Conditions favourable for deep borehole disposal exist at many locations, particularly on geologically stable continental cratons. A system of regional deep borehole disposal sites could possibly help address waste management equity issues and perhaps transportation concerns.

In 1957 the U.S. National Academy of Sciences Committee on Waste Disposal considered both deep borehole disposal of radioactive waste (in liquid form) and mined storage of radioactive waste in a positive light [1]. The intervening half-century has seen high-level waste and spent nuclear fuel disposal efforts in the United States and other nations focus primarily on mined repositories. Nonetheless, evaluations of the deep borehole disposal concept have periodically continued in several countries (for example, [2-7]).

The deep borehole disposal concept consists of drilling a borehole into crystalline basement rock (typically granite) to a depth of about 5000m, emplacing waste canisters containing spent nuclear fuel or vitrified radioactive waste from reprocessing in the lower 2000m of the borehole, and sealing the upper 3000m of the borehole. The concept is illustrated in Figure 1, showing the borehole disposal depth relative to the typical depth for mined repositories of several hundred meters. Waster in the deep borehole disposal system is several times deeper than for typical mined repositories, resulting in greater natural isolation from the surface and near-surface environment.

The viability and safety of the deep borehole disposal concept are supported by several factors. Crystalline basement rocks are relatively common at depths of 2000 to 5000m in the United States and many other countries, suggesting that numerous appropriate sites exist. Low permeability and high salinity in the deep continental crystalline basement at many locations suggest extremely limited interaction with shallow fresh groundwater resources, which is the most likely pathway for human exposure. The density stratification of groundwater would also oppose thermally induced groundwater convection from the waste to the shallow subsurface, as shown in Figure 1. Geochemically reducing conditions in the deep subsurface limit the solubility and enhance the sorption of many radionuclides in the waste, leading to limited mobility.

Preliminary estimates for deep borehole disposal of the entire projected waste inventory through 2030 from the current U. S. fleet of nuclear reactors suggest a need for a total of about 950 boreholes, with a total cost that could be less than a mined repository disposal system at Yucca Mountain [8].

The legal and regulatory framework governing the disposal of high-level radioactive waste in the U. S. and other countries is oriented toward mined geological disposal and likely would need to be revised to implement deep borehole disposal. In particular, regulations specific to the potential retrieval of waste would need to be modified to reflect the more permanent disposal nature of a deep borehole disposal system. Although retrievability would be maintained during emplacement operations, waste may not be fully

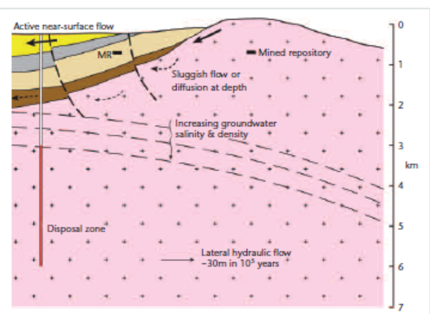


Fig. 1: The general deep borehole concept, drawn schematically as a cross-section through the earth's crust, after Chapman & Gibb [18].

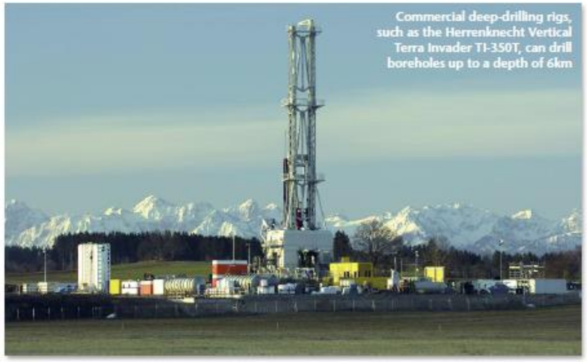
Looking down the bore

*Deep borehole waste disposition research has not progressed to demonstration. **Fergus Gibb** reviews the steps necessary before drilling can begin.*

Historically, reluctance to pursue deep borehole disposition centred on the fact that, while boreholes a few metres in diameter were possible and holes could be drilled to depths in excess of 10 km, the combination of a hole several tens of cm in diameter to a depth of 4 km or more has never been attempted (largely because the hydrocarbon, geothermal energy and other industries have had no need for it.) This gave rise to allegations of "immature technology" and concerns that to develop the necessary capability could take many years and prove prohibitively expensive or even impossible.

In 2000 SKB commissioned a feasibility study [14] into drilling the boreholes required for their VDH concept. The original well design was modified to give a deployment zone diameter of 0.83m with a 0.76m outer diameter casing, using steel for the containers and casing instead of titanium. In addition to well design, this report also gave engineering details of canister design, emplacement technology and retrieval mechanisms. It was concluded that it was possible to drill the borehole with the-then existing technology but that it represented one of the biggest challenges to the drilling industry. It was estimated that it would take around 137 days to drill the hole and it would cost around EUR4.65 ($6.8) million.

The most recent and comprehensive study of the status of drilling technology for DBD was carried out for the NDA in 2008 [17]. It was concluded that in an appropriate geology such as granite, a borehole with a clear, useable diameter of 0.5m, drilled and cased to a depth of 4km, is perfectly practicable using existing technology with some development of tools and systems. Larger holes, diameter up to 0.75m, would be difficult to implement beyond 3km, while 1.0m holes are considered impractical at the present time. Among the other outcomes of this study were that it would take around nine months to drill and case a 4km deep, 0.5m borehole and between 6 months and 2 years to emplace the waste packages, depending on size, number and method used. The first such borehole would require a lead-in time of two years and cost about GBP20 ($32) million, although savings on subsequent holes, especially on the same site, could approach 50%.



Commercial deep-drilling rigs, such as the Herrenknecht Vertical Terra Invader TI-350T, can drill boreholes up to a depth of 6km

The maximum size and depth of practical boreholes restricts the types of wastes for which DBD would be appropriate to those with small to moderate volumes, mainly high-level wastes, including spent fuel. A kilometre of 0.5m borehole can dispose of approximately $200m^3$ of packaged waste or 690 vitrified HLW containers.

THEORETICAL STUDIES

A criticality analysis will be important for concepts in which large amounts of potentially fissile material are disposed of, such as LTVDD-2 [see p17], in which spent fuel pins are closely packed in the containers. Taking this as an example, the first stage to consider is when water gains access to the container, and might form thin films between the fuel pins and the enclosing lead. However under these conditions there is no possibility of criticality. At the other extreme is the post-closure situation when the container has failed completely and aqueous fluids have leached out most of the lead matrix around the fuel pins.

Notwithstanding the facts that fluid flow rates at the depths in question are too low for this to happen and that there are no foreseeable hydrogeochemical processes that could bring it about, this would effectively leave the pins surrounded by water. Such a situation would be analogous to the consolidated storage of used fuel pins in metal boxes in ponds – where again there is no question of criticality arising. Nevertheless, a full criticality analysis of the disposal that takes account of predictable changes in the isotopic composition of the spent fuel over long periods must be undertaken.

Then, after this criticality analysis, and following a successful performance assessment [see p18], the next step would require practical tests.

DEMONSTRATION

Demonstration, testing and development of several of the necessary technologies require a full sized (0.5m inner diameter) cased borehole, but one that is shortened to a depth of a few hundred metres. The only other constraints are that it be in granitic host rock and that its bottom end should be readily accessible from pre-

Blue Ribbon Commission

January 2010- January 2012

- DBD mentioned in first open meeting opening remarks March 2010

The Blue Ribbon Commission on America's Nuclear Future (BRC) was formed by the Secretary of Energy at the request of the President to conduct a comprehensive review of policies for managing the back end of the nuclear fuel cycle and recommend a new strategy. It was co-chaired by Rep. Lee H. Hamilton and Gen. Brent Scowcroft. Other Commissioners are Mr. Mark H. Ayers, the Hon. Vicky A. Bailey, Dr. Albert Carnesale, Sen. Pete Domenici, Ms. Susan Eisenhower, Sen. Chuck Hagel, Mr. Jonathan Lash, Dr. Allison M. Macfarlane, Dr. Richard A. Meserve, Dr. Ernest J. Moniz, Dr. Per Peterson, Mr. John Rowe, and Rep. Phil Sharp.

The Commission and its subcommittees met more than two dozen times between March 2010 and January 2012 to hear testimony from experts and stakeholders, to visit nuclear waste management facilities in the United States and abroad, and to discuss the issues identified in its Charter. Additionally, in September and October 2011, the Commission held five public meetings, in different regions of the country, to hear feedback on its draft

- Note participants subsequent career positions

Nuclear Waste Technical Review Board Meeting
Las Vegas, NV - February 16, 2011

- "The Board certainly agrees with your conclusions on the technical aspects of deep borehole disposal and it appears that it is time to plan to move forward with a common vision for the technology."

- "It is time for detail implementation plans to be developed that include drilling, design of infrastructure and facilities to handle waste, and demonstrations with surrogate material; paper study of this disposal option is relatively complete."

UNITED STATES
NUCLEAR WASTE TECHNICAL REVIEW BOARD
2300 Clarendon Boulevard, Suite 1300
Arlington, VA 22201-3367

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By [illegible]

March 1, 2011

S. Andrew Orrell
Sandia National Laboratories
P.O. Box 5800, MS-0771
Albuquerque, New Mexico 87185

Dear Andrew:

Thank you very much for your participation at the February 16, 2011, meeting of the Nuclear Waste Technical Review Board meeting in Las Vegas. Your participation in helping put this meeting together when time was short is duly noted by all of us. The Board certainly agrees with your conclusions on the technical aspects of deep borehole disposal and it appears that it is time to plan to move forward with a common vision for the technology. It is time for detail implementation plans to be developed that include drilling, design of infrastructure and facilities to handle waste, and demonstrations with surrogate material; paper study of this disposal option is relatively complete.

Once again, thanks for your participation and help.

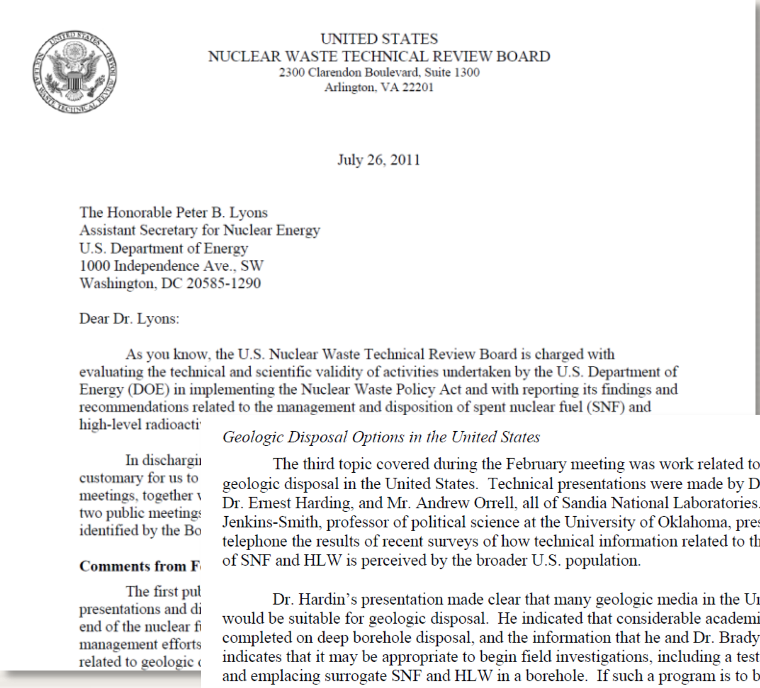
Sincerely,

B. John Garrick
Chairman

Telephone: 703-235-4473 Fax: 703-235-4495

NWTRB Letter to Assistant Secretary for Nuclear Energy, July 2011

- To follow-up on the presentations at the February meeting, the Board would like to know more about the progress being made regarding borehole disposal and other geologic-specific disposal programs that are under consideration. We are planning to make this a central part of the Board meeting we are planning for the spring of 2012 and will be contacting you or your staff regarding this in the near future. In this regard, we are particularly interested in work directed at optimizing the characteristics of the waste forms intended for disposal in specific geologic media.



UNITED STATES
NUCLEAR WASTE TECHNICAL REVIEW BOARD
2300 Clarendon Boulevard, Suite 1300
Arlington, VA 22201

July 26, 2011

The Honorable Peter B. Lyons
Assistant Secretary for Nuclear Energy
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585-1290

Dear Dr. Lyons:

As you know, the U.S. Nuclear Waste Technical Review Board is charged with evaluating the technical and scientific validity of activities undertaken by the U.S. Department of Energy (DOE) in implementing the Nuclear Waste Policy Act and with reporting its findings and recommendations related to the management and disposition of spent nuclear fuel (SNF) and high-level radioacti

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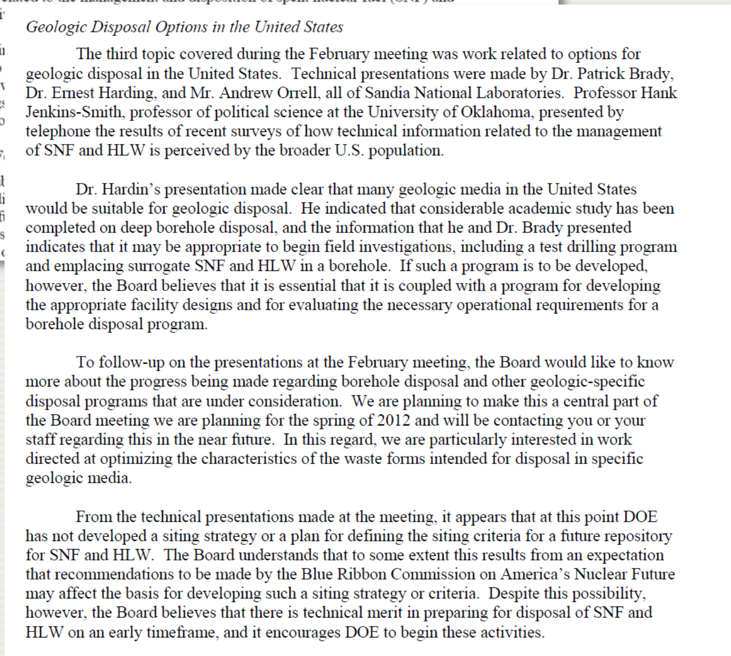

Geologic Disposal Options in the United States

The third topic covered during the February meeting was work related to options for geologic disposal in the United States. Technical presentations were made by Dr. Patrick Brady, Dr. Ernest Harding, and Mr. Andrew Orrell, all of Sandia National Laboratories. Professor Hank Jenkins-Smith, professor of political science at the University of Oklahoma, presented by telephone the results of recent surveys of how technical information related to the management of SNF and HLW is perceived by the broader U.S. population.

Dr. Hardin's presentation made clear that many geologic media in the United States would be suitable for geologic disposal. He indicated that considerable academic study has been completed on deep borehole disposal, and the information that he and Dr. Brady presented indicates that it may be appropriate to begin field investigations, including a test drilling program and emplacing surrogate SNF and HLW in a borehole. If such a program is to be developed, however, the Board believes that it is essential that it is coupled with a program for developing the appropriate facility designs and for evaluating the necessary operational requirements for a borehole disposal program.

To follow-up on the presentations at the February meeting, the Board would like to know more about the progress being made regarding borehole disposal and other geologic-specific disposal programs that are under consideration. We are planning to make this a central part of the Board meeting we are planning for the spring of 2012 and will be contacting you or your staff regarding this in the near future. In this regard, we are particularly interested in work directed at optimizing the characteristics of the waste forms intended for disposal in specific geologic media.

From the technical presentations made at the meeting, it appears that at this point DOE has not developed a siting strategy or a plan for defining the siting criteria for a future repository for SNF and HLW. The Board understands that to some extent this results from an expectation that recommendations to be made by the Blue Ribbon Commission on America's Nuclear Future may affect the basis for developing such a siting strategy or criteria. Despite this possibility, however, the Board believes that there is technical merit in preparing for disposal of SNF and HLW on an early timeframe, and it encourages DOE to begin these activities.

Sandia Progress

Workshop: Pilot Testing Deep Borehole Disposal of Nuclear Waste, October 2011

SANDIA REPORT
SAND2011-6749
Unlimited Release
Printed October 2011

Reference Design and Operations for Deep Borehole Disposal of High-Level Radioactive Waste

Bill W. Arnold, Patrick V. Brady, Stephen J. Bauer, Courtney Herrick, Stephen Pye, and John Finger

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Approved for public release; further dissemination unlimited.

Sandia National Laboratories

In October, 2011 Sandia brought together twenty representatives from the fields of radioactive waste disposal and drilling to:

- review the state of deep borehole science and engineering;
- identify the necessary features of a deep borehole pilot demonstration; and,
- consider organizational approaches to implementing a deep borehole pilot.

Blue Ribbon Commission on America's Nuclear Future
Report to the Secretary of Energy, January 2012

- "In its deliberations, the Commission focused chiefly on two deep geologic disposal options: disposal in a mined geological formation and disposal in deep boreholes. The former has been the front-running disposal strategy in the United States for more than 50 years; it is also the approach being taken in other countries with spent fuel or HLW disposal programs. By contrast, disposal in deep boreholes may hold promise but this option is less well understood and the development of an appropriate safety standard, along with further RD&D is needed to fully assess its potential advantages and disadvantages.
- A number of possible advantages have been cited that support further efforts to investigate the deep borehole option. These include the potential to achieve (compared to mined geologic repositories) reduced mobility of radionuclides and greater isolation of waste, greater tolerance for waste heat generation, modularity and flexibility in terms of expanding disposal capacity, and compatibility with a larger number and variety of possible sites. On the other hand, deep boreholes may also have some disadvantages in terms of the difficulty and cost of retrieving waste (if retrievability is desired) after a borehole is sealed, relatively high costs per volume of waste capacity, and constraints on the form or packaging of the waste to be emplaced.

Blue Ribbon Commission on America's Nuclear Future

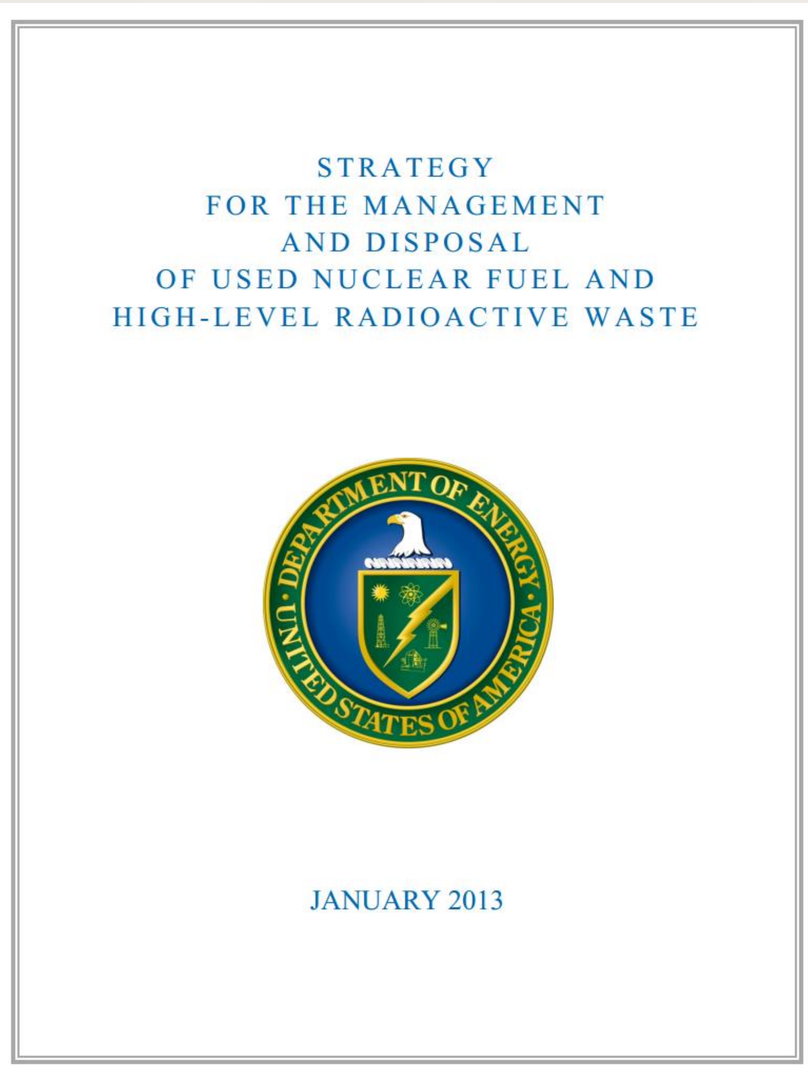
U. S. Department of Energy

Blue Ribbon Commission on America's Nuclear Future
Report to the Secretary of Energy, January 2012

- Overall, the Commission recommends further RD&D to help resolve some of the current uncertainties about deep borehole disposal and to allow for a more comprehensive (and conclusive) evaluation of the potential practicality of licensing and deploying this approach, particularly as a disposal alternative for certain forms of waste that have essentially no potential for re-use.
- 9.3 Recommendations for Developing Future Disposal Facility Standards—
  - *7. EPA and NRC should also develop a regulatory framework and standards for deep borehole disposal facilities (p. 105).*
  - The Commission has identified deep boreholes as a potentially promising technology for geologic disposal that could increase the flexibility of the overall waste management system and therefore merits further research, development, and demonstration. While a regulatory framework and safety standards for deep boreholes would have much in common with those for mined geologic repositories, the technologies also have key differences. For this reason the Commission recommends that EPA and NRC develop a regulatory framework and safety standard for deep boreholes as a way to support further RD&D efforts aimed at developing a licensed demonstration project (*though we also note that this effort should not detract in any way from the expeditious development of revised generic regulations for mined geologic repositories).*

- 12. Near Term Actions
  - Disposal
    - DOE should develop an RD&D plan and roadmap for taking the borehole disposal concept to the point of a licensed demonstration (p. 134).
  - Regulatory Actions
    - The Administration should identify an agency to take the lead in defining an appropriate process (with opportunity for public input) for developing a generic safety standard for geologic disposal sites. The same lead agency should coordinate the implementation of this standard-setting process with the aim of developing draft regulations for mined repositories and deep borehole facilities (p. 135).

Administration Response to BRC January 2013


STRATEGY
FOR THE MANAGEMENT
AND DISPOSAL
OF USED NUCLEAR FUEL AND
HIGH-LEVEL RADIOACTIVE WASTE

JANUARY 2013

"The ability to retrieve used nuclear fuel and high-level radioactive waste from a geologic repository for safety purposes or future reuse has been a subject of repository design debate for many years. A recently completed technical review by Oak Ridge National Laboratory found that approximately 98 percent of the total current inventory of commercial used nuclear fuel by mass can proceed to permanent disposal without the need to ensure post-closure recovery for reuse based on consideration of the viability of economic recovery of nuclear materials, research and development (R&D) needs, time frames in which recycling might be deployed, the wide diversity of types of used nuclear fuel from past operations, and possible uses to support national security interests. This assessment does not preclude any decision about future fuel cycle options, but does indicate that retrievability it is not necessary for purposes of future reuse."

- **this is open recognition of support for direct disposal AND no need for retrievability for reuse**

"In FY 2013, the Department is undertaking disposal-related research and development work in the following areas: an evaluation of whether direct disposal of existing storage containers used at utility sites can be accomplished in various geologic media; an evaluation of various types and design features of back-filled engineered barriers systems and materials; evaluating geologic media for their impacts on waste isolation; evaluating thermal management options for various geologic media; establishing cooperative agreements with international programs; and developing a research and development plan for deep borehole disposal, consistent with BRC recommendations."

- **explicit recognition of deep borehole development as on the R&D agenda**

October 2014

Other countries have also begun to explore DBD: Germany, China, Korea, Ukraine…

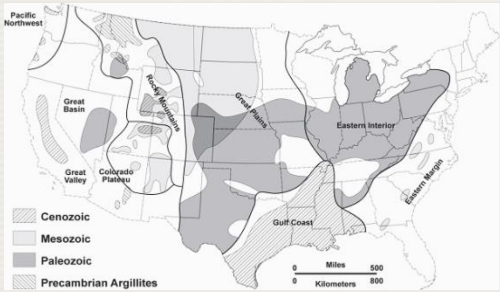
Final Thoughts

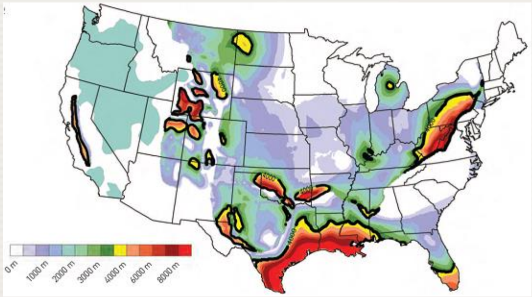
CAN DBD BE ‘FASTER, CHEAPER, BETTER’?

Potential Repository Host Rocks

Property	Salt	Shale	Granite	Deep boreholes
Thermal conductivity	High	Low	Medium	Medium
Permeability	Practically impermeable	Very low to low	Very low (unfractured) to permeable (fractured)	Very low
Strength	Medium	Low to medium	High	High
Deformation behavior	Visco-plastic (creep)	Plastic to brittle	Brittle	Brittle
Stability of cavities	Self-supporting on decade scale	Artificial reinforcement required	High (unfractured) to low (highly fractured)	Medium at great depth
In situ stress	Isotropic	Anisotropic	Anisotropic	Anisotropic
Dissolution behavior	High	Very low	Very low	Very low
Sorption behavior	Very low	Very high	Medium to high	Medium to high
Chemical	Reducing	Reducing	Reducing	Reducing
Heat resistance	High	Low	High	High
Mining experience	High	Low	High	Low
Available geology*	Wide	Wide	Medium	Wide
Geologic stability	High	High	High	High
Engineered barriers	Minimal	Minimal	Needed	Minimal

Favorable property | Average | Unfavorable property

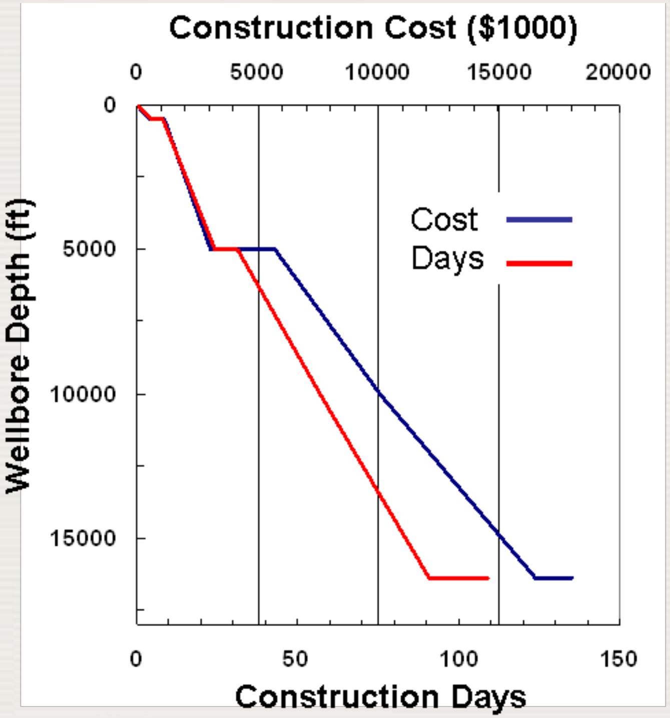




Feasibility

Note: All costs are in 2011 $US and approximately for 2011 expenses.	**Cost per Borehole**
Drilling, Casing, and Borehole Completion	$27,296,587
Waste Canisters and Loading	$7,629,600
Waste Canister Emplacement	$2,775,000
Borehole Sealing	$2,450,146
Total	**$40,151,333**

from Arnold et al. (2011)



- Faster
  - estimated time for drilling, borehole completion, waste emplacement, and sealing is about 186 days (not decades)
- Cheaper
  - low initial costs
  - low investment risk
  - scaled costs
  - estimated disposal costs are $158/kg heavy metal (compared to nuclear waste fund fee of roughly $400/kg, Gibbs, 2010)
- Better
  - extremely low peak dose assessments

Source: Polsky, Y., L. Capuano, et al. (2008). *Enhanced Geothermal Systems (EGS) Well Construction Technology Evaluation Report,* SAND2008-7866, Sandia National Laboratories, Albuquerque, NM

However…

- Like ‘paper reactors*’ the same should be said of ‘paper repositories’; things always look good on paper.
    - Thus, the desire to implement a field-scale demonstration

- The point is <u>not</u> that Deep Borehole Disposal is the best or only solution for geologic disposal.

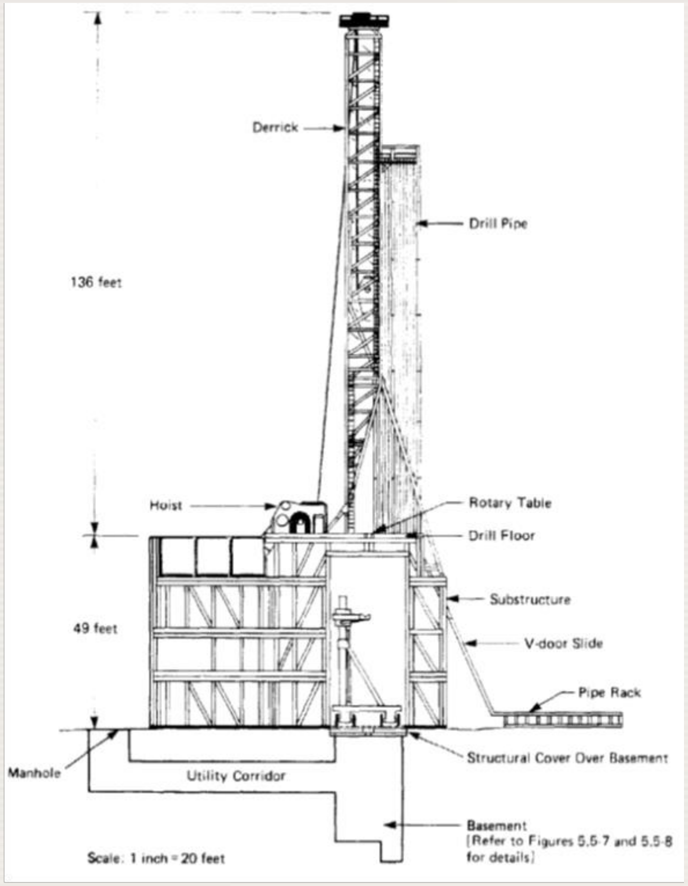
- The point is the concept holds such significant promise that it warrants consideration of an effort to accelerate its pilot demonstration, and to vet its true feasibility and viability.

- The concept has merit for programs with both large and small waste burdens; it may be worth considering a multinational collaborative effort.

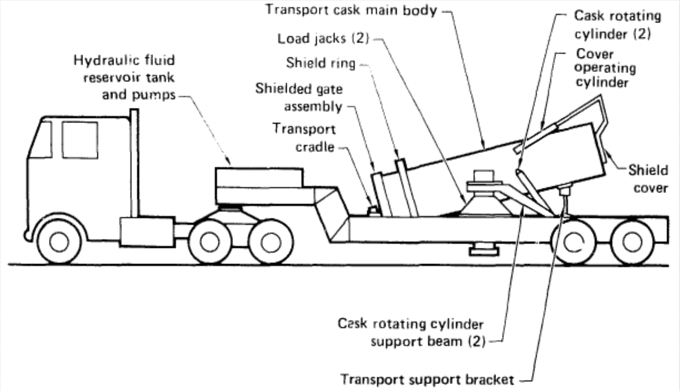
* Admiral H.G. Rickover, "Paper Reactors, Real Reactors" (5 June 1953)

Thank You

- Sit down before fact with an open mind. Be prepared to give up every preconceived notion. Follow humbly wherever and to whatever abyss Nature leads or you learn nothing. Don't push out figures when facts are going in the opposite direction. (Admiral Rickover)



from Woodward-Clyde Consultants (1983)



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

Nirex Report

A Review of the Deep Borehole Disposal Concept for Radioactive Waste

nirex

Nirex Report N/108

A Review of the Deep Borehole Disposal Concept for Radioactive Waste

June 2004

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

Conditions of Publication

ISBN 1 84029 353 5

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ABSTRACT

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

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

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

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

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

EXECUTIVE SUMMARY

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

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

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

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

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

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

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

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

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

LIST OF CONTENTS

1 INTRODUCTION

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

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

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

2 DEVELOPMENT OF THE CONCEPT

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

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

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

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

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

---

[1] This is synonymous with [6].

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

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

Five questions were posed:

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

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

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

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

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

---

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

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

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

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

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

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

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

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

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

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

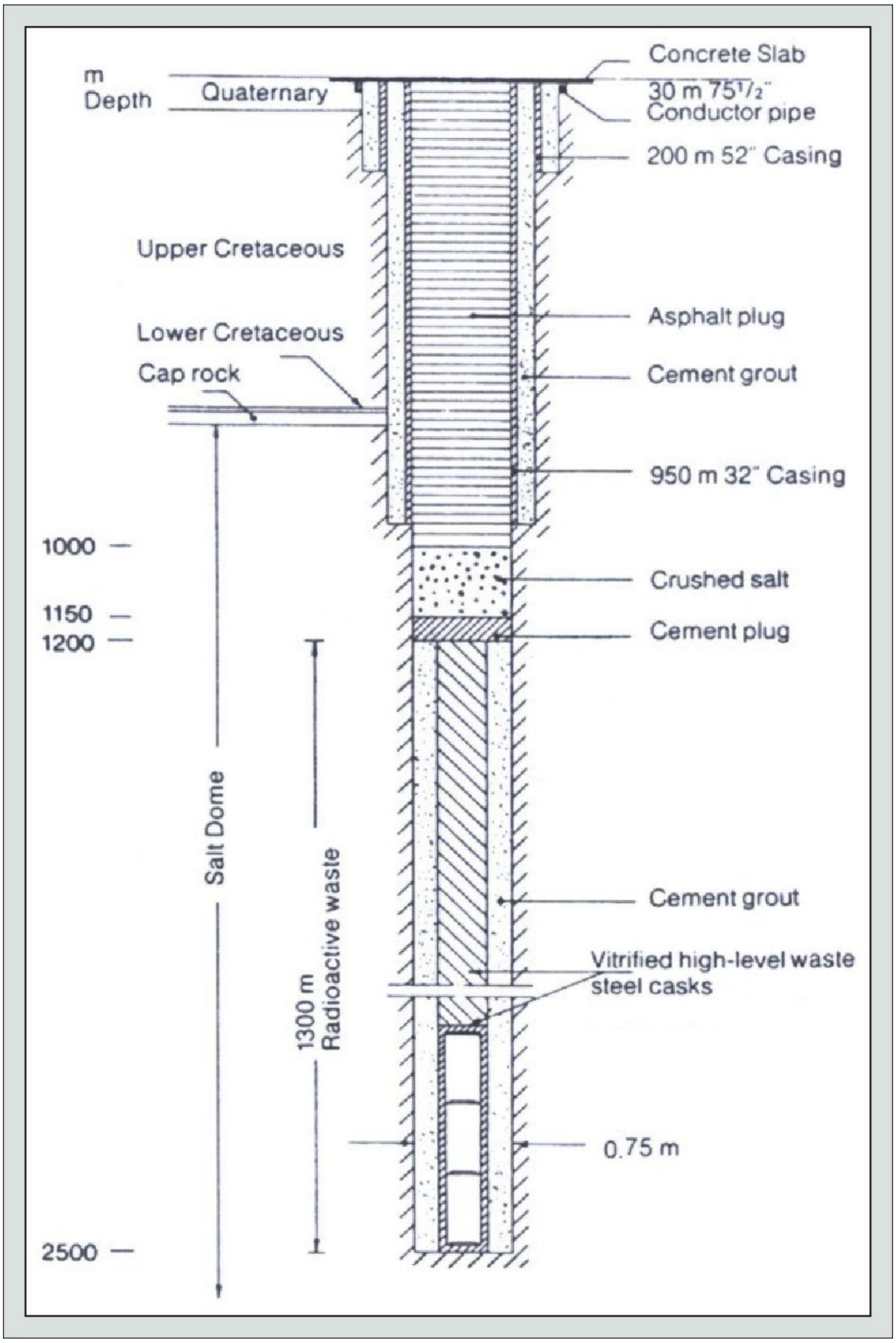
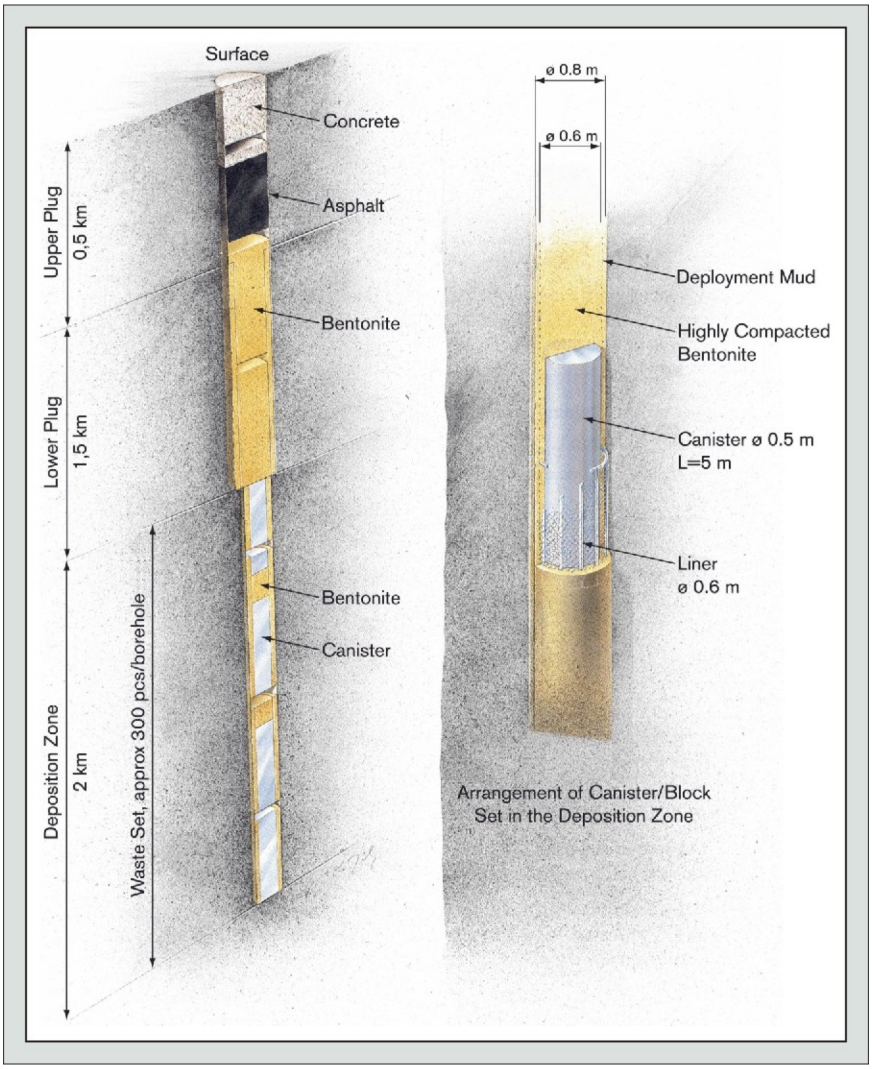


Figure 2 The deep borehole disposal concept, as presented by SKB in their PASS Project [11].



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

3 REVIEW OF DEEP BOREHOLE CONCEPTS

3.1 Early disposal concepts

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

3.1.1 Early work in the USA

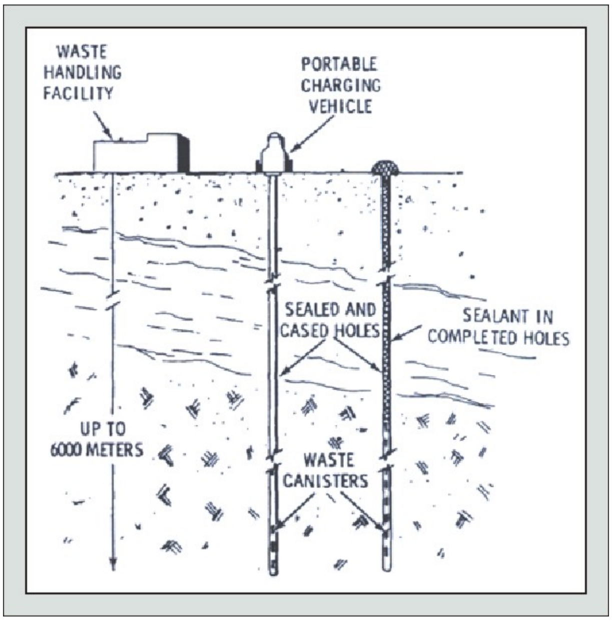
Information on the disposal concepts considered in the USA is presented in [2] and subsequent to that in reports such as [4], and much of the work was carried out by contractors to USDOE who also published their work in reports such as [3]. The deep borehole concept was compared with the other concepts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

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

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

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

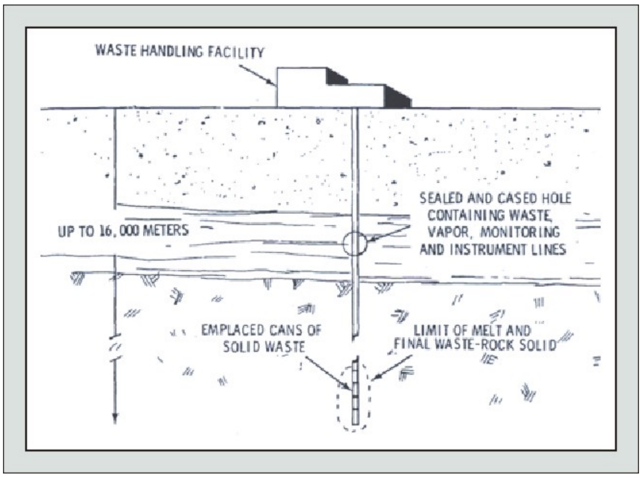
Figure 3 Disposal concept referred to as: Solid waste emplacement in a matrix of drilled holes – no melting (from Schneider & Platt [2]).



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

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

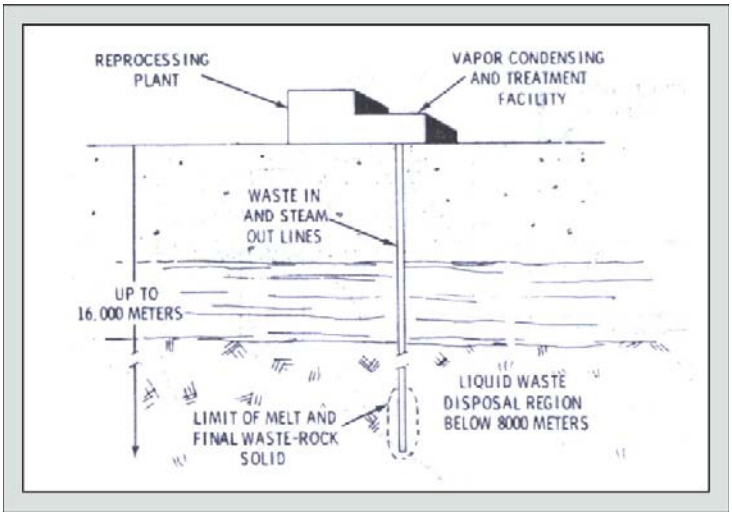
Figure 4 Disposal concept referred to as: Solid waste emplacement in a deep hole with in-place conversion to a rock-waste matrix (from Schneider & Platt [2]).



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

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

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



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

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

3.1.2 Later work in the USA

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

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

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

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

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

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

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

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

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

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

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

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

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

Technology had to be available by 2000.

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

Slow moving groundwater and very long flowpaths at depth.

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

Isolation of the radionuclides from the biosphere.

Minimal thermal impact.

Potential applications to a diverse range of geological environments.

Limited work force and equipment at the surface.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

A requirement for the deep borehole concept to contain the waste within the repository zone during the period when radiation and thermal output are dominated by fission produce decay.

A requirement for a minimum depth for the deep borehole concept, so that containment could be defined within the repository zone for a sufficient period, in comparison with the mined repository concept where containment is achieved by the waste canister, (this also required that the geometry of the repository zone would need to be defined).

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

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

For the case of HLW, 850 canisters would be equivalent to 1785 MTHM and 38 such boreholes would be required.

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

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

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

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

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

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

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

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

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

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

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

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

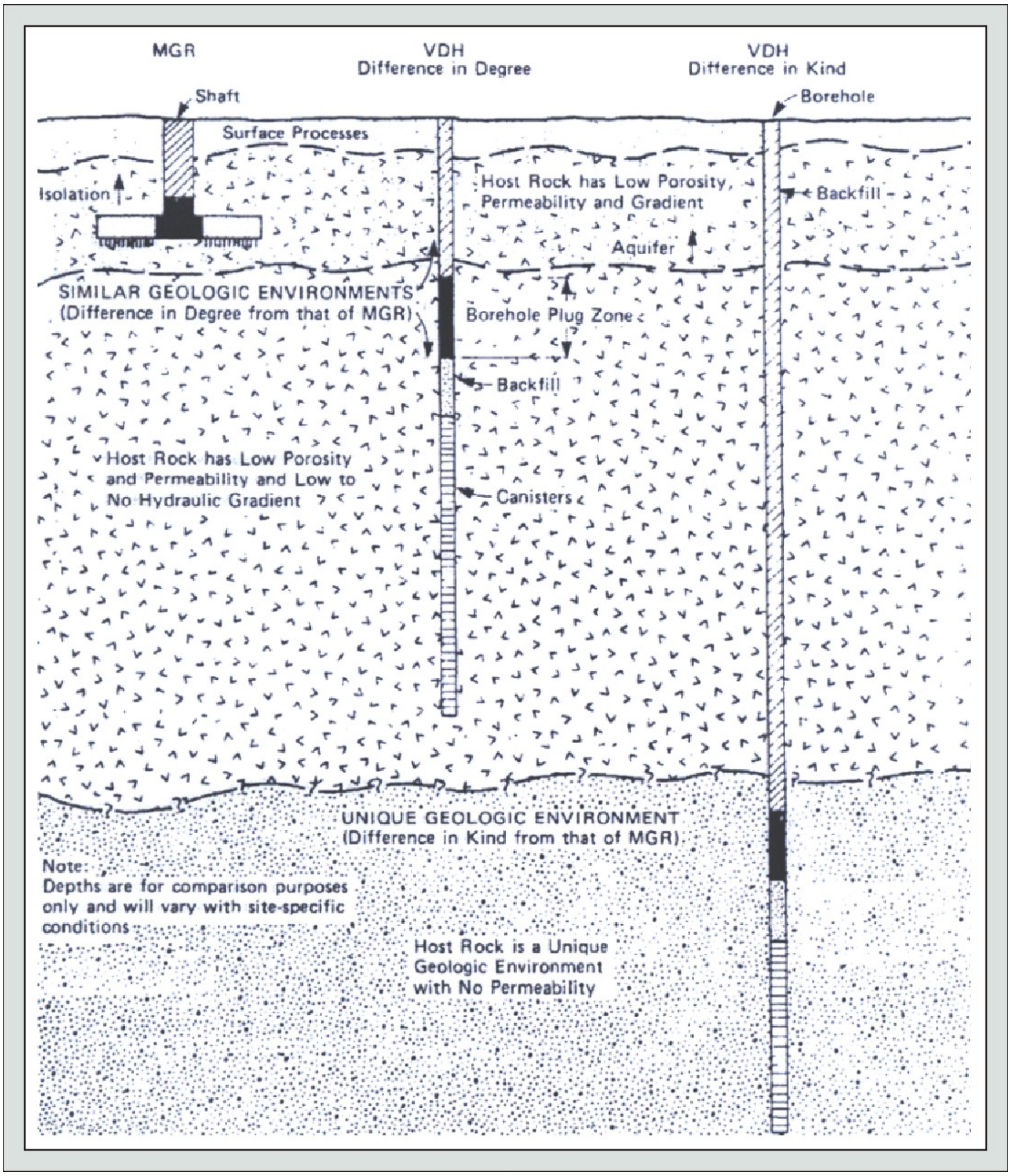


**Figure 7	Schematic of reference borehole design for deep borehole disposal concept (from ONWI [5]). The *repository zone*, which includes the containment plug, begins at 6200 ft (1880 m approx.) depth and the *disposal* or *emplacement zone* at 10,000 ft (3 km approx.) depth.**

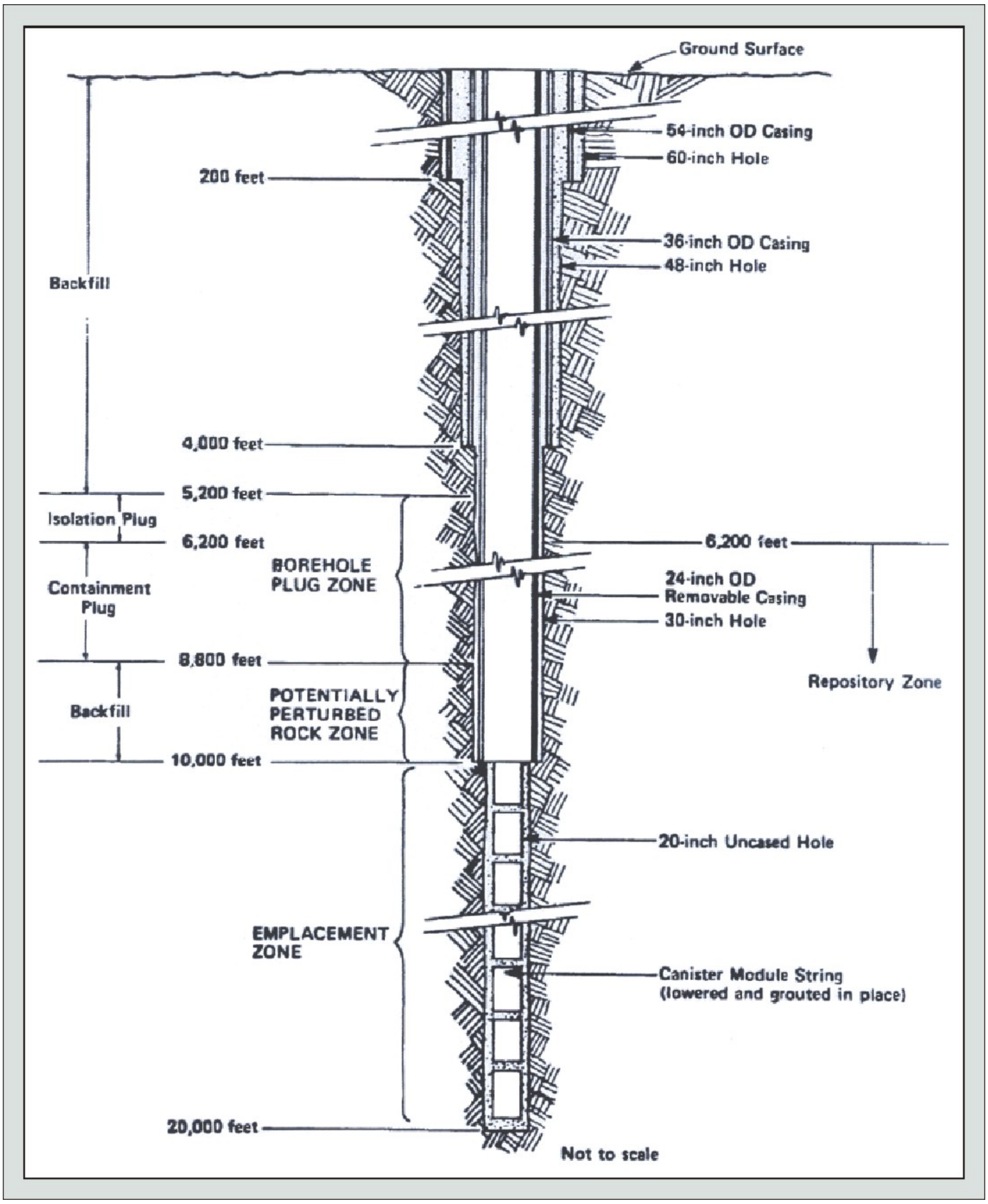


Figure 8 Borehole wall temperature increase against time for HLW disposed in deep borehole [5]. The expected ambient temperature in the disposal zone is likely to lie in the range 85 - 160°C (assuming a geothermal gradient of 25 °C km^{-1}), so that the actual maximum temperature could lie in the range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

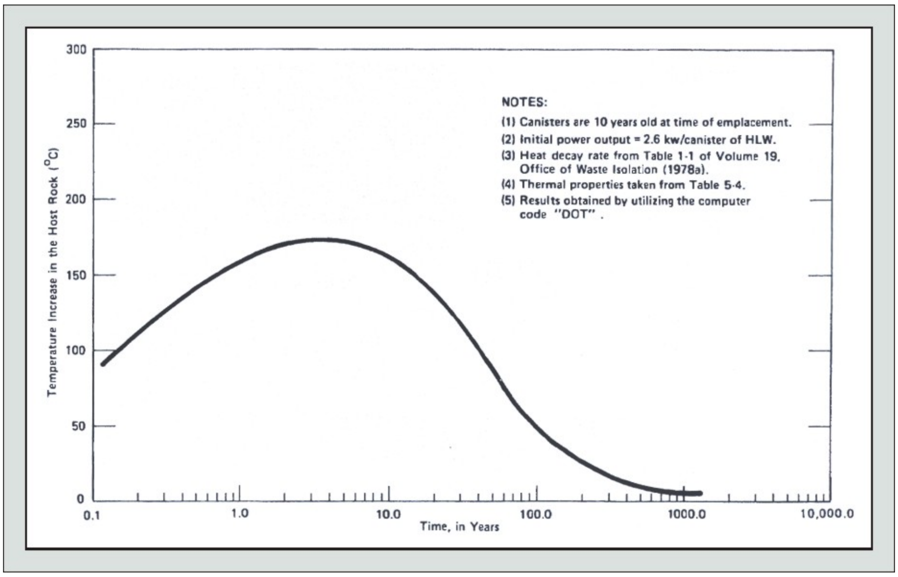
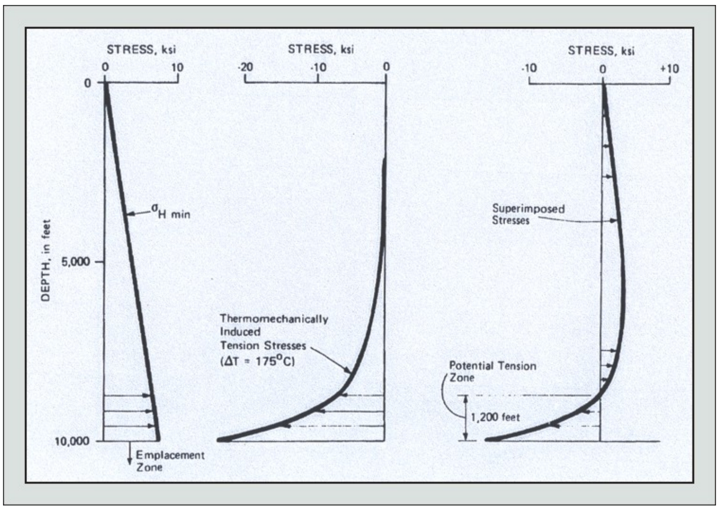


Figure 9 Thermomechanical stresses induced by the emplacement of HLW in a deep borehole over the depth range below 10,000 ft (3 km). The minimum horizontal *in situ* stress ($\sigma_{h\ min}$) is assumed to equal 0.67σ_v, thermally-induced tensional stresses (in units of ksi) are shown developed above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



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

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

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

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

Cement grout.

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

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

3.1.3 Early work by Nagra

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

The remit given to Forex Neptune was to assume that:

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

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

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

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

Nine boreholes would be required.

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

3.1.4 Early work in Denmark

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

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

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

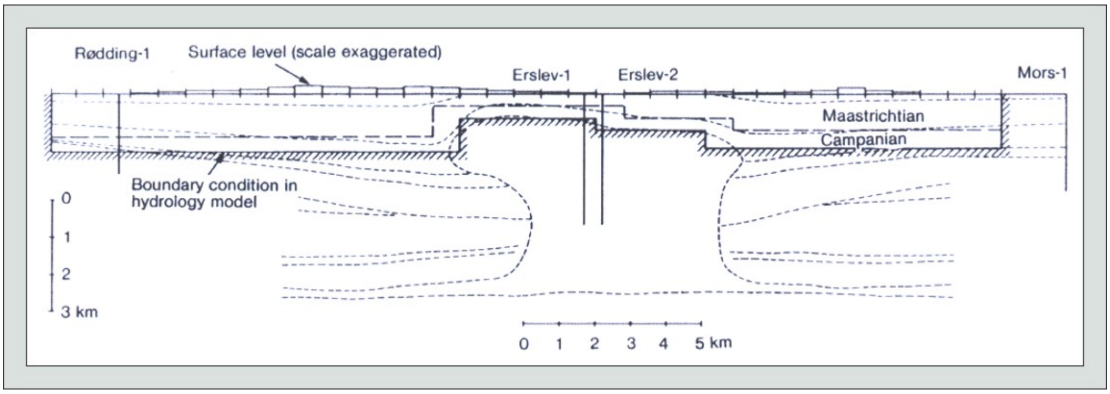
In this design 645 sets of three vitrified waste containers in steel overpacks would be placed in each borehole between 2500 and 1200 m depth. The boreholes would contain saturated brine during their emplacement, but the annular space between canister and the borehole wall would be sealed by pumping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

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

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

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

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



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

4 MORE RECENT DISPOSAL CONCEPTS

4.1 The SKB PASS Project

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

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

4.1.1 The Gravberg-1 borehole [10]

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

> The boreholes should be 5-6 km deep with a disposal zone from 2-3 km depth.
>
> The borehole diameter should be in the range of 300-375 mm at the bottom of the hole.
>
> For reasons of both operational and long-term safety, the boreholes should be cased from top to bottom during emplacement of the waste (i.e. so that the boreholes remained stable and so that there would be fewer problems associated with waste emplacement).

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

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

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

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

The variability of the crystalline rocks in these boreholes.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

P = Fluid pressure (% above hydrostatic)

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

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

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

Below about 1000 m the rock is less fractured and its seismic velocity is dependent mainly upon its composition.

Fracture zones will be present at all depths and have considerably lower (seismic) velocities and may have significantly higher permeabilities than the surrounding rock. These fracture zones may contain different groundwater systems that are not in good hydrogeological contact with one another.

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

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

The siting of a deep borehole disposal site is likely to be based on surface geophysical investigations, with a small number of deep boreholes.

In comparison with investigations at shallower depths, deep boreholes will be more dependent on geophysical borehole logging. For studies of, for example, fracture density and orientation at great depth *in situ* measurements would be preferable to core logging. Stress release, core losses and drilling-induced fractures would make any interpretation based on core logging rather uncertain.

Recent advances in wireline logging, as well as in borehole seismic techniques, would allow investigation of the rock mass well away from the borehole itself. These techniques, together with cross-hole seismics, should make it possible to identify any major fracture zones running parallel to the borehole itself, as well as make it easier to identify ones that intersected the borehole.

Compared with investigations at shallower depths it would be much more difficult and expensive to make hydraulic measurements in deep, large diameter boreholes and the accuracy of such data is unlikely to be equal to those at shallower depths.

It was recommended that an analysis should be carried out of the deep boreholes that had been drilled in the Soviet Union[9] and that information should also be obtained from the deep boreholes that were planned in Germany and elsewhere.

4.1.2 The NEDRA study

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

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

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

[9] This was carried out; see [36] and Chapter 4.1.2 of this report.
[10] NEDRA is the Scientific Industrial Company on Superdeep Drilling and Comprehensive Investigation of the Earth's Interior.

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

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

Structural conditions

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

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

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

Hydrogeological and hydrochemical conditions

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

[11] A process by which the core breaks into relatively thin discs as a result of stress relief, due to the release of the core from high in situ stresses. In high angle and vertical boreholes core discing is as a result of high horizontal stress.
[12] Basic and ultra basic rocks are dark, heavy rocks with a silica content of less than about 53% and containing magnesium and iron minerals but not quartz. An example of a basic rock is basalt.

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

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

Zone 1: a zone of free circulation characterised by fresh or slightly mineralised meteoric groundwater (TDS (Total Dissolved Solids) up to 50-60 g l^{-1}) in fractures.

Zone 2: a zone of reduced circulation characterised by weak or medium brines with values of TDS up to 200 g l^{-1}.

Zone 3: a zone of deep groundwater, characterised by strong basement brines, indicating a long period of water-rock interaction, or groundwater with a metamorphic origin with TDS values up to 350 g l^{-1}.

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

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

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

Summary of NEDRA study

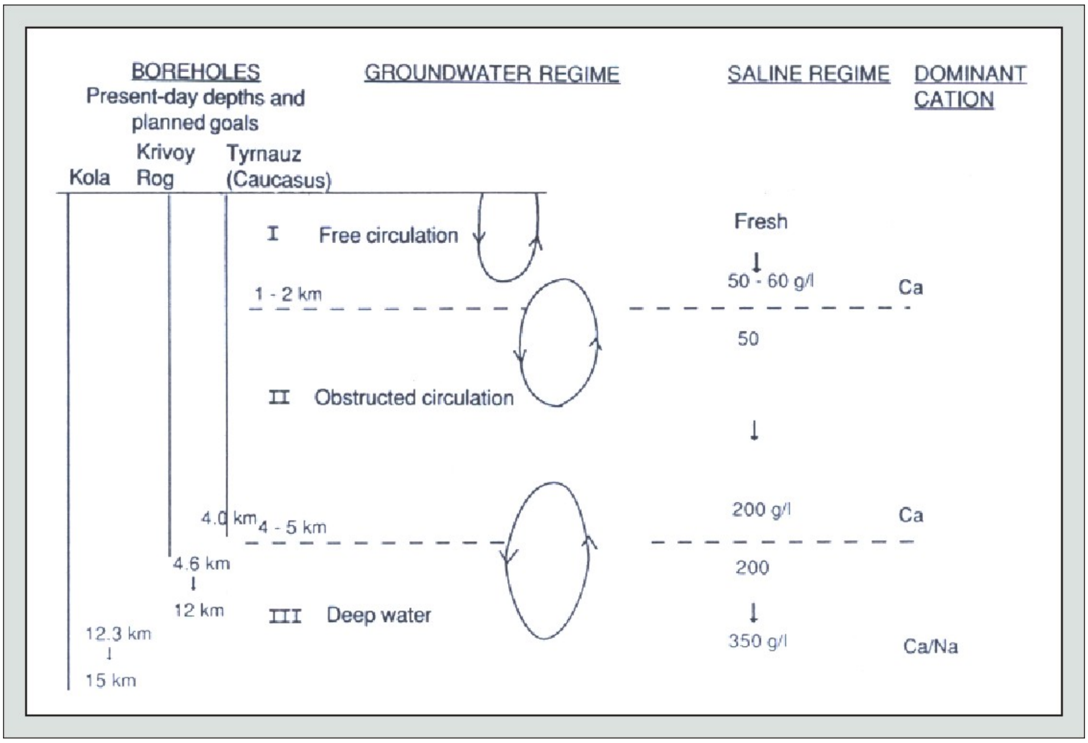
NEDRA [36] condensed the observed hydrogeological and geothermal characteristics in these crystalline basement formations into a generalised model, with the rock mass encountered to a depth of 5 km and greater being envisaged as a three-layer medium, which reflected the vertical hydrogeological and geothermal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

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

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

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

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



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

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

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

4.1.3 Juhlin & Sandstedt [10] – Part II

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

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

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

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

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

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

Geological aspects.

Multiple disposal sites.

Adaptability to technological innovations.

Possible economic advantages.

Retrievability.

Geological aspects

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

Multiple disposal sites

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

Adaptability to technological innovations

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

Possible economic advantages

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

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

Retrievability

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

4.1.4 The PASS study

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

- The groundwater in contact with the waste canister would be considerably more saline than that likely to exist at 500 m depth.
- The consequence of this higher salinity would be that the corrosion rate of the VDH waste canisters would be considerably greater than that experienced by a normal copper/steel canister in the KBS-3 concept.
- The VDH waste canister would have to be considerably smaller (538 mm diameter) than that envisaged in the KBS-3 concept (840 to 920 mm, depending on the design).
- The smaller VDH waste canister would contain fewer SF rods, thereby requiring a considerably greater number of canisters (though this number could be reduced if *consolidated assemblies* were used). These consolidated assemblies would require the fuel assemblies to be dismantled and the SF rods to be consolidated so that they fitted inside a special container. In this manner the number of waste canisters in the PASS study believed necessary for the VDH concept was reduced from 11,235 to 5,548. This compared with the assumed number of canisters for the KBS-3 concept of 3745.

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

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

- The canister could consist of either a titanium canister with a concrete fill (with either intact BWR (Boiling Water Reactor) assemblies or consolidated assemblies) or a copper canister fabricated using HIP (Hot Isostatic Pressing). In both cases the external dimensions of the canister were the same.
- The canisters would be stacked on top of each other, separated by compressed bentonite (Figure 12).

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

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

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

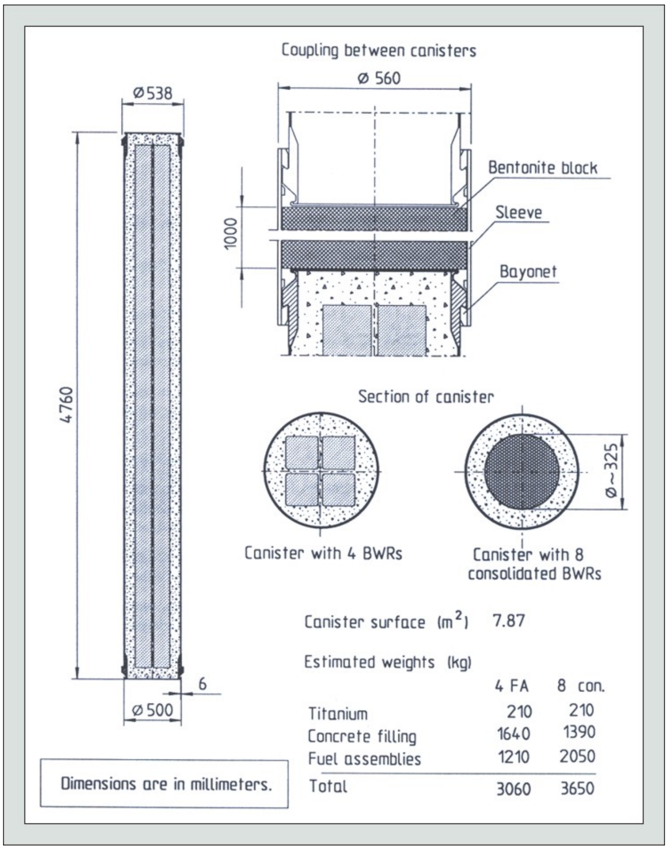
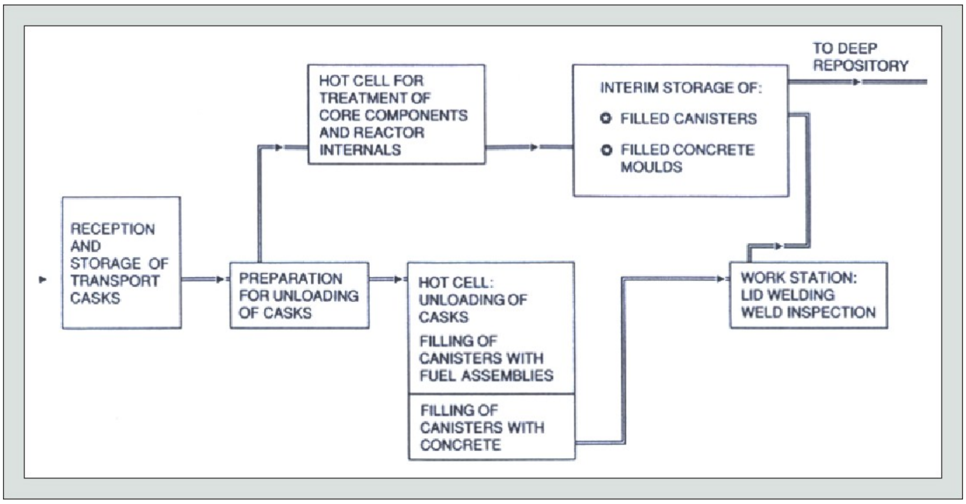


Figure 13 Flow diagram presented in the PASS study illustrating the encapsulation of consolidated assemblies for use in the VDH disposal concept [11].



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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Summary

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

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

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

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

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

4.2 Follow-on work to PASS

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

4.3 Progress since RD&D 98

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

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

- Overall requirements.
- Environmental requirements – represented by the consumption of materials for the EBS and the volume of extracted rock and also by the overall environmental requirements.
- Safety requirements – represented by the number of movements involved in canister handling and by the overall safety requirements.
- Radiation shielding requirements.

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

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

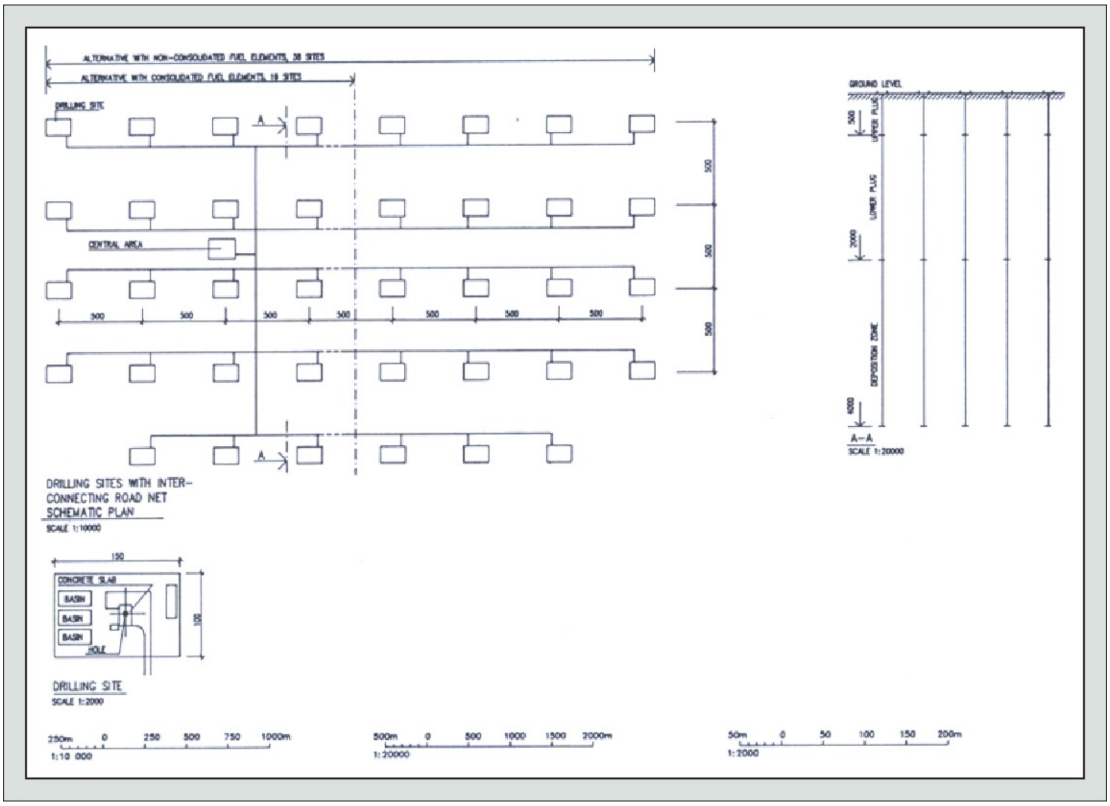


Table 5 Summary of results of the SKB PASS study [11] in which four disposal concepts were compared under the subject areas of Technology, Long-term performance and safety and Costs. [MLH = Medium Long Holes; VLH = Very Long Holes; VDH = Very Deep Holes]

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

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

4.3.1 Proposed design of the VDH concept

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

Facility design and safety functions

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

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

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

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

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

The separation of fracture zones is likely to be greater.

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

Site selection and site investigations

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

Construction

Structure, flexibility and safety

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

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

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

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

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

Use of land, contaminants and consumption of resources

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

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

Operation

Implementation and operating safety

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

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

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

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

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

Loss or tilting of the drill rod during lowering.

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

Deposition at the correct depth.

Problems in releasing the canister package from the drill rod.

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

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

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

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

[18] No waste emplacement has taken place by the oil industry but substantial objects have been emplaced at depth in boreholes using similar equipment to that proposed for use here.
[19] It is important to compare the difficulty of retrieving such a canister, or group of canisters, from a deep borehole with the situation of a damaged canister or waste package that might require retrieval from a conventional mined repository.

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

Contaminants, radioactive substances and radiation doses

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

Safeguards

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

Long-term safety

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

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

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

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

Safeguards

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

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

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

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

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

= Neutral

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

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

The VDH concept requires comprehensive technological and theoretical development to become a realisable alternative, and it is thought that this could take some time.

The VDH concept is considered to have environmental advantages, partly due to a small volume of extracted rock, partly to potentially fewer restrictions on the future use of the disposal site.

The VDH concept is thought to have disadvantages relative to the other methods, both in terms of safety during operation and in terms of long-term safety after sealing.

Both the KBS-3 and the VLH concepts are considered to fulfil the radiation shielding requirements, but neither the WP-Cave nor the VDH concept do so. With sufficient knowledge it may be possible to demonstrate that these alternatives also meet these requirements, however, the VDH concept would require major technological and theoretical development to do so. This makes both these alternatives more expensive than KBS-3 and VLH.

As regards safeguards, the alternatives are regarded as equal during the operating stage, whilst the VDH concept is considered superior to the tunnel alternatives after the facility has been sealed.

The safety and radiation shielding requirements weigh most heavily in an overall assessment. The result of the systems analysis was that KBS-3 was chosen by

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

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

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

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

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

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

State of knowledge and geoscience research programme

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

State of knowledge and research programme related to engineered barriers.

State of knowledge and development programme for safety assessment.

Timetables and costs.

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

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

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

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

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

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

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

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

Using casings of steel instead of copper bronze.

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

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

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

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

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

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

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

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

The characterization of the bedrock.

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

Drilling technology.

Canister design.

Methods to be employed for emplacing waste canisters.

Buffer design.

Retrievability.

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

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

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

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

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

5 DISPOSAL OF PLUTONIUM

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

5.1 USDOE weapons-usable Pu disposal

5.1.1 Introduction

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

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

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

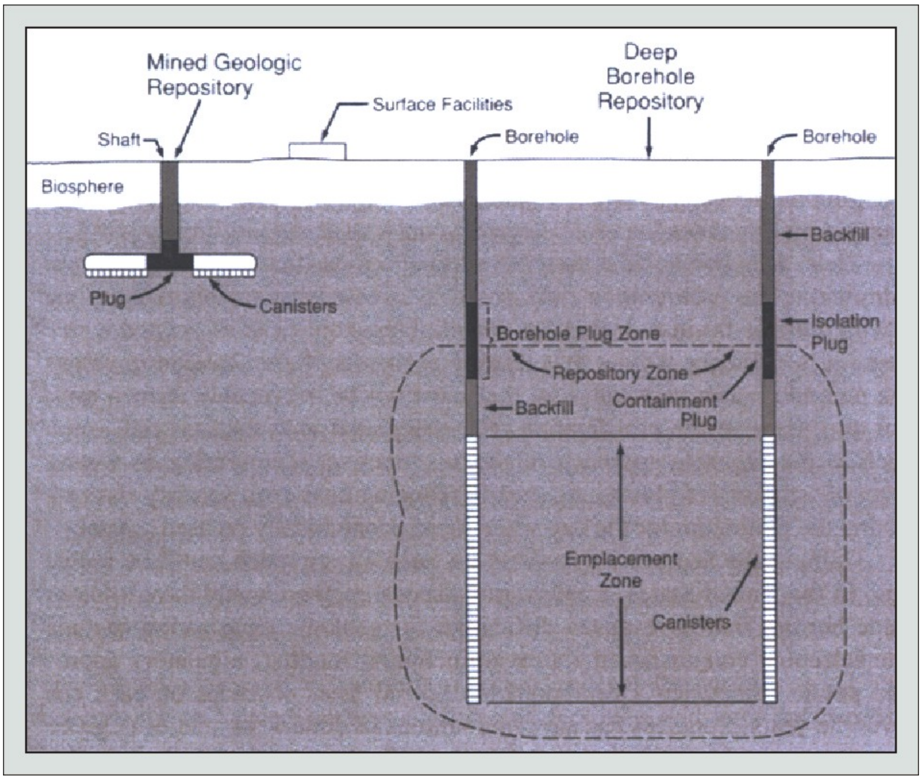
and the description of Pu disposal below is, unless otherwise stated, based exclusively on [41].

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

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

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

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

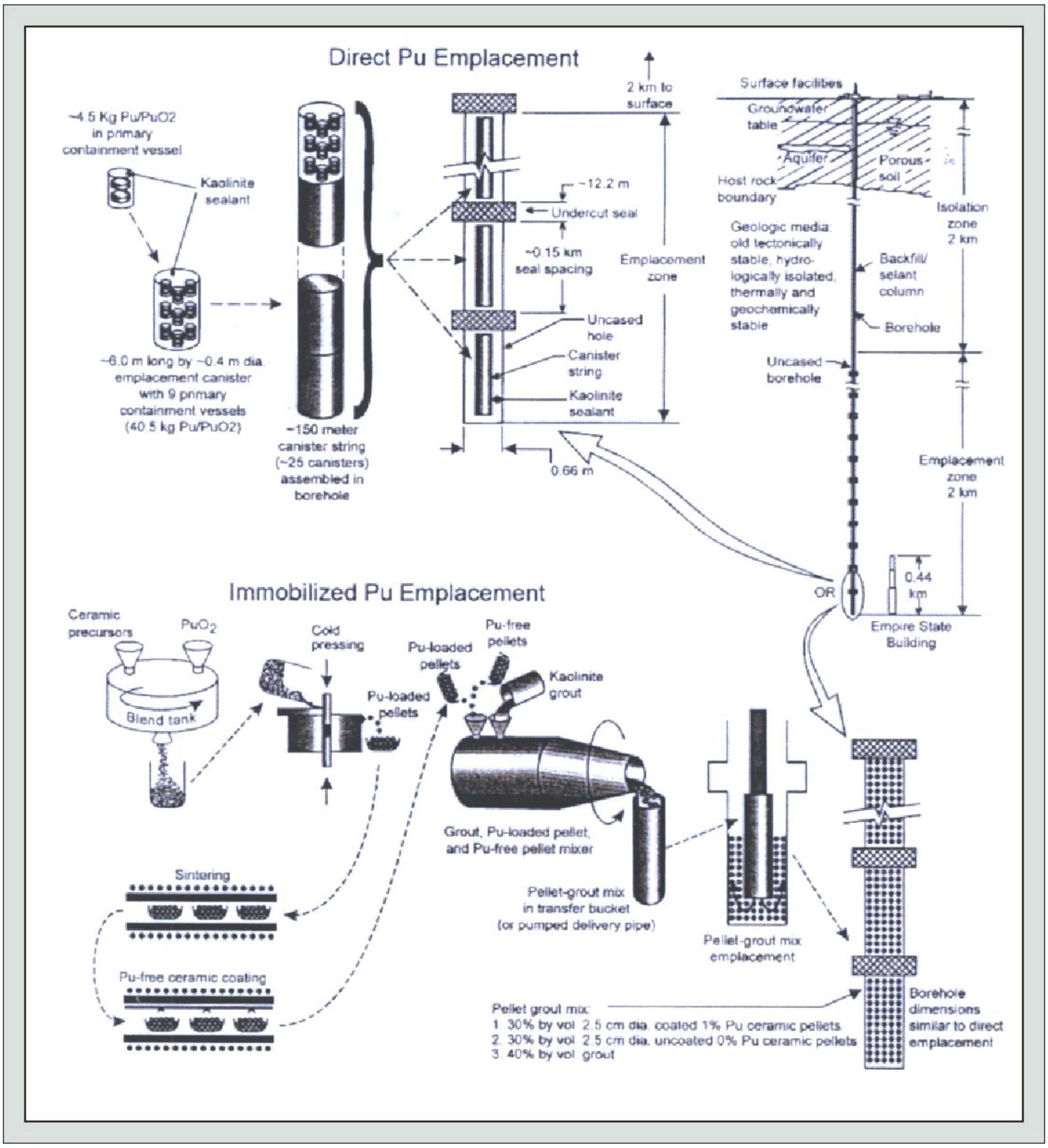


The characteristics of the two alternative deep borehole disposal concepts, either *direct emplacement* or *immobilised emplacement* are summarised in Table 9 and illustrated in Figure 16. Both alternatives assume a disposition rate of 5 tonnes per year over a ten year operational period, although it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

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

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

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



5.1.2 Direct Emplacement Alternative

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

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

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

5.1.3 Immobilised Emplacement Alternative

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

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

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

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

5.1.4 Technical status and assessment

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

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

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

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

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

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

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

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

The great depth of burial.

The high resistance to mobilisation of the selected disposal forms.

The properties of the subsurface rock and brines.

The low permeabilities of fractured rock at great depths.

The lack of driving forces for fluid flow at sites selected according to the site selection criteria developed for deep borehole disposition[22].

5.1.5 Costs

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

[22] See discussion in Section 5.2.

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

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

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

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

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

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

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

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

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

5.2 Site selection

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

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

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

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

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

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

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

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

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

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

A region that is tectonically stable.

An area located away from population centres.

---

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

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

Why these particular factors were selected is not discussed.

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

Rock characteristics:

Disposal over the depth range of 2 – 4 km.

Free of vertical faults.

Very low permeability.

Crystalline rock.

Absence of faults.

Absence of faulting for many million years to come.

Tectonics:

Free of geological activity.

Geochemistry:

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

Homogeneity of rock properties.

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

5.3 National Academy of Sciences Report

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

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

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

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

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

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

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

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

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

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

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

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

Mechanisms for possible transport of radionuclides to the surface.

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

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

Approaches to monitoring and retrieval of emplaced waste.

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

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

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

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

5.3.1 Cost

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

5.3.2 Retrievability

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

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

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

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

5.3.3 Policy issues

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

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

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

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

6 ALTERNATIVE DISPOSAL OPTIONS IN DEEP BOREHOLES

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

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

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

6.1 Comparison of disposal concepts

6.1.1 Disposal concept from Chapman and Gibb

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

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

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

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

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

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

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

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

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

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

6.1.2 Alternative approaches to deep borehole disposal

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

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

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

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

6.1.3 Comparison of different concepts

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

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

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

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

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

6.2 Comments on alternative disposal options

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

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

7 SUMMARY OF ISSUES IDENTIFIED

7.1 Introduction

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

- It is more difficult to provide stable borehole conditions in sedimentary sequences in which there is a succession of alternating sedimentary formations with different mechanical properties, as the design of the borehole casing programme is made more complex (a good example of this is provided by some of the deep boreholes at Sellafield). In addition, each reduction in casing size means that the initial borehole diameter will need to be increased.
- It is more difficult to investigate the basement if it is overlain by a sedimentary succession (again Sellafield provides a good example, as do the investigations for Andra's potential URL site near Limoges in the 1990s).

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

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

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

7.2 The key elements of the deep borehole disposal concept

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

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

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

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

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

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

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

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

    The types of waste being emplaced.

    The diameter of the borehole.

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

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

7.3 Important questions regarding the disposal zone

The important questions regarding the disposal zone itself are:

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

The impact of borehole fluids on the waste emplacement procedure.

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

Whether the boreholes should be vertical.

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

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

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

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

7.4 R&D requirements

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

The performance of the disposal system, especially the thermal and hydraulic environment around the disposal zone and its seals.

The engineering aspects of borehole construction and package handling, which will require thorough evaluation of safety during the operational phase.

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

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

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

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

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

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

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

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

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

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ISBN 1 84029 353 5

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All users of IAEA safety standards are invited to inform the IAEA of experience in their use (e.g. as a basis for national regulations, for safety reviews and for training courses) for the purpose of ensuring that they continue to meet users' needs. Information may be provided via the IAEA Internet site or by post, as above, or by email to Official.Mail@iaea.org.

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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

IAEA SAFETY STANDARDS SERIES No. SSG-1

BOREHOLE DISPOSAL FACILITIES FOR RADIOACTIVE WASTE

SPECIFIC SAFETY GUIDE

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2009

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Vienna International Centre
PO Box 100
1400 Vienna, Austria
fax: +43 1 2600 29302
tel.: +43 1 2600 22417
email: sales.publications@iaea.org
http://www.iaea.org/books

Printed by the IAEA in Austria
December 2009
STI/PUB/1418

IAEA Library Cataloguing in Publication Data

Borehole disposal facilities for radioactive waste : safety guide. — Vienna : International Atomic Energy Agency, 2009.
p. ; 24 cm. — (Safety standards series, ISSN 1020–525X ; no. SSG-1)
STI/PUB/1418
ISBN 978–92–0–109109–3
Includes bibliographical references.

1. Radioactive waste disposal — Safety measures. 2. Radioactive waste repositories. I. International Atomic Energy Agency. II. Series.

IAEAL 09–00609

FOREWORD

The IAEA's Statute authorizes the Agency to establish safety standards to protect health and minimize danger to life and property — standards which the IAEA must use in its own operations, and which a State can apply by means of its regulatory provisions for nuclear and radiation safety. A comprehensive body of safety standards under regular review, together with the IAEA's assistance in their application, has become a key element in a global safety regime.

In the mid-1990s, a major overhaul of the IAEA's safety standards programme was initiated, with a revised oversight committee structure and a systematic approach to updating the entire corpus of standards. The new standards that have resulted are of a high calibre and reflect best practices in Member States. With the assistance of the Commission on Safety Standards, the IAEA is working to promote the global acceptance and use of its safety standards.

Safety standards are only effective, however, if they are properly applied in practice. The IAEA's safety services — which range in scope from engineering safety, operational safety, and radiation, transport and waste safety to regulatory matters and safety culture in organizations — assist Member States in applying the standards and appraise their effectiveness. These safety services enable valuable insights to be shared and I continue to urge all Member States to make use of them.

Regulating nuclear and radiation safety is a national responsibility, and many Member States have decided to adopt the IAEA's safety standards for use in their national regulations. For the contracting parties to the various international safety conventions, IAEA standards provide a consistent, reliable means of ensuring the effective fulfilment of obligations under the conventions. The standards are also applied by designers, manufacturers and operators around the world to enhance nuclear and radiation safety in power generation, medicine, industry, agriculture, research and education.

The IAEA takes seriously the enduring challenge for users and regulators everywhere: that of ensuring a high level of safety in the use of nuclear materials and radiation sources around the world. Their continuing utilization for the benefit of humankind must be managed in a safe manner, and the IAEA safety standards are designed to facilitate the achievement of that goal.

THE IAEA SAFETY STANDARDS

BACKGROUND

Radioactivity is a natural phenomenon and natural sources of radiation are features of the environment. Radiation and radioactive substances have many beneficial applications, ranging from power generation to uses in medicine, industry and agriculture. The radiation risks to workers and the public and to the environment that may arise from these applications have to be assessed and, if necessary, controlled.

Activities such as the medical uses of radiation, the operation of nuclear installations, the production, transport and use of radioactive material, and the management of radioactive waste must therefore be subject to standards of safety.

Regulating safety is a national responsibility. However, radiation risks may transcend national borders, and international cooperation serves to promote and enhance safety globally by exchanging experience and by improving capabilities to control hazards, to prevent accidents, to respond to emergencies and to mitigate any harmful consequences.

States have an obligation of diligence and duty of care, and are expected to fulfil their national and international undertakings and obligations.

International safety standards provide support for States in meeting their obligations under general principles of international law, such as those relating to environmental protection. International safety standards also promote and assure confidence in safety and facilitate international commerce and trade.

A global nuclear safety regime is in place and is being continuously improved. IAEA safety standards, which support the implementation of binding international instruments and national safety infrastructures, are a cornerstone of this global regime. The IAEA safety standards constitute a useful tool for contracting parties to assess their performance under these international conventions.

THE IAEA SAFETY STANDARDS

The status of the IAEA safety standards derives from the IAEA's Statute, which authorizes the IAEA to establish or adopt, in consultation and, where appropriate, in collaboration with the competent organs of the United Nations and with the specialized agencies concerned, standards of safety for protection of health and minimization of danger to life and property, and to provide for their application.

With a view to ensuring the protection of people and the environment from harmful effects of ionizing radiation, the IAEA safety standards establish fundamental safety principles, requirements and measures to control the radiation exposure of people and the release of radioactive material to the environment, to restrict the likelihood of events that might lead to a loss of control over a nuclear reactor core, nuclear chain reaction, radioactive source or any other source of radiation, and to mitigate the consequences of such events if they were to occur. The standards apply to facilities and activities that give rise to radiation risks, including nuclear installations, the use of radiation and radioactive sources, the transport of radioactive material and the management of radioactive waste.

Safety measures and security measures[1] have in common the aim of protecting human life and health and the environment. Safety measures and security measures must be designed and implemented in an integrated manner so that security measures do not compromise safety and safety measures do not compromise security.

The IAEA safety standards reflect an international consensus on what constitutes a high level of safety for protecting people and the environment from harmful effects of ionizing radiation. They are issued in the IAEA Safety Standards Series, which has three categories (see Fig. 1).

Safety Fundamentals

Safety Fundamentals present the fundamental safety objective and principles of protection and safety, and provide the basis for the safety requirements.

Safety Requirements

An integrated and consistent set of Safety Requirements establishes the requirements that must be met to ensure the protection of people and the environment, both now and in the future. The requirements are governed by the objective and principles of the Safety Fundamentals. If the requirements are not met, measures must be taken to reach or restore the required level of safety. The format and style of the requirements facilitate their use for the establishment, in a harmonized manner, of a national regulatory framework. The safety requirements use ‘shall’ statements together with statements of

[1] See also publications issued in the IAEA Nuclear Security Series.

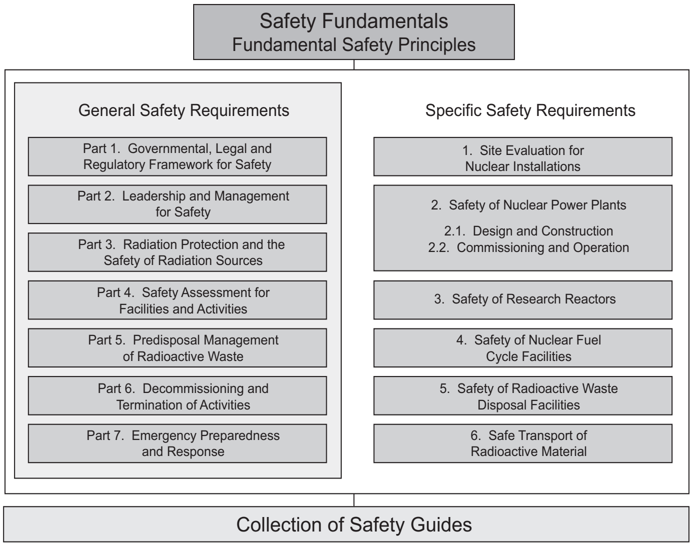

FIG. 1. The long term structure of the IAEA Safety Standards Series.

associated conditions to be met. Many requirements are not addressed to a specific party, the implication being that the appropriate parties are responsible for fulfilling them.

Safety Guides

Safety Guides provide recommendations and guidance on how to comply with the safety requirements, indicating an international consensus that it is necessary to take the measures recommended (or equivalent alternative measures). The Safety Guides present international good practices, and increasingly they reflect best practices, to help users striving to achieve high levels of safety. The recommendations provided in Safety Guides are expressed as ‘should’ statements.

APPLICATION OF THE IAEA SAFETY STANDARDS

The principal users of safety standards in IAEA Member States are regulatory bodies and other relevant national authorities. The IAEA safety standards are also used by co-sponsoring organizations and by many organizations that design, construct and operate nuclear facilities, as well as organizations involved in the use of radiation and radioactive sources.

The IAEA safety standards are applicable, as relevant, throughout the entire lifetime of all facilities and activities — existing and new — utilized for peaceful purposes and to protective actions to reduce existing radiation risks. They can be used by States as a reference for their national regulations in respect of facilities and activities.

The IAEA's Statute makes the safety standards binding on the IAEA in relation to its own operations and also on States in relation to IAEA assisted operations.

The IAEA safety standards also form the basis for the IAEA's safety review services, and they are used by the IAEA in support of competence building, including the development of educational curricula and training courses.

International conventions contain requirements similar to those in the IAEA safety standards and make them binding on contracting parties. The IAEA safety standards, supplemented by international conventions, industry standards and detailed national requirements, establish a consistent basis for protecting people and the environment. There will also be some special aspects of safety that need to be assessed at the national level. For example, many of the IAEA safety standards, in particular those addressing aspects of safety in planning or design, are intended to apply primarily to new facilities and activities. The requirements established in the IAEA safety standards might not be fully met at some existing facilities that were built to earlier standards. The way in which IAEA safety standards are to be applied to such facilities is a decision for individual States.

The scientific considerations underlying the IAEA safety standards provide an objective basis for decisions concerning safety; however, decision makers must also make informed judgements and must determine how best to balance the benefits of an action or an activity against the associated radiation risks and any other detrimental impacts to which it gives rise.

DEVELOPMENT PROCESS FOR THE IAEA SAFETY STANDARDS

The preparation and review of the safety standards involves the IAEA Secretariat and four safety standards committees, for nuclear safety (NUSSC), radiation safety (RASSC), the safety of radioactive waste (WASSC) and the safe transport of radioactive material (TRANSSC), and a Commission on

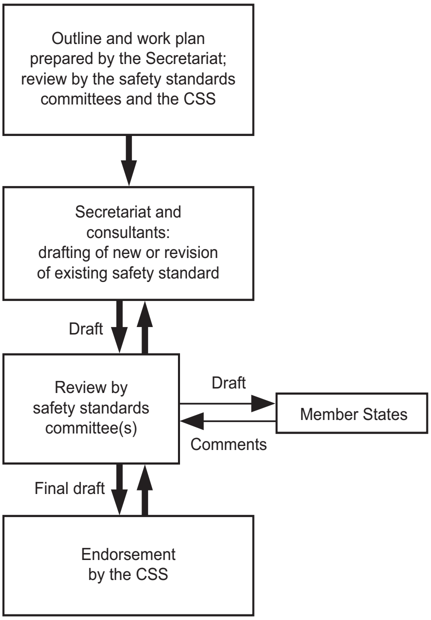

FIG. 2. The process for developing a new safety standard or revising an existing standard.

Safety Standards (CSS) which oversees the IAEA safety standards programme (see Fig. 2).

All IAEA Member States may nominate experts for the safety standards committees and may provide comments on draft standards. The membership of the Commission on Safety Standards is appointed by the Director General and includes senior governmental officials having responsibility for establishing national standards.

A management system has been established for the processes of planning, developing, reviewing, revising and establishing the IAEA safety standards. It articulates the mandate of the IAEA, the vision for the future application of the safety standards, policies and strategies, and corresponding functions and responsibilities.

INTERACTION WITH OTHER INTERNATIONAL ORGANIZATIONS

The findings of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and the recommendations of international expert bodies, notably the International Commission on Radiological Protection (ICRP), are taken into account in developing the IAEA safety standards. Some safety standards are developed in cooperation with other bodies in the United Nations system or other specialized agencies, including the Food and Agriculture Organization of the United Nations, the United Nations Environment Programme, the International Labour Organization, the OECD Nuclear Energy Agency, the Pan American Health Organization and the World Health Organization.

INTERPRETATION OF THE TEXT

Safety related terms are to be understood as defined in the IAEA Safety Glossary (see http://www-ns.iaea.org/standards/safety-glossary.htm). Otherwise, words are used with the spellings and meanings assigned to them in the latest edition of The Concise Oxford Dictionary. For Safety Guides, the English version of the text is the authoritative version.

The background and context of each standard in the IAEA Safety Standards Series and its objective, scope and structure are explained in Section 1, Introduction, of each publication.

Material for which there is no appropriate place in the body text (e.g. material that is subsidiary to or separate from the body text, is included in support of statements in the body text, or describes methods of calculation, procedures or limits and conditions) may be presented in appendices or annexes.

An appendix, if included, is considered to form an integral part of the safety standard. Material in an appendix has the same status as the body text, and the IAEA assumes authorship of it. Annexes and footnotes to the main text, if included, are used to provide practical examples or additional information or explanation. Annexes and footnotes are not integral parts of the main text. Annex material published by the IAEA is not necessarily issued under its authorship; material under other authorship may be presented in annexes to the safety standards. Extraneous material presented in annexes is excerpted and adapted as necessary to be generally useful.

CONTENTS

1. INTRODUCTION

BACKGROUND

1.1. The use of radioactive material in nuclear research and in industrial, medical and other applications has led to the generation of small but significant volumes of radioactive waste. Some of this waste (e.g. disused radioactive sources from industrial and medical uses) is intensely radioactive. Consequently, many States now have various types of radioactive waste, all of which need to be managed and disposed of robustly and safely. The Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management [1] places an obligation on Contracting Parties to control and manage such radioactive waste safely.

1.2. When the activity in waste is relatively low and half-lives are less than about 30 a, near surface disposal will often be suitable. Some waste, however, is too radioactive and too long lived for near surface disposal. Such waste requires higher levels of containment and isolation than can be provided by near surface facilities, implying the need for disposal at greater depths. In States where there is a significant nuclear industry, possibilities for deep disposal may exist or, more often, may be planned. Such States are relatively few in number, however. More often, States have radioactive waste, but lack the possibility of safe disposal for such waste types, or even the prospect of such. For example, radioactive sources used in industry and medicine may be high energy photon emitters that require heavily shielded containers for their safe use, transport and storage. At the end of their useful lifetime, it is possible in some cases to return these sources to their manufacturer for recycling. In many cases though, this is not possible and even though they may be 'spent' sources (i.e. no longer radioactive enough for their intended use), they still present a significant hazard. This is evident from a number of incidents and accidents, including fatalities, that have arisen from their misuse [2].

1.3. Where the radionuclides in the waste have relatively short half-lives (e.g. ^{60}Co, half-life 5.3 a) and an activity of less than a few tens of MBq, it may be reasonable to assume that they can safely be placed in a facility, such as a near surface disposal facility, for the ten to twenty half-lives necessary to allow the radioactivity to decay to safe levels. For longer lived and higher activity sources and other waste, however, storage is merely an interim solution that is acceptable only as long as the search continues for a long term solution. One potential long term solution for such waste is deep disposal in an engineered, cavern type repository.

1.4. An alternative solution is disposal in specially engineered and purpose drilled boreholes (loosely referred to as 'borehole disposal' [3]), which offers the prospect of economic disposal on a small scale while, at the same time, meeting all the safety requirements. The comparative ease of borehole construction and site characterization may make this method of disposal particularly suitable for States, or regional groupings of States, that have limited amounts of waste. Disposal in borehole disposal facilities is seen as having particular value for the disposal of disused sealed radioactive sources. As a general rule, however, disused sealed radioactive sources containing materials that may pose hazards to inadvertent intruders or that may be used in radioactive dispersal devices should not be placed in near surface disposal facilities.

1.5. Borehole type facilities have been used in the past in a number of States for the storage and disposal of radioactive waste; all of them are located on existing waste repository sites [3]. In the Russian Federation, for example, there has been more than 40 a of experience with borehole disposal facilities of up to 15 m in depth [4] and new facilities are being planned there [5]. Also, the Greater Confinement Test facility in Nevada, United States of America, has already been used to dispose of waste in boreholes 10 m deep by 3 m in diameter [6]. Examples such as these are considered in this Safety Guide with a view to identifying good practices. There are, however, some cases of questionable practice: concerns have been expressed, for example, over the degree of isolation provided by certain existing borehole disposal facilities in terms of their siting and depth, the reliability and efficiency of the isolation barriers and the adequacy of the associated safety assessments. These concerns highlight the need for guidance on the evaluation of the safety of existing facilities so that decisions can be taken on the necessity for remedial measures.

OBJECTIVE

1.6. The objective of this Safety Guide is to provide guidance on the design, construction, operation and closure of borehole disposal facilities for the disposal of radioactive waste in accordance with the relevant safety requirements [7–9]. The guidance can also be used as a basis for reassessing the safety of existing facilities. Compliance with the safety requirements should provide protection for people and the environment from exposure to ionizing radiation. The safety objectives and associated criteria for borehole disposal are no less stringent than for geological disposal or near surface disposal. However, because of the relatively small quantities (in terms of both volume and activity) of waste, considerably less effort would be required to meet these objectives and the associated criteria — and to demonstrate that they will be or have been met — than would be the case for the larger scale practices.

1.7. As a practice, the disposal of radioactive waste in borehole disposal facilities falls between the two well-established options of disposal in near surface facilities and disposal in geological facilities. This Safety Guide, therefore, complements both the Safety Guide on near surface disposal [10] and the Safety Guide on geological disposal [11].

1.8. The Safety Guide is intended to support a practical and systematic approach to decision making for borehole disposal such as would be required within the framework of a management system providing for the necessary level of quality (see Appendix VI).

SCOPE

1.9. Existing or proposed borehole disposal facilities exhibit a wide range of diameters and depths, including shafts and small diameter boreholes sunk to various depths. While the present Safety Guide is relevant for all these possibilities, its main focus is on boreholes having a diameter of no more than a few hundred millimetres and a depth beyond a few tens of metres and up to a few hundred metres (i.e. the depth range between near surface disposal and geological disposal).

1.10. While borehole disposal facilities may also be suitable for other types of waste, this Safety Guide concentrates on disused sealed sources and small volumes of low and intermediate level wastes. Throughout this Safety Guide, the term ‘disused sealed sources’ refers to sealed sources that, for whatever reason, have fallen out of use and have been categorized as waste. The typical radionuclides to be found in disused sealed sources are listed in Table 1. It is envisaged that the type of radionuclides and/or waste for which borehole disposal is most likely to be suitable would need to be:

(a) Too long lived for decay storage (e.g. a half-life greater than a few years);
(b) Too long lived and/or too radioactive to be placed in a simple near surface facility;
(c) Small volume waste for which no other disposal facility is available.

TABLE 1. TYPICAL RADIONUCLIDES PRESENT IN DISUSED SEALED SOURCES

Radionuclide	Half-life	Maximum expected activity (MBq)	Application
	<100 d		
Au-198	2.7 d	1.5E3	Manual brachytherapy
Y-90	2.7 d	5E2	Manual brachytherapy
I-131	8.0 d	1.5E3	Manual brachytherapy
P-32	14.3 d	2E2	Vascular brachytherapy
Pd-103	17.0 d	1.5E3	Manual brachytherapy
Sr-89	50.5 d	1.5E2	Vascular brachytherapy
I-125	60.0 d	1E4	Bone dosimetry
Ir-192	74.0 d	5E6	Industrial radiography
	100 d to ≤30 a		
Po-210	138.0 d		Static electricity eliminators
Gd-153	242.0 d		Bone dosimetry
Co-57	271.7 d	5E5	Markers
Ru-106	1.0 a	5E4	Manual brachytherapy
Cf-252	2.6 a	5E3	Calibration facilities
Pm-147	2.6 a	5E5	Sources as standards in instruments
Co-60	5.3 a	5E4	Sterilization and food preservation
Kr-85	10.8 a		Thickness gauges
H-3	12.3 a	5E6	Tritium targets
Sr-90	29.0 a	5E4	Thickness gauges
Cs-137	30.1 a	5E5	Sterilization and food preservation

TABLE 1. TYPICAL RADIONUCLIDES PRESENT IN DISUSED SEALED SOURCES (cont.)

Radionuclide	Half-life	Maximum expected activity (MBq)	Application
	>30 a		
Pu-238	87.7 a	3.7E3	Static electricity eliminators
Ni-63	100 a	5E2	Electron capture detectors
Am-241/Be	433 a	8E5	Well logging, fire detection
Ra-226	1600 a	3.7E3	Manual brachytherapy
C-14	5700 a		
Cl-36	3E5 a	4.00	Sources as standards in instruments
I-129	1.6E7 a	4.00	Sources as standards in instruments

1.11. Consideration is given to operational safety, the security of the waste and the achievement of post-closure safety. It is recognized that, while radiological safety is of paramount importance, it is only part of a broader context that includes planning, financial, economic and social issues, and non-radiological safety. These other issues are not specifically covered in this Safety Guide.

1.12. This Safety Guide is intended for those persons whose prime interest is in the regulation and implementation of the safe disposal of radioactive waste.

STRUCTURE

1.13. In this Safety Guide, the background to, concept of, and protection and safety objectives for, borehole disposal are set out in Sections 1–3. Recommendations on how to apply the relevant safety requirements to borehole disposal are provided in Sections 4 and 5. Section 6 describes the application of the safety strategy to existing borehole disposal facilities.

2. BOREHOLE DISPOSAL AND THE SAFETY OF RADIOACTIVE WASTE MANAGEMENT

BOREHOLE DISPOSAL CONCEPT

2.1. The borehole disposal concept (shown schematically in Fig. 1) entails the emplacement of disused sealed radioactive sources and small volumes of low and intermediate level wastes in an engineered facility bored or drilled and operated directly from the surface. In this Safety Guide, borehole disposal is envisaged mainly as a small scale activity that can be carried out without a large programme of scientific and site investigation.

2.2. In this Safety Guide, a depth of 30 m is used to differentiate between near surface disposal and disposal at intermediate and greater depths. This depth is widely accepted as the lower level of the 'normal residential intrusion zone' (i.e. a depth beyond which human intrusion is limited to drilling and significant excavation activities, such as tunnelling, quarrying and mining) [12]. In applying this distinction, the key parameter is not the maximum depth of the borehole but, rather, the minimum depth at which waste is located within the

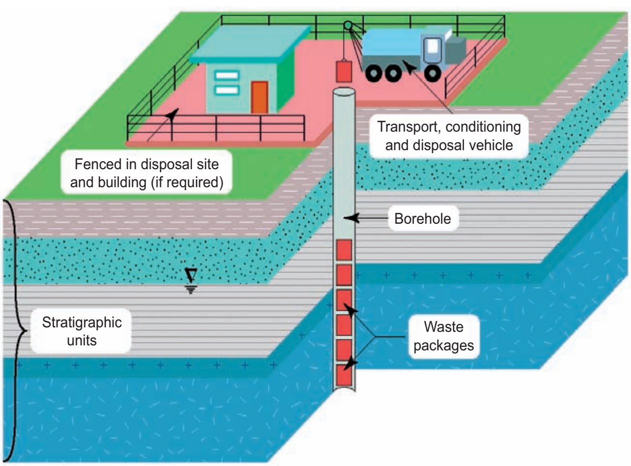

FIG. 1. Schematic layout of a borehole disposal facility.

borehole. So, even if a borehole is several hundred metres deep, if the column of waste within it extends to less than 30 m below the surface, the borehole will be considered to be a near surface disposal facility. If all the waste is located at a depth that exceeds 30 m below the surface, it will be referred to as an intermediate depth disposal facility.

2.3. From a safety perspective, borehole disposal is not conceptually different from either near surface disposal or geological disposal of radioactive waste. Indeed, because the range of depths accessed by borehole disposal approaches the depths normally associated with both near surface disposal and geological disposal, consideration is given to elements of both. As for near surface disposal and geological disposal, a combination of natural barriers and engineered barriers contribute to safety for borehole disposal. In combination, these barriers are designed to contain radioactive material until it has decayed to insignificant levels, and to provide sufficient isolation and containment to ensure an adequate level of protection for people and the environment.

APPLYING THE SAFETY PRINCIPLES IN RADIOACTIVE WASTE MANAGEMENT

2.4. The safety principles applicable to all facilities and activities, including waste disposal activities, are established in the Fundamental Safety Principles [13]. Because borehole disposal facilities are used to dispose of waste at a range of depths, from depths associated with near surface disposal to depths approaching those associated with geological disposal, and because of the nature of the waste intended for disposal, guidance needs to be provided on how the safety requirements for both geological disposal [8] and near surface disposal [9] can be met for these facilities.

2.5. The graded application of the safety requirements for near surface disposal and geological disposal to borehole disposal will ensure an adequate level of safety. In all cases, reasonable assurance of safety should be demonstrated to the regulatory body and to other stakeholders. However, the level of effort required to comply with these safety requirements for a facility with a relatively small inventory of radionuclides will generally be significantly less than for large scale repositories in terms of safety assessment, site characterization and facility construction, operation and closure. The use of generic safety assessment, which could assist in the assessment of particular sites, to facilitate safety assessment for borehole disposal facilities is discussed in paras 5.7–5.9.

3. BOREHOLE DISPOSAL AND THE PROTECTION OF HUMAN HEALTH AND THE ENVIRONMENT

RADIATION PROTECTION DURING THE OPERATIONAL PERIOD

3.1. The objective for radiation protection during the operational period of a borehole disposal facility and the related safety criteria are the same as for any licensed nuclear facility and are as required by the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (BSS) [7] (see Box 1). In radiation protection terms, the source is under control, releases can be verified, exposures can be controlled and actions can be taken if needed. Optimization of radiation protection is the primary goal (application of principle 5 of Ref. [13]). See also under the heading 'Objective' in Box 2.

3.2. Only very minor releases of radionuclides (such as small amounts of gaseous radionuclides) may be expected during pre-disposal activities and during the operation of a borehole disposal facility. The design should be such that, even in the event of an accident involving the breach of a waste package, releases are not likely to have any impact outside the facility. Relevant considerations should include the packaging, the waste form, the radionuclide content of the waste and control of contamination on packages and equipment.

3.3. A radiological protection programme should be in place during the operational period. This should ensure that doses to workers are controlled and that the requirements for dose limitation are met [14, 15]. In addition, contingency measures should be in place to deal with accidents and incidents so that any associated radiation hazards are controlled to the extent possible. This is described more fully in paras 5.39–5.59, which deal with the operation of the disposal facility.

3.4. Doses and risks associated with the transport of radioactive waste to the borehole disposal facility should be managed in the same way as those associated with the transport of other radioactive material. Of particular importance in this respect are external dose rates and contamination of waste packages (or any overpack used during transport). Transport safety is achieved by complying with the requirements of the Regulations for the Safe Transport of Radioactive Material [16].

Box 1: Radiation protection in the operational period

Requirement [7]

The radiation doses and risks to workers and members of the public exposed as a result of operations at the borehole disposal facility are required to be kept as low as reasonably achievable, economic and social factors being taken into account, and the exposures of individuals are required to be kept within applicable dose limits.

Criteria

Radiation dose limits and constraints for workers and for members of the public are set out in Schedule II of the Basic Safety Standards [7]. This publication in particular specifies that:

(a) "The occupational exposure of any worker shall be so controlled that the following limits be not exceeded:

- an effective dose of 20 mSv per year averaged over five consecutive years;
- an effective dose of 50 mSv in any single year" (Sche-II, para. II-5, Ref. [7]).

(b) "The estimated average doses to the relevant critical groups of members of the public that are attributable to practices shall not exceed the following limit:

- an effective dose of 1 mSv in a year" (Sche-II, para. II-8, Ref. [7]).

Members of the public could receive exposures from a number of practices and sources. To comply with the above limit, a "facility [such as a borehole disposal facility] (considered as a single source) is designed [and operated] so that the estimated average dose or average risk to members of the public who may be exposed in the future as a result of activities involving the disposal facility does not exceed a dose constraint of not more than 0.3 mSv in a year or a risk constraint of the order of 10^{-5} per year[a]" [8] (according to the models and assumptions recommended by the International Commission on Radiological Protection (ICRP)).

[a] Risk in this context is to be understood as the probability of death or serious hereditary disease.

Box 2: Radiation protection in the post-closure period [7, 8, 18]

Objective

"[Borehole] disposal facilities are to be sited, designed, constructed, operated and closed so that protection in the post-closure period is optimized, social and economic factors being taken into account, and an assurance is provided that doses or risks to members of the public in the long term will not exceed the applicable dose or risk that was used as a design constraint"[8].

Criteria

"The dose limit for members of the public from all practices is an effective dose of 1 mSv in a year [7], and this or its risk equivalent is considered a criterion not to be exceeded in the future. To comply with this limit, a [borehole] disposal facility (considered as a single source) is designed so that the estimated average dose or average risk to members of the public who may be exposed in the future as a result of activities involving the disposal facility does not exceed a dose constraint of not more than 0.3 mSv in a year or a risk constraint of the order of 10^{-5} per year[a]"[8].

In relation to the effects of human intrusion in the post-closure period, ICRP-81 [18] recommends that, if human intrusion is expected to lead to an annual dose of less than about 10 mSv per year to those living around the site, efforts to reduce the probability of human intrusion or to limit its consequences are not likely to be justifiable. If human intrusion is expected to lead to an annual dose of more than about 100 mSv per year to those living around the site, then it is almost always justifiable to make reasonable efforts at the stage of development of the facility to reduce the probability of human intrusion or to limit its consequences. Similar considerations apply where the thresholds for deterministic human health effects in relevant organs are exceeded. This recommendation of ICRP-81 [18] is not accepted by all regulatory bodies, however.

"It is recognized that radiation doses to individuals in the future can only be estimated and that the uncertainties associated with these estimates will increase for times further into the future. Care needs to be exercised in using the criteria beyond the time where the uncertainties become so large that the criteria may no longer serve as a reasonable basis for decision making"[8].

[a] Risk in this context is understood as the probability of death or serious hereditary disease.

RADIATION PROTECTION FOR THE POST-CLOSURE PERIOD

3.5. The primary goal of borehole disposal is to dispose of radioactive waste in a manner that protects human health and the environment in the long term, after the borehole disposal facility has been closed. In accordance with the BSS [7], this is achieved by means of design features that result in optimizing doses due to any migration of radionuclides from the facility while also complying with the dose constraints (see Box 2). It is recognized, however, that radiation doses and risks to individuals living in the distant future can only be estimated and the reliability of these estimates will decrease as the time period extending into the future increases (see paras III.2–III.11 of Appendix III). In this context, the optimization of protection is a judgemental process in which social and economic factors need to be taken into account, and it needs to be conducted in a structured but essentially qualitative way, supported by quantitative analysis. Optimization of protection in the post-closure period is explained further in para. 4.38.

3.6. A well-designed and well-located borehole disposal facility should provide reasonable assurance that radiological impacts in the post-closure period will be low both in absolute terms and in comparison with any other waste management options that are currently available at reasonable cost. A site should be identified that provides favourable conditions for containment and isolation of the waste from the biosphere and for preservation of the engineered barriers (e.g. with low groundwater flow and a benign geochemical environment). The borehole disposal facility should be designed to take account of the characteristics offered by the site, to optimize protection and to keep doses within the dose and/or risk constraints. The borehole disposal facility should then be constructed, operated and closed according to the assessed design so that the assumed safety characteristics of both the engineered and the natural barriers are realized.

3.7. In estimating the doses to individuals living in the future, it is assumed that humans will make use of local resources that may contain radionuclides that originate from the waste. The representation of future human behaviour in assessment models must necessarily be stylized, as it is not possible to predict future human behaviour with any certainty. The rationale and the possible approaches to the modelling of the biosphere and the estimation of doses arising as a result of the disposal of solid waste have been considered within the IAEA BIOMASS Project [17] (see Appendix III). In summary, Ref. [17] presents a methodology for the logical and defensible construction of ‘assessment biospheres’ (i.e. mathematical representations of biospheres used in the total system performance assessment for radioactive waste disposal). Reference [17] also presents a series of example reference biospheres: stylized assessment biospheres that, in addition to illustrating the methodology, are intended to be useful assessment tools in their own right.

3.8. Evaluating whether or not the design will provide an optimized level of protection may require a judgement in which other factors will be considered. These factors may include, for example, the quality of the design and of the assessment and the presence of significant qualitative or quantitative uncertainties in the calculation of long term exposures. In general, when irreducible uncertainties make the results of safety assessment calculations less reliable, then comparison with dose or risk constraints should be treated with caution. For a borehole disposal facility, such circumstances are likely to apply when considering:

(a) Design evolution (see definition in Appendix III) at very distant times in the future;
(b) Very low frequency natural events;
(c) Human intrusion events.

3.9. With respect to para. 3.8(a), it is recognized that there is an irreducible uncertainty associated with dose calculations for individuals living far into the future and this uncertainty will increase as the assessment time frame[1] increases. Sometimes, the assessment time frame is specified by the regulatory body; more often it defaults to a time longer than that required to reach peak dose. In the case of geological disposal, assessment time frames of a million years are not uncommon. However, where the wastes to be disposed of in a borehole disposal facility are fairly short lived (i.e. a few tens of years), the assessment time frame could also be relatively short (up to some hundreds of years), thereby diminishing the uncertainty associated with the calculations.

3.10. Very low frequency natural events could degrade the borehole disposal facility barriers, leading to the release of radionuclides to the environment and the exposure of humans to radiation. In circumstances where there is a significant uncertainty associated with the occurrence of an event or process and the consequent exposures, the level of safety is best demonstrated by separate consideration of the probability of occurrence and the potential

[1] The assessment time frame is the time period used in the calculations for the post-closure performance assessment.

magnitude of exposures. In these situations, the treatment of exposures far into the future is considered conceptually similar to potential exposure situations and can be treated in a similar manner [18, 19]. Again, as far as boreholes are concerned, the relatively short half-life of typical waste envisaged for disposal and the consequently shorter assessment time frame will tend to diminish the significance of very low frequency natural events.

3.11. In the event of inadvertent human intrusion into a borehole disposal facility, a few individuals who take part in activities such as drilling or excavating into the facility could receive high doses. The doses and risks to these individuals should be estimated but, according to the latest ICRP recommendations [18], they need not be a deciding factor in assessing the safety and acceptability of the facility. The doses and consequences of such intrusion should be estimated in order to evaluate and determine the appropriate measures (administrative and physical) necessary to prevent intrusion or to mitigate its consequences. Once it is determined that the disposal system includes appropriate deterrents to intrusion commensurate with the safety requirements and the potential consequences of such intrusion, the dose estimates for an intruder need not be used further. The borehole disposal system has a number of inherent features that reduce the likelihood and the consequences of intrusion. These include:

(a) The low probability of occurrence;
(b) The fact that the individuals would be few in number;
(c) The possibility for such individuals to receive appropriate decontamination and medical treatment;
(d) The fact that such hazards may be comparable with other occupational risks;
(e) The possibility that, while doses received due to inadvertent intrusion could be high, the associated risk may be outweighed by the higher level of long term protection afforded by borehole disposal, in comparison with other strategies.

It should be noted, however, that these particular ICRP recommendations are not accepted by all regulatory bodies. Where these recommendations are not accepted, the consequences for the intruders of human intrusion will also need to be addressed.

3.12. A more significant consequence of intrusion is the possibility that it could disrupt the engineered barriers and cause long term harmful consequences for people living in the vicinity of the borehole. In this case, protection is best achieved by means of efforts to reduce the probability of such events. One option is to assess the consequences of human intrusion, for which one or two stylized human intrusion scenarios should be evaluated using the criteria described in Box 1 [18]. Other approaches to assessing the consequences of human intrusion may also be acceptable.

3.13. The small ‘footprint’ of a borehole disposal facility will help to reduce the probability of human intrusion and this can be reduced still further by increasing the depth and length of the disposal zone. Siting of the facility away from known mineral and water resources will also decrease the likelihood of human intrusion. Over shorter timescales, actions such as preserving records, placing restrictions on land use, placing warning signs and maintaining passive institutional control should also help to reduce the incidence of such events.

ENVIRONMENTAL AND NON-RADIOLOGICAL CONCERNS

3.14. In this section, the protection of the environment from the radioactive material in the borehole disposal facility, especially over the long term, is considered. An important additional consideration is the potential impact of non-radioactive substances in the borehole disposal facility. Other, more conventional, environmental impacts, for example, traffic, noise, visual amenity, disturbance of natural habitats and restrictions on land use, together with social and economic factors, may well be subject to regulatory approval, but these fall outside the scope of this Safety Guide.

3.15. In the past, it has been assumed that, subject to appropriate definition of exposed groups, the protection of humans against the radiological hazards associated with a borehole disposal facility would also satisfy the need to protect the environment [19]. The need to consider the protection of the environment against ionizing radiation and possible protection standards is currently under discussion internationally (see, for example, Ref. [20]) and developments are to be expected in this area. It is likely, nonetheless, that in most circumstances the protection of humans will also protect the environment. However, the expectation is that, in future, methodologies for the assessment of doses to other species will allow this to be demonstrated explicitly [21].

3.16. Consequently, while recognizing that estimates of future human doses/risks due to future releases from a borehole disposal facility may serve as indicators of environmental protection, additional indicators that do not rely on assumptions about human habits may also prove valuable. These indicators could include, for example, comparisons of repository derived radionuclide concentrations in environmental media with natural radionuclide concentrations and comparisons of radionuclide fluxes from a repository with fluxes from naturally radioactive mineralization [22].

3.17. The impact of non-radioactive materials present in a borehole disposal facility should also be assessed. Factors that should be considered may include the content of chemically or biologically toxic materials in the waste or in the engineered barrier materials, the protection of groundwater resources and the ecological sensitivity of the environment into which contaminants may be released. For example, if disused sealed sources were to be disposed of together with their lead shielding, safety assessments would need to examine the potential migration of the lead.

4. SAFETY IN THE PLANNING OF NEW BOREHOLE DISPOSAL FACILITIES

GENERAL

4.1. This section provides guidance on how, for a new borehole disposal facility, the predisposal activities may be organized to deliver the required operational and post-closure safety (i.e. how the protection requirements and associated criteria specified and discussed in Section 3 may be satisfied).

4.2. The guidance is set out under four main headings: (i) legal and organizational framework, (ii) safety approach, (iii) safety design principles and (iv) security.

LEGAL AND ORGANIZATIONAL FRAMEWORK

4.3. The discussion of the legal and organizational framework is subdivided into the responsibilities of government, regulatory bodies (‘the regulatory body’), facility developers and operators or would-be operators (‘the operator’) and waste generators. The overall aim is that the safety and security of potential radioactive waste should be provided for at all stages of waste management from creation through to disposal. Particular attention should be given to the issues of the appropriate legal and regulatory framework and the allocation of adequate financial resources. Funds will be required for disposal and for regulatory review and assessment. Consideration should be given as to when and how financial and legal responsibilities for the waste might pass from one body to another.

Government responsibilities

4.4. General requirements for establishing a national system for radioactive waste management are set out in Ref. [23]. In addition to the development of the necessary technical and operational capability, ensuring the safe management of radioactive waste requires relevant laws and regulations, a regulatory body that is independent of the operator, and a regulatory process that defines the steps to be taken in the licensing and development of the facility. Legislation should require a demonstration of safety and should require that the demonstration be independently reviewed by the regulatory body. Such provision is a principle of the Safety Fundamentals [13], is also required under the terms of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management [1] and is a requirement for government responsibility for geological disposal established in Ref. [8].

4.5. The effort required under the legal and regulatory arrangements for controlling radioactive waste disposal in boreholes should reflect the potential hazard represented by the waste. Where small scale disposal of disused sealed radioactive sources is envisaged, the extent and complexity of the legal and regulatory arrangements should be commensurate. Matters that should be considered in the formulation of a national policy for radioactive waste management include the following:

(a) The early establishment of a comprehensive national inventory of radioactive waste will help to ensure that the resources and the facilities envisaged to deal with the waste will be adequate so that, for instance, late design changes are not introduced to cope with initially unforeseen waste. In general, it is the amount (i.e. volume, activity) and nature (e.g. half-life and physicochemical properties) of the inventory that should largely determine the resources needed for its disposal.
(b) The definition of the overall process for the development of borehole disposal facilities should clearly specify the legal (e.g. licensing) requirements at each step (see para. 5.1).

(c) The means of making the necessary scientific and technical expertise available to both the operator and the regulatory body should be considered. For instance, the government may require the national institutes for geology and hydrology to maintain or develop competence in this field so that they can give support to the regulatory body.
(d) The interdependences between the various steps in the waste management process should be considered so that, overall, the safety and the effectiveness of radioactive waste management are balanced.

4.6. The national policy and regulations should include the establishment of an operator with appropriate duties and responsibilities. This may, for instance, be a government department that then designates or subcontracts an expert body (or bodies) to design, build and operate the required facilities.

Responsibilities of the regulatory body

4.7. The regulatory body should advise the government on the necessity for, and the effectiveness of, the national policy for radioactive waste management and should provide assistance in its updating and improvement.

4.8. As with any other practice for radioactive waste disposal, the regulatory body should establish regulatory arrangements for borehole disposal facilities (see, for example, the requirements for regulatory body responsibility for geological disposal established in Ref. [8]). The regulatory arrangements should be established after consultation with all interested parties and they should be settled well in advance of any licence application. The arrangements should cover all stages of the development process for the facility, specifying the principles, requirements and criteria that will be used to regulate the practice and stating what should happen in the event of non-compliance. The arrangements should also cover more general issues such as:

(a) Clearance levels for waste with very low levels of radioactivity and the arrangements for regulating the release of such material [24];
(b) Regulatory approval of storage of radioactive waste prior to disposal;
(c) Licensing of borehole disposal at an existing radioactive waste disposal facility.

4.9. The regulatory body should also provide guidance on the implementation of the regulations, on the procedures that the operator is expected to follow in terms of licence applications and safety case submissions, on the timescales likely to be required for consideration of the licence application, and on the likely duration of any period of institutional control. While the regulatory arrangements should be comprehensive, they should also be commensurate with the scale and potential hazard of the facilities under regulatory control.

4.10. A licence for construction and operation of the facility will be issued only when, following regulatory review and assessment of the licence application, there is reasonable assurance that the safety requirements will be met and it is clear that funds are, or will be, available to finance the programme through all its stages (i.e. construction, operation, closure and any planned post-closure institutional control period). As explained in para. 5.1, a step by step approach to licensing and implementation should clarify the decision making process and highlight the key issues that will influence the various decisions. The licence application at each step should describe, as far as is known, the entire disposal programme so that early steps in the disposal programme can be seen to be compatible with later steps.

4.11. It is good practice for the licence to have sufficient flexibility to accommodate, through a change control process, unforeseen changes (e.g. in design) made as a result of improved knowledge. The conditions under which the operator can make changes without needing to apply to the regulatory body for permission should be specified in the licence. The burden imposed by the change control process should be commensurate with the size of the potential hazard.

4.12. Independent regulatory review and evaluation of the safety case (see paras 5.12 and 5.13) may vary considerably depending on the existing national regulatory practice, the potential hazard of the waste and the stage reached in the development process of the facility. The regulatory body should ensure that it has the independent capability to carry out the review and evaluation of the safety case that is needed to determine whether the facility will be safe and what conditions of authorization should be specified in the licence. This may be undertaken in various ways, such as by consultation with independent experts, by collaboration with other States that are using similar processes and by the use of generic safety assessment.

4.13. When it is envisaged that a disposal facility will remain in operation for some years, with new boreholes being added from time to time, safety should be reassessed periodically. Alternatively, the licence could approve the site but require that each new tranche of boreholes be licensed separately. This would allow the regulatory body formally to reassess safety as operation of the site yields new data and as safety standards are developed. Either way, requirements for the reassessment of safety should be made clear early in the development process for the facility.

4.14. The regulatory body should ensure that the operator exercises adequate control at all stages in the development of the borehole disposal facility. A regulatory inspection plan should be developed for activities important to safety, such as construction, operation and closure. The regulatory inspections will help to ensure compliance with the licence and the operational procedures (e.g. acceptability of waste packages and their satisfactory emplacement). Appendix I provides an example of a regulatory inspection plan for a borehole disposal facility. When non-compliances are discovered, the actions required by the regulatory body should reflect the safety significance of the non-compliance. Very serious cases should result in activities at the site being restricted or curtailed. Minor breaches may simply require remedial action.

4.15. In some States, it is normal for borehole or surface disposal facilities that have been closed to be periodically reassessed for safety in the light of monitoring results and such good practice should be adopted.

Operator responsibilities

4.16. The requirements for operator responsibility for geological disposal established in Ref. [8] place an obligation on the operator to develop a disposal facility that is both practicable and safe and to demonstrate its safety in compliance with regulatory requirements. In some cases, this may include collection of the waste at the waste generators' premises and its transport to the disposal site. In meeting this obligation, the operator should take into consideration the characteristics and quantities of disused sealed sources that are radioactive and other radioactive waste to be disposed of, the transport infrastructure, the sites available, the drilling and engineering techniques available, research needs and the national legal framework and regulatory requirements. Where the operator employs contractors to perform the work, the operator is responsible for ensuring that they also comply with the regulatory requirements.

4.17. The operator is charged in particular with the responsibility for preparing and submitting to the regulatory body a safety case (see paras 5.2–5.13) on which decisions about the development of the disposal facility can be based. Borehole construction should not proceed until a licence has been granted.

4.18. The operator should be responsible for conducting or commissioning the research and development needed to support the feasibility and safety of the facility design. This should include site investigations. The operator also has the responsibility for carrying out or commissioning all the investigations of sites and materials necessary to assess their suitability and to provide data for safety assessments. In the case of borehole disposal facilities, it is envisaged that the designs will rely almost entirely on tried and tested materials and working practices. This will largely confine research to desk studies and will shift the emphasis of the work towards demonstrations of the operability of the design and the suitability of the site.

4.19. The operator should establish and set limits, controls and conditions (e.g. technical specifications) derived from the safety assessments to ensure that the disposal facility is developed and operated in accordance with both the safety case and the licence conditions. This will require the recruitment and training of suitably qualified staff, the exercise of due control over the receipt, transport and emplacement of waste (e.g. waste acceptance criteria, see para. 5.60), and the implementation of appropriate security measures. Any changes to the design or operation of the facility that may have a potential impact on safety should be subject to a change control process (see para. 4.11).

4.20. The operator should retain all the information relevant to the safety case, the supporting safety assessments for the disposal facility and the inspection records that show compliance with regulatory requirements and the operator's own specification, at least up until the information is superseded or responsibility for the disposal facility is passed to some other appointed agency (e.g. at closure). When this responsibility is transferred, the operator should hand over all the information that is relevant to the safety of the facility. The operator should also cooperate with the regulatory body and supply all the information that the regulatory body may require to fulfil its responsibilities. The operator should report to the regulatory body on a regular basis and should report on non-compliances as they occur.

4.21. The operator should take full responsibility for the waste upon receipt. The operator should also have the responsibility for verifying that the waste is fully and correctly described in the accompanying documentation. The description may include the dose rate at the surface of the package and at 1 m distance, as well as details of removable surface contamination, volume, mass and physical status, and chemical and radionuclide composition of the waste.

Responsibilities of the generator of the radioactive waste

4.22. The generator of the radioactive waste should work with the regulatory body and the operator to ensure that the waste can be safely managed through all steps of the waste management process. In recognition of the interdependences between the various steps in waste management from waste generation to disposal, in making decisions relating to one step, the impacts and/or the needs of subsequent steps should be considered. This will require coordination of activities and the timely exchange of information. The generator of the waste should not treat, condition (including encapsulation) or store the waste in an inappropriate way or do anything that will make the waste more difficult to manage at a later stage in the waste management process.

4.23. The generator of the waste should characterize the waste and treat and condition it to ensure compliance with the waste acceptance criteria that are specified by the operator and approved by the regulatory body (see paras 5.60–5.65), unless this is the responsibility of the operator. Adequate characterization, treatment and conditioning may be ensured by independent inspection and audit of the various processes and representative sampling from the waste packages that have been produced.

4.24. Generators of waste should also maintain records. For sealed sources, for instance, purchase details should be preserved, together with a history of their usage, and instances of damage especially should be recorded. The generator of the waste should also have responsibility for the safe transport of the waste to the operator's site, unless the operator takes over this responsibility before the waste leaves the premises of the generator of the waste.

SAFETY APPROACH

4.25. Even a relatively straightforward borehole disposal facility may take several years to develop. Key decisions, for example, on siting, detailed design, construction, operational management and closure, are expected to be made as the project develops. Decisions will be made on the basis of the information available at the time and the confidence that can be placed in that information. Decisions on facility development will be influenced by external factors, such as national policies and preferences and the availability of a suitable host geology.

4.26. In accordance with the requirements concerning the importance of safety in the development process established in Ref. [8], at each major decision point, the safety implications of available options are considered and taken into account. Ensuring safety is the overriding factor at each decision point. If more than one option is capable of providing the required level of safety, then other factors may also be considered. These other factors may include public acceptability, cost, security, site ownership, existing infrastructure and transport routes.

Passive safety

4.27. A borehole disposal facility should be sited, designed and constructed so that, when closed, the post-closure safety of the facility will not depend on actions that would need to be taken after the closure. This allows the facility to comply with the requirements concerning passive safety established in Ref. [8].

4.28. The requirement to provide for safety by means of passive design features means that for the post-closure period there should be no need for active management of a borehole disposal facility once this phase is reached. For boreholes of an intermediate depth (i.e. boreholes where the waste is placed more than 30 m below the surface), the natural and engineered characteristics of the closed disposal system should be sufficient, on their own, to ensure the safety of the waste and the protection of people and the environment. In the case of near surface boreholes (where waste is less than 30 m below the surface), institutional control to reduce the risk of human intrusion may also be an element of the safety case. Near surface boreholes are not likely to be suitable for waste that would pose unacceptable risks associated with human intrusion or security. Institutional controls and monitoring are discussed further in paras 5.68–5.80.

4.29. In practice, even for intermediate depth boreholes, passive institutional controls, including controls on land ownership and restrictions on land use, could be maintained for some time after closure of the facility to reduce further the possibility of inadvertent intrusion and to provide additional public assurance. This would facilitate, among other things, monitoring for the purpose of providing assurance and confidence in the safety of the facility.

4.30. Regardless of the degree and duration of post-closure institutional control, safety assessments should be conducted with the aim of providing reasonable assurance of an adequate level of passive safety for boreholes of both types. Factors contributing to passive safety include the use of chemically stable waste forms, high integrity containers, borehole backfill between the containers and the borehole casing, disposal at a depth greater than 30 m, non-chemically reactive groundwater, stable geology and disposal in a location that benefits from a low probability of human intrusion.

4.31. Passive safety is not a requirement for the operational period, although, clearly, if the operational activities are organized to reduce the number of active measures needed to ensure safety, this will be beneficial. An example is the incorporation of shielding in packages to allow them to be contact handled. Passive safety is also assisted by keeping the operational period short. For instance, to avoid keeping a borehole open for an extended period, it may be preferable to drill, construct, emplace, backfill and close a borehole only when there is sufficient waste for disposal to allow this full sequence of activities to be enacted. This may require the capability to store the waste safely at the facility for a period of time.

Adequate understanding of, and confidence in, safety

4.32. A borehole disposal facility should be designed and sited so that there is sufficient understanding of the features, events and processes that influence post-closure safety to gain the reasonable assurance of safety that is required to be established. This understanding should cover the time period during which the waste constitutes a significant potential hazard or, at least, over the time frame of the post-closure safety assessment (which may be fixed by regulation or agreed with the regulatory body).

4.33. The understanding of the behaviour of the system in the post-closure period will evolve as more data are accumulated and as scientific knowledge is developed. Early in the development of the concept, the data and understanding should be sufficient to give the confidence necessary to commit the resources to further investigation. Before the start of construction, during emplacement and at closure, the understanding embodied in the safety case should be sufficient to give reasonable assurance that the relevant regulatory requirements will be satisfied. Demonstrating reasonable assurance entails the presentation of an assessment of the safety of the total disposal system together with the uncertainties in the assessment. This will be facilitated by identifying the system's features and processes that provide safety and also the external features, events and processes that might be detrimental to safety, and showing that these and their interactions are sufficiently well characterized and understood.

4.34. A database of features, events and processes relevant to near surface disposal is under development by the IAEA [25]. This constitutes a useful starting point for the compilation of a list of features, events and processes for borehole disposal. Which features, events and processes are relevant and which are not will depend on the specific circumstances. Some features, events and processes will clearly need to be incorporated into the post-closure safety assessment. Radionuclide solubility, for instance, will almost always be included. Other features, events and processes will clearly not be relevant. For the majority of features, events and processes, though, the question of whether to include them or not will be a matter of judgement. Guidance can be obtained by referring to previous examples of safety assessments (see, for example, the generic borehole post-closure assessment described in Ref. [26]). Most important of all is the acknowledgement of the exclusion or omission of any features, events and processes, together with the underlying reasoning.

4.35. Confidence in post-closure safety is considerably improved by the adoption of methodologies that are both comprehensive and systematic. Useful guidance in this connection has been provided by the OECD Nuclear Energy Agency [27] and through the IAEA's ISAM project [28]. Paragraph 5.2 of this Safety Guide further discusses this aspect.

Optimization of protection

4.36. Ensuring that doses will be below the regulatory approved dose constraints is a necessary but not by itself sufficient condition for regulatory approval. This is because, for the optimization of protection, it is required that if safety can be enhanced without undue detriment, then it should be, economic and social factors being taken into consideration. Optimization of protection will often be judgemental because the decision on when a detriment changes from being acceptable to being undue will ultimately depend on the individual circumstances and the value judgements of those doing the judging. It follows that the optimization of protection is an issue that should be discussed in the light of the individual circumstances and, wherever possible, agreed in advance with the regulatory body. Safety assessments provide some of the most important inputs to the process of optimization.

4.37. The optimization of protection during the operational phase of a facility is a key element of the design of the disposal facility itself, the predisposal facilities and the above ground operations. Relevant considerations include the separation of drilling and waste emplacement operations, the use of remote handling and radiation shielding during predisposal and disposal operations, the control of working environments, the reduction in the potential for accidents and their consequences and the minimization of maintenance requirements in radiation and contamination areas. Many of these issues are common to the operation of nuclear facilities generally and guidance is available [29].

4.38. The optimization of protection for the post-closure period entails taking judgemental decisions [18]. However, a judgement on whether protection for a proposed disposal facility has been adequately optimized or not should still be capable of resolution using objective criteria. Protection should be deemed to be optimized if all the following conditions are met [18], namely, that:

(a) Due attention has been paid during the development process to the post-closure safety implications of the various options, which should include all the design and siting related issues discussed in paras 5.14 and 5.20;
(b) The assessed doses and risks fall below the relevant constraints;
(c) The probability of any events that might give rise to doses above the dose constraint has been reasonably reduced by means of siting or design;
(d) The design, construction, operation and closure programmes have been subjected to a management system which will ensure the necessary level of quality in safety related aspects of the project.

4.39. In some cases, there may be competing demands between operational and post-closure safety. A higher standard of packaging (e.g. a fully welded container or waste treatment to avoid gas generation) may benefit post-closure safety at the expense of somewhat higher occupational doses during predisposal activities (though doses should still fall below the regulatory dose constraint). It should be the responsibility of the operator to design the facility so that an appropriate balance is reached between any competing demands.

SAFETY DESIGN PRINCIPLES

4.40. In general, post-closure safety is achieved by designing and implementing a disposal system in which the components work together to provide and ensure the required level of protection. This approach offers flexibility to the designer of a borehole disposal system to adapt the facility layout and engineered barriers to take advantage of the natural characteristics and barrier potential of the host environment. Operational safety should also be ensured and this may require consideration of a number of complex issues, including the possible impact of predisposal and disposal operations on the post-closure performance.

Containment

4.41. The requirements concerning containment established in Ref. [8] call for the engineered barriers[2], which include the waste form and packaging, to be designed and the natural barriers to be selected to provide containment of the radionuclides in the waste, especially during the initial period when the level of activity is most intense and radioactive decay can significantly reduce the hazard posed by the waste. This will allow the majority of shorter lived radionuclides to decay in situ. At the same time, release of gaseous radionuclides and a small fraction of some other highly mobile species may be inevitable from waste package of some types, but generally these radionuclides present relatively minor radiological hazards. In any event, the safety assessment should demonstrate that doses and risks arising from such releases fall within the regulatory constraints.

4.42. Waste of higher radiotoxicity, which may include some disused radioactive sources, can be surrounded by an encapsulation matrix and placed in durable containers. The purpose of the encapsulation matrix is to contain the radionuclides in the waste through a combination of physical and chemical functions that are effective for hundreds or even thousands of years. Other engineered barriers, such as a borehole backfill, may allow this containment period to be extended even further, but complete containment of all radionuclides for all time cannot be expected. Containment of radionuclides is also provided by the natural barriers by means of geochemical and physicochemical retention processes that lead to retardation of the transport of radionuclides in the geosphere. Evidence from natural analogues indicates that these processes can be effective over very long timescales.

4.43. A distinguishing feature of borehole disposal is that it is not limited to the depth ranges considered for near surface disposal (metres to tens of metres) or geological disposal (hundreds of metres). On the contrary, it may be relatively straightforward and cost effective to select an appropriate geological horizon (and therefore a suitable hydrogeological condition) for the disposal, with due consideration given to the containment of radionuclides and their isolation from humans. It is envisaged that the appropriate depth would lie in an

[2] A barrier in this context is a physical obstruction that prevents or inhibits the movement of radionuclides, or provides shielding against radiation. There are two types of barrier: engineered barriers and natural barriers. In this context, a barrier is a physical entity that provides, or contributes to, safety.

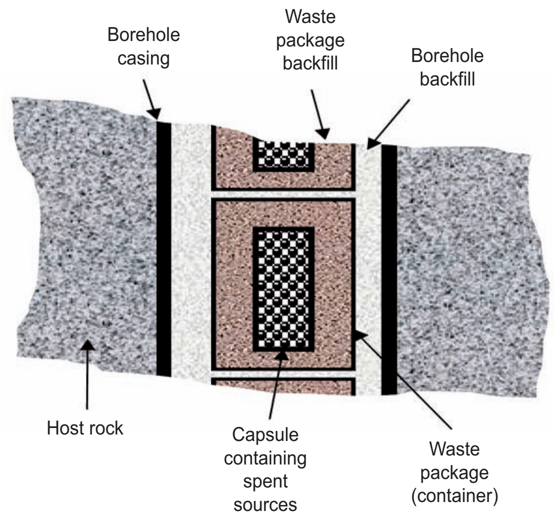

FIG. 2. Scheme of some possible components of a borehole disposal system.

intermediate depth range (e.g. 30 m to a few hundred metres), between near surface and deep geological disposal. Figure 2 shows some typical components of a borehole disposal system.

Isolation

4.44. While containment refers primarily to the radionuclides in the waste, isolation is more concerned with the waste itself and the need to keep this potentially dangerous material away from humans, human influence, resources used by humans and the biosphere for as long as it remains a significant hazard. The isolation period of 'several thousand years' mentioned in the requirements concerning containment established in Ref. [8] would not apply if the radionuclides in the waste were short lived. In choosing sites, consideration should be given to erosion, tectonic uplift and landslip that might cause the waste to be brought close to the surface over the assessment period. One of the aims of isolation is to prevent human intrusion, which could affect the subsequent isolation of the waste and containment of the radionuclides within it. It is clear that isolation is also important in promoting security. While human intrusion is inherently unpredictable, some actions can be taken at the design stage to lessen both its probability and its consequences. If possible, for instance, borehole disposal facilities should be located away from known underground mineral and water resources. In general, disposal at greater depth should improve security and should help to reduce both the probability and the consequences of human intrusion.

4.45. In the absence of institutional control, a depth of 30 m should be considered the minimum necessary to achieve waste isolation. This should therefore be the minimum depth required for waste that might constitute a security risk (see paras 4.52–4.54). However, for waste that would otherwise be eligible for near surface disposal and for short lived radionuclides, where the waste may no longer constitute a hazard after, perhaps, one hundred years, disposal at a shallower depth together with institutional control could be an option. Engineered anti-intrusion barriers that are mechanically strong and heavy may also be useful in enhancing isolation. For a small scale borehole disposal facility, the resources needed for institutional control could be reduced by locating the boreholes at a site with an existing security infrastructure, for example, at an existing nuclear facility.

4.46. For waste placed deeper than 30 m, isolation is primarily provided by the geosphere and the main factors to be considered in determining a depth that will provide an appropriate level of isolation are the rate of surface erosion, the timescale of the assessment and the depth of any permafrost. Of course, isolation is not the only issue to be considered when determining borehole depth: the influence of the host geological environment on containment should also be considered.

Multiple safety functions

4.47. A safety function is a specific purpose that must be accomplished for safety; the safety function could be provided by a physical or chemical quality or process that contributes to safety. Examples of safety functions include low groundwater flux, impermeability to fluids, resistance to corrosion, insolubility of radionuclides, adsorption of radionuclides onto engineered materials and surrounding rocks and disposal in geological formations having a low groundwater flow. In the case of a near surface disposal facility (i.e. where the waste is within 30 m of the surface), it is reasonable for administrative measures (i.e. an institutional control period during which the waste decays to insignificant levels) to provide a safety function [9].

4.48. To provide confidence in long term safety, a waste disposal system should employ a number of complementary engineered and natural barriers. Often, these barriers will be effective over different timescales and will provide a number of safety functions. Depending on the hazards associated with the waste, the barriers may vary in number and complexity. They may include, for instance:

(a) A waste container made of a corrosion resistant material that gives a container lifetime of about a thousand years;
(b) A cement based backfill placed between the container and the borehole casing to create high pH conditions that limit solubility and promote sorption and so provide chemical containment for thousands of years;
(c) A location where the rate of groundwater movement and the degree of radionuclide sorption onto the surrounding rocks together ensure that the radionuclides would take many thousands of years to migrate to the biosphere.

4.49. Although the safety of a borehole disposal facility will ultimately be judged by global measures of the total system performance, these barriers should not be unduly dependent on each other. So, for instance, in the example just outlined, the container lifetime may be extended by the high pH conditions provided by water leaching from the cement backfill, and the longevity of the backfill will be assisted by low groundwater flow. However, a groundwater flow that is higher than expected should not result in rapid corrosion of the container and the release of its contents. Similarly, failure of the cement to provide the expected high pH conditions should not lead to failure of the container or a more rapid migration of radionuclides through the surrounding rocks. These unwanted possibilities could be prevented by using a container material that shows adequate corrosion resistance over a range of pH conditions and sufficient cement backfill to provide long lived high pH conditions even if the groundwater flow were at the top end of the range of possibilities. In this way, a worse than expected performance from one of the barriers would not lead to the failure of the entire system.

4.50. Multiple barriers and multiple safety functions should be used to enhance both safety and confidence in safety by ensuring that the overall performance of the disposal system is not unduly dependent on a single barrier or function. This should provide reasonable assurance that, if a barrier does not perform as expected, then a sufficient margin of safety remains (see the requirements for multiple safety functions established in Ref. [8]).

4.51. The various components of the engineered and natural systems also need to be complementary. Examples of non-complementary components are:

(a) The use of ordinary Portland cement when the surrounding groundwater or geology has high levels of sulphate (common in some types of clay);
(b) The use of swelling clays in highly saline environments or in groundwater with high levels of potassium.

SECURITY

4.52. It is a requirement of the BSS that "sources shall be kept secure so as to prevent theft or damage…" (para. 2.34, Ref. [7]). The operator of a borehole disposal facility will be responsible for the security of the waste from the time it is received from the waste generator. If the handover occurs at the waste generator's premises, the operator will also be responsible for the safety and security of the waste during its transport through the public domain to the waste conditioning and/or waste disposal site [30]. Precautions should be taken at the disposal site to prevent persons from carrying out unauthorized actions that might jeopardize safety or allow unauthorized removal of the waste [31]. The extent of security arrangements should reflect the potential for damage to the facility and the assessed risk of unauthorized removal of the waste. The arrangements should, at least, include measures to prevent unauthorized access to the site during site operations. Clearly, waste such as high activity disused sealed radioactive sources will require stricter security than low level waste. Arrangements and appropriate liaison with competent authorities should be established to obtain timely assistance if this is required.

4.53. In the case of disposal in near surface facilities, the proximity of the waste to the surface may make it appropriate for security measures to be continued into the post-closure period to prevent human intrusion and/or unauthorized removal of the waste. The security measures would remain in place until the sources no longer constituted a potential hazard. In general, waste that constitutes a significant security risk (e.g. sealed radioactive sources for which the radioactive material is in a dispersible form) will not be suitable for near surface disposal.

4.54. Even where all the waste in a borehole disposal facility is placed at a depth of more than 30 m, a site security presence will be required throughout the operational period. In cases where disposals occur in a series of campaigns, it may be preferable to seal all the boreholes that contain waste at the end of each campaign. Subsequent sealing of the boreholes (para. 5.53) and closure of the site (para. 5.66) should aim to allow the lifting of security measures at the site.

5. SAFETY AND DISPOSAL IN NEW BOREHOLE DISPOSAL FACILITIES

FRAMEWORK FOR DISPOSAL

5.1. Consistent with requirements for step by step development and evaluation in Ref. [8], the appropriate framework for the development of a geological disposal facility is a step by step approach that is supported, through all stages of the project, by iterative evaluations of the design and management options, system performance and overall safety. This is necessary owing to the extensive investigation and assessment required to provide sufficient confidence to move through the various stages in the lifetime of the facility and associated licensing activities. The development framework will normally be specified in the governing legislation. A step by step process for a small disposal programme will need less investigation and assessment, and an example of an appropriate programme is provided in Appendix II.

SAFETY CASE AND SAFETY ASSESSMENTS

General

The safety case

5.2. The safety case comprises the collection of arguments and evidence that describe, quantify and substantiate the safety, and the level of confidence in safety, of a radioactive waste disposal facility. The safety case is an essential input into all the important decisions and authorizations that concern the facility. It provides the arguments as to why the facility is considered to be safe and includes the safety assessment (see below) and other analyses explaining the relevance of the various arguments and their strengths and weaknesses. After disposal, some of the information in the safety case, specifically that concerned with the post-closure safety of the facility (see paras 5.68–5.73 on post-closure institutional controls), should be preserved for the benefit of future generations. This information should be defined, compiled and placed in suitable storage (e.g. a national archive).

5.3. The safety case may also need to cover other issues arising from legislation on environmental impact assessment and, less formally perhaps (though no less importantly), the need for public acceptance.

5.4. The safety case should be a ‘living document’ that is developed in parallel with the development programme for the waste disposal facility. Regardless of the stage that the programme has reached, a safety case submitted for regulatory scrutiny should cover the complete programme (even though this may not have been fully developed) so that the regulatory body can put the licence application into its correct context. This includes areas where there are significant uncertainties and the work planned to reduce them. The overall aim is to demonstrate, with a level of confidence appropriate to the stage that the programme has reached, that the complete programme is feasible and can be completed to plan.

Safety assessment

5.5. Safety assessment is an essential part of the development of any radioactive waste disposal facility. It can be used to examine the safety of a complete proposal or any aspect of it, such as transport, operation or the post-closure period, or any part of these. The step by step approach encourages the various iterations of the safety assessment to be progressively developed as the project moves through its different stages. Early in the process, the safety assessment will tend to be generic (i.e. non-site specific). Later, the safety assessment will become progressively more site specific. Safety assessment provides inputs to ongoing decision making in relation to, for example, the selection of conceptual designs, guidance of research, site selection, site characterization, development of assessment capability, allocation of resources (including funding) and the development of waste acceptance criteria. The safety assessment will also identify key safety relevant processes and contribute to developing an understanding of the operational safety of the disposal facility and its post-closure performance. This understanding provides the basis for the safety arguments presented in a safety case.

5.6. The timing and level of detail of the safety assessment are a matter for the operator in consultation with the regulatory body. In the case of a small scale borehole disposal facility, where the small inventory results in the calculated dose falling well below the regulatory constraint (i.e. there is a large margin of safety), it is likely that the safety assessment and the associated investigations would be relatively simple. Appendix III provides further information on the safety case and safety assessment for borehole disposal facilities.

Generic safety assessment

5.7. Generic (i.e. non-site specific) safety assessment is a tool that can be used in many aspects of a waste disposal programme. For example, at the concept development stage and in support of site screening, generic safety assessment can be used:

(a) To help identify radionuclide inventories suitable for disposal;
(b) To help determine suitable levels of engineering;
(c) To help determine suitable site characteristics;
(d) To help determine the need for, and duration of, an institutional control period.

5.8. Even when a site has been chosen for investigation, generic safety assessment may help in:

(a) Identifying the key parameters that need to be characterized for a site specific assessment and the extent of site characterization required;
(b) Providing a basis, consistent with good practice, for any site specific assessment that might be undertaken and helping to build confidence in that site specific assessment.

In such cases, rather than developing a site specific safety assessment, it could be sufficient to undertake site specific investigations to confirm that the site conditions, design and inventories fall within the generic safety assessment's envelope of assumptions and data.

5.9. Generic safety assessment in general may also be used to examine operational and transport safety (see, for example, Refs [32] and [33]), and a separate report has been developed on such a generic safety assessment for the small diameter borehole concept design. The annex to this Safety Guide is based on a report on generic safety assessment.

Site specific safety assessment

5.10. Once a site has (or sites have) been selected for detailed investigation, post-closure safety assessment (in particular) will be an important determinant for the site characterization programme(s). By replacing some of the generic information contained in the safety case with site specific information, the site specific safety assessment covering all aspects of safety can then be developed with the aim of determining whether disposal facilities constructed at a site would be capable of meeting the regulatory requirements. These site specific safety assessments will be an important component of the safety case for the site. Where a generic safety assessment has been performed, it may be possible to simplify the site specific assessment by limiting it to a confirmation that, in all important respects, the safety of the proposed facility is adequately described by the generic safety assessment.

5.11. Where it is proposed to create a borehole disposal facility at an existing near surface disposal site, the impact of the borehole disposal facility on the safety of the near surface facility and vice versa should be considered. This may be best done by modifying the existing safety assessment to include the proposed borehole disposal facility. A relatively straightforward modification of the safety case may be possible in the case where the proposed borehole contains similar waste which is emplaced at a depth similar to that of the near surface facility. Where the proposed borehole extends to greater depths, the effects on the safety case will be more far reaching, since the consequences of placing radionuclides in a different geological and/or hydrogeological horizon should be considered.

Independent review and assessment

5.12. The operator of a borehole disposal facility should submit the safety case and its associated safety assessment to the regulatory body for independent review and assessment. The principal aim of the review is to judge the quality of the safety case in the context of the regulatory requirements and the stage that the project has reached. Essentially, this requires an examination of the arguments, data and level of understanding (e.g. uncertainties) presented by the safety case.

5.13. Independent review and assessment should judge, among other things, whether:

(a) The safety requirements will be complied with.
(b) The safety case contains sufficient detail.
(c) The data and information presented are sufficiently accurate.
(d) The safety case demonstrates that the design has been optimized and, with reasonable assurance, that the safety objectives and criteria will be met.
(e) The management system(s) is adequate (in this regard, separate Safety Guides are available for predisposal [34] and disposal activities [35]).
(f) The arrangements proposed for the preservation of records are adequate (more detailed guidance on this subject is presented in Ref. [35]).

DEVELOPMENT OF BOREHOLE DISPOSAL FACILITIES

Design of the disposal facility

General design considerations

5.14. Safety assessment is an important tool for demonstrating the optimization of the facility's design. The expected performance of the natural barriers in containing radionuclides will have implications for the required level of engineered containment and the way in which waste emplacement and borehole sealing operations and closure should be carried out. The choice of design for a borehole disposal facility will depend on many factors, including the quantity and nature of the waste to be disposed of, the availability of suitable disposal environments and the availability of appropriate engineering technologies and materials.

5.15. An important issue that should be decided relatively early in the programme is the selection of an appropriate design of waste package, i.e. the container and its contents. This is essential for both the predisposal and the disposal periods as it provides containment for the waste during storage, transport, disposal operations and the post-closure phases. Factors such as the amount of in-built shielding (and therefore the need to handle the waste package remotely) and the dimensions and weight of the waste package, lifting and handling arrangements, corrosion and radiation resistance and the method of emplacement in the borehole will all have an influence on operational feasibility and safety (see the discussion on the operation of the disposal facility in paras 5.39–5.59). The long term performance of the waste package may play an important part in the post-closure safety of the disposal system. The durability of the waste package will depend on the properties of the materials used in its construction and their interactions with the other engineered barriers and in the geochemical environment.

5.16. During the early development of the borehole disposal facility, a number of site, design and operational options will be available. Choices should be made with a view to striking an optimum balance of operability, containment and isolation within reasonable financial cost. The multiple safety function approach should be utilized so that the safety of the facility does not depend unduly on a single barrier or a single chemical or physical property. Safety assessment should be used to examine the various design options: first, to see whether compliance with the regulatory constraints is achievable, and second, to help deliver the constrained optimization described in paras 4.36–4.39.

5.17. It is likely that the operator will be given the task of disposing of a known volume and inventory of waste. The operator should then design a facility consisting of a single borehole or a series of boreholes to accommodate this waste. Clearly, there are many ways of doing this, ranging from a large number of small volume boreholes to a single, deep, large diameter shaft. The optimum design will depend on the individual circumstances, but some general points can be made:

(a) The risk arising from human intrusion will be reduced when the 'footprint' is small and the waste is placed below the residential intrusion zone.
(b) An increasing depth of disposal will usually increase the transit time for radionuclides to migrate to the surface; the main exception to this is when disposal at a lesser depth would allow disposal in the unsaturated zone or in very low permeability rocks.
(c) The variable cost component of excavation increases approximately exponentially with depth.

Choice of engineered barriers

5.18. The engineered barriers can provide a significant degree of containment for the radionuclides in the waste. The use of corrosion resistant materials should allow the engineered barriers to be sufficiently long lived to make a useful contribution to safety. Thus, the safety case should be able to take some credit for a period of containment within the package itself. The engineered barriers may include (see, for example, Fig. 2):

(a) The original casing (for disused sealed sources).
(b) Welded metal (e.g. plain carbon or stainless steel) capsules for some small volume waste (e.g. radium sources).
(c) A metal (e.g. plain carbon or stainless steel) waste container.
(d) An encapsulation matrix (e.g. cement grout, bentonite or lead) within which radioactive waste (e.g. radium sources) may be embedded, creating the waste form within the container[3].
(e) Borehole backfill (e.g. cement grout) surrounding the waste packages.
(f) Metal or plastic borehole casing to support borehole walls during drilling or emplacement operations; following waste emplacement, it may be beneficial to remove the casing above the disposal zone.
(g) Behind casing seal to fill any voids between the casing and the borehole.
(h) Borehole seal — a clay or cement plug several metres long placed in the borehole above the disposal zone (which can sometimes be complemented by a plug at the bottom of the disposal zone).

5.19. The effectiveness of, and confidence in the effectiveness of, the engineered barriers will be greatest when they employ a range of chemical and physical properties to contain the radionuclides. So, for instance, whereas the role of the waste container is primarily one of physical containment, a cement based encapsulation matrix can provide some chemical containment by reducing radionuclide solubility and providing surfaces that radionuclides can sorb onto. An important consideration in the choice of engineered barriers is their compatibility with the surrounding geochemical environment (e.g. para. 4.51) and their durability and integrity over the period of time for which the waste remains hazardous.

Site selection

5.20. In locating a suitable site for a borehole disposal facility, due consideration should be given to scientific, technical, socioeconomic and planning factors. Sites may be identified as possible sites in the selection process because they are on the locations of existing nuclear, waste

[3] The waste package is defined as the product of conditioning that includes the waste form and any container(s) and internal barriers (e.g. absorbing materials and liner), as prepared in accordance with requirements for handling, transport, storage and/or disposal. This includes an outer container and, if included, an encapsulation matrix that fills the void space within the container. The waste form is the combination of waste and waste encapsulant.

management or governmental facilities and such sites are sometimes given a high weighting on the grounds of availability, practicality, transport needs and existing institutional control. A well-planned systematic approach will help with the site selection process and will provide opportunities for the involvement of stakeholders (interested parties). Meeting the required safety objectives is a primary consideration in site selection and the rest of this section focuses on this aspect.

5.21. General guidelines for siting radioactive waste disposal facilities are presented in two IAEA publications [36, 37]. However, the borehole concept requires some interpretation of these guidelines, not least because of the wide range of possibilities that it represents.

Site characteristics

5.22. Reference [9], in discussing the suitability of a site for near surface disposal, states that the following topics are required to be considered as a minimum: geology, hydrogeology, geochemistry, tectonics and seismicity, surface processes, meteorology, climate and the impact of human activities. Although primarily directed towards near surface facilities, investigation of these aspects can, with some change of emphasis for boreholes of intermediate depth, be used to evaluate:

(a) The possible contamination of groundwater resources.
(b) The impact of climate driven surface processes such as flooding, erosion, landslip or weathering on the capability of the disposal system to isolate the radioactive waste.
(c) The extent to which events such as faulting, seismic activity or volcanism could compromise the isolation capability of the repository.
(d) The extent to which foreseeable human activities could compromise the isolation capability of the repository; this requires the consideration of land ownership and the resource and development potential of the site and its immediate surroundings.
(e) The extent to which the geochemistry of the surrounding area could impair the longevity of engineered barriers.
(f) The extent to which the geology provides physical and chemical stability.
(g) The extent to which the geology, hydrogeology and geochemistry tend to restrict the movement of radionuclides from the site to the accessible environment.

(h) The access routes that would allow waste packages and excavation equipment to be moved to the site; the site may also need services such as water and electricity.

Initial approach to site selection

5.23. In all cases, it is prudent to concentrate on the most robust solutions for achieving safety and on searching for sites with simple or well-understood geological and surface environments. The objective of this approach is to reduce the level of effort required to develop an acceptable disposal system in consideration of the characteristics specified above.

5.24. Typically, this information might include existing geological, topographical and hydrogeological mapping data, climate records and data from environmental surveys. In many regions, information in the form of detailed national surveys and maps may be scarce, which puts an even greater weight on finding geologically simple, stable regions. Much of this information would be readily available at an existing near surface disposal site. Further discussion of site characteristics is provided in Appendix IV.

Site characterization

Characterization activities

5.25. As expressed in the requirements for site characterization in Ref. [8], the overall aim of site characterization is to gain a general understanding of the site in terms of its regional setting, its past evolution and its likely future natural evolution over the time frame of the assessment (see para. 3.9). This will include, for instance, investigating the site characteristics listed in para. 5.22. This section considers the essential aspects of site characterization that should be carried out to obtain information for design and safety assessment purposes. As a minimum, these should include geology, hydrogeology, geochemistry, tectonics and seismicity, surface processes, meteorology, climate and the impact of human activities [9]. While the extent of the efforts needed for the characterization of these properties for large near surface and geological disposal facilities is considerable, given a relatively simple site and borehole disposal on a small scale, the amount of effort need not be too onerous, as explained below.

5.26. Once preferred areas or sites have been identified in the site selection process, the next steps would involve field activities, in particular the confirmation of the geological structure and hydrogeology down to the disposal zone by means of surface mapping. Preliminary geological, hydrogeological and hydrological models of the area would normally be developed from the mapping and from existing data and be used to identify the target disposal zone. The amount of information needed will depend on how complex the site is and on the margin of safety indicated by the post-closure safety assessment. Wherever possible, long term regional meteorological records should be consulted to give an indication of the range of conditions likely to occur in the future. These data may be used to estimate the susceptibility of a site to severe weather conditions (e.g. flooding) and also to estimate the recharge of groundwater from the site itself.

5.27. Following the surface mapping, normally at least one initial investigatory borehole would be drilled at the preferred site. This borehole should be designed to extract rock core to show the geological sequence down (if possible) to the base of the host formation. Rock samples should be characterized and preserved; others may, if necessary, be used to evaluate the radionuclide retardation properties of the rock (sorption, rock matrix diffusion). The investigatory borehole should also allow water sampling, ideally with flowmeter measurements, and standard geophysical logging.

5.28. For borehole disposal facilities of intermediate depth, the incidence of rock breakout in the wall of the investigatory borehole should be monitored, since breakouts could hinder the operation of the facility and might require the use of casing. In this regard, it may be helpful to measure rock stress.

5.29. In broad terms, drilling one or more investigatory boreholes has three main purposes:

(1) To gather sufficient hydrogeological data to construct a model of groundwater movement through the disposal zone and the surrounding rocks;
(2) To determine the nature of any chemical reactions (especially undesired reactions) between the engineered barrier system and the surrounding environment;
(3) To gather data relevant to the feasibility of constructing the facility and, for instance, the need for borehole casing.

5.30. Boreholes used for the purpose of site characterization should normally be sealed after use. Alternatively, if suitable, they may be used for waste disposal by becoming part of the facility.

5.31. Site characterization should also include characterization of the biosphere of the site and areas into which groundwater from the vicinity of the facility could discharge in the post-closure period. The information collected should cover land use, habits of the local population (especially the consumption of foodstuffs) and sources of drinking water. The nature of the present day biosphere will help to set the context for the biosphere model used in post-closure safety assessment. Similarly, data on food consumption are likely to be required for defining critical groups and estimating doses (e.g. Ref. [17]).

5.32. In post-closure safety assessment, the transport of radionuclides in groundwater (the 'groundwater pathway') is usually the dominant mechanism for the migration of radionuclides from the waste. Consequently, unsaturated sites or sites where groundwater movement is very slow (e.g. sites with rocks of very low permeability) may be advantageous in that, other things being equal, it will usually be easier to demonstrate compliance with a dose constraint or risk constraint than it would be for a site where groundwater movement were relatively rapid. Consequently, a saturated site in permeable rocks will generally require more effort to be expended on site characterization than would be the case for an unsaturated or very low permeability site. This subject is discussed at greater length in paras IV.21–IV.26 of Appendix IV.

Construction of the borehole disposal facility

5.33. Borehole construction should not proceed until a licence has been granted. This requires the regulatory body to review, assess and approve the impact of the proposed construction on radiological safety during both the operational and the post-closure periods. For example, the regulatory body should decide whether the proposed method of construction will be capable of fully delivering the proposed design in terms of borehole dimensions, borehole straightness, length of casing, capability to place a behind casing grout, etc. In addition, the regulatory body should decide whether the safety case adequately explains and justifies the actions to be taken in the event of abnormal events such as the loss of a drill bit, excessive water ingress or unexpected failure of the borehole wall. The safety case should describe measures for sealing 'failed' boreholes (i.e. boreholes where waste emplacement proves to be impracticable).

5.34. Whether the construction of a borehole disposal facility is straightforward or complex depends primarily on rock conditions, the borehole diameter and the depth. Clearly, though, facility construction should deliver the approved design while also preserving the post-closure safety functions of the geological barrier (see the requirements for geological disposal facility construction in Ref. [8]). This is most likely to be achieved when construction is straightforward (i.e. when rock conditions are amenable to the required borehole dimensions).

5.35. Construction should be accompanied by a planned programme of testing, commissioning and inspection (which is likely to include regulatory inspection). This programme should have the aim of demonstrating that construction of the facility is in accordance with the design and the associated technical specifications, and that the features revealed by its construction are consistent with what is known from the site characterization. This may require the removal and preservation of rock and groundwater samples.

5.36. Borehole construction should be carried out by suitably qualified and experienced personnel following previously approved written procedures [35]. These procedures should be derived from assessments of conventional construction safety and should be updated as practical experience is gained. Borehole construction records should provide a complete description of the history of construction, including when, how and by whom the borehole was constructed, its depth and diameter, the geological formations encountered and any non-compliances with regard to the construction procedures.

5.37. Construction of new boreholes could continue after the commencement of emplacement operations in boreholes already constructed. Such overlapping construction and operation activities should be planned and carried out to ensure both operational and post-closure safety following the specified licensing conditions.

5.38. Where boreholes pass through different hydrogeological regimes, drilling should avoid unnecessary disturbance. For instance, while the emplacement zone should avoid aquifers, it may be necessary to drill through an aquifer to reach the emplacement zone, and this will necessitate casing the borehole to isolate waste from the aquifer and to avoid the creation of pathways between different strata. Rock conditions and hydrogeology will vary from one borehole to another and there should be sufficient flexibility in the underground engineering techniques and/or the programme either to remediate marginally unsuitable boreholes or else to seal them off and close them without emplacing any waste. There are many ways in which a borehole can fail and contingency plans are needed to cover these eventualities.

Operation of the disposal facility

General

5.39. The operational phase of a borehole disposal facility includes commissioning activities, waste reception, waste emplacement, borehole backfilling, borehole sealing and site decommissioning and closure (the last two of these are discussed in paras 5.66 and 5.67). In addition, there can be various engineering tasks, including temporary storage or final conditioning of the waste. Operation of a borehole disposal facility will not, of course, be commenced until a licence has been granted. This requires that the regulatory body review and approve all aspects of operational safety to satisfy itself (i) that the design and the management procedures will allow the facility to be operated safely with regard to both workers and the general public, and (ii) that the operations will provide the post-closure safety functions on which the safety case depends (see the requirements for disposal facility operation in Ref. [8]). The operational safety case should include a radiological protection policy that describes how radiological hazards to workers and to members of the public are to be controlled under normal circumstances and what arrangements will be in place to deal with abnormal situations (e.g. emergencies). The safety case should also describe how the facility is to be commissioned and then operated. Only waste that complies with the waste acceptance criteria can be accepted for disposal. These issues are discussed in more detail below.

Radiological protection programme

5.40. International guidance on the engineering means and practical means of achieving radiological protection during the operational period is well established [14, 15, 38]. An essential component of this protection is the radiological protection programme (termed a radiological protection policy in the BSS [7]), which should document, with an appropriate level of detail:

(a) The assignment of responsibilities for occupational radiological protection and safety to different management levels, including corresponding organizational arrangements and, if applicable (e.g. in the case of itinerant workers), the allocation of the respective responsibilities between employers and the registrant or licensee;
(b) The designation of controlled or supervised areas;
(c) The local rules for workers to follow and the supervision of work;
(d) The arrangements for monitoring workers and the workplace, including the acquisition and maintenance of radiological protection instruments;

(e) The system for recording and reporting all relevant information relating to the control of exposures, the decisions regarding measures for occupational radiological protection and safety, and the monitoring of individuals;
(f) The education and training programme on the nature of the hazards and protection and safety;
(g) The methods for periodically reviewing and auditing the performance of the programme;
(h) The plans to be implemented in the event of intervention (e.g. accidents and emergencies and discovery of unforeseen chronic exposures);
(i) The health surveillance programme;
(j) The requirements for the quality management and process improvement.

5.41. The radiological protection programme is an essential part of the operational safety case and, as such, is subject to regulatory approval. Translation of the programme into action requires the employment of suitably qualified and experienced personnel.

Recruitment and training of personnel

5.42. Well before commencing operation, the operator should determine the organization's personnel requirements in terms of numbers, responsibilities and expertise, and then proceed to recruit and train suitably qualified persons. The training programme should identify the activities that are significant for safety and should provide the knowledge and practical experience necessary for these activities; it should also foster the development of a safety culture. The training should give operational staff a high degree of awareness of the design features of the repository that are significant for safety. The training programme should be updated in the light of experience and staff should be retrained as necessary.

5.43. Technical expertise is likely to be needed in operational radiological protection, remote handling, waste packaging, waste transport, borehole construction and closure, and safety assessment.

Commissioning

5.44. The operational techniques should be tested and confirmed, especially those used for putting in place the engineered barriers and for emplacing the waste packages in the borehole. This may be done through the use of an inactive test facility and, later, through on-site commissioning tests.

5.45. For deeper, smaller diameter boreholes, where access and retrieval of waste packages are more difficult, consideration should be given to ensuring that:

(a) The possibility of dropping waste packages is very unlikely.
(b) Waste packages are correctly positioned in the facility.
(c) Waste packages are correctly backfilled.

Written procedures

5.46. The operator should prepare a set of rules, incorporating limits, controls and conditions derived (mainly) from the operational and post-closure safety assessments, to ensure that the facility is operated safely and in compliance with the conditions of the licence and national regulations. These rules should reflect consideration of:

(a) Protection criteria for occupationally exposed workers and members of the public in normal operation and accidents;
(b) The limiting assumptions used in the safety assessment.

5.47. To ensure that identified controls are in place and that limits and conditions are observed, operations impacting on safety need to be specified in written procedures and instructions [8, 35]; the operator is also responsible for ensuring that workers follow these procedures and instructions carefully. Operating procedures are derived from the technical specifications for operations which, in turn, are based on the operational safety assessment. The overall aim is to provide safety by ensuring that the work that is actually done during operation is adequately covered by the safety assessment and the safety case and that it achieves the design aims for operation. Demonstration of this achievement should be provided by means of inspection, auditing and record keeping (see below). It is also important that proper attention be given to safety during the modification of equipment or operating procedures. Formal change control procedures should be used (see para. 4.11).

5.48. The operator should also establish procedures for prescribed actions in the event of (i) emergencies or non-routine occurrences (e.g. jamming of waste packages in boreholes) and (ii) receipt of waste that does not conform to the waste acceptance criteria. The procedures should also specify when reports should be made to the regulatory body.

Emplacement strategies

5.49. The operation of borehole disposal facilities may be performed on a continuous basis or a campaign basis or a combination of the two. With continuous operation, packages are placed in the borehole disposal facility as they arise and the operator may, therefore, need to exercise operational control over the site for several years. Campaign operation involves the accumulation of waste in stores until there is sufficient waste to be disposed of in a new borehole. This provides a short term operational disposal period and would allow individual boreholes to be drilled, filled and sealed in one complete exercise, thus reducing the chances of boreholes degrading or being mismanaged between disposal operations. Provided that waste packages are weather resistant, they could be stored in a secure, access controlled, open air compound. It is likely that continuous operation would be most appropriate in the case of large capacity boreholes where quite extensive storage facilities would be needed. In this case, rainwater and surface water should be prevented from entering the borehole, which should be fitted with a secure cover when operations are pending.

5.50. In facilities where different types of waste are to be disposed of, it is sometimes suggested that packages containing high activity or long lived waste should be placed in the bottom part of the borehole and packages containing low activity, short lived radionuclides at the top. This could improve post-closure safety and limit the consequences of human intrusion. However, such emplacement strategies might be difficult to operate in practice, requiring longer storage times, more complicated on-site storage facilities, greater assurance regarding the location of individual waste packages and, probably, higher operator doses. In general, it is preferable for facility designers to aim for a simple, robust scheme in which any waste packages can be placed in any borehole in any order. It is recognized, of course, that this may not always be possible, especially for boreholes where the waste emplacement zone comes close to the surface and where there are significant numbers of high intensity sources to be disposed of.

Backfilling boreholes

5.51. Following waste emplacement, there will usually be a need for the borehole to be backfilled. Materials that could be used for backfilling include cement, bentonite slurry, or a loose fill of bentonite granules, sand and so on. It may be necessary to design and to demonstrate measures to reduce the possibility of leaving voids after backfilling. These could include backfilling in stages.

5.52. For deeper boreholes, backfill would be introduced following the emplacement of individual packages. In this case, it may be possible to use pressure grouting to introduce the backfill, provided that the borehole is uncased (or screen cased). When boreholes of this type are fully cased and sealed at the bottom, it will be necessary to rely on gravity, although backfill placement could be assisted by pumping out the air beforehand.

Sealing of boreholes

5.53. Following waste emplacement and backfilling, the operator will seal each borehole following the method prescribed in the licence and the safety case. This activity, which may be overseen by the regulatory body, will place the borehole into its final configuration and preserve the safety functions on which post-closure safety depends (see the requirements for geological disposal facility closure in Ref. [8]). Boreholes may be sealed and closed individually or collectively at the end of a disposal campaign. If seals are not put in place for a period of time after the completion of waste emplacement, then the implications for operational and post-closure safety should be considered in the safety case. Likewise, the implications of any unexpected postponement of sealing should be considered.

5.54. In the case of intermediate depth boreholes of smaller diameter, sealing requires sections above the disposal zone to be filled with a low permeability material to prevent shallow groundwater penetrating the waste, or to prevent pore waters that are saturated with waste from moving upwards from the disposal zone. Standard borehole cementing and sealing approaches are likely to be appropriate, with the precise technique depending on the size of the hole, whether it is cased or not, and the geology. Where a borehole is uncased, a seal, at least, should be placed within the host rock formation. In general, it will be beneficial to remove the casing above the disposal zone since this will allow the installation of a monolithic seal grouted into the adjacent rock and will remove a potential leakage pathway to the surface along degraded casing or poor grout-to-casing bonds.

Inspection and review

5.55. Safe operations should be achieved through the application of recognized technical and managerial principles [35]. Thus, the licence to operate may require the operator to conduct periodic reviews covering issues such as quality assurance audits, operating conditions, environmental sampling and analysis, occupational health and safety, and maintenance of records. The results of these reviews should then be submitted to the regulatory body.

5.56. The regulatory body may also carry out independent audits, inspections and reviews to satisfy itself that appropriate technical and managerial principles are being effectively applied. Corrective actions and repeat inspections should be applied when this is found not to be the case.

Records

5.57. An important operational requirement is the recording of relevant information, as stipulated by the regulatory body. With respect to the waste itself, much of this information will have been obtained from the waste generators and will form part of an already existing national waste inventory. Each waste package should have a unique identification. For each waste package, information should be compiled on its principal characteristics (e.g. origin of the waste, radionuclide content of the package, method of encapsulation, materials of the waste container, method of closure).

5.58. Operational records should describe when, how and by whom an operation was carried out and, especially, any non-compliances with the operating procedures. When waste is emplaced, for instance, the position of the waste package should be recorded (e.g. the number and location of the borehole and the position within the borehole). Processes such as backfilling and sealing should be similarly recorded.

5.59. Consideration should be given to the form of the records to ensure that information is available when needed without interruption or loss. This information will form part of the safety related information archived for the benefit of future generations (see the section on post-closure institutional controls beginning at para. 5.68). Further information on the maintenance and preservation of records is provided in Ref. [35].

Waste acceptance criteria

5.60. A key component of the assemblage of limits, controls and conditions to be applied by the operator is the waste acceptance criteria. No waste package can be accepted for disposal unless it is compliant with the waste acceptance criteria, which aim to ensure that waste packages are consistent with the safety case, especially the safety assessments for transport, predisposal operations, disposal operations and post-closure. Waste acceptance criteria are usually developed by the operator and approved by the regulatory body, although sometimes the regulatory body may specify criteria. Consequently, waste acceptance criteria are usually used to ensure that waste packages are compatible with all stages of waste management through the imposition of a series of technical and management controls. Waste acceptance criteria are a safety relevant component of the facility design and they should therefore be subject to a change control process that entails internal safety reviews and regulatory scrutiny.

5.61. In the early stages of a programme for the development of a facility, not all the details of the safety case (e.g. the site) will have been settled and, in principle at least, this could make it difficult to determine the waste acceptance criteria. In practice, this rarely seems to be a significant problem, since several IAEA Member States are already conditioning and packaging waste in the absence of a known disposal site. This is possible because most disposal concepts are specifically designed for the disposal of waste inventories that, from the outset, are known to contain many kinds of waste, some of which will already have been packaged. This prevents the waste acceptance criteria from being drawn too narrowly. Consequently, provided that there is a good understanding of the range of wastes that should be disposed of, it should be possible, even at an early stage in the programme, to formulate waste disposal criteria that are sufficiently flexible for a wide range of wastes to be accepted. Nonetheless, close attention should be paid to waste that was conditioned and packaged prior to the adoption of waste acceptance criteria and the associated quality management regime. For the small number of waste packages that cannot be accepted for disposal, repackaging may be an option.

5.62. Waste acceptance criteria commonly impose:

(a) A limitation to the use of only solid waste forms;
(b) Limits on the radionuclide content, fissile content, total activity and radiation level on the surface of a package, as well as total limits for the borehole and the entire facility;
(c) Waste forms with stable chemical and physical properties (e.g. no putrescible material);
(d) Allowable and non-allowable encapsulation materials;
(e) Limits on gas release rates;
(f) Limits on the weight and physical size of waste packages;
(g) Specifications for waste containers (e.g. acceptable materials, dimensions, weld testing);
(h) Management systems for waste characterization, packaging, handling and storage.

5.63. The existence of waste acceptance criteria implies a need for waste characterization, and this is usually the responsibility of the waste generator, made on the basis of guidance provided by the operator and approved by the regulatory body. Modelling of waste behaviour and/or testing may also be required to demonstrate compliance with the waste acceptance criteria. Typically, waste packages are tested for their physical and chemical stabilities under disposal conditions by the use of laboratory simulations. Similarly, tests may be used to examine the performance of waste packages in accident conditions or abnormal conditions. For well-known materials, such as "Grade 316 stainless steel" and "Ordinary Portland cement", most of the relevant information may already be available. It should usually be the responsibility of the waste generator to demonstrate compliance with the waste acceptance criteria and to provide this information to the operator.

5.64. Procedures should be in place that describe the actions to be taken on receipt of waste that does not conform to the waste acceptance criteria. Depending on the severity of the non-conformance, the actions may range from notification to the waste packager and remediation on-site to enforced shutdown of the production process for waste packages. For significant non-conformances, the regulatory body should be notified.

5.65. Sealed sources that contain radionuclides in category I and II quantities (particularly radionuclides of longer half-life, such as ^{90}Sr, ^{137}Cs, ^{238}Pu and ^{241}Am) [39] should not be disposed of in near surface boreholes unless there are additional physical or administrative controls in place to prevent or reduce the likelihood of intrusion and/or mitigate its consequences. Otherwise, intermediate depth disposal should be considered.

Decommissioning of buildings and closure of the disposal facility

5.66. When all boreholes are backfilled and sealed, the site itself should be closed. Regulatory approval for decommissioning and site closure (which are regarded as operational activities) will require the submission of an updated safety case using current data to demonstrate that the required post-closure performance will be achieved. The safety case should also include detailed plans for both decommissioning and closure. These plans should describe the decommissioning activities (e.g. site surveys, decontamination and removal of any redundant buildings and equipment, site remediation, final survey to confirm any necessary site cleanup and transfer of documents to other premises) and demonstrate that the closure activities will not impair the post-closure performance of the facility. An IAEA technical report discusses the decommissioning of small facilities [40].

5.67. The closure plan should also describe any arrangements intended for the post-closure institutional phase. These arrangements should include a system for archiving and preserving records. They might also include, especially in the case of facilities that extend to within 30 m of the surface, control of access to the site, maintenance of site security, a surveillance programme and a radiological monitoring plan. In each case, the closure plan should identify the organization responsible for conducting these activities. Ownership of the site should be clearly and appropriately allocated. When the closure operations have been satisfactorily completed, the period of post-closure institutional control can begin. Depending on the regulatory framework and the conditions of the licence, this may or may not require separate regulatory approval.

Post-closure institutional controls

5.68. Institutional control is defined as any form of institutional activity, from oversight by international agencies and national governments to very specific activities such as environmental monitoring. It is generally expected that institutional controls will assist with the societal acceptability of the disposal. Institutional controls are generally classified into 'active' and 'passive' controls. Active institutional controls include:

(a) Maintaining signs, fences and guards at sites to prevent unauthorized access and intrusion by animals.
(b) Maintaining access, maintaining the grounds, weed control, etc.
(c) Monitoring and surveillance (see paras 5.74–5.80).
(d) Performing any remedial work that may become necessary, for instance, on the basis of the monitoring and surveillance programme.

Passive institutional controls include:

(a) Long term markers;
(b) Restrictions on land use and ownership;
(c) Preservation of records;
(d) Financial assurances.

5.69. Whether the duration of the institutional control period is defined by law or established on a case by case basis through the approval of closure plans, it should be specified in the site closure plan (see the requirements concerning post-closure and institutional controls in Ref. [8]) and justified by reference to its potential future hazard (e.g. the rate of radioactive decay of the waste, human intrusion scenarios or historical experience of the retention of information). Institutional control periods, often of the order of 100–300 a, are frequently part of the safety concept for many near surface disposal facilities associated with nuclear power programmes. The site closure plan, including any newly proposed institutional control period, should require the review and approval of the regulatory body before being implemented.

5.70. The post-closure arrangements should be documented and should identify the institutional controls that are to be provided during the institutional control period, who is responsible for providing them and how long each control will stay in place. Earlier removal of any institutional controls should need the prior approval of the regulatory body.

5.71. In general, small scale borehole disposal facilities at intermediate depth represent lesser hazards in terms of the surface 'footprint', proximity of the waste to the surface and the amount of waste disposed of. The safety of the facility will not depend on institutional controls and quite short periods may be justifiable, so land could soon be returned to local community use with, possibly, restrictions on ownership and use within a period of a few years.

Information to be archived

5.72. Passive institutional controls can help to maintain knowledge of the facility's location and characteristics within societal institutions. Information that should be preserved with respect to a borehole disposal facility is primarily:

(a) Its precise location;
(b) Its geology, geochemistry and hydrology derived from site characterization data (paras 5.25–5.32);
(c) Design details of the facility, including descriptions of, for example, the backfill, casing and seals (paras 5.18, 5.19, 5.51–5.54);
(d) Detailed descriptions of the waste packages, including waste origin, radionuclide content, encapsulation matrix and containers (paras 4.22–4.24, 5.18, 5.19);
(e) Descriptions of the construction and operation, including dates and details such as measured water inflows to boreholes and, especially, any non-conformances and actions taken to rectify them (paras 5.33–5.59);

(f) The facility safety case (Appendix III) and supporting information (e.g. from site characterization (paras 5.25–5.32));
(g) A description of the post-closure arrangements (para. 5.68);
(h) Outputs from the surveillance and monitoring programme, including baseline surveys (paras 5.74–5.80).

5.73. Such information should be retained for as long as possible to provide a basis for any future decisions concerning the site. This may be most easily done by making use of national archives. Long term site markers may also help, although consideration should be given to their possible implications for security.

Surveillance and monitoring programmes

5.74. A programme of surveillance and monitoring should form part of the safety case and should commence before a disposal facility becomes operational — usually during the site characterization programme. As the disposal programme moves from one phase to the next, the objectives of the surveillance and monitoring programme will change and additional surveillance and monitoring activities will be added [41]. Some of these activities may continue through into the period of post-closure institutional control. Through the various phases of development of the facility, the surveillance and monitoring objectives should be set to allow the surveillance and monitoring programme to contribute to the building of confidence in the safety case by testing assumptions and demonstrating compliance. For example, Ref. [1] lists the main objectives of the post-closure surveillance and monitoring phase as follows:

(a) To show compliance with reference levels established by the regulatory body for the purpose of ensuring the protection of human health and the environment;
(b) To confirm, as far as possible, relevant assumptions made in the safety assessment;
(c) To provide indications of any malfunctioning of the containment leading to unpredicted releases of radionuclides;
(d) To provide reassurance to concerned persons living in the vicinity of the waste disposal facility.

5.75. An important principle of the surveillance and monitoring of facilities is that the programme should be designed and implemented so as not to reduce the overall level of post-closure safety (see the requirements concerning monitoring programmes in Ref. [8]). The surveillance and monitoring programme should not place an undue burden on the operator by being too elaborate; for a small scale disposal facility especially, the arrangements may be relatively simple. Appendix V provides such an example.

5.76. As part of site characterization, a baseline of environmental levels, radiation levels and activity concentration levels should be established for the purpose of subsequently determining the changes (if any) brought about by the emplacement of the waste. These data may include surface radiological data such as gamma radiation fields, the radionuclide content of airborne dust and the radionuclide (including radon) content of the soils, water and air on and around the site. These data and their current impact on humans should be used to gain an understanding of radionuclide transfer pathways, especially in areas where groundwater from the vicinity of the facility could discharge. The monitoring should also cover wider environmental information such as that on the local ecology, chemical pollutants, population density and habits, local agriculture, and natural and artificial features of the environment that might affect radionuclide transfer pathways [41].

5.77. The results of predisposal surveillance and monitoring will assist in building confidence in the safety and post-closure performance of the borehole disposal facility and will aid in decisions on its future development. The monitoring programme may also be useful in creating the geosphere and biosphere models to be used in the post-closure safety assessment.

5.78. Borehole disposal facilities with boreholes less than 30 m deep should be subject to post-closure surveillance and monitoring of a similar nature to that proposed for near surface disposal facilities [42]. Facilities containing intermediate depth boreholes in saturated environments may be monitored for potential releases through the nearby water bearing horizons, even if releases of radionuclides are anticipated to occur only in the distant future. Where monitoring boreholes are used, they should be sealed after use.

5.79. The regulatory body should provide, if necessary, guidance on the establishment of a surveillance and monitoring programme to be used (i) to demonstrate compliance with the regulatory constraints and any other licence conditions, (ii) to monitor any migration of radionuclides to the environment and (iii) to assess the environmental impact of construction, operation, closure and post-closure activities. The operator would normally carry out this programme and would take the necessary actions to ensure that the requirements established by national authorities are met. The regulatory body should:

(a) Check the surveillance and monitoring data provided by the operator;
(b) Regularly review surveillance and monitoring arrangements, including arrangements for emergency monitoring;
(c) Audit the management systems;
(d) Provide evidence that can satisfy the public that there are no unauthorized sources of exposure.

5.80. In addition, the regulatory body may carry out an independent surveillance and monitoring programme.

Accounting and control systems for nuclear material

5.81. Systems for accounting and control of nuclear material have been developed to provide for the accountability of nuclear material so as to detect, in a timely manner, its diversion to unauthorized or unknown purposes in the short and medium terms. As presently organized, systems for accounting and control of nuclear material rely on active surveillance and controls. The discussion of the requirements in paras 3.79–3.81 in Ref. [8] makes it clear that for some radioactive waste, particularly that containing fissile material such as spent nuclear fuel, certain requirements on accounting and control of nuclear material have to continue, even after the fuel has been sealed in a geological disposal facility. Possible malicious uses of other (non-fissile) material do not fall within the system for accounting and control of nuclear material.

5.82. Borehole disposal is designed primarily to dispose of small volume waste (e.g. disused sealed sources), particularly when they arise in States that lack well-developed systems for dealing with high level radioactive waste deriving from the nuclear fuel cycle. Such waste may pose a potential security risk, but, because of its low fissile content, will not fall within the system for accounting and control of nuclear material.

Management systems

5.83. Management systems are applicable to any organization, but, in the context of radioactive waste management, they apply most importantly to the operator. This subject is discussed at greater length in Appendix VI.

6. IMPLEMENTATION OF THE SAFETY STRATEGY FOR EXISTING BOREHOLE DISPOSAL FACILITIES

6.1. Standards, procedures and practices all change over time and therefore some older borehole disposal facilities may not be consistent with the safety guidelines presented in this Safety Guide. Specifically, human intrusion scenarios at some older borehole disposal facilities could lead to doses in excess of 10 mSv/a, at which level remedial action should be considered in intervention situations. Intrusion in some facilities may even lead to doses exceeding 100 mSv/a, a generic reference level above which intervention should be considered almost always justifiable. This section considers past practices in borehole disposal from a regulatory perspective. In this context, it is particularly relevant to note that the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management [1] requires contracting parties to report on past practices and possible interventions. Furthermore, for both closed facilities and operating facilities, the periodic reassessment of safety constitutes good practice.

6.2. The purpose of a safety reassessment for an existing waste disposal facility should be:

(a) First, to assess whether the facility satisfactorily provides protection from radiation for future generations in accordance with the Fundamental Safety Principles [13] and the requirements of the BSS [7];
(b) Second, if appropriate standards are not met, to determine whether there is justification to intervene at the facility and to retrieve the waste or take other corrective action.

6.3. Straightforward application of these guidelines may in some cases suggest a need to carry out some corrective actions or to retrieve waste from the disposal facility. However, it should be emphasized that the application of these criteria to possible future doses is far from straightforward. Intervention should be based on justification and optimization [8]. Put succinctly, any corrective action should do more good than harm.

6.4. In the current context of borehole disposal, this means that national authorities, which are responsible for taking such decisions, should balance the possible future risks to individual members of the public against actual risks to the workers who would be associated with the intervention. If the approach is applied to existing borehole disposal facilities, it is likely to lead to a situation where one of the following options should be chosen.

Option 1: Carrying out additional site studies and applying justified corrective actions

6.5. The simplest corrective action at an existing disposal facility will, typically, depend on some form of institutional control (e.g. restrictions on access) and will therefore only be effective so long as the period of active institutional control continues. Such controls could be accompanied by other measures, such as the use of anti-intrusion barriers. Where the radionuclides in the waste are mostly short lived, such approaches will usually be adequate. However, where the radionuclides are long lived (and especially where there is significant in-growth), such corrective actions will not alter the long term dose projections for the facility.

6.6. A slightly different approach would be to focus the site characterization and data collection efforts to address issues raised by the safety assessment, in the expectation that new data would allow conservatisms in the safety assessment to be reduced so as to bring the dose projections within the acceptable range. However, the removal of conservatisms usually leads to increased complexity in modelling and data requirements. This is, nonetheless, still likely to be the most cost effective approach.

Option 2: Retrieving the waste

6.7. In evaluating the advisability of this option, several issues should be considered. First, the optimization of doses should be considered. This means that doses to workers incurred during the retrieval of any waste should be considered and these should be optimized against the possible doses associated with leaving the waste in place. While a number of Member States have carried out, or are planning, the retrieval of waste from certain facilities, there is, at present, no clear consensus on an appropriate approach to carrying out such an optimization. In addition, if waste were retrieved, it would eventually have to be disposed of somewhere. Such disposal would inevitably lead to potential exposures that should be accounted for in the optimization assessment. Finally, if the waste were to be retrieved, the associated activities would have to be carried out safely and in conformity with the BSS [7].

Option 3: Accepting possible risks associated with the existing situation

6.8. If the risks and costs associated with corrective actions or waste retrieval outweigh the benefits, then it may be considered to be acceptable to leave the waste in place. In this situation, the risks associated with the existing situation would be accepted, even if the projected doses exceed the dose constraints applied to new facilities of the same type. Such a decision should only be made on the basis of a careful assessment of the alternatives. While no corrective actions would be initiated, it would be prudent to enhance the institutional controls on local land use to minimize the likelihood of future exposures.

6.9. In the end, a decision to carry out an intervention should be endorsed by the regulatory body, which should take into account the following aspects:

(a) Interventions should preferably only be carried out after the subsequent steps in the management of the waste have been decided upon and their consequences evaluated.
(b) All possible sites that are candidates for intervention in the Member State (or a region within it) should be investigated and a priority established.
(c) The implications should be considered of having to demonstrate compliance with additional regulatory requirements or requirements established in different regulatory regimes (for transport, environmental, nuclear, radiation and waste safety).

Appendix I

REGULATORY INSPECTION PLAN FOR A BOREHOLE DISPOSAL FACILITY: ITEMS THAT MAY BE SUBJECT TO INSPECTION

I.1. Structure and organization of the operator:

(a) General management of the organization;
(b) Appropriate allocation of responsible experts (in radiological protection, security, waste acceptance, etc.);
(c) Job descriptions;
(d) Arrangements for reporting to the competent regulatory bodies.

I.2. Operational procedures:

(a) Characterization and control of received waste;
(b) Radiological protection programme;
(c) Environmental monitoring programme;
(d) Personnel monitoring programme;
(e) Plans and programmes for training and qualification of personnel;
(f) Emergency plan (on-site and off-site);
(g) On-site handling procedures;
(h) Procedure for on-site storage of waste;
(i) Procedure for the management of waste that is non-compliant with safety requirements, waste acceptance criteria and other limits, controls and conditions;
(j) Internal audit and inspections;
(k) Reporting and notification of competent authorities;
(l) Quality management programme.

I.3. Actual status of the facility:

(a) Design of the facility and waste packages in compliance with the authorized safety case;
(b) Security and access to the facility (register of people able to access the site);
(c) Personnel monitoring equipment;
(d) Environmental monitoring equipment;
(e) Application of operational procedures;

(f) Register of received waste on the site;
(g) Record of periodic individual monitoring;
(h) Register of disposed waste;
(i) Record of periodic on-site and off-site environmental monitoring;
(j) Testing of the on-site (and where appropriate the off-site) emergency plan;
(k) Recording and evaluation of feedback from operational experience.

I.4. Compliance with licensing conditions:

(a) Control over waste acceptance criteria and limits, controls and conditions on the basis of the safety case;
(b) Control over compliance with additional conditions for authorization(s);
(c) Change control procedures.

I.5. Fulfilment of prescriptions and recommendations from previous inspections.

Appendix II

THE STEP BY STEP APPROACH

II.1. In consideration of the lower level of hazard associated with wastes that might be disposed of in a small scale borehole disposal facility, the application of the step by step approach to the development of a borehole disposal facility should be relatively simple. It should, nonetheless, still aim to provide a framework in which confidence in both feasibility and safety is progressively increased as the development proceeds. This may be done by breaking down the development programme and the licensing process into a series of steps that allow stakeholder inputs at key decision points.

II.2. The framework for a small scale borehole disposal facility could, for example, consist of two steps with two decision points, both of which could be preceded by public consultation:

Decision 1 would adopt borehole disposal as the favoured solution and put in place the required legal and regulatory framework. A licence would allow step 1, predisposal activities, to proceed, including:

(a) Definition of the inventory for disposal;
(b) Formulation of a conceptual design;
(c) Generic assessment of safety;
(d) Waste conditioning and packaging;
(e) Site selection following predetermined criteria and process;
(f) Characterization of the most favoured site;
(g) Development of a site specific design and safety assessment;
(h) Recommendation of the most favoured site.

Decision 2 would approve the most favoured site and site specific design and safety assessment. A licence would allow step 2, waste disposal and closure, to commence, including:

(a) Borehole construction;
(b) Waste emplacement;
(c) Borehole sealing;
(d) Decommissioning and closure of the disposal facility;
(e) Commencement of any post-closure institutional control period.

II.3. A larger scale programme of disposal of radioactive waste in boreholes would usually require additional steps to be introduced. For instance, a more gradual and consultative approach to site selection may be appropriate. Another consideration is that a larger scale disposal programme may require the disposal site to remain operational for a period of decades. In this case, it may be appropriate to approve the site but to require each new tranche of boreholes to be licensed separately. This would allow the safety case to be updated and subjected to regulatory review in the light of new data. Finally, with a decades long operational period, it may be convenient to put decommissioning, closure and commencement of post-closure institutional control into a separate sequence that requires a separate licence.

II.4. A more detailed action plan for disposal in a borehole is suggested in Ref. [3].

Appendix III

SAFETY CASE AND SAFETY ASSESSMENT FOR BOREHOLE DISPOSAL FACILITIES

Preparation of the safety case and safety assessments

III.1. The first iteration of the safety case will be prepared early in the development process for the facility and, if no site has been identified, it will be generic. An important early task is to identify the intended inventory for disposal since this will determine the overall size of the programme, including the extent of the radiological protection measures that should be taken during transport and operation and the level of isolation and containment required in the post-closure period. Ideally, the inventory for disposal should include all the sources or waste types that are expected to arise. The safety case will then be progressively refined as the site and details of the design are decided, finally allowing the preparation of a site specific safety assessment.

Post-closure safety assessment

III.2. An important component of the safety case is the post-closure safety assessment, which should aim to demonstrate that the ultimate goal of disposal — post-closure safety — will be achieved. A methodology for the assessment of both operational and post-closure safety of near surface disposal facilities has been developed by the IAEA's ISAM project on International Safety Assessment Methodologies for Near Surface Disposal Facilities [28]. The methodology has been applied illustratively to a borehole disposal facility as part of the ISAM project and has also been used in a generic assessment of the African Regional Cooperative Agreement for Research Development and Training Related to Nuclear Science and Technology Borehole Disposal Concept [43]. The ISAM approach provides a comprehensive framework for post-closure safety assessments, the importance of the context of safety assessment being stressed — the underlying reasons for carrying out an assessment — in helping to define such things as the scope of the assessment and how it is to be documented. The key components of the methodology are illustrated in Fig. 3.

III.3. A disposal facility may be affected by a range of possible evolutions and events, some of which will be more likely than others. In assessing post-closure safety, common practice is to construct a design evolution scenario for the

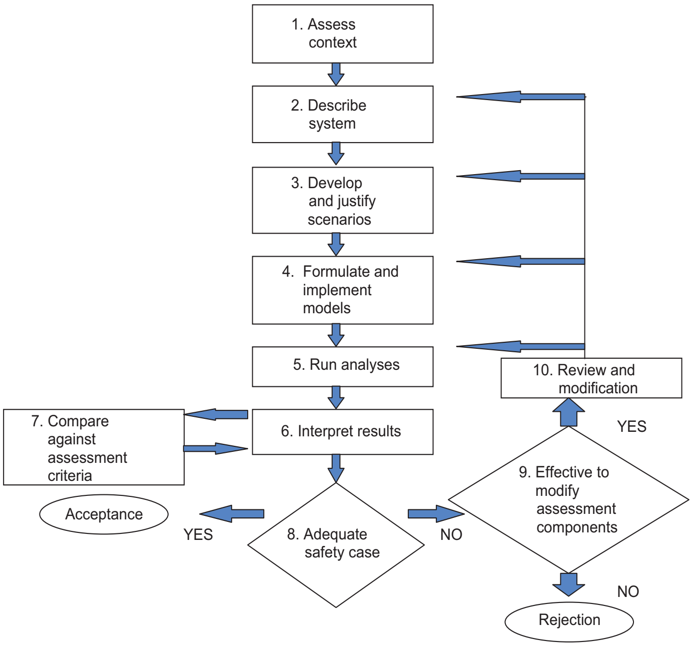

FIG. 3. The ISAM approach for post-closure safety assessment.

facility, which is the scenario that is thought to have the greatest likelihood of occurring. The design evolution scenario should incorporate all the natural processes and natural events (Table 2) that might reasonably be expected to give rise to radiation exposure of the public. Some possible design evolution scenarios are indicated in Table 3. For the design evolution scenario, estimates of long term dose (and the corresponding risk) can then be made by assuming that humans will be present and that they will make use of local resources that may contain radionuclides originating from the waste. A methodology for doing this, developed alongside a series of reference biospheres, has been put forward in the IAEA BIOMASS project [17].

III.4. Variants of the design evolution scenario in which there is a reduced system performance should be explored (Table 2) with the aim of evaluating the importance of the various barriers (remembering that the overall performance of the disposal system should not be unduly dependent on a single barrier or function). These variants might arise, for instance, from alternative interpretations of the hydrogeology or by assuming that some waste containers are faulty. A common way of investigating these variants is through the use of a probabilistic approach to post-closure safety assessment.

III.5. Less likely scenarios (Table 2) are triggered by a subset of features, events and processes sometimes termed external features, events and processes. These less likely scenarios should also be investigated. Typically, they include:

(a) Unlikely natural events that significantly disrupt the facility (e.g. meteorite impact);
(b) Human intrusion.

III.6. Less likely scenarios should be assessed by means of illustrative 'what if' calculations. Here, the aim is to judge the robustness of the system to external features, events and processes. These calculations may point out a need for additional research or even design changes to ensure that if such external features, events and processes do occur, they do not lead to widespread loss of safety functions. In assessing the risk that arises from human exposure to radiation in less likely scenarios, the probability of occurrence of the scenario should be taken into account.

III.7. Human intrusion studies should be focused on any disruption to the engineered and natural barriers caused by inadvertent human intrusion and the subsequent effect of this disruption in terms of increased dose to the general public.

III.8. As indicated by the typical scenarios shown in Table 3, for near surface borehole disposal facilities (i.e. where the waste is placed less than 30 m below the surface), the types of inadvertent human intrusion that might be envisaged for a borehole disposal facility include:

(a) Excavation of deep building foundations, deep cuttings for roads or railways, cut and cover tunnel construction, standard tunnelling, open cast mining, etc. (in general, these would result in high levels of dilution owing to the large volume of uncontaminated material that would be involved);
(b) Exploratory drilling for water or natural resources, which may be important after the physical containment has been breached.

TABLE 2. EXAMPLES OF SCENARIOS AND CORRESPONDING DOSE/RISK TARGET LEVELS

Scenario	Design evolution scenario[a]	Variant scenario with reduced system performance	Illustrative, less likely scenarios			
			Natural disruptive events	Environmental change	Societal change	Human intrusion
Scenario description	Anticipated system performance, including expected rates and levels of barrier degradation	Includes rates and levels of barrier degradation considered to be unlikely	Events considered to be very unlikely but with potentially serious consequences for safety	Global or regional climate change leading to different ecology, change in sea level	Societal change resulting from war, famine, collapse of societal infrastructure	Premature barrier failure caused by human intrusion
Examples	Container degradation at expected rate; expected range of times for groundwater to return to the biosphere	Premature barrier failure, so the time needed for groundwater to reach the biosphere is significantly less than modelled	Seismic events, volcanism, meteorite impact	Premature ice age caused by interruption of the Gulf Stream	Hunter–gatherer lifestyle Subsistence community	Exploratory drilling Deep water abstraction
Reference dose/risk target level[b]	Annual dose <0.3 mSv	Annual risk $<10^{-5}$	Annual risk $<10^{-5}$	Annual risk $<10^{-5}$	Annual risk $<10^{-5}$	Annual dose <10 mSv

[a] There could be more than one design evolution scenario if, for instance, different climate sequences are thought to be equally likely.
[b] It should be understood that the crucial issue for safety is design optimization. Target dose/risk levels are ancillary to this. Risk constraints apply to the four middle columns because this allows the probability of the event to be taken into account.

TABLE 3. EXAMPLES OF DIFFERENT ASSESSMENT SCENARIOS FOR NEAR SURFACE BOREHOLES AND BOREHOLES AT INTERMEDIATE DEPTH[a]

Scenario	Applicable to
Design evolution	
Residence on the waste Farming on the waste	near surface borehole
Contamination of aquifer/drinking well/agricultural well Contamination of surface water bodies Contamination of near surface groundwater	borehole at intermediate depth
Natural disruptive events	
Erosion Seismicity Meteorite impact	near surface borehole and borehole at intermediate depth
Human intrusion	
Excavation (e.g. road building) Tunnelling	near surface borehole
Exploratory drilling	borehole at intermediate depth

[a] For further information see, for example, Ref. [26] and the Annex.

III.9. As mentioned previously (para. 4.28), in the case of near surface boreholes, it is reasonable for the safety case to claim credit for active controls exercised during the post-closure period. In such cases, the controls and the period of time over which they are assumed to be effective should be specified as conditions of the relevant licence or authorization [9].

III.10. For borehole disposal facilities where the waste is deeper than the 30 m 'normal residential intrusion zone' [12], it is likely that the only mode of potential human intrusion would be exploratory drilling (Table 3).

III.11. The outputs from models used for post-closure safety assessment will inevitably be subject to greater uncertainty since the results are projected further into the future. Here, other arguments may also be used to demonstrate safety. They may, for example, be based on bounding analyses and comparisons with natural phenomena such as the behaviour of naturally occurring radioactive deposits.

Documentation of the safety case and safety assessments

Scope

III.12. A safety case should use sound science and engineering to describe the level of protection to be provided. It should address all aspects of safety: operational safety, post-closure safety, plus, if these are the responsibility of the operator, predisposal activities and transport. This is carried out by performing safety assessments. As stipulated by the requirements concerning documentation of the safety case and safety assessments in Ref. [8], the safety case is also required to describe the managerial (e.g. quality management) arrangements and other limits, controls and conditions (e.g. waste acceptance criteria) that will be applied to ensure that the relevant safety standards will be met. It should also address security. In the absence of an overarching environmental impact assessment, it could also be used to examine the full range of options available at that stage of the decision making process and also non-radiological environmental impacts.

III.13. The scope of the safety case should cover the design of the disposal facility, its location and how the waste is to be transported there, and how the facility is to be operated, closed and managed during any period of post-closure institutional control. A more detailed list of issues that should be covered by the safety case may be extracted from paras 5.14–5.83. Finally, the safety case should present the arguments for safety during the post-closure period by means of a post-closure safety assessment.

III.14. The volume of information and the degree of uncertainty associated with it will change as the facility development programme moves forward. In the early stages, when a site has not been selected, for instance, some of the information will be very uncertain. The safety case should identify key uncertainties, explain how they affect the safety case and describe further work intended to resolve them.

III.15. Throughout the development programme, an important function of safety assessment is to identify these key areas of uncertainty (i.e. those that impinge most directly on the calculated dose), so that activities such as site characterization and research can be properly targeted. This is often done by means of sensitivity studies. Sometimes, these key uncertainties will relate to individual parameters used in safety assessment (e.g. the inventory of a specific radionuclide). More often, the key uncertainty will be related to a combination of models and parameters. For example, the anticipated container lifetime will depend not just on material properties and environmental conditions, but on the method (i.e. the model) used to extrapolate short term laboratory data to the long timescales needed for safety assessment. Similarly, the time taken for a specific radionuclide to migrate through the geosphere will depend on hydrogeological and other models as well as on parameters such as the sorption coefficient. Here, improvements to the safety assessment can be obtained by means of additional data and model refinements. In many cases, the analysis of new data will itself suggest ways of improving a model.

III.16. In summary, the safety case should describe how the facility will meet the various safety objectives and criteria discussed in Section 3. This entails explaining:

(a) How, and to what degree, workers and the general public will be protected during site operations (including abnormal (i.e. accident) conditions) and during predisposal activities and the transport of waste to the site, if these are the responsibility of the operator;
(b) How the facility design and the site location will provide isolation and containment during the post-closure period, with account taken of the important uncertainties, so that radiological impacts for the critical group are within the defined dose limits and risk limits.

Level of detail

III.17. A safety case and the accompanying safety assessments should be written so as to be intelligible to the audiences to whom they are addressed. Beyond this, the requirements concerning documentation of the safety case and safety assessments in Ref. [8] demand that, at each step, the safety case should be sufficiently detailed and comprehensive as to provide the necessary technical input to support whatever decisions are needed. It should also be of sufficient quality to allow independent review and assessment by the regulatory body. Clearly, the level of detail will tend to increase as the programme progresses. However, in broad terms, it should always be sufficient to demonstrate that:

(a) The assessments (e.g. of transport safety, operational safety or post-closure safety) encompass all relevant scenarios (i.e. both design and non-design aspects).
(b) The chosen models (both conceptual and mathematical) are fit for purpose.
(c) The parameters used in the models are appropriate.

(d) Reasonable variability in the conceptual models and parameters has been taken into account.
(e) Overall, optimization has been achieved (paras 4.36–4.39).

III.18. The level of detail needed to demonstrate all of this will very much depend on the outcome of each assessment. Where an assessment (whether of transport safety, operational safety or post-closure safety) indicates that there is a large 'margin of safety' (i.e. that the calculated doses fall orders of magnitude below the regulatory constraint), demonstration of compliance may be straightforward and may be achieved with relatively few resources by showing that even quite conservative assumptions about the scenarios, models and parameters do not lead to non-compliance. However, where an assessment produces an outcome that is close to the regulatory constraint, conservative assumptions will sometimes lead to non-compliance, so here it may become necessary to justify discounting some of the more conservative scenarios and to establish with some precision what constitutes reasonable (and unreasonable) variability in the models and parameters. Such needs often entail quite far reaching investigations in terms of the development of conceptual models and the determination of uncertainties in parameters.

III.19 While these considerations apply equally to small scale and to larger scale disposal activities, other things being equal, the smaller, less hazardous inventory associated with borehole disposal should enable post-closure safety to be demonstrated more simply than for larger scale practices.

Justification, traceability and clarity

III.20. Crucial considerations in the documentation of any safety case are justification, traceability and clarity. These are especially important for confidence building, regardless of the stage reached in the development programme for a borehole disposal facility.

III.21. Justification means explaining the reasoning behind the various decisions taken, especially those that relate to safety. The justification should cover arguments both for and against the decision and should explain why one option was chosen over another.

III.22. Traceability means that an independent qualified person should be able to go back to the original sources of the various elements of the safety case and be able to understand how these elements have been put together to form the safety case.

III.23. Justification and traceability both require a well-documented record of (a) decisions and assumptions made in the development of the disposal facility and (b) the models and data used in arriving at a given set of results of the safety assessment. Good traceability is essential in enabling independent review.

III.24. Clarity requires a good structure and a presentation with sufficient explanation to allow not only the outcome of the safety assessments to be understood, but also the underlying reasons. This requires that the work should be presented in the documents in such a way that the intended audience can gain a good understanding of the safety arguments and their basis. Different styles and levels of document may be required to provide material that is useful to different audiences.

Appendix IV

SITE CHARACTERISTICS AND CHARACTERIZATION OF THE HYDROGEOLOGICAL PROPERTIES OF A SITE

IV.1. This appendix discusses characteristics relating to near surface and intermediate depth boreholes. It also outlines the main site characterization activities. In general, the selection of a site that combines favourable characteristics and avoids unfavourable ones will allow post-closure safety to be demonstrated more simply and with fewer resources than would otherwise be the case.

Boreholes with waste at a depth of less than 30 m below the surface

IV.2. With regard to the need to avoid the contamination of groundwater resources, a significant advantage of near surface boreholes is their potential capability to utilize permanently unsaturated host rocks. In some arid regions, there may be practically no near surface groundwater movement at all. In other circumstances, there may be some infiltration of meteoric water and percolation down to the water table. The absence of significant quantities of groundwater — a major medium for radionuclide transport — will delay the interactions between the radionuclides and the saturated zone, reducing the importance of the groundwater pathway and allowing time for radionuclides to decay in the unsaturated zone. All this is advantageous to post-closure safety and allows safety to be demonstrated more simply and with fewer resources.

IV.3. To provide reasonable confidence that the host rocks would remain unsaturated over the relevant containment period, it would be necessary to characterize the site so as to estimate possible future movements of the groundwater table or temporary saturation of the host rock. In this characterization, account should be taken of present and past hydrogeological conditions, future climatic conditions and possible rates of erosion. This is not to say that saturation must be entirely avoided, but sites where the rocks in the waste disposal zone would be saturated fairly frequently — seasonally or perhaps every few years — should generally be avoided. This is because cyclical wet and dry conditions or even a permanently partly saturated environment can produce severe corrosion conditions. The reason for this is that ephemeral groundwaters have oxidizing properties and may contain high concentrations of solutes. At some sites, the need to avoid saturated conditions may represent a special challenge: that of reconciling the need for placing the waste deep enough to provide adequate isolation with the need for keeping the waste above the water table. Borehole cores may preserve evidence of past groundwater levels.

IV.4. Where a near surface borehole is to be placed in a saturated environment, there should be a low groundwater flow. This is most likely to arise from low permeability rocks (e.g. clay), probably combined with low hydraulic gradients, and will result in a low flux of radionuclides out of the borehole. If this is combined with strong sorption (see para. IV.14) in the surrounding rocks, this will produce further retardation of radionuclides and allow a more simple demonstration of post-closure safety.

IV.5. Saturated near surface sites where there is very low groundwater flow may also have anoxic or chemically reducing conditions. This can benefit disposal by reducing corrosion and, perhaps, by reducing the solubility of a few polyvalent radionuclides such as technetium and plutonium. In many cases, it may be possible to induce limitations on solubility by providing a cementitious (and therefore alkaline) environment. Other aspects of the local geochemistry can have a negative effect on the engineered barriers. These include sulphate-bearing groundwaters, which may lead to the early degradation of concrete made from ordinary Portland cement. Also, high chloride levels can be detrimental to containers by causing corrosion.

IV.6. As a result of weathering, rock competence near the surface will usually be insufficient to allow a near surface borehole (especially one of large diameter) to be self-supporting. For this reason, borehole casing will often be required. This implies that formations in which it is practicable to place good, behind casing seals or grout-to-rock seals are to be preferred. Ground where the levels have been changed by moving or importing material should be avoided because of its generally lower stability.

IV.7. Sites should be examined for surface processes such as flooding, landslip, erosion and weathering. The incidence of flooding should be of particular concern because of its influence on erosion through valley deepening and also because of its capability to disrupt operation of the facility. For the same reason, the incidence of extreme meteorological events should also be considered in site selection. In general, the active part of the borehole disposal system should be located below the local erosion base and, in any event, the rate of erosion should be sufficiently low to avoid exposure of the waste over the assessment time frame (see para. 3.9).

IV.8. Near surface borehole disposal facilities will be more susceptible to inadvertent human intrusion than deeper boreholes and the resource and development potential of the site and its immediate surroundings should therefore be considered. Outright ownership of the site should be obtained and sites situated close to possible water or mineral resources should be avoided. The possibility of groundwater extraction, quarrying, tunnelling, mining and mineral exploration by drilling should be considered. To reduce the possibility of inadvertent intrusion due to construction activities, near surface sites that are close to areas of high population density or that are on the fringes of expanding urban areas should not be chosen.

IV.9. Environments where there is ongoing local tectonic activity should be avoided. Thus, sites that are close to active fault lines or areas prone to frequent seismic activity are unlikely to be suitable.

IV.10. Other factors that are likely to be influential in site selection for near surface borehole disposal facilities are:

(a) Geological and hydrological complexity, which will considerably complicate both site characterization and modelling and will increase the resources required for these tasks.
(b) Access, which should be good enough to allow heavy vehicles (e.g. excavators or truck mounted drilling rigs) to reach the site; for small scale disposals, mobile supplies of electricity and water should be adequate.

Boreholes with radioactive waste disposed of more than 30 m below the surface

IV.11. For intermediate depth boreholes, disposal can also be in the unsaturated zone and, exactly as explained above for boreholes at lesser depths, such sites are highly advantageous from the point of view of post-closure safety. More probably though, intermediate depth boreholes will be located in fully saturated conditions at greater depth. Here, the significance of the groundwater pathway for many radionuclides should be diminished by means of a low groundwater flux. A low groundwater flux arises from the presence of low permeability rocks, combined with low hydraulic gradients. For intermediate depth boreholes sunk to depths of a hundred metres or more, suitable host rock formations may contain old, possibly saline, groundwater indicative of very slow flow and little mixing with shallower waters over time periods that are equivalent to the containment periods of interest. Saturated conditions at greater depths will often provide anoxic or even reducing conditions, which, as explained above, are beneficial in reducing corrosion and, possibly, reducing the solubility of a few polyvalent radionuclides. As with near surface borehole disposal, sites where conditions alternate between saturated and unsaturated should be avoided.

IV.12. Important considerations for fully saturated sites are dilution by mixing and dispersion, which can be useful mechanisms for attenuating the impact of disposal, especially in the long term, when engineered barriers begin to fail and the migration of some radionuclides becomes inevitable. For dilution and dispersion to be effective, the prime necessity is radionuclide containment. Thus, in the case of dilution, a small flux of radionuclides (in becquerels per year) migrating into, and mixing with, a large volumetric flux of groundwater (in cubic metres per year) will produce a low concentration of radionuclides in the groundwater (in becquerels per cubic metre), which will result in low doses. Dispersion refers to the spreading out in time and space of a radionuclide plume migrating from a repository. By far the most important aspect is dispersion in time and, again, this is most effective in reducing calculated doses when the retention and retardation of radionuclides are at their greatest.

IV.13. Both dilution and dispersion are assisted by strong containment of radionuclides, which is determined by the effectiveness of the engineered barriers and, importantly in a site selection context, long radionuclide migration times to the surface. This will be produced by low groundwater flow (see para. IV.11) and strong radionuclide sorption (see para. IV.14) in the surrounding geosphere. High levels of dilution due to mixing may also be achieved where there is a strong contrast in groundwater flow between the disposal horizon with very low flow and the nearer surface horizons with higher flow.

IV.14. Strong sorption (for the radionuclides to be disposed of and their radiologically significant progeny) in the host rocks and overlying formations is another favourable factor that aids containment. At the same time, it has to be acknowledged that some non-sorbing ions (e.g. chloride) exhibit little sorption regardless of rock type. The term sorption is used to describe a range of processes, including adsorption, ion exchange and chemical reaction, that allow radionuclides to attach themselves to near field materials such as bentonite or cement or to rocks in the geosphere. This retards the transport of these radionuclides, giving more time for radioactive decay to occur. Sites where sorption causes radionuclide transport to be slow and where dilution by mixing and dispersion are high should give rise to calculated doses that fall well below the regulatory constraint. Where this is the case, the demonstration of post-closure safety may be possible with relatively less effort.

IV.15. It is advantageous to the construction of the borehole if the host rock is self-supporting and, for this reason, rock competence will be important. Rock and deep soil formations that have poor stability for boreholes should be avoided, particularly for the host unit. Where competent rock is combined with a small borehole diameter, it may be possible to dispense with a borehole casing in the disposal zone. However, close to the surface, because of lower rock competence (due to weathering), casing will often be required. Where borehole casing is to be installed in the disposal zone, a behind casing seal will need to be installed. Such seals are usually created by pumping cement grout into the annulus between the casing and the rock. Rock formations where good grout-to-rock bonding is possible are therefore to be preferred. Ground where the levels have been changed by exporting or importing material should be avoided because of its generally lower stability.

IV.16. For intermediate depth boreholes, the likelihood and the consequences of human intrusion will usually be less than for near surface boreholes. Nonetheless, disposal sites should be chosen to reduce the possibility of inadvertent human intrusion by avoiding areas with useful natural resources (e.g. plentiful groundwater, minerals or hydrocarbons). With respect to access, unpaved roads should be adequate for small scale disposals and it should be possible to use mobile supplies of electricity and water.

IV.17. Again, as with near surface boreholes, sites should be chosen to avoid areas of ongoing tectonic activity.

IV.18. Surface processes, while they are less important for an intermediate depth borehole site, should still be considered: it is likely, for instance, that erosion and weathering will be more tolerable for an intermediate depth borehole than for a near surface borehole. Areas susceptible to flooding and landslip should again be avoided, as much for reasons of operational safety as for post-closure safety.

IV.19. With respect to climate and extreme meteorological events, the principal concern for intermediate depth boreholes is their effect on regional groundwater flow. Disposal in formations where the groundwater shows strong seasonal variability should be avoided.

IV.20. Owing to the difficulty of characterizing deep formations by boreholes alone, a simple, easily characterized geological structure and hydrogeological system is advantageous. Areas of high geological complexity should be avoided because they could be difficult (and therefore expensive) to characterize and this could limit the degree of confidence in the results of the safety assessment.

Hydrogeological characterization activities

IV.21. To help describe the hydrogeological characterization of a site, it is useful to define three situations:

(1) A borehole situated in an unsaturated zone;
(2) A borehole situated in a saturated environment with high to low permeability rocks;
(3) A borehole situated in a saturated, very low permeability (e.g. clay) environment.

IV.22. The following three subsections briefly describe the characterization activities likely to be needed for hydrogeological characterization of each type of site. The discussion presupposes (a) that the disposal is on a small scale and (b) that the geology, hydrology and geochemistry of the site are not complex. In all three cases, an early and important component of the work will be to establish the geochemistry of the site at the proposed disposal depth. The purpose of this component is to provide assurance that the local geochemistry (e.g. sulphate and chloride levels) will not unduly affect the engineered barriers.

Hydrogeological characterization of an unsaturated site

IV.23. Even in temperate and wet tropical regions, the water table may sometimes lie 10–20 m below the surface: sufficiently deep to allow a near surface borehole to be located in the unsaturated zone. On the other hand, unsaturated zones that are sufficiently deep to accommodate an intermediate depth borehole are likely to be confined to arid regions.

IV.24. At a site where the water table is tens or even hundreds of metres below the disposal zone, the investigatory borehole should normally extend to the water table and, for near surface boreholes, to the aquitard that supports it. Provided that the regional hydrogeology is generally understood, one investigatory borehole may be sufficient for a small scale disposal facility. This borehole should provide core from the host formation (at least) and water samples from the underlying aquifer. Key information to be established includes evidence for previous levels reached by the water table, the amount and rate of percolation of meteoric water through the unsaturated zone, and the characteristics of the groundwater in the underlying aquifer. These characteristics include details of its chemistry, origin, age, flow and pressure, which are used to estimate its transit time to the biosphere. Where the testing fails to provide confidence in the regional hydrogeological model, additional boreholes may be necessary to help develop one.

Hydrogeological characterization of a saturated site in high to low permeability rocks

IV.25. The second example is a borehole disposal facility situated in high to low permeability rocks that are permanently saturated. Here, to confirm that there are no structures or hydrogeological features such as underlying high pressure zones that could affect performance, the investigatory borehole should be sunk at least to the bottom of the host formation (unless this is very deep). Hydrogeological investigations should include measurements of pressure and water inflow rate at different horizons and pump testing to establish the effective hydraulic conductivity of the host rocks. Additional investigatory boreholes, distributed in the surrounding area, are also likely to be needed. These should be used to establish the pressure gradient and the degree of homogeneity of the host rocks. These secondary boreholes should normally be drilled at least to the disposal depth. In the case of near surface boreholes situated in or close to the saturated zone, the secondary boreholes should also be used to determine the morphology of the water table and how it varies seasonally. Extracted core may provide evidence of past water table levels. For the intermediate depth borehole disposal facilities, water samples taken from different depths should be used to assess the degree of stratification of the water column.

Hydrogeological characterization of a saturated site in very low permeability rocks

IV.26. At sites where the disposal zone is situated in saturated, very low permeability rocks (e.g. plastic clay), the rate of water ingress into investigatory boreholes may be very low or even undetectable, and this may make the collection of water samples and the measurement of hydrogeological properties difficult. In some cases, it may be possible to extract water samples from extracted core and it may be necessary to assign a figure to the groundwater flow rate on the basis of the limit of detectability of water ingress to the borehole. The hydraulic conductivity of the host rock can be measured from extracted core. The thickness of the host rock layer should be measured to establish the distance between the disposal zone and more permeable rocks.

Provided that the host rock is relatively homogeneous, a single investigatory borehole may be sufficient for a small scale disposal facility. Otherwise, it may be necessary to sink shallow boreholes or use other techniques to locate, for instance, lenses or layers of higher permeability material.

Appendix V

A POSSIBLE SURVEILLANCE AND MONITORING PROGRAMME SUITABLE FOR A SMALL SCALE BOREHOLE DISPOSAL FACILITY

V.1. The surveillance and monitoring activities described here are not intended to be prescriptive — the operator of a disposal facility should justify the extent of the proposed programme. However, for a borehole disposal facility consisting of fewer than twenty boreholes for disused sealed sources, the following suggestions may be adequate.

Pre-operational (baseline) surveillance and monitoring

V.2. Baseline measurements should be made well before the site becomes operational (e.g. during the site characterization phase). The purpose of baseline surveys is to build up a reliable and comprehensive database of information relating to the site so that any future changes can be readily detected. These could cover a period of at least one year (i.e. covering all the seasons) and should consist of meteorological data gathered daily and continuous seismic data, together with:

(a) Surface samples: monthly measurements of activity levels in air, soil (including radon if it is anticipated that the sources will contain radium) and surface water (if any), with identification of the principal radionuclides.
(b) Borehole groundwater samples: monthly measurements of activity levels in groundwater in the disposal horizon, if this is water bearing, or otherwise just below the groundwater table, provided that this is no more than 100 m below the disposal horizon. Again, the principal radionuclides should be identified.

V.3. Surface sampling should be done at about ten locations within and around the boundary of the proposed site. About half of these locations would be used repeatedly; the other locations would be changed each month so that, over the full year, sampling points are uniformly distributed over the area to be covered. Other surface sample points would be located at the nearest human habitation and the point of putative groundwater discharge (e.g. a nearby topographic low). If borehole water is used at locations nearby, this should also be monitored.

V.4. For borehole groundwater sampling, two to four boreholes should be located on the site boundary to sample water in the disposal horizon upstream and downstream of the waste. Once a reliable database has been established, the frequency of sampling could be reduced to twice yearly.

Surveillance and monitoring during the operational period

V.5. When the operational period begins, the amount of on-site surveillance and monitoring should be increased. For instance, the measurements should include monitoring of personnel, monitoring of newly received waste packages for radioactive contamination and monitoring for the spread of contamination from packages to handling equipment. When waste handling is in progress, air monitoring for particulates should be continuous, with filters being removed for analysis after every major site operation. Following waste emplacement, soil samples should be used to monitor contamination (if any) of the soil around the borehole.

V.6. Beyond the site boundary, sampling and analysis of air, soil and water should continue at the same twice yearly frequency as previously — provided, of course, that the results continue to be satisfactory. Meteorological and seismic measurements should also be continued.

Surveillance during the post-closure period of institutional control

V.7. Following closure of the facility, surface sampling of air, soil and water should continue at the same frequency as during the operational period. Again, about ten surface sample locations should be sufficient, with additional samples taken at the nearest human habitation, a topographic low and any nearby boreholes used for water extraction.

V.8. For groundwater sampling, two monitoring boreholes should be sufficient, one upstream of the waste, the other downstream. If the institutional period is to exceed five years, the number of surface samples could be halved, the upstream borehole could be sealed and the sampling frequency could be reduced to once a year. The final monitoring borehole would be sealed when the period of institutional control ends.

Appendix VI

MANAGEMENT SYSTEMS

Setting up a management system

VI.1. The first requirement for the establishment of a management system is the formal endorsement of such a system at the highest level of management of an organization and a commitment to ensuring that it is fully implemented throughout the organization [35]. A management system is a means of ensuring that an organization's goals are achieved efficiently and effectively. It follows that the organization's goals should be a focal point of the management system. If, for example, in establishing the remit of an operator of a borehole disposal facility, a government were to stress the importance of cost efficiency, this should appear as one of the operator's goals.

VI.2. With the organization's goals clearly stated, a management system should be developed and implemented to achieve these. This is often done by breaking down the goals in a hierarchical way — into 'activities' and 'tasks' for instance — and structuring the organization to reflect this breakdown. This means that the organizational structure and job descriptions form part of the management system. How the goals–activities–tasks are to be performed and by whom is documented in policies, procedures, work instructions, quality plans, etc. In Ref. [35], all of these are called 'working documents' and this convention will be followed here. The management system should apply to all the work of an organization, i.e. from conceptual design through to the ending of institutional control. The management system should also extend to suppliers and contractors, who should also be expected to work to agreed procedures. In this context, nationally and internationally recognized codes, regulations and standards provide practical, widely understood benchmarks and should be followed whenever possible.

VI.3. In the case of an operator, the management system should extend to the waste producers who might have their waste packaging arrangements audited by the operator. In turn, the operator's management system should be approved by the regulatory body.

Working documents

VI.4. Working documents should describe what work is to be performed, how and by whom so as to complete it successfully (i.e. in such a way that the work contributes to the achievement of the organization's goals). The working document should also require the production of documentary evidence to prove that the working document was followed. Working documents should be written by someone with experience in carrying out the task and should be independently approved, preferably by someone at the senior management level.

VI.5. The level of detail and prescription in a working document should depend on how important the work is for safety and its susceptibility to failure. In general, the safety case and, more particularly, the safety assessments within it should be used to help identify and justify the level of detail and prescription needed in individual procedures. The safety case should also provide a methodology for identifying information that should be preserved either as an audit trail for past decision making or because it could be important for future safety assessments.

VI.6. For example, in early design work, it is invention, not prescription, that is needed and, although the final design will be strongly safety related, a great deal of checking and testing will take place before the early design ideas become finalized. Consequently, the working document should focus on providing a clear description of the aim and the constraints of the design, together with a requirement to explain the reasoning behind the various design decisions. On the other hand, backfilling of a borehole should be tightly prescribed because (i) post-closure safety may depend on it, (ii) it may be difficult to check that it has been done correctly and (iii) a badly backfilled borehole could be very difficult to remedy. The accompanying documentation should aim to provide evidence that backfilling was (or was not) completed successfully. It could, for instance, state the volume of backfill placed in the borehole and the measured change in level in the borehole. For a third example, the ISAM approach [28] described in Appendix III provides an illustration of a well thought out working document for performing a post-closure safety assessment. Particularly useful is the initial 'context' step, which allows the supporting documentation to become more or less voluminous, depending on how the safety assessment is to be used.

Documentation

VI.7. A key function of the management system is the production and retention of documentary evidence to demonstrate that the correct procedures have been followed. Regular audits, which should also be documented, should provide additional evidence of this. Audits should be carried out by the organization itself (internal audits) and by external agencies. Where the organization is an operator, the actions and procedures to be followed by the operator in the event of the discovery of a non-compliance with safety procedures should be specified and approved by the regulatory body.

VI.8. By ensuring that compliance with the relevant safety requirements and criteria forms part of the operator’s goals, activities and tasks, a management system will contribute to delivering compliance and, through the associated documentation, will provide evidence for this.

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Annex

GENERIC POST-CLOSURE SAFETY ASSESSMENT FOR BOREHOLE DISPOSAL OF DISUSED SEALED SOURCES

A–1. This annex is based on a report on a generic post-closure radiological safety assessment (GSA) for the borehole disposal concept, with the purpose of identifying the concept's key safety features, under varying disposal system conditions, in order to support the concept design and licensing processes and facilitate its site specific implementation. The report is one of a series that is being developed to support the implementation of the borehole disposal concept. The report is to be issued by the IAEA as a Safety Report.

A–2. Many countries now have radioactive sources that need to be managed and disposed of carefully and in a safe and secure manner. These sources contain different radionuclides in highly variable quantities. Many sources are small in physical size. However, they can contain very high activities, with typical levels in the megabecquerel (10^6 Bq) to petabecquerel (10^{15} Bq) range. Therefore, if they are not managed properly, radioactive sources can represent a significant hazard to human health and to the environment. Storage in a secure facility can be considered as an adequate final management option for sources containing quantities of short lived radionuclides, which decay to harmless levels within a few years. However, for most other sources, a suitable disposal option is required.

A–3. Many countries have existing or proposed near surface radioactive waste disposal facilities for low and intermediate level wastes. However, the specific activity of many sources exceeds the waste acceptance criteria for such facilities, since the source constitutes a high, localized concentration in the facility. Deep geological disposal offers the highest level of isolation available within disposal concepts currently being actively considered. Such facilities are under consideration for the disposal of spent nuclear fuel, high level waste and intermediate level waste in a number of countries. However, they are expensive to develop and only viable for countries with extensive nuclear power programmes. Therefore, increasing attention has been given to the disposal of disused sources in borehole disposal facilities with a view to providing a safe and cost effective disposal option for limited amounts of radioactive waste and, particularly, disused sources.

A–4. A variety of borehole designs have been used for the disposal of radioactive waste at differing depths (a few metres to several hundred metres) and diameters (a few tens of centimetres to several metres). The design evaluated in this report is based on the narrow diameter (0.26 m) design developed under the IAEA's AFRA project (see Figs 1 and A–1) since this design has been developed specifically for the disposal of disused radioactive sources and uses borehole drilling technology that is readily available in all countries. The design can accommodate disused sources of less than 110 mm in length and 15 mm in diameter. This means that the design is applicable to a wide range of sources. It is assumed that the sources are disposed of at least 30 m below the ground surface. The geological, hydrogeological and geochemical conditions considered in this report have been selected to represent a broad spectrum of site conditions.

A–5. The GSA has been undertaken using an approach that is consistent with best international practice. Specifically, the approach developed by the Coordinated Research Project of the IAEA on Improving Long Term Safety Assessment Methodologies for Near Surface Radioactive Waste Disposal Facilities (the ISAM approach) has been used, with the aim of ensuring that the assessment is undertaken and documented in a consistent, logical and transparent manner. The ISAM approach consists of the following key steps:

(a) Specification of the assessment context;
(b) Description of the disposal system;
(c) Development and justification of scenarios;
(d) Formulation and implementation of models;
(e) Presentation and analysis of results.

Each of these steps is applied to the GSA of the borehole disposal concept and the application is described in this report.

A–6. The main report is supported by a series of appendices that provide detailed information relating to specific aspects of the assessment study, namely:

(a) The selection of the radionuclides and the geochemical conditions assessed in the GSA;

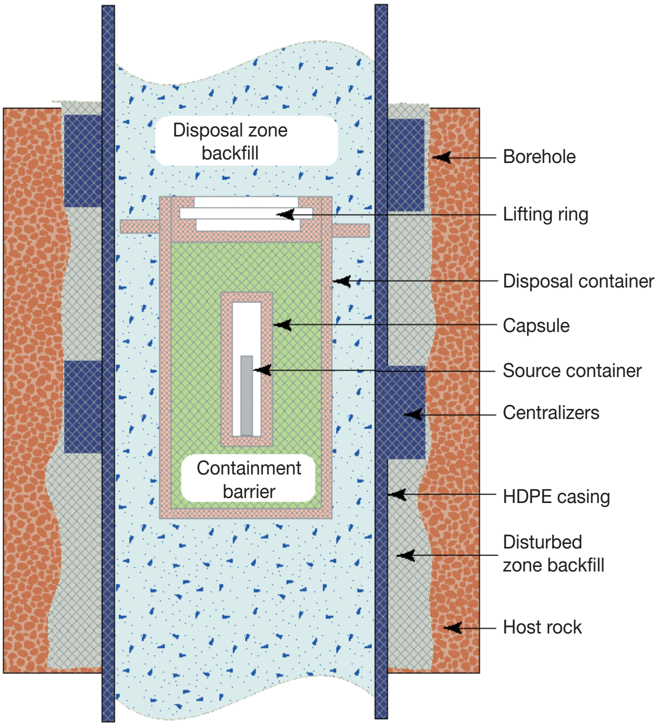

FIG. A–1. Illustrative section through a borehole used for disposal.

(b) The approach used to identify scenarios and conceptual models for consideration in the GSA and the screening of associated features, events and processes (in particular those associated with the borehole itself);

(c) The detailed models used to undertake the calculations of cement degradation and the corrosion of stainless steel waste capsules and disposal containers in the different environmental conditions considered;

(d) The assessment level models and data used to calculate the impacts of disposals to the borehole disposal concept;

(e) The results of the associated calculations.

A–7. The GSA has been developed so that it can serve as the primary post-closure safety assessment for specific disposal sites that lie within the envelope of conditions assessed in this report. For situations falling outside the envelope, additional calculations ranging from minor variations of the GSA to a full, site specific safety assessment may be required. In such cases, the GSA could be used to guide and support the development of the site specific assessment. Furthermore, the derived generic reference activity values could be used as a benchmark against which to compare values derived from the site specific assessment.

A–8. The results show that with a suitable combination of inventory, near field design and geological environment, the borehole disposal concept is capable of providing a safe solution for the disposal of both long lived and short lived radionuclides. For most radionuclides, including longer lived radionuclides such as ^{226}Ra, post-closure safety does not place unduly restrictive limitation on the radionuclide inventory that could be disposed of using the borehole disposal concept. Even for radionuclides such as ^{238}Pu, ^{239}Pu and ^{241}Am with exceedingly long lived progeny (i.e. half-lives in excess of 100 000 a), the concept has the potential to dispose of around 1 TBq in a single borehole.

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STI/PUB/1073 (29 pp.; 1999)
ISBN 92-0-101099-0 Price: €12.50

Safety through international standards

The fundamental safety objective is to protect people and the environment from harmful effects of ionizing radiation.

This fundamental safety objective of protecting people — individually and collectively — and the environment has to be achieved without unduly limiting the operation of facilities or the conduct of activities that give rise to radiation risks.

— Fundamental Safety Principles: Safety Fundamentals,
IAEA Safety Standards Series No. SF-1 (2006)

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA
ISBN 978–92–0–109109–3
ISSN 1020–525X