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NUCLEAR FUEL CYCLE TECHNOLOGY AND POLICY PROGRAM

A Review of Geology-Related Aspects of Deep Borehole Disposal of Nuclear Wastes

For the MIT Study on The Future of the Nuclear Fuel Cycle

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ABSTRACT

This report updates work carried out at MIT since 2003 on the conceptual design and performance assessment of deep borehole repositories for disposal of high level nuclear wastes.

The focus is on 40 to 50 cm diameter holes drilled into crystalline granitic bedrock using available oil/gas/geothermal industry technology. The holes are fully lined using grouted-in-place standard steel drillpipe. Newer features include reduction in maximum depth to 3 km, with a 1 km waste emplacement zone, and the use of graphite "sand" as a lubricating/thermally conducting infill between the waste canister string and borehole wall liner, to increase the prospects for retrievability. The reduced bottom-hole lithostatic pressure also helps avoid hole collapse; likewise, the reduced depth limits maximum hydrostatic pressure, should the borehole flood, to levels which will not crush the waste canister string. Finally, the shorter emplacement zone reduces the weight of the canister stack to values which will not crush the bottom-most canisters, with a significant factor of safety.

Since 2003 the main focus at MIT has been on disposal of separated minor actinides and troublesome fission products (e.g., Tc-99, I-129) as a strategy for facilitating conventional disposal in shallow mined repositories such as Yucca Mountain, and other such, worldwide.

Future R&D requirements are identified covering the entire spectrum of needs.

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Chapter 1 Introduction

1.1 Foreword and Objectives

This report updates work carried out at MIT since 2003 on the conceptual design and performance assessment of deep borehole repositories for disposal of high level nuclear wastes. It also calls attention to pertinent developments reported by the other groups currently active in this area: NIREX and Sheffield University in the UK, and SKB/MKG/KASAM in Sweden.

Even among the wider nuclear community there is a demonstrable need for up-to-date information. For example, in the latest (6^{th}, 2009) edition of a widely employed and highly respected textbook (1-14), the following quote is expressed regarding the deep borehole waste disposal option:

> "3. Deposit canisters in mile-deep holes in the Earth. The method is impractical with available drilling technology."

This observation may be due to the misperception that a transport/transfer multiassembly shield cask will be disposed of together with its contents: an unnecessary requirement which would require a very large diameter hole.

Appendix A is a Bibliography, complete with abstracts, of the five theses completed at MIT from September 2004 through September 2008. In addition, useful findings from an equal number of internal student class project and summer intern program reports will be worked into this report's text, where appropriate.

The 2003 start date was selected for a number of reasons. It was the publication date of the MIT Study on the Future of Nuclear Power, which suggested re-examination of the borehole alternative, which in turn inspired feedback on its perceived drawbacks and uncertainties – which we will address in this report. Other key motivators are the DOE's post-2000 initiatives in their AFCI and GNEP programs, which refocused emphasis onto reprocessing waste forms rather than intact spent fuel assemblies. In addition, the uncertain prospects of the Yucca Mountain repository motivates renewed consideration of supplementary and alternative approaches.

Worth mentioning is a possible factor inhibiting research in this area – the prohibition in the US Nuclear Waste Policy Act of 1982, as amended in 1987, of the evaluation of disposal into granite; to quote Sec. 161:

> (c) TERMINATION OF GRANITE RESEARCH. – Not later than 6 months after the date of the enactment of the Nuclear Waste Policy Amendments Act of 1987, the Secretary shall phase out in an orderly manner funding for all research programs in existence on such date of enactment designated to evaluate the suitability of crystalline rock as a potential repository host medium.

Sociopolitical motives are widely acknowledged as the reason for this provision. In view of the strong technical justification of, and commitment to, emplacement in granite in Sweden and Finland, this restriction is probably reversible.

1.2 An Abbreviated History of the Deep Borehole Concept

Prior to the late 1980s, deep boreholes were considered for nuclear waste disposal, but passed over in favor of mined repositories, both in the US and worldwide. This was due in part to the lack of experience in drilling to suitable depths in those days. Note in particular that our attention is limited to disposal of solid, encapsulated wastes, and not liquid waste injection, as extensively practiced in the former Soviet Union (1-1).

Far more significant, for present purposes, were the studies in the 1990s, of deep boreholes as a means for disposition of excess weapons material (1-2). Most of the features devised are quite similar to the reference concept described elsewhere in this report. One major difference was the objective of making retrieval difficult, even for the host nation. Particularly useful is a siting handbook prepared as part of this effort (1-3).

The more recent revival of the deep borehole approach for spent nuclear fuel disposal is typified by work reported by researchers at MIT (1-4 and Appendix A), Sheffield University in the UK (1-5), and SKB in Sweden (1-6). Table 1.1 identifies these principal earlier studies. References (1-10), (1-11) and (1-12) are informative post-2003 reviews of the concept. Additional references will be cited in the relevant sections of this report.

Perhaps the most significant new development has been the acceleration of interest in enhanced geothermal systems (EGS), in which deep wells are drilled into hot dry rock (1-7). Several such projects are now underway worldwide. There is considerable overlap in all areas of technology, the major difference being the preference for large vertical temperature gradients for EGS (versus small for waste disposal) and use of horizontal fracturing for EGS (versus maintenance of rock integrity for waste disposal).

Table 1.1 Summary Comparison of Deep Borehole Concepts

Proponent (Vintage)	MIT Kuo (1995	MIT Hoag (2006)	MIT (2009)	LLNL (1996	UK (2008)	SKB (1989)	Aust-ralia (2001)	Woodward-Clyde (1983)
Total Depth (Waste fill Length) m	2250 (1250)	4000 (2000)	3000 (1000)	4000 (2000)	4000 (1000)	4000 (2000)	4000 (2500)	6000 (3000)
Hole Bottom ID (Casing ID)	50.8 (45)	50.8 (38.7)	50.8 (38.7)	66	80	80 (60)	120	50.8
Waste Type	Spent Fuel	Spent Fuel	Spent or Reprocessed Fuel	Pu	Fuel or Glass	Spent Fuel	SYNROC	Spent Fuel or Processed
Canister Capacity	1 PWR Assy.	1 PWR Assy.	1 PWR Assy.	~6 kg/m	~2 kW/m	4 BWR or 1 PWR & 2 BWR	~1.5 kW/m	3 PWR or 1 PWR
Hole-to-Hole Spacing, m	96 m	100	200	Only 4 Holes	100	500	6000	180-800
References	(K-1)	(H-1)	This Rept.	(W-1)	(G-1)	(S-1)	(S-2)	(O-1)

References for Table 1.1:

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1.3 Reference Borehole Repository Description

Specification of certain essential features is an essential prerequisite to any analysis and assessment of deep borehole suitability, particularly since important details vary among what various proponents and critics have in mind. Accordingly, Fig. 1.1 has been prepared to make clear the most recent features of the approach resulting from an evolutionary process over the past two decades of work at MIT. Key parameters such as depth, diameter, spacing and loading are shown. The rationale will emerge from the analyses and discussion presented in subsequent sections of this report. At this point it will suffice to note that the current version is essentially that of Ref (1-8), but with depth reduced to 3 km (from 4 km), and with many features in common with the UK and Swedish versions. Of particular relevance is the NIREX (1-10) suggestion that reduced depth (2.5 km total, 1.25 km deposition zone) be looked into, for reasons which also motivated our current modifications: e.g., better borehole stability and increased deposition zone diameter.

Equally important are the basement rock properties assumed. They are summarized in Table 1.2. Where a range of data were given in the literature, values considered to be conservative for present purposes were chosen. For those less familiar with the nature of granitic bedrock, a brief primer with references is provided as Appendix E.

Layout

Vertical Surface	Hole	Hole	Hole Casing (OD/ID), cm
≤ 1 km Sedimentary rock			Upper (50.8/48.6)
1 km Basement rock, plug zone			Mid-Zone (47.3/45.1)
1 km Waste emplacement zone	◄──────►		Lower (40.6/38.7)

Hole Spacing = 200 m
Square Array

Waste String "Canister" Casing

34 cm OD, 31.5 cm ID*
5 m length (half of usual 10 m)
Capacity: One PWR Assembly

Weights, kg:		
	Casing**	600
	Spent Fuel***	700
	Sand Fill	700
	Total	2000

*To accommodate 21.4 cm. width assemblies (30.3 cm diag.)
**Including end plugs
***Of which 500 kg is (as-loaded) heavy metal

Borehole Repository Field

200 Canisters (assemblies) per hole
100 MTHM/Hole (5 reactor years' worth)
Hole Array: 20 x 40 = 800 Holes, i.e. 4 km x 8 km field
Capacity: 80,000 MT (~Yucca Mountain)
Uranium loading: 100 kg/m as waste,
300 kg/m in rock (@ 3 ppm in granite)

Cost: 4×10^6 \$ per completed, lined, cemented borehole = 40 \$/kg HM

Figure 1.1 2009 Version of Deep Borehole HLW Disposal Concept

Table 1.2 Basement Rock Properties

	Value
Type	Granitic; Precambrian, Plutonic crystalline
Density: ρ, kg/m^3	2600
Heat capacity: Cp, kJ/kg °C	0.79
Thermal Conductivity: k, W/m °C	2.6
Thermal Diffusity: $\alpha = \frac{k}{\rho c p}$, $\frac{m^2}{yr}$	40
Geothermal Gradient: °C/km	15
Porosity, %	< 0.1%
Permeability, m^2	< 10^{-17} (~ 10^{-5} Darcy)
Lithostatic Pressure (ρg x 10^{-3}), MPa/km	25.5
Uranium Content, ppm	3
Poisson Ratio, υ	0.2
Youngs Modulus, E, MPa	50,000
Mechanical Strength in Compression, MPa	> 100
Tensile Strength, MPa	~ 10
Coefficient of linear thermal expansion, α*, cm/cm °C	8.0 x 10^{-6}

Table 1.3 Drillpipe Steel Properties

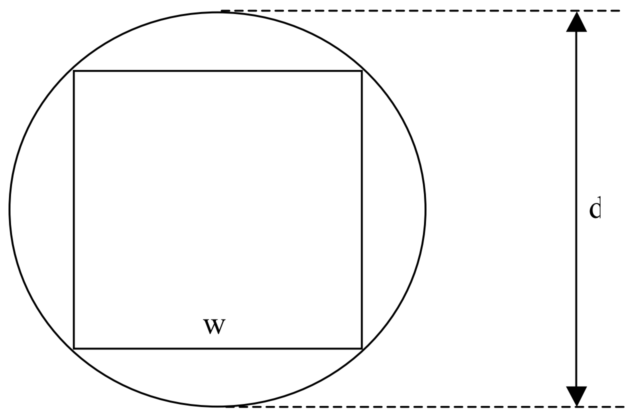
Min. Yield Strength,* MPa	**760**
Min. Tensile Strength,* MPa	**860**
Density, kg/m^3	**7850**
Youngs Modulus, MPa	**190,000**
Poisson's Ratio, ν	**0.26**
Thermal Conductivity, k, W/m °C	**40**
Coefficient of Thermal Expansion, α*, per °C	**1.2 x 10^{-5}**

*for P110 steel (a high-strength material) used for bottom-most string: parameters are about twice more common steels

Table 1.4 Downhole Saline Water Properties

Salinity/Density, % /kg/m^3	10/1100
Redox Potential, E_h, V	-0.3
Thermal Conductivity W/m°C	0.67
% increase in density per km H_2O	0.4
% decrease in density per 100°C	6.7
Hydrostatic Pressure, MPa/km	10.8

Table 1.5 PWR Assembly Properties



PWR Assembly Width, w = 21.4 cm

Dia. of circumscribed circle, d = 30.3 cm
(minimum ID of waste canister string)

Actual canister ID = 31.5 cm. (see Fig. 1.1)

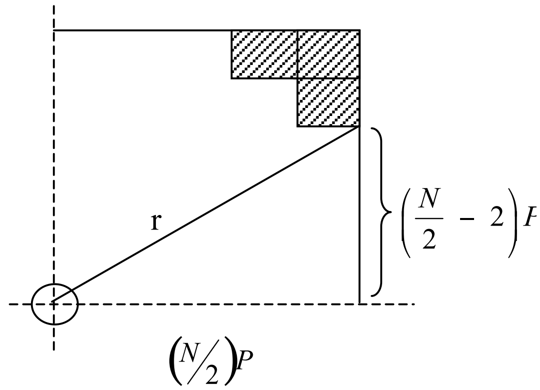
d can be reduced by 3.6 cm by removing corner rods (see Table 1.6)

3 BWR assemblies can be accommodated in a 34.6 cm ID canister

d can be reduced to 18.1 cm by reconstitution into a close-packed circular bundle

Weight of heavy metal = 500 kg (also see Fig. 1.1)

Table 1.6 Reducing Assembly Diameter by Removing 3 Corner Rods



N x *N* assembly, fuel cell width = *P*

$$r^2 = \left(\frac{N}{2} - 2\right)^2 P^2 + \left(\frac{N}{2}\right)^2 P^2$$

thus

$$\left(\frac{r}{P}\right) = \sqrt{2}\left[\left(\frac{N}{2}\right)^2 - N + 2\right]^{1/2}$$

compare to the case with corner rods present:

$$\left(\frac{r_o}{P}\right) = \sqrt{2}\left(\frac{N}{2}\right)$$

Hence $\left(\frac{r}{r_o}\right) = \left(\frac{d}{d_o}\right) = \sqrt{1 - \frac{4}{N^2}(N - 2)}$

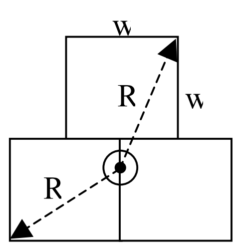
for N = 17

$$\left(\frac{d}{d_o}\right) = 0.89$$

Thus if d_o = 33 cm, d = 29.4; Δd = 3.6 cm reduction
= 1.4 inches

BWR Assemblies

The reference design discussed earlier is based on accommodation of one PWR assembly per canister, on the basis that 75% of the LWRs worldwide are PWRs (66% in the US). However, one must also deal with the remainder – BWRs. The proposed loading is to replace one PWR assembly by three BWR assemblies



where one can readily show that $(R/w) = \sqrt{\frac{425}{256}} = 1.29$.

BWR assembly width is 13.4 cm, hence the circumscribing circle diameter is 34.6 cm. Lower borehole casing ID is 38.7 cm, which allows for a 1.25 cm waste canister wall thickness, and a 0.8 cm gap between the canister and the lower hole casing: much thinner than the 2.35 cm gap for the PWR canister. Thus, increasing borehole diameter or removing corner pins from the assemblies may be worth looking into. Other parameters of interest are:

Weight of 1 BWR fuel assembly = 280 kg (840 kg for 3)
(of which 165 kg is original heavy metal (495 kg for 3))
length of assemblies = 4.47 m
volume & weight of sand fill (313,000 cc; 620 kg)

Hence total loaded canister weight = 2060 kg, about 60 kg heavier than a PWR canister, which is acceptable.

Fuel Assembly Consolidation

Better use of available drilling technology motivates reduction of borehole diameter. One way to do this would be through fuel assembly consolidation: i.e., disassembly of the square assembly, and reassembly into a tightly packed hexagonal array.

A typical PWR assembly has a 17 x 17 array, hence 289 positions, of which 264 are fuel pins.

A hexagonal bundle has a number of fuel rod positions given by:

$$N = 1 + 3n(n + 1)$$

where n is the number of rings surrounding the central rod.

Thus $n = 9$ has 271 positions – enough to accommodate the 264 fuel pins in a PWR assembly.

The maximum hexagonal close packed array diameter of fuel rods having a diameter d_h is given by:

$$d_h = d_p(1 + 2n) = 19\ d_p \text{ in our example}$$

A representative PWR $d_p = 0.95$

hence

$$d_h = 18.1 \text{ cm (7.1 inches)}$$

which is considerably less than the diagonal dimension of the intact assembly:

$$(21.4)\sqrt{2} = 30.3 \text{ cm (= 11.9 inches)}$$

Thus, if the cost of reconstitution is tolerable, this may be a worthwhile tactic, since each assembly must be individually repackaged in any event. A cost of \$10,000/assembly would amount to 20 \$/kg HM, which would be acceptable in view of the likely savings in borehole costs (e.g., if savings exceeds about 2 million dollars for this example).

Other aspects would have to be examined. For example, would a bundle of rods, by itself, have sufficient crush resistance, since filling interstices with sand or cement would be more difficult?

Is the remote possibility of criticality excluded by reducing the water-floodable void space available between fuel pins?

Minor Actinide Repository (1-13)

For historical reasons, past MIT deep borehole studies have focused on disposal of unreprocessed spent fuel. Of late, in response to more recent US DOE program initiatives, attention has turned to ultra high integrity entombment of separated minor actinides and troublesome fission products (e.g., Tc-99 and I-129) as an alternative to their destruction by transmutation – a messy and expensive business.

Recall that each 5 m "canister" (waste string drillpipe section) can hold one intact PWR assembly. Alternatively it can accommodate an annular ceramic waste log containing minor actinides, plus Tc-99 and I-129, from ten PWR assemblies – quarter of a 1 GWe reactor's annual production. Thus a 2 km deep waste zone (i.e., in non-retrievable mode) holds 100 reactor-years worth per borehole, in which case only sixty boreholes can deal with the MA of the current US one-hundred-reactor fleet over their (extended) lifetime of sixty years.

1.4 Issues Raised by Critics

The issuance of the 2003 MIT report inspired several reviewers to compile a list of perceived shortcomings of the use of deep boreholes for high level nuclear waste disposal. In particular, we were informally provided with comments by anonymous reviewers at the CEA and ANL. Self-criticism by the teams at MIT, Sheffield University and SKB has long been part of the historical record. Table 1.7 lists most of the issues of substance, together with a brief commentary on ways to avoid or mitigate them. Chapters 2, 3 and 4 and Appendices A through C will provide additional backup.

1.5 Organization of This Report

Chapter 2 briefly reviews the global perspective on borehole repository siting, to show that there are many areas suitable for this purpose. Technology for narrowing down prospective locations to several kilometer square fields are also discussed.

Chapter 3 focuses on qualification of individual boreholes using available oil/gas/geothermal well-logging technology.

Chapter 4 discusses some back-of-the-envelope level estimates of limiting-case performance metrics. Where available, reference to more sophisticated detailed analyses in the literature will also be cited.

Chapter 5 presents a summary, conclusions and recommendations.

Finally, five appendices are included, summarizing supplementary information and documenting details of several calculations carried out in support of the observations made in Chapters 3 and 4.

Table 1.7 Suggested Shortcomings of the Deep Borehole Approach

Issue	Suggested Exculpation
Difficult, if not impossible, retrievability	• Today's trend is to interim surface storage before final entombment • Can improve prospects using graphite sand between canisters and steel wall liner, limiting depth to 3 km • Not relevant for reprocessing wastes such as minor actinides
Confinement breach by rise of hot water plumes	Salinity (hence density) of deep water negates this phenomenon
Inability of prior characterization and subsequent monitoring	• Oil/gas industry has developed very sophisticated instrumentation for both wide field and downhole monitoring • Some holes will be reserved for permanent instrumentation
Short life of engineered barriers; lack of multiplicity	• Reliance is primarily but not exclusively on geology; analyses show many orders of magnitude of margin • Can line canister with copper, fill with special grout, to obtain defense in depth
More expensive than shallower mined repositories	Recent assessments and field experience for hot-dry-rock geothermal applications show very favorable costs: e.g. 4×10^6 \$ for a fully completed 3 km lined hole
Reducing conditions are no panacea	Most geologists/geochemists prefer a reducing environment. Sweden has studied this issue intensively
Lack of a licensing protocol	• Essential to license as an N by N field of "identical" holes in a uniform rock environment, not each individually • Reliance on geology requires qualification of verification methods
Requires additional repackaging step	• Thwarts DOE plan for multi-purpose casks (store/ship/hold/entomb) • Adds cost

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Chapter 2 Borehole Siting and Drilling Considerations

2.1 Chapter Introduction

Once candidate sites for HLW borehole fields have been selected on the basis of general geological knowledge and socio-political criteria, more intensive surveys must be carried out, encompassing first tens of, then narrowed to several, square kilometers. Two general approaches, borrowing heavily from oil and gas exploration methods, are available: airborne and terrestrial. Both are surveyed in this chapter, as are general issues associated with subsequent drilling operations.

2.2 Regional Site Screening

Before proceeding to discussion of methods for assessment of specific candidate locales, it is necessary to apply more general criteria to narrow down where to look. Fortunately, there are a wide variety of geophysical and other surveys of the US which can be utilized for this purpose, and prior studies have already done so (2-1) (2-2) (2-3) Furthermore, while our interest here is mainly on geological aspects, socio-political criteria are also an essential input to the screening process.

Table 2.1 lists some of the maps which have proven to be useful in this phase of the site targeting process.

Table 2.1 Useful Site Pre-Screening Maps

Maps	Utility
Precambrian Basement Presence Sediment Thickness over Bedrock	Shows where access to stable granitic rock is easiest
Borehole Sites Oil & Gas Exploration	Provides geological information; but need to avoid vertical water conduits
Heat Flow, Geothermal Gradient Temperature at Depth	Want to minimize hole bottom temperature, and avoid areas attractive for geothermal use
Rock Stress, Faulting Volcanic Activity Earthquake Activity	Regions to avoid
CO_2 Emissions Population Density	Indicative of human presence
Precipitation, Aquifer Locations	Prefer dry regions
Prior Glaciation	May be preferable to avoid
Rail, Road, Water Transportation Routes	Want convenient access to site for construction and emplacement

Sources: USGS: www.usgs.gov
or www.nationalatlas.gov
AAPG Publications
USGS/NASA GRACE Project
www.world-stress-map.org

Downselection Process

Given a collection of maps of criterion distributions, they can be overlaid by hand, or better yet using computer graphics, to bring out promising areas for closer scrutiny. We will not show details here. However, it is interesting to note that the criteria are not truly independent – there is significant cross-correlation – and in fact the location of basement rock outcrops identified in Ref (2-1), repeated here as Figure 2.1, can serve as somewhat of an overall consensus and guide for more focused searches. Note that the extent of these fields is greatly expanded if a sedimentary overburden of up to one kilometer is tolerable.

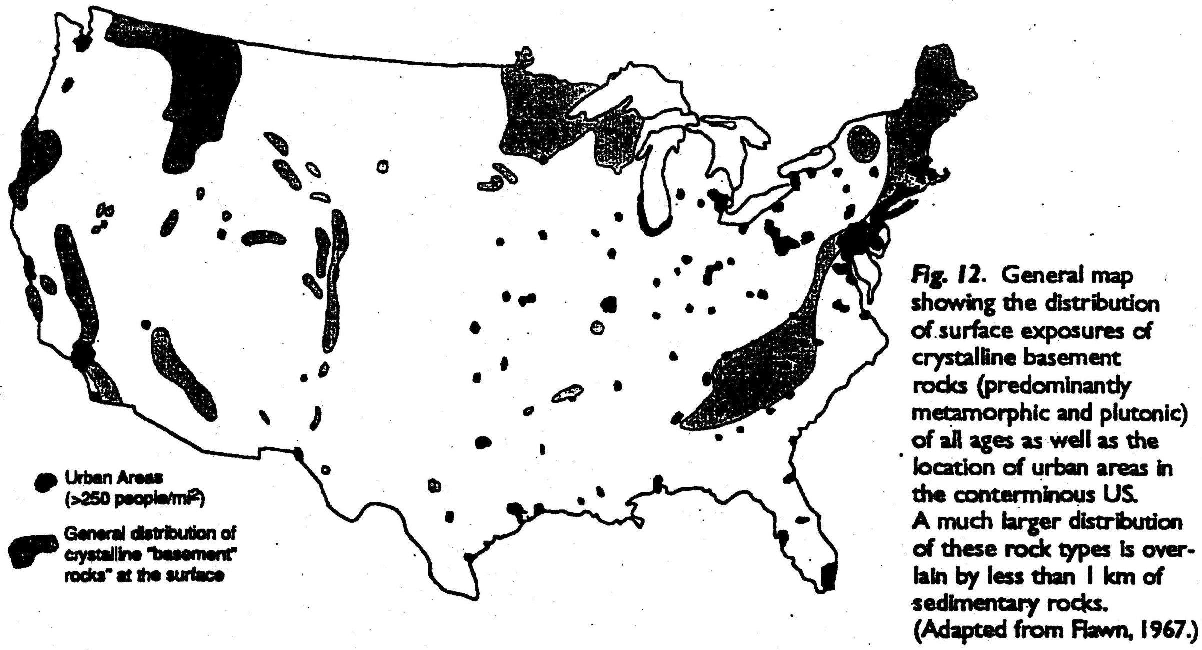


Fig. 2.1 Location of Surface Exposures of Crystalline Basement Rocks in the US (from Ref. (2-1)).

Then given a set of regional candidates, a rank order can be established, using for example, a weighted ranking algorithm. Table 2.2 shows one such approach for a much oversimplified hypothetical example. For the row vector of preferred attributes a grade is assigned (e.g., 1 to 5 in increasing degree of quality). Each attribute is also assigned a weighting based on its overall importance (again, 1 to 5). The sum of the weighting times quality products is then a numerical score for ranking the candidates.

Table 2.2 Illustrative Matrix of Downselection Criteria

	Attribute			
LOCATION	**GS**	**BQ**	**AR**	**Product Sum**
Oz	1	4	2	30 (least preferred)
Podunk	3	5	4	39 (leading candidate)
Erehwon	5	1	3	34 (alternative site)
WEIGHTING	4	5	3	34.3 (avg.)

Key to Attributes:
- GS = Geological serenity
- BQ = Bedrock quality
- AR = Aridity

One development which should be useful in the global survey phase of converging on prospective sites is the project newly initiated by the One Geology Project – a collaborative effort by geologists and computer scientists from more than eighty nations to map Earth's underlying topology. Information on the status of progress can be obtained on the website www.onegeology.org).

2.3 Local Site and Emplacement Zone Characterization

Postulated difficulties in this area largely ignore the last several decades of progress in the oil and gas industries, and of robotic planetary (e.g. Mars) probes. Airborne and satellite surveys can locate promising areas on a macro scale by use of gravimetric, radiometric and magnetometric scans, as well as a newer approach using ground penetrating radar. Compiled and organized geological data from all historical sources also plays an important role. Once screening leads to 10 x 10 km candidates for further scrutiny, the seismic techniques of the oil/gas industry can be used to map out for exclusion any locales having major faults or anomalous composition. Table 2.3 lists some of the principal wide-area survey methods.

Table 2.3 Borehole Wide-Area Survey Methods

	Method	Information
Airborne		
	Visual	Surface water, topography
	Gravimeter	Rock density, hence extent of granitic plutons
	Magnetometer	Location, size, shape of rock masses
	Geoelectricity	Location, size, shape of rock masses
	Ground Penetrating Radar	Depth of sedimentary overburden, underground aquifers
	Radiometric	Radioactive constituents help in site delineation, assessment of uniformity
Terrestrial		
	Visual	Local faulting, water, absence of attractive resources, human habitation, vegetation
	Seismic stratiography (surface and shallow hole)	Depth of sedimentary overburden, underground faulting, intrusions, aquifers
	Precipitation and soil water content	Threat of water intrusion, lack of attractiveness for farming and habitation
	Surface heat flux	Rough estimate of subterranean temperature

The next step is to drill test boreholes and employ well logging methods to determine rock chemical composition, temperature porosity, fluid content, small scale faulting and other physical parameters of interest as discussed in Chapter 3. Some of these holes will be retained as monitoring wells over the lifetime of the repository field.

2.4 Borehole Drilling Experience

Our interest here is in drilling into crystalline granitic bedrock. While the most relevant experience is associated with work underway to exploit hot dry rock geothermal energy, oil, gas and scientific drilling are also relevant.

Table 2.4 summarizes experience in two categories: an early period up to 1987; and a recent period since. Figure 2.2 summarizes the cumulative status: note the extensive experience in the 3000-4000 m depths of current interest. The experience base is such that knowledge of basement rock properties is now adequate to permit a high degree of confidence in deep borehole repository conceptual design. More information is welcome and forthcoming. Of particular use would be a complementary focus on aspects and data of special relevance to nuclear waste disposal.

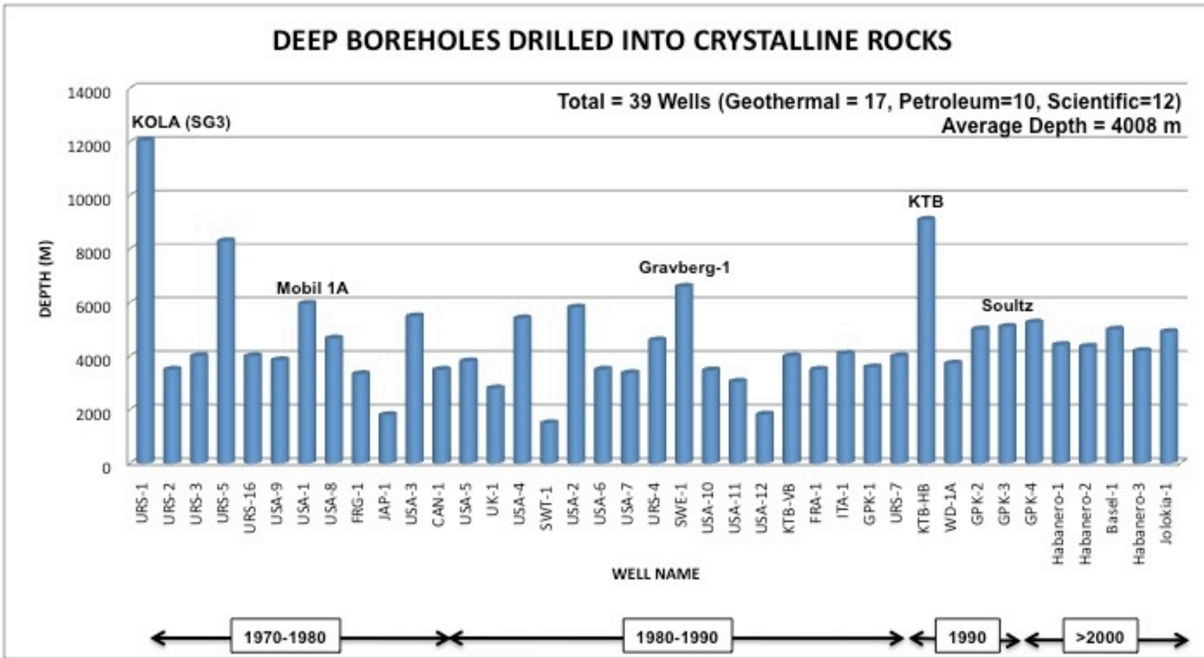
Hot dry rock geothermal applications have much in common with waste disposal, but the following differences should be kept in mind:

(1) The geothermal community is interested in large vertical temperature gradients, °C/km, while HLW applications favor small gradients, to help limit post-emplacement temperature.

(2) The geothermal application requires post-drilling hydraulic fracturing to create horizontal flow paths for the fluid used to extract geothermal energy; for HLW disposal avoidance of fractures of any type is to be preferred (although horizontal fractures should be tolerable). Both HDR and HLW facilities need to avoid significant vertical faulting and fracturing.

(3) The experience summarized in Table 2.4, in almost all instances, involved boreholes of a smaller diameter than useful for HLW disposal – a situation likely to persist in the future.

The paucity of large diameter hole precedents is one of the major factors which has led the MIT program to use as small as practicable values, and ones compatible with oil well drilling technology.



*) Modified from **SKB report 89-39** (1989) with additional data from various sources

Fig. 2.2 Summary of Deep Borehole Drilling into Crystalline Rock

Table 2.4 Experience with Deep Boreholes into Crystalline Rock

Early Period through 1987)
Reference (2-4) lists a total of 28 boreholes having an average depth of 4300 m: 7 for petroleum exploration, 3 into hot dry rock, 4 hydrothermal geothermal, and 14 scientific.

Recent Boreholes into Crystalline Rock (Post 1985)

Country	Project	Depth, m	Bottom Dia.,* cm
United States	Fenton Hill	4700	31
United Kingdom	Rosemanowes	2800	~14
France	Soultz GPK-2	@3700	21.6
Japan	Kakkonda	3700	21.6
Australia	Cooper Basin	4300	21.6
Sweden	Gravberg-1	@4000	31.1
Germany	KTB-HB	@3000	44.5
Switzerland	Basel 1	@4000	25
Russia	URS-4	4600	21.6

*NOTES: (1) Diameter is hole (not liner) diameter at the depth indicated (which is not necessarily the maximum depth).
(2) Crystalline rock is overlain by sedimentary rock in most instances
(3) Projects are selected from a longer list
(4) Diameters are usually quoted in inches: here multiplied by 2.54 to obtain centimeters.

Drilling State of the Art

Oil, gas and geothermal boreholes are all drilled using the same generic technology. Hole and casing stages have progressively smaller diameters with depth, in a telescope-like sequence. Radial clearances between hole and casing range between 2 and 6 cm (2-6).

Figure 2.3 shows a representative hole and casing pairing and sequence for the 9 km deep scientific borehole KTB-HB completed in Germany in 1994 (2-7). It was selected for display here in part because it confirms the availability of technology capable of delivering what is needed for HLW boreholes. Note that the second stage extends down to 3000 m, which is our current objective, and has a casing OD of 16 inches (40.6 cm): just barely sufficient to house a string of HLW waste canisters. If the emplacement zone were left uncased, then canisters could be inserted down to 6000 m. The KTB-HB hole was drilled with a custom-built rig, at the time the world's largest land drilling rig. The maximum drillrig hookload was 850 metric tons – sufficient to lower or hoist a kilometer-long 400 MT waste canister string (if a continuous string were to be employed). Hence, while pushing the envelope, wellbore preparation can be regarded as assured. Also of note is that 58 different logging tools were employed. Reference 2-7 describes these devices, many of which should be useful for HLW borehole interrogation.

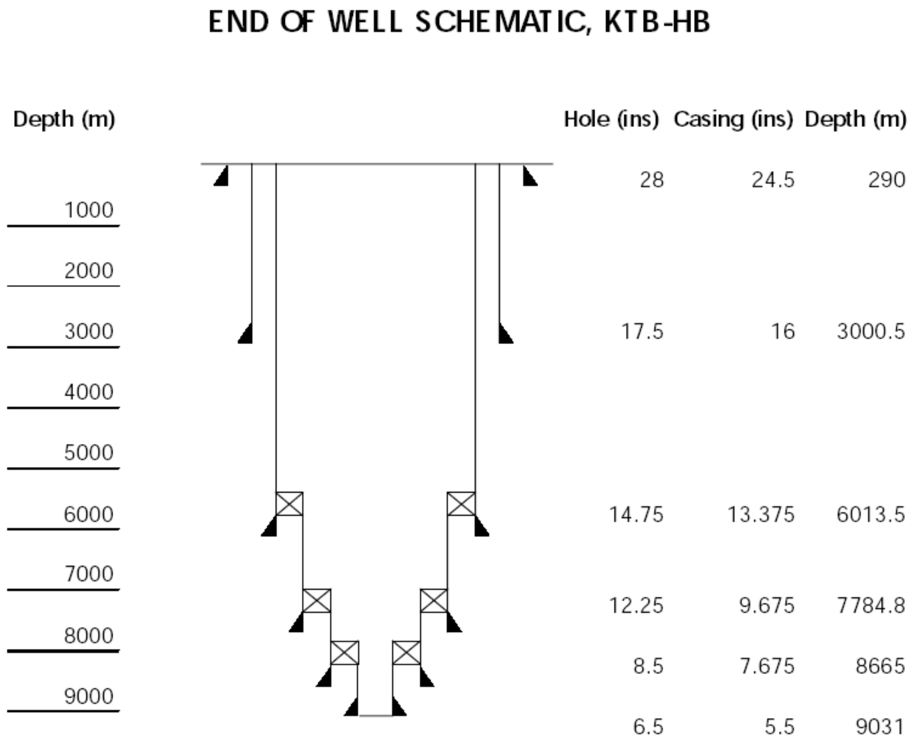


Fig. 2.3 Hole and Casing Sequence for the KTB-HB Borehole

Drilling Costs and Optimum Borehole Depth

References (2-8) and (2-9) plot oil and gas well completed costs versus depth, repeated here as Fig. 2.4.

They are well-fit by a relation of the form (2-9):

$$C = Co\, e^{\mu z}, \text{ million dollars}$$

in which

Co = cost at zero depth (0.2 million dollars)
z = depth in kilometers
μ = slope (0.75 per km)

The cost per km of emplacement zone is

$$\left(\frac{C}{\delta}\right) = \frac{Co\, e^{\mu z}}{(z - z_o)}, \frac{10^6\ \$}{\text{km}}$$

where z_o = depth above emplacement zone.

Setting the partial derivative of (C/δ) with respect to z equal to zero gives the optimum depth for its minimization:

$$(\hat{z} - z_o) = \hat{\delta} = \frac{1}{\mu}$$

Thus for the above curve fit parameters and $z_o = 2$ km, $\delta = 1.33$ km, $\hat{z} = 3.33$ km, which is fairly close to the design values selected in Chapter 1.

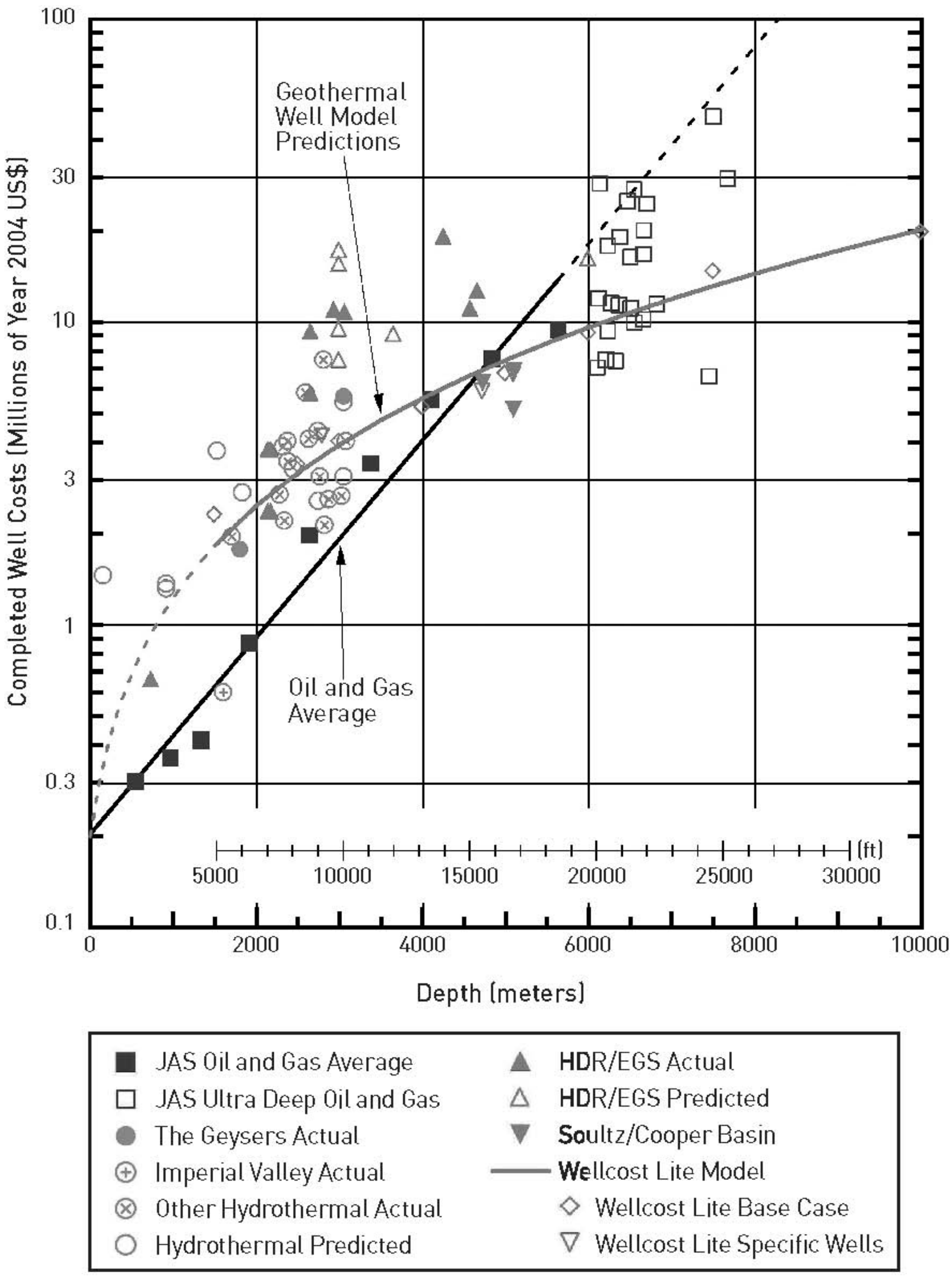
Some cases of interest follow:

z_o, km	z, km	δ, km	(C/δ) 10^6 \$/km
2	2.5	0.5	2.61
	3.0	1.0	1.90
	3.33 (opt.)	1.33	1.83
	4	2.0	2.01
1	2.33 (opt.)	1.33	0.86

The model shows the existence of a relatively weak optimum between depths of 3 and 4 km. The reduction of emplacement interval from 2 to 1 km is also seen to reduce cost. Hence the benefits of reducing canister crushing loads and improving retrievability can be realized at no economic penalty.

The large cost reduction (factor of two) if sealing zone and sedimentary overburden can be reduced is also evident. This encourages seeking out sites where the host granitic bedrock is near the surface.

Note that the optimum value of 1.83×10^6 \$/km corresponds to 18.3 \$/kg for interment of PWR fuel assemblies. But note this does not account for the likelihood that borehole diameter will be larger.



1. JAS = Joint Association Survey on Drilling Costs.
2. Well costs updated to US$ (yr. 2004) using index made from 3-year moving average for each depth interval listed in JAS (1976-2004) for onshore, completed US oil and gas wells. A 17% inflation rate was assumed for years pre-1976.
3. Ultra deep well data points for depths greater than 6 km are either individual wells or averages from a small number of wells listed in JAS (1994-2000).
4. "Other Hydrothermal Actual" data include some non-US wells (Source: Mansure 2004).

Fig. 2.4 Completed geothermal and oil and gas well costs as a function of depth

In contrast, the geothermal well model predictions fit a power law relation fairly well between 3 and 6 km:

$$C = C_1 z^b, \qquad 10^6 \ \$C$$

where $C_1 = 1.1$ and b = 1.2 per km apply.

Proceeding as before, the optimum depth is given by:

$$\hat{z} = \left[\frac{z_o}{1 - (1/b)}\right]$$

and again: $\hat{\delta} = \hat{z} - z_o = (\hat{z}/b)$

For the numerical values given:

$\hat{z} = 6z_o = 12 \text{ km} \text{ if } z_o = 2 \text{ km}$

and $\hat{\delta} = 10 \text{ km}$

Thus much greater depths and emplacement zone thickness are predicted: far beyond the range of the curve fit and waste package durability.

The cost per km, C/δ at $\hat{z} = 12$ km and $\delta = 10$ km is 2.17 x 10^6 \$/km, which is larger than for the oil well model. If we instead impose $z = 3$ km, $\delta = 1$ km, hence $z_o = 2$ km, one has $(C/\delta) = 4.1 \times 10^6$ \$/km, roughly twice the cost using the oil-well-based model.

Reference (2-9) discusses some of the reasons for the differences, which include hole diameter, rock type, number of casing strings, etc. Further work is clearly required to improve drilling cost estimation.

The Issue of Hole Diameter

The present assessment has found that for disposal of HLW as spent fuel, hole bottom diameters of about 50 cm (20 inches) are preferred. Hot dry rock geothermal system diameters are generally smaller, at around 28 cm (11 in); and oil wells even smaller, at about 22 cm (8.7 in). Thus there is a strong incentive to go to larger diameters. This appears to be within the capability of currently available technology, but, of course, at a higher cost.

While considerable attention has been paid to the effect of hole depth on cost, there is less quantitative data on cost vs diameter, all else being equal. Reference (2-8) provides two points and Ref (2-10), three, from which one can infer a rough dependence of cost as proportional to diameter. This leads to a projected cost of about 8 million dollars for a 3 km, 50 cm HLW borehole: hence 80 \$/kg if it houses a 1000 m stack of canisters, each containing a single PWR assembly. This is appreciable but not prohibitive. It nevertheless suggests intensive investigation of ways to reduce drilling costs.

As a final note, it deserves mention that not too much should be made of the issue of diameter, for three reasons:

(1) When dealing with HLW from reprocessed fuel, the waste form can be of smaller diameter, tailored to fit within the then-available drilling practice. Furthermore, since retrievability is not likely required, it should be possible to use an unlined emplacement zone, hence make five or so more centimeters available for waste canister diameter.
(2) Oil, gas, and geothermal wells are typically drilled in 3 to 6 stages, with progressively smaller diameters. The upper stage commonly has a diameter as large as 45 cm, which approaches HLW borehole needs. Hence there is a field-deployed technology base to build on.
(3) The Procrustean strategy of modifying fuel bundles (ranging from removing corner pins to full reconstitution) to fit available oil well hole and casing diameters may prove viable.

Drilling Mud

Oil and gas well drilling is conventionally done with the use of "mud" injection to remove rock fragments and to supply hydraulic pressure to help stabilize the borehole. (2-11)

Inevitably some of the mud is forced into interstices in the host rock, leaving a residue even if the bulk of the mud were to be flushed out. Since bentonite clay is a common mud constituent, this is probably advantageous for HLW boreholes, since bentonite is a good radionuclide sorber, and is made extensive use of in SKB's designs as a viscous emplacement zone both for the waste canisters, and as a major segment (along with asphalt and concrete) of the borehole plug zone. (2-12) (2-13)

We should, therefore, give careful consideration to this approach as an alternative to the less common approach of dry ("air") drilling.

Air Drilling

While there are advanced drilling methods under development (spallation, laser, microwave, hydraulically-vibrated rotary, rock-melter) which may eventually benefit the deep borehole option, there is one approach of long standing – air drilling – which may be of immediate use.

For example, Ref (2-11) states that "In many areas it is both quicker and far cheaper than drilling with mud," Reference (2-14) concurs in that "Penetration rates are higher, footage per bit is greater, and bit cost is lower with air." The negative aspects cited: hydrocarbon-air explosions, drilling into high pressure formations, do not appear to apply to the high quality rock of present interest.

Reference (2-11) also notes that "Air-drilling has been extensively used by the Department of Energy in drilling large-diameter holes for underground nuclear tests in Nevada."

The Swedish SKB group did not prefer air drilling because of its projected shortcomings in levitating, sweeping out and conveying to the surface, the rock cuttings generated during drilling. (2-12)

Overall, however, it is recommended that serious consideration be given to making a more detailed assessment of air drilling. Reference (2-15) is a useful compendium on this subject.

2.5 Chapter Summary

A brief review has been presented of the technical criteria and screening methods for finding and localizing candidate sites for borehole repositories. It all comes down to delineation of some tens of square kilometers of high integrity bedrock, principally in the form of granitic plutons, the closer to the surface the better. In general, the prospecting techniques already in service for oil/gas/geothermal applications appear to be fully adequate for this purpose. A review of various past surveys of the US, with the identified criteria in mind, indicates that there will be a number of promising sites to choose from. What has not been addressed, however, are the socio-political factors which past experience, worldwide, has found to be at least equally important in final downselection.

Conflicting cost modeling prescriptions and a lack of explicit correlations for the effect of hole diameter make it impossible at present to optimize HLW borehole design. One can at present argue for either “as shallow as practicable” or “as deep as possible” as design strategies! The work at MIT has consistently opted to pursue shallower options consistent with stringent confinement goals.

2.6 References for Chapter 2

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(2-13) J. Liu, I Neretnieks, "Physical and Chemical Stability of the Bentonite Buffer," SKB Report R-06-103, Dec. 2006

(2-14) Fundamentals of Petroleum. Univ. of Texas, Austin, 1979

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Chapter 3 Downhole Environment Characterization and Key Performance Attributes

3.1 Chapter Introduction

Another major difference between shallower mined repositories and deep boreholes is the lack of capability for hands-on, eyes-on access to the emplacement zone for the latter. However, oil and gas well downhole instrumentation is now very sophisticated, to the point where most properties of interest can be measured using industrially available techniques. Useful information can also be gleaned by coring and by analysis of drilling debris. Technology developed by NASA for examination of planetary surfaces (e.g., Mars) is also a potential source of instrumentation. This chapter contains a brief review of needs and capabilities. This is followed by a discourse on water-aided escape: the principal challenge to sequestration for repositories of all types.

3.2 Data Needs and Acquisition

Table 3.1 lists data of interest for the performance assessment of HLW boreholes, and Table 3.2 surveys commonly available oil well logging methods and their contribution to property inference. Note that data from several methods are commonly used in conjunction with specially-developed algorithms to yield the results of interest, which in our case can be traced back to the need to quantify the presence, mobility, and salinity (density) of downhole water.

Table 3.1 HLW Borehole Data Needs

Host Rock Downhole Characteristics as a Function of Depth

- texture and grain size
- fractures and faulting, both large and small scale, especially vertical
- chemical composition and crystallography; degree of alteration
- porosity and permeability, hydraulic conductivity
- density
- temperature
- lithostatic pressure
- local stress field and rock strength
- thermal conductivity
- water content: bound, free, and mobile
- depth of sedimentary rock overburden
- bacterial presence

Downhole Water Properties

- salinity, density, chemical composition
- pH
- Eh
- hydraulic pressure
- temperature

Table 3.2 Well Logging Methods and Information Provided

Method	Information Categories
⊙ Electrical Resitivity (several variations: micro-electrodes, induction . . .)	Inference of permeability, sedimentary structure, fractures, rock texture, porosity, water saturation
⊙ Acoustic (sonic) propagation; Borehole seismic	Porosity, hydraulic permeability, fracture, rock type and structure
⊙ Gamma Ray Spectroscopy	Host rock type via U, Th, K radioactivity
⊙ Gamma Ray Interrogation (scattering and absorption)	Density, porosity
⊙ Neutron Interrogation (steady and pulsed)	Composition, density, porosity, water content
⊙ Nuclear Magnetic Resonance (NMR)	Porosity, water content, hydraulic permeability
⊙ EM Propagation	Dielectric permittivity, water-filled porosity
⊙ Video camera (not common)	Rock layering, faulting
⊙ Borehole Radar	Far field fractures
⊙ Drill Cutting Analysis	Mineralogy, geochemistry
⊙ Core Sample Analysis	Rock structure, fracturing

Reference (3-1) states that "Today, there are more than 100 different types of logs available." This was in 1992. Ref (3-2) says "over fifty." Reference (3-4) is particularly informative. It lists some 54 logging tools used in the KTB-HB drilling project in Germany. Reference (3-18) reports on 22 methods for post-closure monitoring of a generic repository – most of which are the same as needed for initial characterization of a completed borehole. Hence our survey is at a generic higher level.

3.3 Transport in, and by, Water

The single most important performance metrics of any repository are those which measure its ability to sequester hazardous radionuclides from the biosphere. As the following scoping calculations show, the presence of water, and especially its mobility, are essential factors. Although initial emplacement will be into very dry host rock, since subsequent flooding over the eons cannot be ruled out, conservative worst-case scenarios based on the presence of water must dominate our concern.

Radionuclide Escape by Diffusion

A simple model can provide a useful estimate of confinement effectiveness. Assume rapid dissolution of emplaced waste and horizontal dispersion through the host rock surrounding a borehole (without precipitation or retardation – a highly conservative oversimplification), followed by slow diffusion upward through the kilometer thick seal zone.

Pulse injection of mass *M* (or in our case, curies of activity) over area *A* gives the well-known expression for a diffusing species as a function of time and distance (3-5) – here modified to allow for simultaneous radioactive decay:

$$C(z,t) = \left(\frac{M/A}{\sqrt{4\pi Dt}}\right)\left(e^{-\frac{z^2}{4Dt}}\right)\left(e^{-\lambda t}\right) \tag{3-1}$$

The maximum value of *C(z,t)* can be obtained by setting its partial derivative with respect to time equal to zero.

One finds the time when *C* is maximum to be:

$$\hat{t} = \frac{z}{2\sqrt{\lambda D}} \tag{3-2}$$

Substitution back into Eq (3-1) gives for the peak concentration:

$$\hat{C}(z,\hat{t}) = \left(\frac{M}{A}\right)\left(z\sqrt{\frac{\lambda}{D}}\right)^{1/2}\left(\frac{e^{-z\sqrt{\frac{\lambda}{D}}}}{\sqrt{2\pi}\ z}\right) \tag{3-3}$$

It is instructive to next apply this prescription to two radionuclides which are among the most limiting with respect to repository performance: the transuranic Np-237, and the fission product Tc-99. Table 3.3 summarizes relevant properties:

Table 3.3 Key Radionuclide Properties

Property	Np-237	Tc-99
$T_{1/2}$, half life, years	2.14×10^6	2.13×10^5
λ decay constant, $\ln 2/T_{1/2}$, sec.$^{-1}$	1.025×10^{-14}	1.030×10^{-13}
Fission yield Curies/metric ton (@ 60 MWd/kg fuel burnup)	0.55	27
Borehole content,* Curies	55	2700
M/A,** picocuries/cm^2	1.38×10^5	6.75×10^6

* 1 hole, 1000 m emplacement zone, hence 200 PWR assemblies, 100 MT heavy metal

** for 200 m square array, hence $A = 4 \times 10^4$ m^2

Next consider a repository having a 1000 m bedrock cap zone over the emplacement zone. Conservatively assume z = 1000 m = 10^5 cm, ignoring the 1000 m of sedimentary rock above that, and also the likelihood that the radionuclide source plane would, on average, be about halfway down the 1000 m emplacement zone.

Then for a representative effective diffusion coefficient $D \approx 10^{-5}\ \text{cm}^2/\text{s}$, assuming stagnant-water-filled interconnected porosity,* Eq (3-3) can be used to estimate the peak radionuclide concentrations at the top of the bedrock, as recorded in Table 3.4.

Table 3.4 Peak Escaped Radionuclide Concentrations

	Np-237	**Tc-99**
Time at peak, $\hat{t}$, years	4.94×10^6	1.56×10^6
Peak Concentration, picocuries/cc	0.04	3.4×10^{-3}
Compare to allowable picocuries/cc discharge to sewer (from 10 CFR 20)	0.2	600

As evident in Table 3.4, peak concentrations are trivial, and occur beyond the million year time horizon commonly considered in repository performance assessment. There are also another 1000 m of rock between our datum plane and the surface.

If one instead considers non-aqueous diffusion in dry rock, and assumes an upper limit estimate for the diffusion coefficient, D, of 10^{-7} cm^2/s, the results are even more reassuring. For example, Np-237 activity then peaks at 49 million years, at a value of 39 x 10^{-14} picocuries/cc. This shows the extreme sensitivity to the value of D. Table 3.4 also shows the strong effect of long half life: Tc-99's is a factor of ten shorter than that of Np-237, and peak concentration is also reduced by approximately a factor of 10.

This leads us to focus on <u>mobile</u> water as the most important threat to waste sequestration.

Cumulative Diffusive Escape

A second performance measure of interest is total release over all time. Net current flowing past the horizontal plane at z can be obtained by applying Fick's Law:

$$J(z,t) = -D \frac{\partial c(z,t)}{\partial z} \tag{3-4}$$

Integration of the result over all time gives the escape fraction:

* i.e., a value of 3 x 10^{-5} cm^2/s in pure water divided by a tortuosity factor of 3.

$$EF = \left(\frac{1}{M/A}\right)\int_{t=0}^{\infty} J(z,t)dt = \frac{1}{2}\,e^{-z\sqrt{\frac{\lambda}{D}}} \qquad (3\text{-}5)$$

Inserting parameters for Np-237 yields:

EF = 0.02, hence 1.1 Curies,

or an impressive 2% escape. However, this is meted out over millions of years and spread out over 40,000square meters (if all boreholes in the square array are leakers).

Nevertheless, this shows how cumulative (i.e., integral) performance measures can present a less rosy picture unless contextually interpreted. It also motivates more sophisticated modeling: in particular taking into account the likely significant reduction in D due to adsorption on rock pore surfaces. Similarly, the added protection provided by the lower quality kilometer of upper rock should be taken credit for.

Diffusion Retardation

In real world situations, diffusion is greatly reduced compared to that in pure water. The effective diffusion coefficient is smaller by a retardation factor R:

$$D_{eff} = \frac{D}{R} \qquad (3\text{-}6)$$

Reference (3-2) reports values of D_{eff} plutonium in water diffusing through porous media which contain bentonite clay. Values less than 4 x 10^{-10} cm^2/s were measured. This would give an escape fraction for our Np-237 example of:

EF = 10^{-220}, i.e., effectively zero.

This drives home the necessity of incorporation of retardation into realistic performance assessments. However, it also explains the prevalent use of bentonite backfill and plugs in confinement concepts.

Measurements have been made in Finland for diffusion of Tc, U, Pu and Np in granitic bedrock core samples (3-7). Values less than 10^{-9} cm^2/s were typical under anoxic conditions.

This would give for our Np-237 example, an escape fraction of

EF $\leq$ 10^{-138}, also effectively zero,

which is again entirely negligible, and engenders considerable confidence in borehole repository performance.

Hence incorporation of retardation into the escape model is essential to a realistic assessment. Appendix D expands upon this topic.

Escape by Vertical Water Transport

Movement of water in a porous medium under a hydraulic gradient is characterized by Darcy's law (3-17); the velocity across a unit of transverse area (not the much higher velocity in the pores) is given by:

$$\upsilon = \left(\frac{k}{\eta}\right)\left(\frac{\Delta P}{\Delta z}\right) \tag{3-7}$$

where k is the intrinsic permeability coefficient, frequently expressed in Darcies.

1 Darcy = 0.97 x 10^{-12} m^2

$\frac{\Delta P}{\Delta z}$ = net pressure gradient in the direction of assumed flow, bar/cm

η = dynamic viscosity of fluid (here water) centipoise
(1 centipoise = 10^{-3} kg/m s)
≈ 0.5 centipoise for water at 55°C

An alternative formulation employs hydraulic conductivity:

$$K = k\frac{g\rho}{\eta}, \text{ m/s} \tag{3-8}$$

where ρ = density (e.g., 1000 kg/m^3 for pure water)
g = gravitational constant = 9.81 m/s2
η = dynamic viscosity (kg/m s)

Thus if k = 10^{-5} Darcy

$$K = \frac{(10^{-5})(0.97 \times 10^{-12})(9.81)(1000)}{5 \times 10^{-4}}$$

or $K = 1.9 \times 10^{-10}$ m/s

This value is in good agreement with the range cited in SKB studies of their granite:
1 to 10 x 10^{-10} m/s.

However, the corresponding value of 10^{-5} Darcy is at the upper limit of measured values given for granite in Ref (3-8), which extends down to 10^{-9} Darcy. Also note that permeability decreases with pressure.

In the analysis which follows, an upper limit for the pressure gradient is very (perhaps unrealistically) conservatively taken as the difference between lithostatic and hydrostatic pressures, approximately 1.5 x 10^{-3} bar/cm, since this is more than adequate to fracture rock for EGS applications: i.e., 1.1 x 10^{-3} bar/cm, as reported in Ref (3-16). Thus higher gradients are unlikely to have ever been present in the rock of current interest, or it would fail quality assurance testing.

Accordingly for D = 10^{-5} Darcy, $\upsilon = 3 \times 10^{-8}$ cm/s, or 9.5×10^{-6} km/yr, in which case traversing 1 km of rock will take about 100,000 years. Radionuclide decay in transit determines the escape fraction:

$$EF = e^{-\lambda t} \tag{3-9}$$

Table 3.5 shows EF values calculated for Np-237 (half-life = 2.14 x 10^{6} years) as a function of intrinsic permeability.

Table 3.5 Np-237 Escape by Water Transport

Log (k, Darcy)	Log (t yrs)*	EF	Curies
0	0	1	55
-5	5	0.97	53
-6	6	0.72	40
-7	7	0.039	2.2
-8	8	8.6 x 10^{-15}	4.7 x 10^{-13}
-9	9	2.2 x 10^{-141}	1.2 x 10^{-139}

*for laminar slug flow through 1 km granite

Table 3.5 suggests a goal of selecting sites where in-situ rock permeability is less than 10^{-7} Darcy. Note that no allowance has been made for retardation by adsorption on rock pore surfaces (which reduces diffusion coefficients in stagnant water by a factor of on the order of 10^{4}). Likewise no credit is taken for the assumed uppermost kilometer of sedimentary rock. Hence the suggested criterion is extremely conservative and in need of future refinement.

Escape by Thermal Plume Rise

A frequently voiced concern is that local water heated by radioactive waste will decrease in density relative to ambient water to rise, driven by buoyancy (i.e., much like a hot air balloon).

As noted in Table 1.4, a 100°C rise in water temperature can decrease density by about 6.7%: much larger than the 1.2% increase due to 3 km of hydrostatic pressure. However, water in deep boreholes is invariably saline, to 10% and above. Thus the 10% increase in density more than offsets the thermal expansion. Even more significant is the fact that the water must rise through colder rock via very small pores and cracks having dimensions on the order of some tens of microns. In the process heat transfer reduces the water temperature, hence buoyancy. The heat source also decays with time, which reduces the water heatup rate: e.g., by a factor of about ten in 800 years. Reference (3-9) reports the results of a very detailed finite element code analysis which confirms that buoyancy-driven escape does not alter the stability of the groundwater system. In the process it also puts to rest the hypothetical pressure gradient driven phenomenon raised in the preceding section of this chapter.

Selenium Transport in Water

One commentator called special attention to selenium as a species for which the reducing conditions prevalent in deep boreholes may promote enhanced transport. While only specifically tailored laboratory testing can resolve this issue, there are significant indications in the literature pointing to a favorable outcome. (Most commentators, however, cite I-129 as of greater concern.)

First some background. Se-79 (half life = 2.9×10^5 years) is the radionuclide of concern. Compared, for example, to Tc-99 (half life = 2.13×10^5 years), a factor of roughly thirty fewer curies of Se-79 are produced in fission, but allowable environmental release and injection are a factor of seven lower than for Tc-99. Hence given plausible differences in solubility and transportability, selenium could be an important, perhaps limiting case species in escape scenarios. Note the use of a much shorter half-life – 6.4×10^4 years – for Se-79 in earlier work (3-23); the error is presumably traceable to the fact that this isotope is a pure β^- emitter, with a maximum energy of only 0.16 MeV, hence a difficult experimental subject.

As noted in Ref (3-10), Se will exist as selenite (SeO_3^{2-}) in mildly reducing environments (negative E_h) – as expected in deep boreholes – while selenate (SeO_4^{2-}) will predominate under oxidizing conditions (positive E_h).

The Pourbaix diagram for Se from Ref (3-20) is reproduced in Figure 3.1. It is quite similar to that of sulfur, which is just above selenium in group VIa in the periodic table (3-21) (3-22). As can be seen, elemental Se and then $HeSe^-$ are created as o ne moves to even stronger reducing conditions (more negative Eh). Accordingly, one would expect decreasing mobility.

The real situation is even more complicated. For example, Ref (3-19) reports negligible Se sorption at Eh = -0.161 V, but this is at a high pH of 9.94, and very low salinity: 0.1 g/liter. As noted in Ref (3-23), the maximum release rate of Se-79 is reduced by a factor of 160 in saline water.

In saline borehole water, the pH is expected to be in the range 7.2 – 8.5, based on Swedish studies (3-11), which motivated the specification of 8.0 in the geochemical modeling study by Anderson at MIT (3-12). At these values, and below, Reference (3-12) shows that essentially 100% of the selenite is adsorbed on iron oxide. This finding was replicated by work at INL (3-13). Thus the postulated strong transportability of selenium under reducing conditions is, at best, unproven. Accordingly, iron oxides would be a useful addition to fill and plug material. Similarly, corrosion of steel drill pipe could actually aid in selenium retention.

Concern has been expressed that steel lining the borehole will eventually corrode and thereby provide a preferential path for radionuclide escape.

A counterargument is that iron oxide is a good adsorbent – so much so that magnetite beds were tested at one time for LWR coolant purification (3-14). Furthermore, the oxides of iron have roughly twice the volume per gram of original Fe:

Compound	**cc/g Fe**
Fe	0.13
FeO	0.23
Fe_2O_3	0.27
Fe_3O_4	0.27

Thus corrosion would lead to expansion, which would help seal peripheral gaps between steel and grouting between the piping and rock wall, and between the piping and its internal cement plug. However, the best approach may well be to remove the casing in the above-emplacement zone, and seal directly to the host rock.

Relative Importance of Diffusion and Convection

As has been shown, two phenomena contribute to radionuclide movement: diffusion and convective transport (i.e., Darcy flow). Their relative importance can be assessed by calculating the ratio of mean square distances travelled.

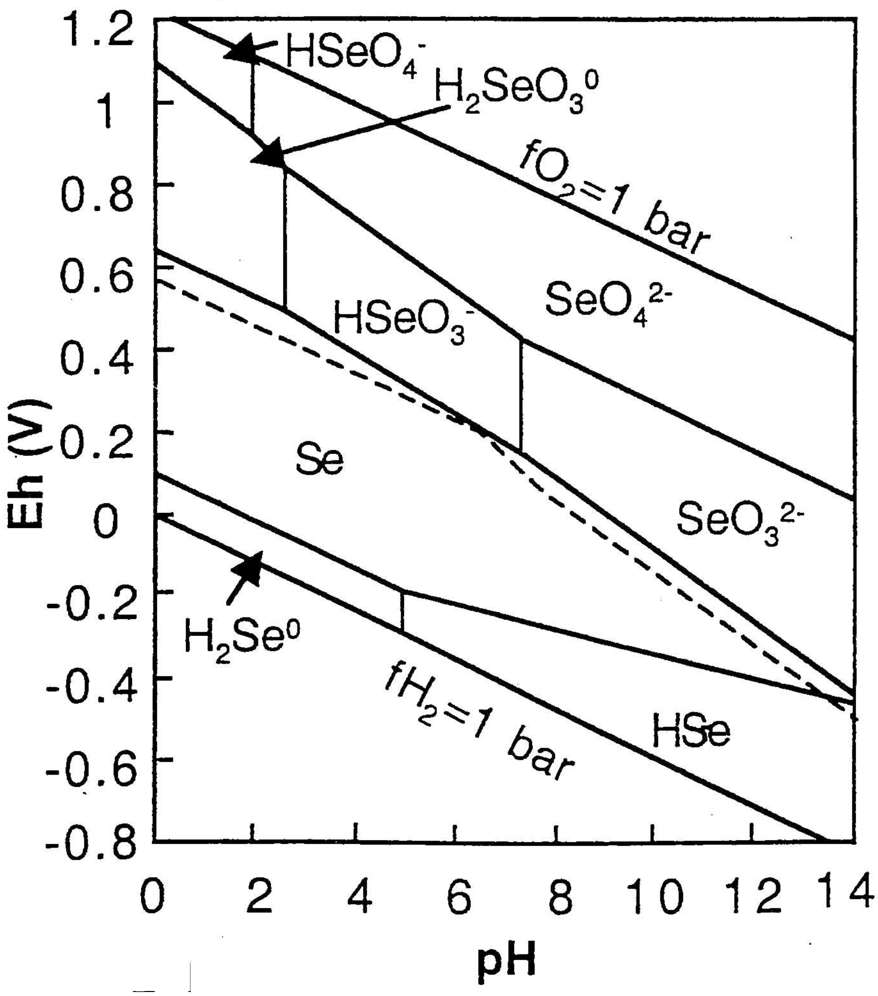

Figure 3.1 pH vs Eh predominance diagram for the aqueous species of selenium (From Ref 3-20)

For diffusion $$\overline{z^2} = \frac{\int_0^\infty z^2 C(z,t)dz}{\int_0^\infty C(z,t)dz} \tag{3-10}$$

which is readily evaluated, to yield:

$$\overline{z^2} = 2Dt \tag{3-11}$$

For convective transport, the pulse moves intact as the velocity of the water flow:

$$\overline{z^2} = z^2 = (\upsilon t)^2 \tag{3-12}$$

Hence:

$$RMS = \frac{2D}{z\upsilon} \tag{3-13}$$

For parameters of present applicability:

D = 10-5 cm^2/s (an upper limit)
z = 1 km = 10^5 cm
υ = 3 x 10^{-8} cm/s

Thus

RMS = 0.0067, and advective transport dominates.

Actually the two effects occur in concert, with diffusion superimposed on the moving wave front (3-15).

3.4 Chapter Summary

Once a prospective site is identified using the methods discussed in Chapter 2, a (small diameter) pilot borehole can be drilled and the downhole instrumentation identified in this chapter can be used to confirm that rock properties meet requirements. These criteria are primarily associated with the presence of mobile water. Diffusion in stagnant water is shown to be ineffective, particularly when retardation by adsorption on rock pore and fracture surfaces is taken into account. Bulk water movement is more of a threat, but rock having the required low permeability should be widely available and its value confirmable by existing logging tools or their plausible refinement, especially if retardation is also taken into account. However a better assessment of the available literature on this aspect than done for this brief synopsis has to be made.

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Chapter 4 Evaluation of Some Key Performance Requirements and Metrics

4.1 Chapter Introduction

Many borehole repository features are a direct consequence of up-front requirements imposed on the designer, either by fiat or by implied socio-political consensus. Two important criteria emphasized in current U.S. regulations are retrievability and multibarrier protection, but it must be recognized that overall system performance is the overarching goal, and that deep boreholes score well in this regard. Hence more emphasis is placed on constraints imposed by Mother Nature in the form of tolerable temperature and stress in the host rock environment. These aspects will be addressed in this chapter. Supporting details are documented in Appendices B and C. Finally some remarks are summarized on cost and licensing issues.

4.2 Retrievability

One of the more contentious issues raised with respect to deep borehole HLW disposal is whether emplaced waste should, or need not, be retrievable. Both sides of the issue have been forcibly argued (4-1) (4-2). Table 4.1 summarizes the main arguments pro and con, and their design implications. A more fundamental point is the questionable validity of the presumption that using boreholes precludes retrieval. The following points suggest otherwise:

(1) In the most recent versions of deep borehole designs, holes are vertical, and limited to about 4 km, in part to avoid lithostatic pressures which might collapse the holes or cause breakout during drilling
(2) The host rock is high-integrity granitic basement rock, and not the weaker sedimentary rock which the critics may have in mind based on oil and gas experience
(3) Holes can be steel lined, as in current oil well practice
(4) In the approach adopted by MIT, a graphite sand filler is used to fill the gap between canisters and hole liner. This increases thermal conductivity and helps lubricate withdrawal.
(5) Oil rig operators have become increasingly adept at retrieval ("fishing") of stuck downhole apparatus, hence the required tools and procedures are standard practice. Even under a worst-case scenario, overdrilling is feasible (but expensive and prone to dispersal of recovered radioactive material).

Table 4.1 Emplacement Options and Strategies

Option	Motivation	Design Implications
RETRIEVABLE CANISTERS	• Recover Pu, U for reuse as fuel • Correct belatedly discovered problems • Allow for upgrades based on future R&D	• Larger diameters and clearances • Line entire hole • Use pourable sand fill inside canister • Use graphite sand lubricant between canisters and casing • Prolong interim surface storage • Periodically demonstrate removal • Use removable borehole plug until final entombment • Develop special tools
UNRETRIEVABLE CANISTERS	• Keep Pu from use in weapons • Avoid accidental disinterment • Maximize efficacy of entombment	• Put SiC sand in plug cement to complexify re-entry drilling • Omit bottom hole liner; grout canisters in place ab initio

Three more recent developments, however, favor emphasis on non-retrievable emplacement. The first is the trend, de facto or intentional, of extended on-surface temporary storage, which allows deferral of entombment until more evidence is at hand, both technical and socio-political. A second is the growing preference in some quarters for reprocessing, in which case selected wastes are clearly unusable and can be converted into high integrity waste forms. Finally, concern over weapons proliferation has motivated initiatives for fuel supply to and takeback from small nations, to remove incentives for their deployment of enrichment and reprocessing facilities. However, accepting foreign-produced wastes is a contentious issue for the supplier nations. Hence a universally applicable local disposal technology such as deep boreholes, in their non-retrievable version, may be welcome, even though it forgoes the opportunity to upgrade downhole features in the future. In any event, there will always be a point at which disposal is permanent.

4.3 Defense in Depth

A common criticism of deep borehole disposal is that it abandons the multibarrier approach mandated for shallower mined repositories: ie., defense <u>by</u> depth alone is substituted for defense <u>in</u> depth (e.g. Ref [4-2]). This, however, need not be the case. In the current version of the design sketched in Chapter 1, it is expected that the waste canisters will be lined with copper (as in the Swedish KBS-3 repository), and filled with a cementitious grout having protective and retentive chemical properties in addition to its primary role of crush-proofing. Hence multiple barriers consisting for spent fuel of UO_2, zircaloy clad, grout, copper clad canister followed by more grout and only then the geological barrier provided by the host rock.

Copper and most of its alloys have a coefficient of thermal expansion roughly 20% larger than high iron content materials, while titanium and zirconium are lower. This raises the possibility of shrink-fitting a (cold/hot) copper sleeve inside/outside a (hot/cold) iron canister tube. This will provide a much-enhanced corrosion barrier.

As for an optimum cement filler, this must be the subject of future R&D. However, there are a number of promising leads: e.g., aluminous cement which is serviceable to above 1000°C; hydraulic cements which expand as they set; and a variety of adsorbing additives (e.g., oxides of Ti, Zr, Fe).

For reprocessing plant wastes such as fission products and minor actinides, the additional barrier of a specially tailored waste form (synroc, glass, etc.) is employed.

4.4 Cost and Licensing Issues

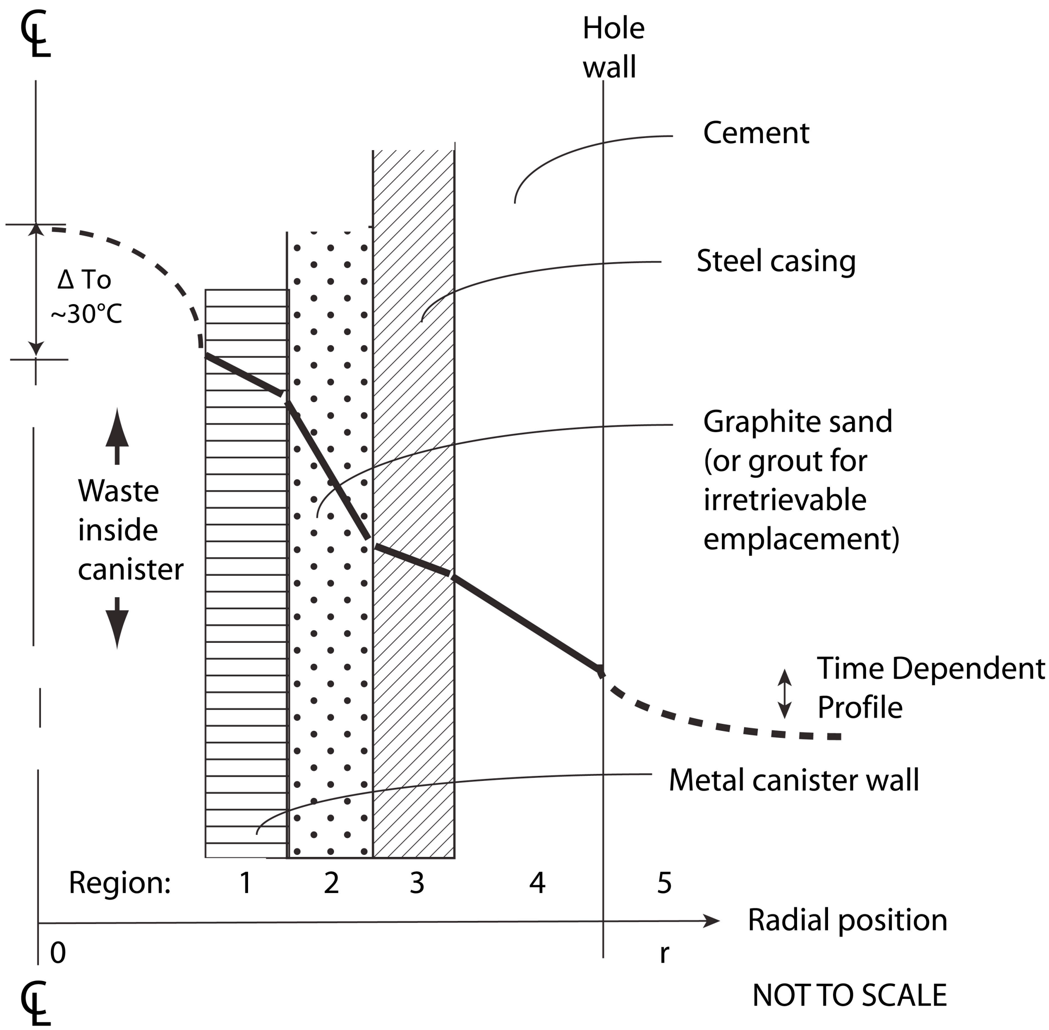
Pragmatic reasons for rejection of the borehole option have centered on these two aspects. However, a good case can be made for discounting such reservations.

The cost issue may be traceable to the estimate of 100 million dollars per hole for weapons plutonium disposal, suggested in the 1990s (4-3). However, a recent evaluation of boreholes for hot dry rock applications reports costs of four million dollars for 3 km holes (Ref 4-4, Fig. 12), which we will double to allow for enlarged diameter. These boreholes are fully lined. Since each hole can accommodate about 100 MT of spent fuel, the hole cost amounts to a significant but tolerable 80 \$/kg, about twenty percent of the ~400 \$/kg total available amount inferable from the 1 mill/kW hre US DOE waste fee. Advanced drilling techniques (e.g., spallation) are also under development, which may lead to further savings. Clearly more precise cost quantification and steps to reduce costs must be a priority goal of any future deep borehole work.

A second misreading of the situation arises because of the apparent assumption that each borehole will have to be individually licensed as a separate entity. The intent, however, is to license them collectively as a "repository field" consisting of an array of identical boreholes drilled in succession into a homogeneous rock formation on a grid pattern (e.g., 20 x 40) on a spacing of a few hundred meters. This is somewhat analogous conceptually to constructing several identical reactors at the same pre-licensed power station site. A repository of this size would accommodate about 80,000 MT of spent fuel: about Yucca Mountain's currently legislated limit. This supposition is the basis for assuming a licensing process no more costly or time consuming than for a mined repository. The critics are correct, of course, in noting that the protocol for proceeding in this manner must be worked out and approved.

4.5 Thermal Environment

Tolerable temperature and stress are two key conditions which determine the allowable borehole waste loading. Some simple "back-of-the-envelope" estimates are invoked in Appendices B and C to ferret out the dominant constraints. Table 4.2 and Fig. 4.1 summarize some of the key findings. The example chosen is a single PWR assembly (or its mass/volume/decay power equivalent of three BWR assemblies). The induced temperature increases and resulting thermal stresses are quite tolerable. They all depend on, and are directly proportional to, the linear power of the assembly. Hence a brief digression on this topic.



Region	ΔT°C*
1	< 0.1°C
2	3.4°C
3	<0.1°C
4	1.8°C
5	22°C (peak)
Total	27.4**

*For PWR spent fuel, 45 MWd/kg burnup, 40 years cooling
** above ambient rock T of ~60°C

Figure 4.1 Representative Radial Temperature Profile in and around a Borehole

Decay Heat Release

For present purposes, a fairly simple relation adequately describes the linear power, W/m, of a spent PWR fuel assembly:

$$q' = \frac{2200}{t^{3/4}}, \quad \text{W/m} \quad (1 < t < 10^6 \text{ yrs}) \tag{4-1}$$

where t is time in years since the end of irradiation. This relation has been developed for a discharge burnup of 60 MWd/kg, and scales roughly proportional to burnup (4-5). Other assumptions invoked are an assembly (original basis) heavy metal loading of 500 kg and an effective canister height of 5 m.

Three BWR assemblies have roughly the same heavy metal loading as one PWR assembly. In the past BWR burnups were lower than for PWRs, but values are now approaching parity. Thus we will assume the linear power per canister is the same, since we can accommodate either one PWR or three BWR assemblies.

Separated wastes, of course, have heat loading which differs in both magnitude and time dependence. Reference (4-6) treats minor actinides, both separately and in combination. Some fission products such at Tc (which includes Tc-99) and I (which includes I-129) have a very low heat load, and hence are suitable for co-disposal.

More important for our purposes is that separated wastes and their waste forms are readily tailored to have the same linear power as an intact PWR fuel assembly and hence essentially the same external temperature field. And, of course, if fuel assemblies are reconstituted, any desired heat loading can be realized, even for spent fuel.

More relevant here is the effect of cooling time. Application of Eq (4-1) shows that interim dry cask storage for 50 to 100 years can reduce decay power by factors of approximately 2 and 4, respectively, relative to ten years' cooling. All temperature rises are directly proportional to the linear power, hence this approach is also an effective way of adjusting borehole heat load.

4.6 Stress

Table 4.2 also summarizes the results of stress calculations. Note that all were made using simplified prescriptions, and no effort was made to aggregate them into combined stress. More importantly, no stress intensification factors or safety factors were applied (as would be required, for example, to meet ASME code requirements): these can amount to multipliers of 1.5 to 3.

What emerges at once is the dominance of canister-crushing stress. Even if one uses high strength steels, as proposed by Hoag (4-7), it is hard to give high assurance that the bottom-most canisters will not be crushed by the weight of those above. This threat was the principal motivation for reducing the emplacement zone thickness from 2 km in Hoag's version to 1 km here. If the oil/gas based drill cost model discussed in Chapter 3 is applicable, this depth is also fortuitously close to the drilling-cost optimum.

If thicker emplacement zones are later found to be preferable, and retrievability is forgone, one could grout canisters in place and interpose intermediate plug zones of, say, 100 m thickness between successive canister zones. These concrete plugs would relieve canister stack vertical stress by transferring most of it to the borehole rock wall.

Table 4.2 Temperatures and Stresses Encountered in a Representative Deep Borehole Application*

Adiabatic Heatup of host rock in 10^4 yrs:		19°C
Axial conduction and radial input at 10^4 yrs:		15°C/km
		1600 W
Vertical rock uplift for ΔT = 20°C		16 cm
Transient peak rock temperature increase		22°C
Temperature differences across		
canister and liner walls		0.03°C
sand-filled canister-liner gap		3.4°C
water flooded gap		0.5°C
Axial buckling (bowing) stress:	limit	8500 MPa
	actual	330 MPa
Compressive (crushing) stress	limit**	760 MPa
	actual	330 MPa
Hydrostatic collapse pressure	max	33 MPa
	to collapse	21.5 MPa
Thermal stress on host rock	experienced	16.7 MPa
	compressive strength	100 MPa
Thermal stress on steel tubing		nil

* See Appendices B and C for calculations for a PWR assembly having 45 MWd/kg burnup and 40 years cooling
** for high strength P11 steel; ordinary drillstring steels are about a factor of two less

Also evident is the need to fill the canister voids with sand or grout to protect against the hypothetical maximum hydrostatic stress causing radial collapse of the canister wall in the deepest region of the emplacement zone.

4.7 Chapter Summary

The first two sections of this chapter were devoted to refutation of the misperceptions that boreholes are totally incompatible with retrievability and must also forego multiple barriers to radionuclide release. Design modifications having a tolerable cost increment would appear to remedy both of these postulated shortcomings.

Cost and licensing issues are very briefly addressed, to accentuate the need to work towards drilling cost containment and reduction, and to license an array of boreholes as a single repository, rather than as individual holes.

Finally, some scoping calculations are summarized which show that temperature increases in the host rock and from canister to rock wall are quite modest. Stress analysis, however, makes clear that resistance to bottom canister crushing due to vertical weight loads and radial hydrostatic loads must be given close attention. The latter threat, while remote, motivated filling the canister with sand or grout in our reference design.

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Chapter 5 Summary, Conclusions and Recommendations

5.1 Summary and Conclusions

This report has updated the past six years' progress at MIT on deep borehole design and assessment, in the context of parallel work elsewhere, primarily in the UK and Sweden, and with special attention to issues raised in critical reviews of earlier work. Basically, the current (2009) status is a borehole and borehole field design similar to that developed by Hoag in 2006 (5-1), but made even more conservative by reducing the emplacement zone and total depth of the boreholes.

In the present report a general survey was presented of the technology available for homing in on both general and localized sites for deep borehole fields. Oil/gas/geothermal technology appears up to the task, but more specific scrutiny is needed on key issues such as the presence, density and mobility of water in the emplacement zone, 2–3 km below the surface.

A set of counterarguments was advanced to counter the common misperceptions that the deep borehole approach entirely forgoes retrievability and the use of multiple barriers to release. But it was also pointed out that other considerations favor non-retrievability in several possible future fuel cycle scenarios.

Finally, the need to pay close attention to provision of adequate assurance, with imposition of conservative factors of safety, of both axial and radial crush resistance was stressed.

5.2 Some General Observations

Flooding

Since it is not possible to confidently predict that each and every borehole will always be either dry or flooded, both possibilities must be taken into account. While flooding might at first appear to create the most aggressive environment, this may not necessarily be the case. For example, if water replaces gas, the effective thermal conductivity increases, in which case the lower temperature can slow deleterious chemical attack and phase transitions. Since eventual water ingress cannot be rule out, this condition should dominate our analyses.

Gas Generation

One must also investigate whether gas produced in situ (e.g., H_2 by corrosion of metals, H_2 and O_2 by radiolysis, and Kr and Xe by escape of fission product gas from fuel) can create differential pressures that will cause bonds or seals to fail, and thereby reduce the barriers to radionuclide release. The goal must be to insure that the robust barriers provided by geology obviate failure due to such causes.

Colloidal Transport

Experimental studies have identified colloid formation as a mechanism for anomalously high transport of some radionuclides – actinides in particular. While this appears to be of greater concern in upper sedimentary strata, where complex organic species are present, it deserves further scrutiny before ruling it out as important in deep borehole host rock. It may be possible to show that colloids are unstable in the high-ionic-strength brines prevalent at emplacement depths.

Tailored Loading

Spent fuel and its contained radionuclides are currently available in the US spanning a factor of two in discharge burnup and over three decades of post-irradiation cooling time. Thus one has a wide selection of heat loadings to choose from. For example, it might prove advantageous to load a hole in the order of lower linear power, kW/m, first so as to help counteract the geothermal gradient of about 20°C/km, and thereby reduce local, average and peak canister temperature. This could also reduce the vertical temperature gradient component due to the waste, which would reduce the resulting buoyancy gradient tending to promote water plume rise. Evaluation of tactics of this sort adds to the motivation for building a detailed thermal-hydraulic model of a borehole and its host rock cell.

Special Cements

There is a great deal of experience with the use of cement and concrete in the oil/gas drilling industry, and also for radiation shielding in the nuclear industry. However, in deep boreholes used for nuclear waste disposal there is a unique requirement for setting of fresh cement in the presence of heating and radiation. Some work has been done using concrete as a LWR waste form, and this needs to be evaluated and extended for borehole-specific conditions.

Horizontal Drilling

The oil and gas industry has become quite adept at drilling holes which start vertical and then turn horizontal (or, at an angle of choice) (5-7). This approach, while more expensive on a per kilometer basis, could be attractive for HLW disposal in a number of respects:

(1) It virtually eliminates the problem of canister crushing by those above, and thus permits use of a longer emplacement zone.
(2) It is suited to drilling several holes from a single site, thereby saving setup time and costs (but complicating concurrent drilling and emplacement operations). One can vary both azimuthal direction and emplacement depth.

(3) It reduces local temperature, hydrostatic and lithostatic pressure in the emplacement zone.
(4) It can increase the seal zone thickness over the uppermost canister – i.e., in the limit all canisters are at the same average depth.

On the downside, smaller hole diameters than for vertical drilling are the norm.

Nevertheless, this variation is worthy of future investigation.

Siting Alternatives

The work at MIT has, to date, been restricted to terrestrial drilling into granitic basement rock, for several reasons, among them: the abundance of candidate sites in the US, the excellent confinement properties of granite, the synergism with the worldwide hot-dry-rock geothermal program, and the favorable results of Swedish R&D on granite as a host for HLW disposal.

However, there are also incentives to broaden the scope of investigation into one or more of the following areas:

(1) Near-shore sub-seabed disposal into sediment or the basement rock beneath (usually granite, rarely basalt on continental shelves). Note that this differs from the more expensive version of deep ocean disposal, as proposed in Ref (5-8). Shallow water sites might prove attractive to nations having less suitable terrestrial siting prospects, or for siting of a collaborative international repository. Resolution of international legal restrictions on ocean disposal is a prerequisite.
    There are some profound consequences of sub-seabed siting:
    (a) Deeper drilling because of the overlayer of water, which is not a creditable barrier to escape (but subsequent dilution could be a mitigating feature)
    (b) Drilling offshore is considerably more expensive. Hence there is a strong incentive to exploit proven commercial technology, and to tailor waste geometry to fit. A cost/benefit analysis should preced more intensive R&D expenditures in this area.
    (c) Post-emplacement removal of wall liner in the sediment zone will allow self-sealing.
    (d) The approach is best suited to irretrievable applications.
    (e) One must accommodate higher maximum hydraulic pressure on canister walls.
    (f) Wastes can be transported to sites by ship.

(2) Drilling into, or down through and under salt beds or domes (on land, or at sea). Salt has been a contender for HLW repository siting of long standing: for example, Lyons Kansas in the early US program, currently in Germany at Gorleben, and recently suggested as a neighbor to WIPP by the mayor of Carlsbad, New Mexico (5-9). Salt (or sediment) as the host stratum or its seal cap have the virtue of self-sealing hole closure, but at the sacrifice of retrievability.

5.3 More Specific Recommendations

The deep borehole approach relies heavily on high-integrity geology and compatible geochemistry. Overall the weakest link would appear to be the borehole plug. Hence future R&D should focus on this feature. The currently preferred approach at MIT is to use specialty cement formulations: one which is best suited to grouting waste canisters in place, and another one or more for the upper kilometer-thick plug sealing the high-integrity rock zone. The canister grout has to set in the presence of heat and radiation fluxes from the encapsulated waste. Any protection it can afford against canister corrosion is a valuable contribution. The main attribute required of the plug-zone cement is retardation of water-borne transport of waste radionuclides. Considerable work has been done on hole plugging, but not necessarily under entirely pertinent conditions. The most relevant studies have been done in Sweden, where layers of cement, asphalt, and bentonite clay are proposed (5-2) (5-3). Gibb and fellow researchers at Sheffield University have raised the possibility of melting granite to form a plug (5-4).

Another issue not fully resolved to our satisfaction is the issue of borehole wall stability (i.e., susceptibility to "breakout": see Appendix C.6) during or following drilling operations. Further analyses, and follow-up on field experience in ongoing geothermal projects, are highly recommended.

Other aspects which may deserve re-examination are several variations considered, but deferred, in the process of arriving at the design sketched in this report. Table 5.1 summarizes the most promising of these alternatives. They have been passed over to date in the interest of using already proven commercial technology, and a very conservative approach. In this latter regard future work could profitably be done on eliminating excess conservation – for example, going deeper, closer borehole spacing, reducing plug thickness, and so forth.

Upgrading the computer code modeling of temperature fields, stresses and radionuclide transport is also a priority in the US effort. In these areas the Swedish and UK are much more advanced – see, for example, References (5-4) and (5-5). While exercising of their tools has confirmed highly effective performance under very similar conditions to that in the US, an independent US capability is needed for verification, site-specific studies, and for licensing purposes.

As a final recommendation to those wishing to explore the subject in much more detail, the SKB website, www.SKB.se, is a source of several useful e-copy reports on all aspects of deep boreholes for nuclear waste disposal. Reference (5-2), with its six appendices, was found to be particularly informative.

Table 5.1 Design Variations of Continuing Interest

Feature	Attributes
Horizontal emplacement zone	• uses proven oil/gas well drilling technology • can drill a dozen or so wells at same upper vertical hole site • eliminates self-induced compressive stress on canister string: can have more waste per hole • but retrieval is more problematical
Use titanium or copper canisters or cladding	greatly improves corrosion resistance; validated in Swedish program
Use cement grout to fill canister internal voids in place of sand	• improved thermal conductivity • better crush resistance • but makes fuel recovery from canister more difficult
Add differential pressure relief to canister	• burst disk and/or porous plug on bottom of canister to equalize internal and external pressure when ΔP is excessive
Employ advanced drilling methods: spallation, laser melting, etc. (5-6)	• under development for other applications. Can be used if and when ready. Significant savings possible. • for near term application, air drilling should be evaluated
Cost modeling and optimization	• develop explicit cost vs diameter relation • optimize depth • evaluate fuel assembly consolidation
Diffusion and transport	• collect and evaluate retardation data for water transport of radionuclides in granite and borehole plug materials • develop or import a detailed computer model
Temperature and stress	• develop or import a detailed computer model • focus on axial and radial crush resistance of the waste canisters
Siting	• continue screening of US and World data to strengthen the technical case • develop a better socio-political approach • more thoroughly evaluate technology

5.4 References for Chapter 5

(5-1) C. I. Hoag, "Canister Design for Deep Borehole Disposal of Nuclear Waste," SM Thesis, MIT Dept. of Nuclear Science and Engineering, May 2006

(5-2) SKB Technical Report 89-39, "Storage of Nuclear Waste in Very Deep Boreholes," Dec. 1989

(5-3) J. Liu, I. Neretnieks, "Physical and Chemical Stability of the Bentonite Buffer," SKB Report R-06-103, Dec. 2006

(5-4) F. G. F. Gibb et al., "Modeling Temperature Distribution around Very Deep Borehole Disposals of HLW," Nuclear Technology, Vol. 163, July 2008

(5-5) N. Marsic, B. Grundfelt, M. Wiborgh, "Very Deep Hole Concept: Thermal Effects on Groundwater Flow," SKB Report R-06-59, Sept. 2006

(5-6) The Future of Geothermal Energy, MIT, 2006, http://geothermal.inel,gov

(5-7) "Drilling Sideways – A Review of Horizontal Well Technology and Its Domestic Application," DOE/EIA-TR-0565, April 1993

(5-8) C.D. Hollister and S. Nadis, "Burial of Radioactive Waste under the Seabed," Scientific American, Vol. 278, No. 1, Jan. 1998

(5-9) NEI SmartBrief, March 27, 2009

APPENDIX A: BIBLIOGRAPHY OF MIT WORK

The list which follows identifies the major publications by the MIT group on the subject of deep borehole HLW disposal. It is limited to material which is readily retrievable. An equal number of other student reports were prepared; in general, the results are reflected in the eight publications listed.

One noteworthy trend is that the initial emphasis on intact spent fuel disposal, first in space-limited overseas countries (e.g., Taiwan, Japan, Korea), later shifted to the US because of concerns over slow progress on Yucca Mountain, and most recently focused on separated reprocessing wastes, such as minor actinides, as an alternative to the partitioning and transmutation strategy envisioned under the US AFCI program.

(1) W.-S. Kuo, M. J. Driscoll, J. W. Tester, "Re-evaluation of the Deep Drillhole Concept for Disposing of High-Level Nuclear Wastes," Nuclear Science Journal, Vol. 32, No. 3, June 1995

(2) W.-S. Kuo, "Evaluation of Deep Drillholes for High Level Nuclear Waste Disposal," Nucl. Eng./SM Thesis, MIT Nuclear Engineering Dept., 1991

(3) C. G. Sizer, C. I. Hoag, S. Shaikh, M. J. Driscoll, "Partitioning and Interment of Selected High Level Wastes," Trans. Am. Nucl. Soc., Vol. 96, June 2007

(4) C. G. Sizer, "Minor Actinide Waste Disposal in Deep Geological Boreholes," SB Thesis, MIT Dept. of Nuclear Science and Engineering, May 2006

(5) C. I. Hoag, "Canister Design for Deep Borehole Disposal of Nuclear Waste," SM Thesis, MIT Dept. of Nuclear Science and Engineering, Sept. 2004

(6) V. K. Anderson, "An Evaluation of the Feasibility of Disposal of Nuclear Waste in Very Deep Boreholes," SM Thesis, MIT Dept. of Nuclear Science and Engineering, Sept. 2004

(7) S. Shaikh, "Effective Thermal Conductivity Measurements Relevant to Deep Borehole Nuclear Waste Disposal," SM Thesis, MIT Dept. of Nuclear Science and Engineering, Jan. 2007

(8) T. A. Moulton, "Parametric Study of the Total System Life Cycle Cost of an Alternate Nuclear Waste Management Strategy Using Deep Boreholes," SM Thesis, MIT Dept. of Nuclear Science and Engineering, Sept. 2008

Abstracts for the theses listed follow.

EVALUATION OF DEEP DRILLHOLES FOR
HIGH LEVEL NUCLEAR WASTE DISPOSAL
BY
WENG-SHENG KUO

Submitted to the Department of Nuclear Engineering
on October 8, 1991 in partial fulfillment of the
requirements for the Degrees of Nuclear Engineer and
Master of Science in Nuclear Engineering

ABSTRACT

This thesis re-examines in a comprehensive way the concept of deep drillholes for final disposal of nuclear high-level waste. Earlier studies of the deep drillhole concept were reviewed, focusing on how improvements in technology might make this approach more attractive.

The scope of the present reevaluation included (1) a brief investigation of some features of candidate rock types for geological disposal; (2) an assessment of drilling techniques, including conventional oil-well drilling and advanced thermal spallation methods; (3) a preliminary but conservative heat transfer analysis; (4) an assessment of suitability with respect to radionuclide release; (5) a brief discussion of well logging technology; (6) a description of a conceptual deep drillhole system and investigation of some alternatives; and (7) a simple and preliminary waste disposal cost analysis. All the assessments were compared with baseline data for a mined repository system, namely the Yucca Mountain site.

The main findings are that (1) granite is the best host rock for the deep drillhole system; (2) both oil-well drilling and thermal spallation drilling methods can be used to drill deep boreholes for disposal, with preference given to the thermal spallation method for hot dry rock drilling; (3) the overall thermal performance was found to be as good as or better than that projected for the Yucca Mountain site; (4) the deep drillhole concept can match or exceed mined repository performance criteria for radionuclide release; (5) well logging can provide useful geophysical and geochemical parameters for site qualification; (6) the overall system cost is comparable to that for the Yucca Mountain site, and the borehole cost is not a dominant factor in concept selection; (7) the concept of using SiC or other solid particles as a fill material in the waste canister appears to be an acceptable means to add to the crush resistance of the canister; and (8) the uncertainty of the efficacy of current technology for post-emplacement retrieval operations, and the uncertain impact of accidents involving stuck canisters during emplacement/retrieval are found to be the major drawbacks of the deep drillhole concept.

The main recommendations for future work are: (1) more explicit concept-specific safety criteria/limits for design and analysis should be established; (2) the issues of retrievability and borehole stability, radionuclide release and escape scenarios should be investigated more comprehensively; (3) concept performance and cost optimization should be carried out with particular focus on the potential benefits of fuel assembly consolidation and exploitation of the inherently modular, incremental, dispersible nature of the concept.

Thesis Supervisor: Dr. Michael Driscoll
Title: Professor Emeritus, Nuclear Engineering
Thesis Supervisor: Dr. Jefferson Tester
Title: Director, Energy Laboratory/Professor, Chemical Engineering

MINOR ACTINIDE WASTE DISPOSAL IN DEEP GEOLOGICAL BOREHOLES

By

CALVIN GREGORY SIZER

Submitted to the Department of Nuclear Engineering on May 19th, 2006.

In Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science in Nuclear Science and Engineering

ABSTRACT

The purpose of this investigation was to evaluate a waste canister design suitable for the disposal of vitrified minor actinide waste in deep geological boreholes using conventional oil/gas/geothermal drilling technology. The nature of minor actinide waste was considered, paying particular attention to nuclides whose decay energy and half lives were of relative significance to the minor actinide waste as a whole. Thermal Analysis was performed based on a reference borehole design, by Ian C. Hoag. The strategy of the thermal analysis is aimed at finding peak temperatures within the configuration, paying particular attention to the heat transfer under deep geological conditions in the air gap between the canister and the borehole. A first order economic analysis was made to compare the designed canister emplacement costs to that of intact spent fuel.

The results of this analysis show that three minor actinide nuclides dominate heat generation after ten years cooling: Cm-244, Am-241, and Am-243 account for 97.5% of minor actinide decay heat. These three nuclides plus Np-237 account for 99% of the minor actinide mass. The thermal analysis was based on an irretrievable canister design, consisting of a 5 meter long synroc waste form, with minor actinides loaded to 1% wt, an outer radius of 15.8 cm and inner annular radius of 8.5 cm. Filling the annulus with a vitrified technetium and iodine waste form was found to be feasible using a multi-stage emplacement process. This process would only be required for three of the fifty boreholes because technetium and iodine have low heat generations after 10 years cooling. The suggested borehole waste form has a maximum centerline temperature of 349C. The costs of drilling boreholes to meet the demand of 100,000MT of PWR waste are estimated to be 3.5% of the current nuclear waste fund, or about $9.6/kg of original spent fuel.

Thesis Supervisor: Michael J. Driscoll

Title: Professor Emeritus of Nuclear Science and Engineering

CANISTER DESIGN FOR DEEP BOREHOLE DISPOSAL OF NUCLEAR WASTE

By Christopher Ian Hoag

Submitted to the Department of Nuclear Engineering on May 12th, 2006 in partial fulfillment of the requirements for the degree of Master of Science in Nuclear Science and Engineering

Abstract

The objective of this thesis was to design a canister for the disposal of spent nuclear fuel and other high-level waste in deep borehole repositories using currently available and proven oil, gas, and geothermal drilling technology. The canister is suitable for disposal of various waste forms, such as fuel assemblies and vitrified waste. The design addresses real and perceived hazards of transporting and placing high-level waste, in the form of spent reactor fuel, into a deep igneous rock environment with particular emphasis on thermal performance.

The proposed boreholes are 3 to 5 km deep, in igneous rock such as granite. The rock must be in a geologically stable area from a volcanic and tectonic standpoint, and it should have low permeability, as shown in recent data taken from a Russian deep borehole. Although deep granite should remain dry, water in flooded boreholes is expected to be reducing, but potentially corrosive to steel. However, the granite and plug are the containment barrier, not the canister itself.

The canisters use standard oil drilling casings. The inner diameter is 315.32mm in order to accommodate a PWR assembly with a width of 214mm. At five meters tall, each canister holds one PWR assembly. The canister thickness is 12.19mm, with an outer diameter of 339.7mm. A liner can extend to the bottom of the emplacement zone to aid in retrievability. The liner has an outer diameter of 406.4mm and a thickness of 9.52mm. The standard drill bit used with a liner of this size has an outer diameter of 444.5mm.

Sample calculations were performed for a two kilometer deep emplacement zone in a four kilometer deep hole for the conservative case of PWR fuel having a burnup of 60,000 MWd/kg, cooled ten years before emplacement. Tensile and buckling stresses were calculated, and found to be tolerable for a high grade of steel used in the drilling industry. In the thermal analysis, a maximum borehole wall temperature of 240°C is computed from available correlations and used to calculate a maximum canister centerline temperature of 337°C, or 319°C if the hole floods with water. Borehole repository construction costs were calculated to be on the rate of 50 \$/kg spent fuel, which is competitive with Yucca Mountain construction costs. Recommendations for future work on the very deep borehole concept are suggested in the areas of thermal analysis, plugging, corrosion of the steel canisters, site selection, and repository economics.

Effective Thermal Conductivity Measurements Relevant to Deep Borehole Nuclear Waste Disposal.

By Samina Shaikh

Submitted to the Department of Nuclear Engineering on January 15th, 2006 in partial fulfillment of the requirements for the degree of Masters in Science in Nuclear Science and Engineering and Bachelors in Science in Nuclear Science and Engineering

Abstract

The objective of this work was to measure the effective thermal conductivity of a number of materials (particle beds, and fluids) proposed for use in and around canisters for disposal of high level nuclear waste in deep boreholes. This information is required to insure that waste temperatures will not exceed tolerable limits. Such experimental verification is essential because analytical models and empirical correlations can not accurately predict effective thermal conductivities for complex configurations of poorly characterized media, such as beds of irregular particles of mixed sizes.

The experimental apparatus consisted of a 2.54 cm. diameter cylindrical heater (heated length $\approx$ 0.5 m) , surrounded by a 5.0 cm inner diameter steel tube. Six pairs of thermocouples were located axially on the inside of the heater sheath, and in grooves on the air-fan-cooled outer tube. Test media were used to fill the annular gap, and the temperature drop across the gap measured at several power levels covering the range of heat fluxes expected on a waste canister soon after emplacement.

Values of effective thermal conductivity were measured for air, water; particle beds of sand, SiC, graphite and aluminum; and an air gap subdivided by a thin metal sleeve insert. Results are compared to literature values and analytical models for conduction, convection and radiation. Agreement within a factor of 2 was common, and the results confirm the adequacy, and reduce the uncertainty of prior borehole system design calculations. All particle bed data fell between 0.3 and 0.5 W/mºC, hence other attributes can determine usage.

Thesis Supervisor: Professor Michael J. Driscoll
Title: Professor of Nuclear Science and Engineering

An Evaluation of the Feasibility of Disposal of Nuclear Waste in Very Deep Boreholes

by

Victoria Katherine Anderson

Submitted to the Department of Nuclear Engineering on August 11, 2004 in Partial Fulfillment of the Requirements for the Degree of Master of Science in Nuclear Engineering

ABSTRACT

Deep boreholes, 3 to 5 km into igneous rock, such as granite, are evaluated for next-generation repository use in the disposal of spent nuclear fuel and other high level waste. The primary focus is on the stability and solubility of waste species, waste forms, and canister materials in saline, anoxic water, which is the most severe potential downhole environment given the sparse data available.

Pourbaix (Eh-pH) diagrams and solubility products were calculated for 20 materials of interest. In general, extremely low dissolved concentrations were estimated. Copper was identified as the best canister material. Wall-to-far-field temperature increases were estimated to be about 20° C for canisters containing two PWR assemblies, which is quite tolerable. Aspects requiring further work in the near term are detailed canister interior design to withstand crushing under a 1 km stack of same, and development of a borehole plug concept having a comparable or better impermeability and radionuclide holdup than the surrounding granite bedrock.

Thesis Supervisor: Michael J. Driscoll
Title: Professor Emeritus of Nuclear Engineering

Thesis Reader: Karen L. Noyes, Sc.D.
Title: Postdoctoral Associate, Department of Nuclear Engineering

Parametric Study of the Total System Life Cycle Cost of an Alternate Nuclear Waste Management Strategy Using Deep Boreholes

by

Taylor Allen Moulton

Submitted to the Department of Nuclear Science and Engineering on August 8, 2008 in Partial Fulfillment of the Requirements for the Degree of Master of Science in Nuclear Science and Engineering

Abstract

The Department of Energy recently submitted a license application for the Yucca Mountain repository to the Nuclear Regulatory Commission, yet even the most optimistic timetable projects that the repository will not now open until at least 2020. The Office of Civilian Radioactive Waste Management recently revised the official undiscounted total life cycle cost of the waste management system upward by $22B (2000$), an increase of nearly 40% over the previous estimate, published in 2001. In this thesis a waste management tool, named SNuFManager (**S**pent **Nu**clear **F**uel **Manager**), has been developed which deterministically simulates the stocks and flows of spent fuel in the United States and estimates annual expenditures based on the system's behavior. The tool allows policy makers to quickly and cheaply estimate the economic consequences of various decision alternatives under an array of scenarios in order to make quantitatively informed decisions and identify ways to mitigate or reverse recent increases in life cycle costs. The results are expressed in 2000 dollars, enabling a convenient comparison with the government's 2001 total system life cycle cost analysis.

For each year of delay beyond 2020 in opening the repository and transferring ownership of spent fuel to the federal government, the total waste management system life cycle cost is estimated to increase by another $330M (2000$). The model also estimates that switching from the current mined geologic repository approach to a deep borehole disposal strategy would reduce the undiscounted total system life cycle cost by $19.4B, or 32%. Assuming a 10% discount rate, the net present cost of the deep borehole strategy is 18% less than that of the mined geologic repository approach. Finally, the model illustrates the economic benefits of opening a centralized interim storage facility of significant capacity as soon as possible. For example, if a 40,000 metric tonne facility, comparable in scale to the proposed Private Fuel Storage Facility in Utah, was opened by 2020, and the mined repository was opened in the same year, the total life cycle cost would be reduced by $1.5B relative to the case with no interim storage. If, moreover, the opening date of the mined geologic repository were delayed until 2040 or 2060, the savings provided by interim storage increase dramatically, to $4.9 and $8.1B, respectively. The thesis concludes with a discussion of the political and strategic consequences of several key policy choices.

Thesis Supervisor: Richard K. Lester
Title: Professor of Nuclear Science and Engineering

Thesis Reader: Michael J. Driscoll
Title: Professor Emeritus of Nuclear Science and Engineering

APPENDIX B Temperature Field Estimates

The temperatures in the waste and its surrounding host rock are, arguably, the most important constraints which dictate key deep borehole repository features. Waste loading per can, can and hole diameters, and hole-to-hole spacing all follow directly from the need to keep temperature rises within tolerable bounds. The sections which follow document a series of simple scoping calculations to define the temperature field in and around a loaded deep borehole, as follows:

B.1 Radial Conduction in Host Rock

B.2 Adiabatic Heatup of Host Rock

B.3 Axial Conduction in Host Rock

B.4 Thermally Induced Uuplift of Host Rock

B.5 Transient Temperature Peaking in Host Rock

B.6 Radial Conduction in Waste-to-Wall Intervening Layers

B.7 Temperature Rise inside Waste Form

B.8 Effect of Temperature on Reaction Rates

B.1 Radial Conduction in Host Rock

Our analysis assumes relatively rapid spread of energy in the radial direction.

The time constant for radial conduction from a line source in an infinite medium is:

$$\tau = \frac{R^2}{4\alpha}$$

where the thermal diffusivity α is

$$\alpha = \frac{k}{\rho c_p}$$

$$\simeq 40 \text{ m}^2/\text{yr (see Table 1.2 of Chapter 1)}$$

Thus for our case R = 100 m, centerline to cell boundary

$$\tau = \frac{(100)^2}{4(40)} = 62.5 \text{ years}$$

This is relatively short in terms of the times of interest. Hence in the long run we can assume uniform adiabatic heatup of an axial slice through the cell (i.e., cylinder of rock surrounding a borehole).

Another way of looking at this situation is to estimate the fraction of energy from an instantaneous pulse which diffuses beyond R in time t, namely:

$$F = e^{-\tau/t}$$

Hence, in 100 years $F = 0.54$, more than half.

B.2 Adiabatic Heatup of Host Rock

If one assumes that energy accumulates in radial slices, without axial movement, an estimate can readily be made of the surrounding rock temperature.

To a good approximation, the linear power of a discharged PWR fuel assembly is approximated by

$$q' = \frac{2.2}{t^{0.75}}, \qquad \text{kW/m}$$

for t in years. This value is for a burnup of 60 MWd/kg, and scales up or down roughly in direct proportion to burnup.

Thus between t_1 and t_2, the total energy release is given by the result of integration, as:

$$E' = 8.8 \left(t_2^{0.25} - t_1^{0.25}\right) \text{ kWyr/m}$$

For example, if burnup is 45 MWd/kg, $t_1 = 40$ years cooling, and $t_2 = 10{,}000$ yrs, one finds

$$E' = 49.4 \text{ kWyr/m}$$

The total heat capacity of a 200 m x 200 m x 1 m slice of rock is 0.82×10^8 kWsec/°C $= 2.6$ kWyr/m°C. Hence the temperature increase would be $48.4/2.6 =$ 19°C, a tolerable value.

If one expands the adiabatic time horizon to a million years, the temperature increase would be much larger. However, axial conduction would intervene long before to prevent this hypothetical eventuality.

B.3 Axial Conduction in Host Rock

Consider axial conduction for (an added) gradient of 15°C/km. The axial heat removal in a waste cell is:

$$Q = k\,A\frac{\Delta T}{\Delta z} = 2.6 \text{ W/m°C } (4 \times 10^4 \text{ m}^2)\,\frac{15°\text{C}}{1000 \text{ m}}$$

or $Q = 1560$ W, axial losses.

This can be compared to the radial input, at say 10^4 years, from the 1000 m long waste string of fuel burned to 45 MWd/MT, of 1650 W: very nearly equal to axial removal. This indicates that a balance will be struck which prevents further rock heatup in roughly this time frame.

The axial loss for a 15°C/km gradient is spread over 4×10^4 m^2, corresponding to a surface heat flux of 39 milliwatts per square meter – which is the estimated normal geothermal heat flux for planet earth, a check on our calculations.

B.4 Thermally Induced Uplift of Host Rock

The vertical column of repository rock will expand as its temperature increases, resulting in surface uplift. An approximate estimate, for an unconstrained block, is given by:

$$\Delta z = \alpha^* L\,\overline{\Delta T}$$

where

α^* = coefficient of linear thermal expansion = 8.0×10^{-6} per °C

L = height of heated zone = 1000 m

$\overline{\Delta T}$ = temperature increase above initial downhole ambient: assume 20°C

in which case

$$\Delta z = 0.16 \text{ m} = 16 \text{ cm}$$

impressive, but arguably tolerable when meted out over thousands of years.

B.5 Transient Temperature Peaking in Host Rock

For a line heat source having a time dependent linear power, the temperature increase above ambient host rock conditions can be estimated as:

$$\Delta T(r,t) = \frac{1}{4\pi r}\int_0^t q'(t)\left[\frac{e^{-\frac{r^2}{4\alpha t}}}{t}\right] dt$$

where t is the time elapsed since emplacement.

The linear power is fairly well represented by the approximation:

$$q'(t) = q'(tc)\left[\frac{tc}{tc + t}\right]^{3/4}$$

where tc is the cooling time post-irradiation prior to emplacement.

Next make the following linearizations:

$$q'(t) \approx q'(tc)\left[\frac{1}{1 + 3/4(t/tc) + \ldots}\right]$$

$$\frac{e^{-\frac{r^2}{4\alpha t}}}{t} \approx \frac{1}{\left(\frac{r^2}{4\alpha}\right) + t + \ldots}$$

Substitution into the relation for ΔT and integrating yields:

$$\Delta T(r,t) = \left[\frac{q'(tc)}{4\pi r}\right] G$$

where

$$G = \left[\frac{1}{1 - (3/4)\left(\frac{r^2}{4\alpha tc}\right)}\right] \ell n \left\{\frac{1 + \left(\frac{4\alpha tc}{r^2}\right)\left(\frac{t}{tc}\right)}{1 + \frac{3}{4}\left(\frac{t}{tc}\right)}\right\}$$

But $\left(\frac{4\alpha tc}{r^2}\right) >> 1$; then for large t one approaches an asymptotic maximum (i.e., because of model limitations there is no maximum at finite t):

$$G \approx \ell n\left(\frac{16}{3}\frac{\alpha tc}{r^2}\right) = \ell n\left(5.33\,\frac{\alpha tc}{r^2}\right)$$

This presumably represents a conservative upper limit estimate.

If linear power instead decays exponentially with a half-life $T_{1/2}$:

$$q'(t) = q'(tc)\, e^{-\lambda t} \approx q'(tc)\left[\frac{1}{1 + \lambda t + \ldots}\right]$$

where $\lambda = 0.693/T_{1/2}$

Proceeding as before:

$$\hat{G} \approx \ell n \left(\frac{4 \alpha T_{1/2}}{\ell n 2 \cdot r^2} \right) = \ell n \left(5.77 \, \frac{\alpha T_{1/2}}{r^2} \right)$$

Assume the numerical values:

α = 40 m^2/yr, tc = 40 years, r = 1 m

then $\hat{G} = 9.05$

Alternatively, let $T_{1/2}$ = 30 years (i.e., Cs-137 + Sr90, which dominate the first century post-irradiation).

Then, G = 8.84
which may be compared to Kuo's value of 7 inferred from HEATING-3 computer model results.

For the waste previously considered (40 year cooling after 45 MWd/kg irradiation)

$$q' = 103 \text{ W/m}$$

hence

$$\hat{\Delta} T = 7 \cdot \frac{103 \text{ W/m}}{4\pi (2.6 \text{ W/m}^\circ\text{C})}$$

or $\hat{\Delta} T = 22^\circ\text{C}$

which, again, is acceptable.

B.6 Radial Conduction in Waste-to-Wall Intervening Layers

There are several thin layers between the waste form and the rock wall: steel/gap filler/grout.

The temperature difference across a thin cylindrical layer is:

$$\Delta T = \left(\frac{q'}{2\pi k} \right) \left(\frac{t}{R} \right)$$

Thus for the waste canister steel at the time of emplacement of a PWR fuel assembly burned to 45 MWd/kg and cooled for 40 years:

$$q' = 103 \text{ W/m}$$

$$k = 40 \text{ W/m}^\circ\text{C}$$

$$t = 1.2 \text{ cm}$$

$$R = 16 \text{ cm}$$

In which case

$$\Delta T = 0.031^\circ\text{C}$$

which is quite negligible.

Since the other outboard layers have very nearly the same *t/R* ratios, their ΔT scales inversely with *k*.

Materials of interest include:

	k, W/m °C	ΔT,°C
graphite sand*	0.37	3.4
common sand*	0.37	3.4
cement grout	0.7	1.8
water:		
conduction only	0.67	1.9
convection*	2.55	0.5
steel wall liner	40	0.03
air:		
conduction only	0.03	41
convection plus radiation	0.073	17

*experimental values from Ref (B-1); hence includes interfacial contact resistances.

As can be seen, with the exception of air, temperature differences are small. Note, however, that in some estimates no allowances are made for contact resistance at interfaces. Hence further tests using an experimental mockup, such as in Ref (B-1), are in order, since contact resistance is automatically incorporated.

B.7 Temperature Rise inside Waste Form

Although not the main focus of the present evaluation, it is worth showing a representative value for the temperature difference from the waste centerline to its surface inside the canister.

Based on Manteufel's analysis (B-2), the effective thermal conductivity of a gas-filled PWR fuel assembly is approximately:

$k_e = 0.27$ W/m°C

For our reference assembly

$q' = 103$ W/m

Then, for a cylinder the centerline to surface temperature is:

$$\Delta T = \frac{q'}{4\pi k_e}$$

or in this example, $\Delta T = 30.4$ °C,

a quite tolerable value. It would, of course, increase for higher burnups and shorter cooling times, and decrease if the canister free volume is filled with sand or cement.

B.8 Effect of Temperature on Reaction Rates

Most chemical reaction rate constants vary with temperature according to the Arrhenius equation:

$$k = k_o \, e^{-E/RT}$$

where E = activation energy: difference between average energy of activated and all molecules
R = gas constant = 1.986 cal/mole K

Thus

$$\frac{dlnk}{dT} = \frac{E}{RT^2}$$

and the percentage increase in reaction rate for a ten °C increase in temperature is:

$$\left(\frac{E}{RT}\right)\left(\frac{1000}{T}\right), \quad \text{\% per 10°C}$$

The following table shows typical values of *E*, and the resulting temperature sensitivity at 100°C (373K):

Reaction	Typical E kcal/mole	Rate Increase % per 10°C
Direct molecular		
(e.g. oxidation)	10-50	40-200*
Free atoms & radicals	1-10	5-40
Adsorption	0.5-1.5	2-6
Diffusion		
Ions in water	1-3	5-15
Gases in gas	1-3	5-15
Atoms in solids	25-70	100-300
Surface diffusion	1-3	5-15

*the source of the "rule of thumb" that reaction rates approximately double for every 10°C rise in temperature

These strong effects of temperature motivate our efforts to keep it as low as practicable by choice of cooler rock strata, limiting entombment depth, and reducing waste heat loading.

References for Appendix B

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(B-2) R. D. Manteufel and N. E. Todreas, "Effective Thermal Conductivity and Edge Conductance Model for a Spent Fuel Assembly," *Nuclear Technology*, Vol. 105, 1994

Appendix C Stress Tests

Some important aspects of deep borehole repository performance depend on the ability of the holes, liners and waste containers to withstand the various stresses imposed upon them. This appendix documents a series of back-of-the-envelope scoping analyses to demonstrate that excessive stresses should not be encountered. It should also be recalled that, ultimately, reliance is placed on geological confinement, not engineered barriers. Hence stress-induced damage is mostly of concern with respect to maintaining retrievability: an important, but not the highest priority goal.

The sections on these aspects are as follows:

C.1 Axial Buckling of Canister String
C.2 Compressive Stress
C.3 External Collapse Pressure
C.4 Thermal Stress on Host Rock
C.5 Thermal Stress on Steel Tubing
C.6 Borehole Wall Breakout

For most of these analyses, the text by Roark (C-1) is the definitive publication.

C.1 Axial Buckling of Canister String

The buckling stress is given by:

$$\sigma_b = \frac{E \cdot t}{\sqrt{3}\,\sqrt{1 - \upsilon^2}\; R}$$

where the steel properties are given in Table 1.3 of Chapter 1, and

t = thickness of wall = 1.2 cm
R = radius of tube = 16 cm

Thus σ_b = <u>8500 MPa</u>.

Roark, however, recommends using 40 to 60% of this value based on actual experimental data: hence 3500 MPa.

The weight of a 1000 m string of canisters, each 5 m long and weighing 2000 kg each is 4×10^5 kg.

The cross-section area of the tube wall is $2\pi rt$ = 120 cm^2; hence the loading is 3.3×10^3 kg/cm^2, or about <u>330 MPa</u>, which is considerably less than the stress at which axial bowing will occur.

Moreover, the lined borehole wall is close fitting, and will restrain bowing, especially if the canister were to be grouted in place for final emplacement.

C.2 Compressive Stress

As calculated in C.1, $\sigma_c = 330$ MPa

For the high strength P11 steel used for (at least) the bottom-most stringers, YS = 760 MPa (see Table 1.3 in Chapter 1).

Thus crushing is avoided by a safety factor of 2.3.

Note that a 2 km waste string, as used in some of our earlier studies, would reduce the safety factor to 1.15: which is too small for conventional engineering practice. Omitting the canister sand filling (our fallback feature to resist radial crushing) would increase this to a satisfactory 1.8.

C.3 External Collapse Pressure

The hydrostatic pressure at 3 km (for 3 km of saline water) is 33 MPa and the lithostatic pressure is 78 MPa, but it is hard to see how a circumferentially uniform lithostatic pressure could be incurred.

For a long, thin elastic tube under external pressure, the collapse pressure is:

$$P_c = \frac{1}{4}\left(\frac{E}{1 - \upsilon^2}\right)\left(\frac{t}{R}\right)^3$$

which, in the present instance, is

$$P_c = 21.5 \text{ MPa},$$

Accordingly, a sand fill is prescribed to resist radial collapse, and to protect against hard-to-quantify scenarios such as earthquakes.

Canadian researchers have shown that a sand fill is a very effective protection, but have only done proof tests to 10 MPa (C-2). Hence this feature needs further validation.

C.4 Thermal Stress on Host Rock

At the inside of a long, thick-walled (here infinite limit) cylinder, the thermal stress is given by:

$$\sigma_t = \frac{E\alpha * \Delta T}{(1 - \upsilon)} \qquad (1\text{-}2)$$

Using rock properties from Table 1.2 of Chapter 1 and a postulated ΔT = 40°C between the hole surface and the far field rock (see Appendix B), one obtains

$$\sigma_t = \underline{16.7 \text{ MPa}}$$

compressive stress at the borehole wall. Since the strength in compression exceeds 100 MPa, this should not pose exceptional problems.

C.5 Thermal Stress on Steel Tubing

One has for a thin walled tube:

$$\sigma_t = \frac{1}{2}\frac{E\alpha * \Delta T}{(1 - \upsilon)}$$

The ΔT through the wall is:

$$\Delta T = \left(\frac{q'}{2\pi k}\right)\left(\frac{t}{R}\right)$$

After 40 years cooling, $q' = 138$ W/m (see Appendix B), thus using steel properties from Table 1.3 and dimensions from C.1, for the waste canister string:

$$\Delta T = 0.041 \text{ °C}$$

and

$$\sigma_t = 0.063 \text{ MPa}$$

which is entirely negligible. Essentially the same result applies to the hole wall liner.

C.6 Borehole Wall Breakout

One concern in any drilling application is the phenomenon of “breakout,” which refers to spalling of rock at the hole wall. This results in creation of a roughly elliptical out-of-round shape of the hole. Debris can in extreme cases lead to drillstring jamming, and out-of-vertical hole deviation.

Fortunately, for the present application, this does not appear to be a major problem. The effect is confined to a small disturbed zone around the hole, occurs mainly during drilling, and stability is rapidly reached thereafter. The concern with breakout arises mainly from the experience in sedimentary rock. However, the compressive strength of sandstones ranges from 7 to 50 MPa: much lower than the 60 – 180 MPa in granite.

An approximate estimate can be made of the stress to cause spalling by noting that deep in continental crust the maximum and minimum horizontal stresses, SH and Sh, relative to the lithostatic stress, are correlated as (C-3)

$$\frac{SH}{Sv} = \frac{0.25}{Z, km} + 0.98$$

$$\frac{Sh}{Sv} = \frac{0.15}{Z, km} + 0.65$$

Thus at 3 km:

SH = 27.6 x 3 = 98.3 MPa

Sh = 18.2 x 3 = 54.6 MPa

The maximum compressive loop stress at the surface of a circular hole is (C-4):

$$\hat{\sigma}_h = 3\ SH - Sh - \Delta P$$

where ΔP is the pressure above local ambient inside the hole (for example, that of drilling mud).

If ΔP = 0, on has, for the present example, $\hat{\sigma}$ = 240 MPa.

This exceeds the representative compressive strength of granite which is about 140 MPa.

Reference (C-6) considers a hole in a medium subjected to a uniform radial stress field, and finds that tangential stress is twice the hole-free value (hence twice lithostatic in our case, or 197 MPa). Roark applies the same factor for a plate with a circular hole under uniform biaxial stress.

To further compound the uncertainty, Ref (C-7) notes a lower bound value of $\nu/(1-\nu)$ times the lithostatic stress: a factor of 0.25 in our case, hence 24.6 MPa. If the stress intensity factor of 2 is applied, the compressive stress at the hole surface is 49 MPa, comfortably below the compressive strength of granite. Clearly, the entire issue of breakout requires further evaluation.

This example provides one motivation for the use of mud during drilling – stabilization of the borehole wall. Actually the computed limit appears overconservative, and experience shows greater stability after the drilling operation is completed. Nevertheless, the increased susceptibility with depth (hence lithostatic pressure) is borne out in practice.

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(C-6) R. K. Penney and F. A. Leckie, “Determination of Creep Effects in Structures,” in The Stress Analysis of Pressure Vessels and Pressure Vessel Components, S. S. Gill, ed. Pergamon, 1970

(C-7) G. C. Howard and C. R. Fast, “Hydraulic Fracturing,” AIME, 1970

Appendix D. Supplementary Information

D.1 Retardation Factor (D-1)

Radionuclides do not move unimpeded through a porous or fractured rock at the same rate as the water in which they are dissolved. Adsorption, absorption, and trapping in unconnected pores all contribute to their delayed passage. It is customary to account for these phenomena by a retardation factor which divides the diffusion coefficient, D:

$$R_d = 1 + \left(\frac{1-\varepsilon}{\varepsilon}\right) K_d \left(\rho_r / \rho_w\right)$$

where ε = interstitial fraction (~ interconnected porosity)

ρ_r, ρ_w = density of host rock and of water, respectively, g/cc

K_d = distribution coefficient: ratio of concentration in solid to that in the aqueous phase, grams radionuclide per gram of rock or water

Assuming that either $\varepsilon << 1$ or that ρ_r is the density of pore-free rock, and $\rho_w \cong 1$ g/cc, a simpler form is often applied

$$R_d = 1 + K_d \left(\rho_r / \varepsilon\right)$$

From such relations one can then work out that $(1/R_d)$ is the mass fraction of radionuclide in the aqueous, hence more rapidly transportable phase. K_d is a case-specific measured, rather than analytically estimated, function of many variables, and must be regarded as semi-empirical. As a result, R_d is quite variable and uncertain, but values of 10^3 are not uncommon. This can make the difference between marginal and excellent sequestration.

An alternative formulation appropriate for fractures is given by (D-2):

$$R_f = 1 + (S/V) K_a$$

in which *(S/V)* = fracture area per unit solution volume (hence 4/dh, where dh is the hydraulic diameter)

= $2/\delta$, where δ = fracture aperture

Hence $K_d = K_a \cdot a_f$

where a_f = specific surface area of rock, m^2/kg

Reference (D-2) also points out that R is the ratio of water velocity to radionuclide velocity.

Note that K values can be measured by both static and dynamic methods, and differences often result between the two approaches.

Measured values for anoxic aqueous conditions for Tc-99, U-233, Pu-236 and Np-237 in granites have been reported to range over 10^{-2} to 10^{-3} m^3/m^2 (D-3). Thus for a 100μ fracture R would be 20 to 200; the corresponding D values are on the order of 10^{-14} m^2/s (10^{-10} cm^2/s), roughly 10^5 times smaller than would be expected for ions in pure water.

The overall conclusion is that retardation is an essential requisite of good repository performance, and that much data has been obtained which assures its adequacy. Nevertheless, considerable uncertainty exists in its prediction, even given experiments on cored samples of actual host rock. This is due in part to the difficulty of replicating downhole conditions in the laboratory. Fortunately, high lithostatic pressure reduces crack apertures, which will improve performance in situ. Another source of error or bias is the frequent use of measurements under static conditions to predict dynamic performance in flowing water. There have been some comparisons to flow-through column data, which provides a certain degree of confidence in this approach.

D.2 References for Appendix D

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(D-3) S. Suksi et al., "The Effect of Ground Water-Rock Interactions on the Migration of Redox Sensitive Radionuclides," in Scientific Basis for Nuclear Waste Management XII, MRS Symp. Proc., Vol. 127, 1988

(D-4) P. Jussila, "Geosphere Transport of Radionuclides in Safety Assessment of Spent Fuel Disposal," STUK-YTO-TR 164, July 2000

Appendix E A Primer on Bedrock Geology

Background (E-1) (E-2) (E-3) (E-4)

The 10 – 15 km thick layer of underlying bedrock on continents is principally granite, in contrast to that under ocean sediments, which is basalt. It is, on average, covered by a kilometer or so of overburden – mostly sedimentary rock, but is exposed to the surface in some areas (see Fig. E-1). Ninety percent of the US, for example, is underlain by Precambrian granite, which is more than half a billion years old. Noteworthy manifestations are the Canadian shield, which is primarily granite and gneiss (recrystallized metamorphosed granite), and which extends down into the northern tier of states west of the Great Lakes; and, in the west, plutons (cooled and crystallized magma intrusions) and the larger batholiths (multiple overlapping plutons).

The widespread use of cut and polished granite facing for major public buildings is a familiar practice. The multiphase color pattern is evident, but unless a fracture surface is exposed, the true crystalline texture of the rock is obscured. This granite is also mined from near-surface outcroppings, hence not necessarily representative of kilometer-deep bedrock. Accordingly, most property measurements reported in the literature are for near surface granite (or deep-down granite measured on the surface – hence at atmospheric pressure), and care must therefore be taken to use depth-appropriate values for deep borehole performance assessment. The most important effects are decreases in permeability and hydraulic conductivity – by orders of magnitude.

Composition

Granite is a granular crystalline coarse grained igneous rock which varies in composition, but a typical version consists of interlocking crystals a few millimeters to centimeters across of three main constituents (see Table E-1):

- 40 vol % quartz: SiO_2, at least 10% visible
- 30% potassium feldspar (orthoclase): $K\,Al\,Si_3\,O_8$
- 30% plagioclase feldspar:
  - $Ca\,Al_2\,Si_2\,O_3$ (anorthite) and
  - $Na\,Al\,Si_3\,O_8$ (albite)

with the proviso that total SiO_2 exceeds 60 w/o for a rock to be called "granite."

A further subdivision is "acidic" if 45 to 75% quartz, and "basic" if high in alkali metal oxides. Texture also counts. For example, rhyolite is a volcanic rock which has the same composition as granite, but made up of (non-visible) microcrystals and glassy material.

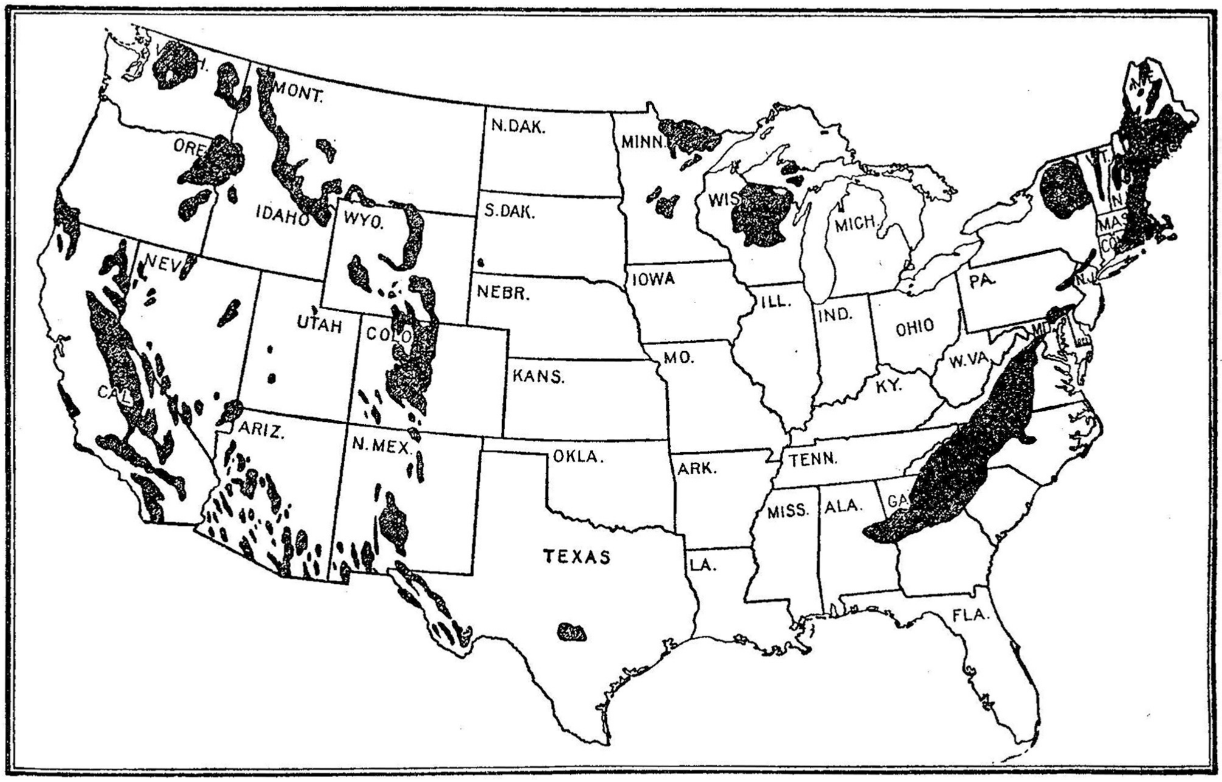

Figure E-1. The principal outcrops of granite and related crystalline rocks in the United States (from Ref [E-4])

Table E-1 Major Granitic Bedrock Minerals

Category	Composition	Colors*
I – Feldspar (aluminum silicates) (60% of all crustal rocks)	Orthoclase: $K\ Al\ Si_3\ O_8$ (very similar to microcline) Plagioclase: Albite $Na\ Al\ Si_3\ O_8$ Anorthite $Ca\ Al_2\ Si_2\ O_8$	 White/buff/pink/red White/pale green/yellow/ gray/red Glassy
II – Quartz (second most abundant after feldspar)	SiO_2	Translucent/white/dark gray/red/blue, etc.
III – Amphibole (hydrous silicates)	Hornblende (calcium rich silicates)	Dark green/brown/black
IV - Phyllite	Mica: Muscovite (isinglass) $K\ Al_3\ Si_3\ O_{10}\ (OH)_2$ Biotite (K, Mg, Fe) Al silicate (these appear as flakes)	 Colorless/white/gray green/ brown green/brown/black

Also:

- granite can undergo metamorphism to form gneiss
- rhyolite is chemically similar to granite, but more glassy (i.e. very fine grained)

*Usually due to minor impurity constituents

Appearance

In addition to its principal constituents, granites contain minor components which are responsible for the distinctive colors of granites marketed for specialty applications (e.g., countertops). They are made up of mixtures of inclusions in grays, blacks and whites, plus brown, silver, blue, green, yellow and gold (E-5). Variety is further increased by a spectrum of different sizes, shapes and patterns of the phases. Reference (E-10) describes and illustrates, in color, some two dozen named commercial ornamental granites, the plainest of which are similar to the types which are candidates for hosting a deep borehole repository. Our interest here, however, is in the more uniform granite making up deep bedrock – commonly a "salt and pepper" variety.

Confinement Capability

The properties of main interest for HLW confinement involve the presence and mobility of water. Porosities and microfractures are central to this concern. Porosity, defined as the volume percent of free (or fluid-filled) inclusions, is small (less than 1% and usually much smaller) in high integrity granite, and decreases with depth. Interconnected porosities and networks of microfractures (locally planar thin gaps) are responsible for rock permeability, which measures the ability of fluid (in our case, water) to ooze through the rock under a pressure gradient. Again, the high lithostatic pressure at depth reduces permeability by orders of magnitude relative to its more familiar near surface values.

Reference (E-6) compiles data on some 500 data points for granitic plutons worldwide, and reports a depth to their roots of 5 to 9 km, inferred from gravity measurements. This can easily accommodate boreholes 3 – 4 km deep, with one km or more seal zones at both top and bottom. Moreover, the rock underneath plutons should also satisfy stringent criteria for radionuclide sequestration.

Formation

The processes by which granite is formed was controversial and much-debated by geologists until late in the 20th century. At present a sequence of transformations, which may originally involve the ubiquitous bedrock basalt, involving melting abetted by a few weight percent water, followed by reactions, crystallization and dehydration to form its final constituents in a coarse grained texture, is the preferred scenario. See for example Refs (E-7), (E-8) and (E-9). Of importance in our context, is the end result and not the prior history, although the extremely long duration of subsequent stability since formation (hundreds of millions of years) is a major argument in favor of selecting granite to host a repository.

Residual Water Content

Granites are formed during cooling of molten magma. Several percent by weight of water are involved in the initial stages of the process, most of which is driven off by its completion. However, even if only 0.1% remains, the 200 m x 200 m x 1000 m block of rock surrounding our reference case borehole emplacement zone would contain about 10^5 m^3 of H_2O, far more than the 10 m^3 or so needed to flood the void space in the loaded borehole. Hence, although trapped and bound water release and migration is extremely slow, flooding over periods in excess of tens of thousands of years can not be ruled out, and thus must be taken into account in repository performance assessment.

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