NUCLEAR FUEL CYCLE TECHNOLOGY AND POLICY PROGRAM

# A Framework for Performance Assessment and Licensing of Deep Borehole Repositories

K.G. Jensen
M. J. Driscoll

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CENTER FOR
ADVANCED NUCLEAR
ENERGY SYSTEMS

Massachusetts Institute of Technology
77 Massachusetts Avenue, 24-215
Cambridge, MA 02139-4307

(617) 452-2660
canes@mit.edu
mit.edu/canes

## Abstract

This is the initial progress report under a Sandia-MIT contract dealing with development of engineering and geological siting criteria for deep borehole disposal of spent nuclear fuel or its separated constituents. Appendix C to this report reproduces the statement of work.

The basic conceptual design used as the basis for assessment is presented, followed by screening for features, events and processes of special relevance, using criteria previously developed in the US for mined repository assessment: specifically those identified in the Environmental Impact Statement and Total System Performance Assessment protocols. Transport of radionuclides dissolved in water through highly impervious igneous bedrock ("granite") is reaffirmed as the dominant mechanism of concern. The important beneficial role of deep-down water chemistry is also highlighted, in that low solubility under reducing conditions, retardation by adsorption, and inhibition of buoyancy and colloid formation by salinity, are all keys to assurance of effective sequestration.

These insights are brought to bear to structure our future work scope.

## Acknowledgements

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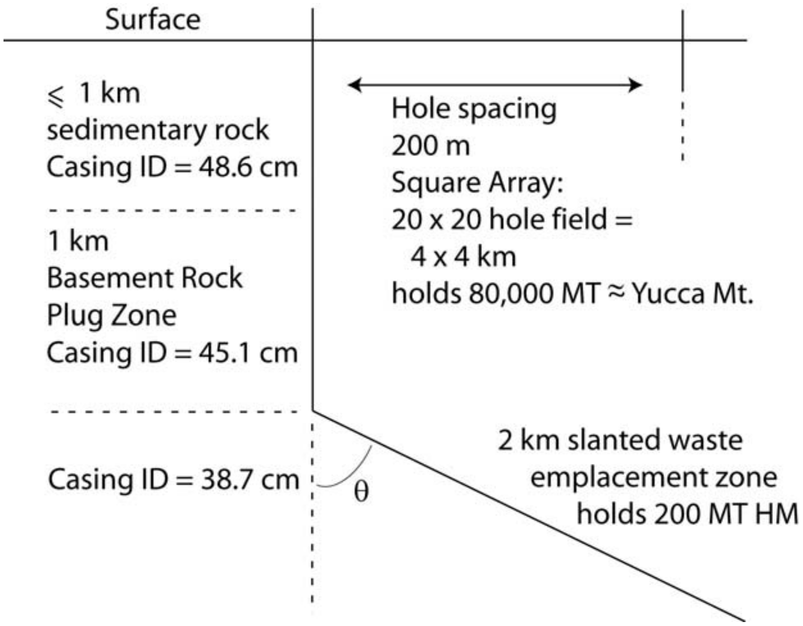
# Chapter 1 Introduction

## 1.1 Foreword: Focus of This Report

The objective of this report is to propose a framework for performance assessment, and ultimately licensing, of deep boreholes for disposal of high level waste arising from the nuclear fuel cycle. It is a follow-up to the status reports prepared by MIT and Sandia for their review meeting in August 2009 (1-1)(1-2). While it is fully recognized that sociopolitical considerations play a key, if not dominant role in the licensing process, this first report in a proposed series will emphasize technical issues, since a sound design and performance assessment are a crucial prerequisite to productive interactions with stakeholders and decision makers. While cost is one of the ultimate arbiters, this aspect will not be addressed in the present report. It is a principal focus of an Engineer's thesis at MIT, slated for publication in June 2010.

## 1.2 Overview of Concept

A clear understanding of the conceptual design in mind is essential to the assessment process. This is of special importance because we have recently added a second option to the vertical borehole approach of long standing, as discussed in a companion report, Ref(1-3). As shown in Fig. 1.1, the emplacement zone is now on a slant path: 80° to the vertical in the example shown. This essentially eliminates the earlier problem of bottom canister crushing by the cumulative weight of the stack of those above. It also allows more flexibility in adding defense in depth features. For completeness, Fig. 1.2 repeats the vertical borehole version, as documented in Ref(1-1). Otherwise most aspects remain the same as before. For a generic site, an allowance is made for approximately one kilometer of sedimentary burden – but note that Ref(1-3) specializes to ideal cases in which the granitic bedrock is exposed at the surface in continental shields.



Weight borne by bottom canister:

$WB = N. \ WC \cos\theta$

where $N$ = number of canisters in emplacement zone
$WC$ = weight per canister
$\theta$ = angle with vertical

Let $\theta = 80^\circ$ ; $\cos\theta = 0.174$
$N = 2000\text{m}/5\text{m} = 400$
$WC = 2000$ kg (casing + fuel + sand fill)

Thus

$WB = 1.4 \times 10^5$ kg

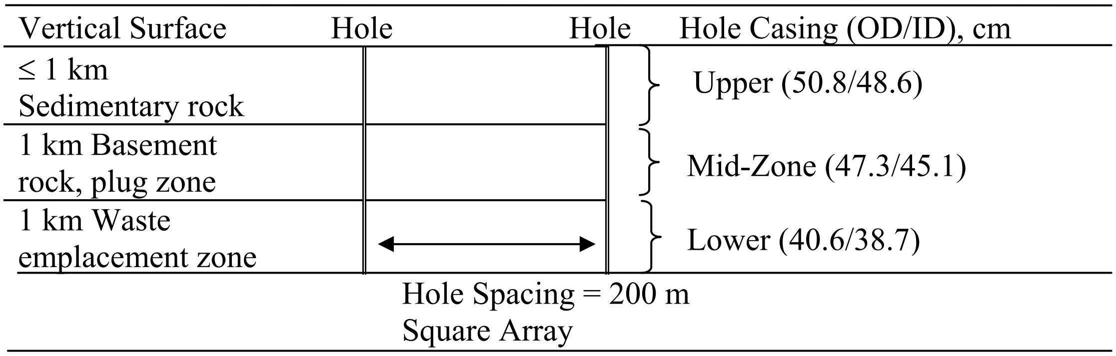
Let $A = 140 \text{ cm}^2$, cross section area of canister tube wall

thus $\sigma = 1000 \text{ kg/cm}^2 = 100$ MPa

compare to 760 MPa yield stress and 3500 MPa to buckle

**Figure 1.1 Generic Slanted Hole Version of a Deep Borehole for HLW Disposal**

**Layout**



**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)

**Figure 1.2 Vertical Version of Deep Borehole HLW Disposal Concept (from Ref 1-1)**

The use of a slant path borehole to alleviate self-induced crushing is not the sole alternative. Gibb et al. in Ref(1-4) propose filling the drill-hole voids with a fine shot of low-melting-point Pb-Sn-Zn alloy. The resulting in-situ dense liquid would make waste canisters close to buoyancy-neutral. Insertion of plugs firmly bonded to the borehole rock wall every several hundred meters is also a promising alternative which will be explored before downselection among approaches. Also see Chapter 5 for another option.

## *1.3 Organization of This Report*

Chapter 2 discusses borehole and site characteristics, since host rock properties play such an important role in assurance of long-term confinement. Also reviewed are defense in depth features, which have two principal components: borehole plug design and canister design. The latter aspect is open to more elaborate measures once the former constraint on crushing by a vertical canister stack has been removed.

Here and elsewhere in this report some of the descriptive material is a condensed version of more detailed information documented elsewhere in earlier (and readily available) MIT reports such as references (1-1) and (1-3).

Chapter 3 reviews assessment approaches developed in the process of making the licensing case for Yucca Mountain: principally its EIS and TSPA. IAEA efforts and those in the UK and Sweden are also considered.

Chapter 4 outlines a proposed framework for future post-closure phase evaluations based on narrowing down escape sequences after sorting out dominant features, events and processes by applying the lessons learned from the historical effort reviewed in Chapter 3.

Chapter 5 presents conclusions and recommendations.

Appendices follow documenting useful supporting information

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(1-2) P. V. Brady et al., "Deep Borehole Disposal of High-Level Radioactive Waste," SAND2009-4401, Aug. 2009
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# Chapter 2 Borehole Sites and Technologies

## 2.1 Chapter Introduction

This brief chapter elaborates on some of the considerations leading to the borehole features sketched in Chapter 1, as a prelude to the identification of key features, events and processes in Chapter 3, which in turn will lead to an agenda for a follow-on assessment program.

Table 2.1 is a condensed list of options considered in the downselection process leading to a final reference design, which can then be subjected to an in-depth assessment. The path forward is necessarily iterative, and some aspects will be carried along in parallel until final judgement is enabled or mandated.

The remaining sections of this chapter will elaborate on selected aspects of the entries in Table 2.1, concentrating on several which were not paid much attention in our prior published work.

**Table 2.1 Condensed Survey of Some Key Options**

| Aspect | Comments |
|---|---|
| I Choice of Host Rock | |
| Continental shields and bedrock | |
| exposed | • reduces needed depth to high quality rock |
| sub-sediment | • available virtually everywhere |
| Granite batholiths and plutons | • expands site choices |
| | • may be closer to subterranean hot spots and magma sources |
| Other granite outcroppings, massifs, etc. | • often in folded layers in mountainous terrain |
| | • sites tend to be more earthquake prone, hence heavily faulted |
| Other rock: | |
| Salt, clay, shale | • common choices for shallower mined repositories |
| | • often too thin for deep boreholes except as a seal cap layer |
| Basalt, gabbro | • mostly available in oceanic seabed |
| | • more expensive to exploit |
| | • complex legal status |
| II Borehole Configuration | |
| Vertical | • can more easily accommodate larger diameters, hence intact assemblies |
| | • susceptible to canister crushing by weight of stack above |
| | • easier to insert waste canisters |
| Slant Path | • alleviates self-crushing threat |
| | • state-of-the-art uses smaller diameters: more suited to reconstituted assemblies and reprocessed waste forms |
| | • harder to insert canister strings |
| Multibranch | • same drawbacks as single slant path option |
| | • significant savings may accrue |
| III Drilling Technology | |
| Conventional Mud-Lubricated | • most widely practiced |
| | • reduces residual damage to borehole wall |
| | • has consequences for post emplacement in-hole chemicals and physical environment |
| | • complicates post-closure cleanup |
| Air Drilling | • used for ~30% of drilling today |
| | • somewhat faster and cleaner, less expensive |
| Advanced Methods (e.g. spallation, etc.) | • being developed for geothermal applications; may become available within ~20 years |
| | • may be less expensive |

**(Table 2.1, continued)**

| Aspect | Comments |
|---|---|
| IV Downhole Characteristics | |
| Lined vs. Unlined | • liner largely prevents hole collapse, and jamming during canister insertion<br>• liner may compromise post emplacement seal integrity unless removed |
| Grouted vs. Voided | • excludes bulk water flooding<br>• can help tailor local chemical environment<br>• increases radial thermal conductivity<br>• if water based, can lead to gas generation by radiolysis |
| V Waste Canister Options | |
| Spent Fuel Assemblies (1 PWR or 3 BWR) | • greatly simplifies handling<br>• requires larger hole diameter than oil wells |
| Reconstituted Fuel | • reduced canister diameter and internal void space<br>• risks damage during added handling<br>• net cost increase expected |
| Filled Interior Voids | • improves crush resistance<br>• special fills can buffer against fuel corrosion, radionuclide release and transport<br>• increases canister weight |

## 2.2 Host Rock Attributes

Selection of candidate sites has been almost exclusively focused on finding the best available rock in the MIT work to date. Our consistent preference has been granitic basement rock. In Ref(2-1) we have extended our overview to encompass ex-US possibilities in the Northern Hemisphere, concentrating on continental shields, especially where surface exposure is present. In this report we return to the US context. Figure 2.1, from Ref(2-2), shows still another map of prominent crystalline basement rock bodies in the continental US. Since a repository field would occupy an area much smaller than a pinhead at this scale, it is obvious that technical candidates abound. Thus it appears acceptable to proceed on the basis of seeking “ideal” overburden-free areas which can satisfy other criteria – including eventually, the all important sociopolitical ones.

Appendices to this report address several important host rock attributes, such as the ability to accommodate waste energy release and resist water movement.

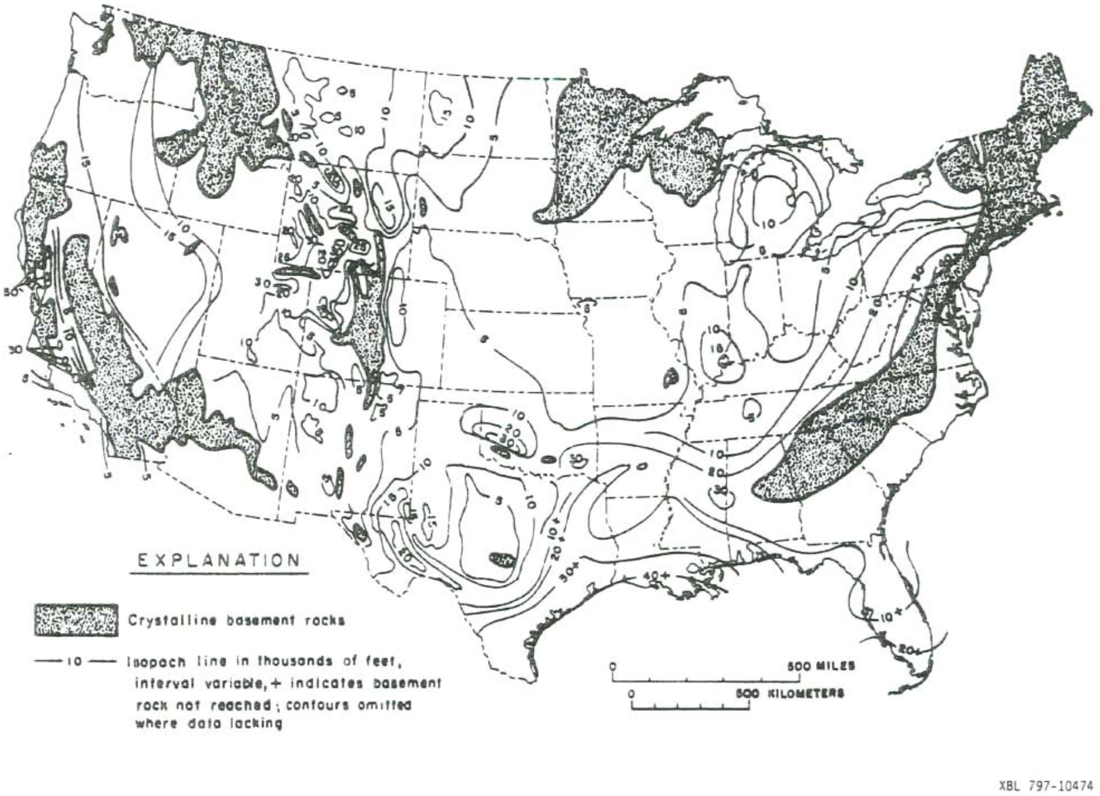
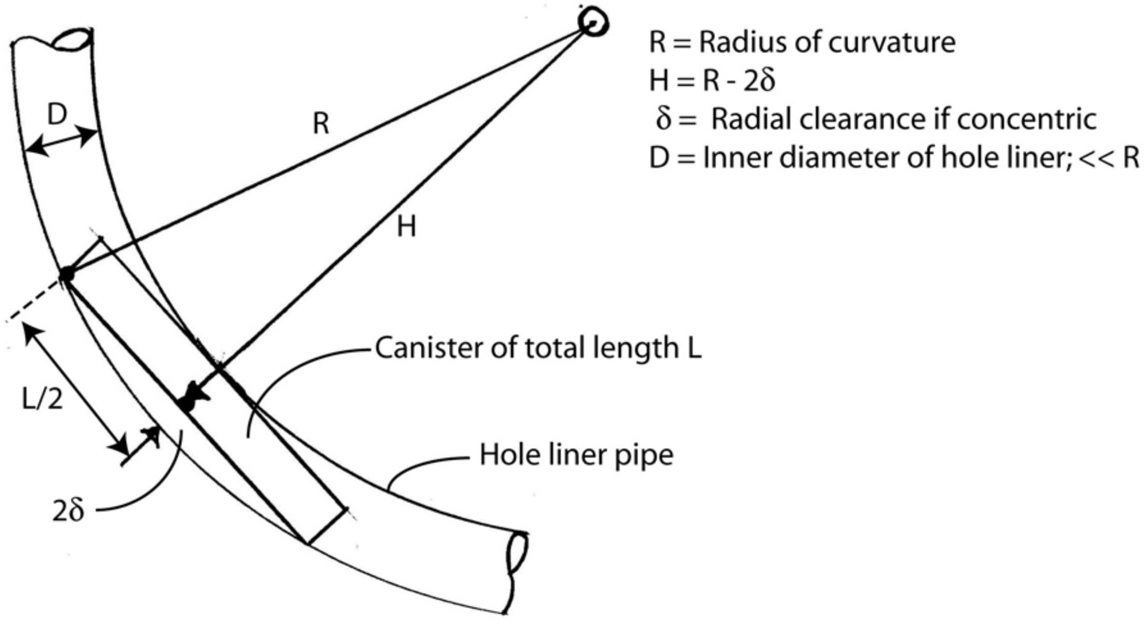


Figure 2.1 Principal areas of intrusive igneous and metamorphic rocks and thickness of sedimentary rocks in the US (from Ref[2-2])

## *2.3 Borehole Attributes: Allowable Radius of Hole Liner Bends*

There is an important constraint on the local radius of curvature which permits passage of a waste canister.

Refer to the sketch in Figure 2.2.



NOT TO SCALE

Figure 2.2 Configuration for Determining Allowable Radius of Curvature

One has

$$H^2 + \left(\frac{L}{2}\right)^2 = R^2$$

But

$$H = R - 2\delta$$

which allows solving for the minimum radius of curvature in terms of canister length, L, and concentric radial clearance, δ:

$$R_{MIN} = \frac{L^2}{16\delta} + \delta \approx \frac{L^2}{16\delta}$$

Thus, for example, let:

$L = 500$ cm (e.g., a spent fuel canister)
$\delta = 2$ cm

Then $R_{MIN} = 7815$ cm $= 78$ m

For reprocessed wastes shorter canisters can be employed: a half-length canister will reduce $R_{MIN}$ to less than 20 m.

Increasing the clearance, δ, can also reduce $R_{MIN}$, but at the expense of increasing hole diameter.

$R_{MIN}$ is of interest even for “vertical” holes because holes typically deviate from true vertical in the drilling process. Hence the roster of post-completion acceptance tests should include a curvature profile traverse and/or test insertion/retrieval.

As an alternative specification, one can define an angle of deviation from straight-ahead (i.e., vertical, if a vertical hole).

In terms of our earlier derivation of the radius of curvature, one has

$$\theta = \frac{L}{2R} = 8\frac{\delta}{L} \text{ radians}$$

$$\equiv 458\frac{\delta}{L} \text{ degrees}$$

hence for $\delta = 2$ cm
$L = 500$ cm

$$\theta = \underline{\underline{1.8^\circ}}$$

This should be within the capability of state-of-the-art, or better yet future, drilling technology.

Note that lining the hole relaxes this requirement on the open hole itself: the liner can be slightly non-concentric (smaller gap on one side than the other) and thereby have a larger radius of curvature/smaller deviation angle.

## 2.4 Drilling Technology: Air Drilling

In common with most other proponents, the reference approach is mud-lubricated rotary drilling, following current oil field practice. However, using air (with foam addition) in place of mud is an option identified in Ref(2-3) as worth evaluation: a point well worth reiteration here.

Reference (2-4) states that “In many areas it is both quicker and far cheaper than drilling with mud,” Reference (2-3) concurs in that “Penetration rates are higher, footage per bit is greater, and bit cost is lower with air.”

Reference (2-4) 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. However, the excerpt below from Ref(2-6) suggests that this problem is surmountable:

> “**IX. Foam**
> “When drilling in a consolidated formation, air drilling is typically used. The air drilling system increases cutting rates in rock by carrying the cuttings away from the drill bit and up the hole. The formation is naturally stable. Therefore, a drilling fluid systems objective is to maintain circulation, lower hydrostatic head, and remove cuttings using the lowest volume of water and compressed air. This is typically done using air, water, foam, and stiff foam, in that order, depending on the formations encountered, depth of hole, diameter of hole, and size of cuttings. When foams drilling, use 1 to 2 pints per 100 gallons of make up water. This should be added to the foam-mixing tank. The foam/water mixture is injected into the air stream from the compressor through the mixing nozzle. The resulting foam is piped through the parts in the bit where it expands and flows back up the hole to the surface bringing with it suspended cuttings.”

Reference (2-7) is another quite recent resource on this subject: it notes that some 30% of onshore oil and gas wells are currently drilled in this manner. Clearly this issue can only be resolved by experience in the field.

## *2.5 Liner and Canister Features*

These aspects will not be given much attention in this report, except to note the following selection of reference attributes:

(a) hole is fully lined during pre-emplacement and emplacement phases
(b) liner in emplacement zone is grouted in place
(c) liner in seal plug zone is removed post-emplacement, prior to installation of seal plug layers (cement/asphalt/bentonite, as in the SKB version)
(d) canister voids are filled with “sand” to improve crush resistance.

Left open at present are whether canisters are grouted to the liner, and any special attributes of canister and canister fill material choices. This is pending more detailed heat removal calculations and the effects of radiolysis on water-containing materials.

## *2.6 Chapter Summary*

This chapter has been devoted to cataloging the conceptual design features of deep boreholes designed for the disposal of high level nuclear waste. Discussion is limited primarily to the point in time when a hole is completed, and ready to accept waste. The procedures and processes required to accept waste at a transportation depot, convert it into a form suitable for encapsulation in specially designed canisters, and then emplace the latter in the ready-to-receive holes are by and large excluded. These topics are clearly a priority for subsequent examination, as are the evolutions involved in installing the borehole plugs. We will, however, in Chapter 4 skip directly to another underserved phase – post closure.

First, however, assessment procedures will be reviewed to help frame the agenda and clarify methodology for such future tasks.

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# Chapter 3 Review of Assessment Approaches and Precedent

## 3.1 Chapter Introduction

The approach to licensing of nuclear reactors has been evolving of late toward a more risk-informed, performance-based methodology embodied in a technology-neutral framework, TNF (3-1). No similar approach has yet been put forth for generic, concept-independent repository assessment. However, a comparable framework can be inferred from the experience gained and documented in the course of developing the mid-2008 Yucca Mountain licensing application to the NRC. Two documents appear to be especially relevant to our current efforts: the Environmental Impact Statement, EIS (3-2), and the Total System Performance Assessment, TSPA (3-3). Their distilled findings have been influential in guiding the most recent work underway at MIT. Also of considerable help is the review of applicable regulatory history carried out by Sandia National Laboratories as part of their recent assessment of the deep borehole concept (3-4).

## 3.2 Environmental Impact

Review of the Yucca Mountain EIS (Ref 3-2) has revealed only a few items where deep boreholes may have a significantly different and significant environmental impact. For purposes of this assessment the summary tables documented in Ref(3-2) proved particularly useful – hence they are reproduced in Appendix A.

The most evident difference lies in the active land use category. Yucca Mountain is debited 3.5 $km^2$, whereas an equivalent deep borehole field will eventually occupy 16 $km^2$. Even so, these values are small compared to total land disturbed, and that lost to creation of transportation access corridors.

Another issue is the fate of the “sand” made up of drilled-out rock. If the total net preclosure borehole void space is about 600 $m^3$ (3 km × 0.2 $m^2$) then the volume of sand is larger (due to void space) by a factor of roughly 1.7 (~60% smear density), hence per borehole one is left with about 1000 $m^3$ of spoils on the surface. About 200 $m^3$ should be useable in the plugging media (and, potentially, lesser amount to fill inside-canister voids, to improve crush resistance). The resulting sand pile has a volume given by

$$V = \frac{1}{3}\left(\frac{\pi}{4}d^2h\right) = 800 \text{ m}^3$$

A cone having $d = h$ (hence a stable angle of repose) then has

$$h = d = 14.5 \text{ m}$$

which has an impressive visual impact.

However, if spread uniformly over the 200m × 200m surficial area per borehole, the depth of cover would be only 2 cm: hence this is the recommended procedure. The impact on indigenous flora and fauna may favor “checkerboarding” of the cover to leave significant interconnected bare space. However, if the spoils are left uncovered, the radon (and its uranium precursor) in the granite can escape into the biosphere. The amounts are truly trivial, but because of the focus on the radiological consequences of the repository and the fact that it creates a background for the performance monitoring system, the subject deserves further attention: see Chapter 4 for additional perspective.

Also problematical is the environmental impact of the drilling mud pit, assuming that conventional oil well drilling practice is employed, rather than the less common method of air drilling. Again see Chapter 4.

## *3.3 Total System Performance Assessment*

Review of the TSPA was greatly facilicated by the earlier Sandia effort (3-4) (based on their experience in drafting the TSPA for Yucca Mountain) to review and compare features, events and processes (FEPs) – Table B-1 in Appendix B of Ref(3-4); and, of special interest, to sort out high priority borehole FEPs in Table B-2. Figures 3.1 and 3.2 outline the performance assessment process according to Ref(3-2).

Without mere recapitulation of their listing, our review identified a mostly similar roster of concerns; in particular:

- borehole flooding (likelihood conceded)
- emplacement zone fractures and faults
- radiolysis (of water in mud, concrete, host rock)
- seal plug leakage avoidance
- drilling damage to borehole walls
- retrievability (issue raised, but forgone)
- fluid advection and its inhibition

We have addressed several of these categories in earlier publications, but they will be of current and continuing concern.

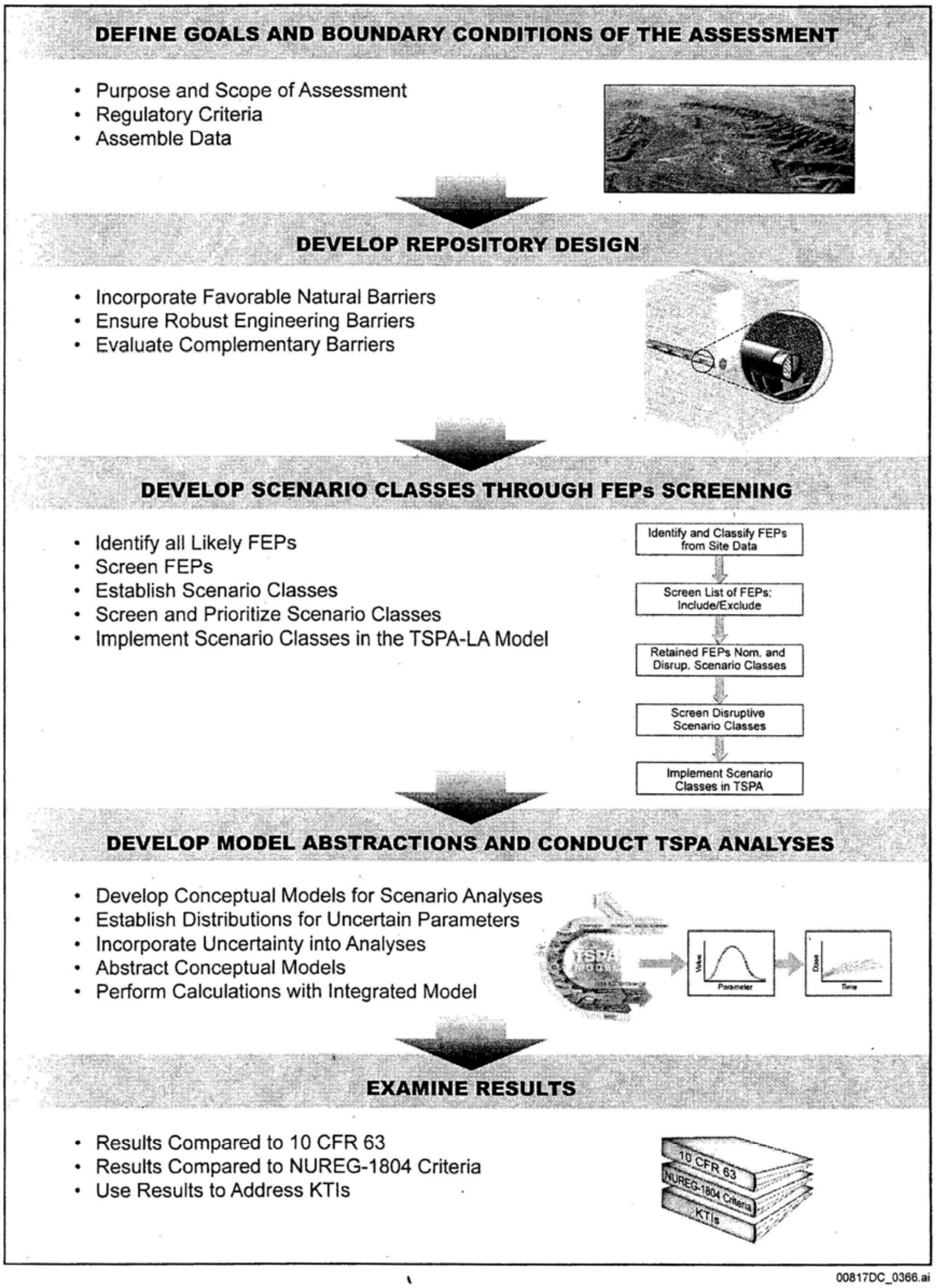

**Figure 3.1 Structure of the Process of the TSPA (Figure ES-3 of Ref 3-2)**

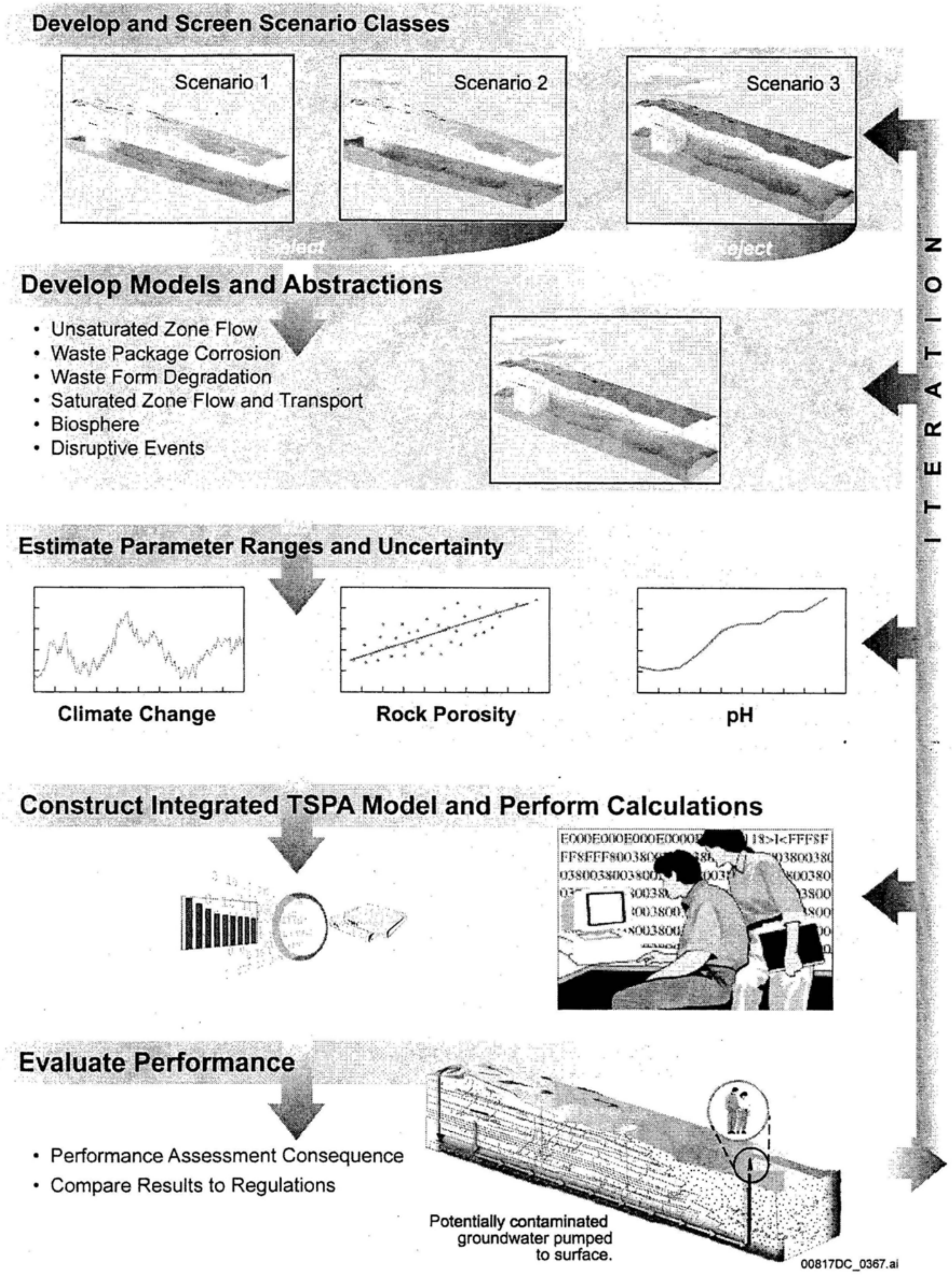

**Figure 3.2 Major Steps in a Generic Performance Assessment (Figure ES-4 of Ref 3-2)**

## 3.4 IAEA Guidance

While siting in the US is our main concern, it is important to recognize the significant attention paid to waste disposal by the IAEA, as documented in their extensive series of "WS" reports in the form of both Requirements (WS-R series) and Guidelines (WS-G series), accessible via their website www.iaea.org/books. This is especially the case in view of the international siting survey carried out as part of a separate MIT project (Ref 3-5). It is also relevant because IAEA compatibility will facilitate arrangements for future synergistic collaborative international RD&D. It is likewise inevitable that IAEA guidelines will play a role in informing and influencing reviewers of US licensing submissions, by the NRC, and by public interest groups.

The most relevant input at present is summarized in a 2006 Safety Standard (Ref 3-6), in which publishing of a companion Safety Guide is committed to.

We have reviewed this standard and found that it is mostly concerned with high-level requirements, which are essentially completely consistent with those adopted in the US. Some specific points of interest are as follows:

- deep boreholes are specifically noted as an option (P5)
- dose-related criteria of < 0.3 m Sv/yr(30 mrem/yr) and $10^{-5}$/yr risk of death or serious hereditary disease (P11)[1]
- multiple, diverse physical and chemical barriers are called for (P19)
- criticality must be analyzed (P30)
- satellite monitoring after closure is suggested (P33)
- local human presence should be assumed for long-term post-closure assessment (P36).

## 3.5 Expert Opinion

As part of the ongoing project planning process, two interviews were conducted during Fall 2009: with Prof. George E. Apostolakis of MIT, a current member (and former chairman) of the NRC's Advisory Committee on Reactor Safety, and with Prof. of the Practice Andrew C. Kadak, a current member of the Nuclear Waste Technical Review Board. Other MIT staff were also consulted in a less formal manner.

A principal recommendation emerging from these discussions was to make use of the Environmental Impact Statement (EIS) and the Total System Performance Assessment (TSPA) prepared during the Yucca Mountain license submission process as templates for assessment of deep borehole disposal. Hence, a first look at such a process was the subject of earlier sections of this chapter.

---

[1] Compare to NRC final rule on Yucca Mountain (3/13/09 Federal Register) of 15 mrem/yr for the first 10,000 years and 100 mrem/yr thereafter.

The other major recommendation to emerge from these discussions is that we should avoid making extremely over-conservative assumptions in the interest of making simple first-cut bounding calculations of system performance. The propensity to oversimplify has admittedly been characteristic of much of our quantitative attempts to date. To guard against untoward future consequences the best compromise appears to insist on large margins before conclusions could be overturned, and to include a disclaimer statement wherever applicable.

**Table 3.1 Summary of Expert Comments on Deep Borehole Concept**

- The Yucca Mountain EIS and TSPA reports are a good framework upon which to base a review of new concepts.
- Some attention to engineered barriers and defense in depth is still advisable despite the heavy reliance on geology and geochemistry
- The issue of retrievability needs explicit attention, considering both mission time and the nature of the material (e.g., used fuel vs. separated minor actinides).
- Avoid excessive over-conservatism solely for the purpose of simplifying analysis.
- Avoid over-reaction to current policy-imposed restrictions; however public acceptance will continue to be the dominating factor.
- Rare events such as large earthquakes and volcanism will still need to be addressed. In addition a $10^6$ year time horizon appears appropriate.
- In addition to dose at the top of the holes, far field effects must be considered, if only to show that they are negligible. Dose to workers during handling and loading must also be addressed.
- A good case will have to be made on heat load in view of its key role for shallower mined repositories and their larger waste canisters.

## 3.6 Contemporary Work in Other Programs

Deep borehole studies over the past two decades have been dominated by two international programs: that by the Swedish SKB organization; and in the Immobilisation Science Laboratory, University of Sheffield, UK. Review of this work has been quite informative for structuring our current program plans.

Although the Swedish authorities have now committed to the siting of a mined repository at Forsmark, they carried along a parallel series of studies on the deep borehole alternative. References (3-7) through (3-10) are a selected sample of their activities and findings. Their work is particularly germane from a technical point of view because their host rock is granite – as is ours. Their focus on water transport and the interaction of temperature and salinity as the dominant scenario in performance assessment motivates special attention to this aspect. They conclude that buoyancy-induced escape is not a worrisome challenge – a conclusion which must also be verified independently in our case.

Work in the UK is summarized in Ref (3-11) (and some dozen references which it lists). The most noteworthy phase of their attention has been on the transient temperature field induced in the surrounding host rock. This indicates the need for careful attention to waste heat loads as a dominant constraint on repository borehole and field design. Hence this must also be given significant attention in our work.

## 3.7 Chapter Summary

This chapter consists of a condensed summary of the consensus best-available sources of guidance for assessment of the performance capabilities of a deep borehole repository.

Table 3.2 summarizes the key features, events, and processes identified in prior work and in this retrospective review. Also shown are some special topics not yet investigated in sufficient detail to justify ignoring them.

The bottom line is the need to put first and foremost the susceptibility of pressure-gradient-driven water flow in deep-down host rock and the borehole plug. Simply put, if flow is sufficiently suppressed, radionuclides cannot wend their way back to the biosphere over even a million year time horizon. There are a whole host of other features, events, and processes which can add to or subtract from this dominant contributor, but none have a significant probability of either offsetting the consequences of fast water transport or adding more than several orders of magnitude to the efficacy of a low flow rate.

**Table 3.2 Selected Features, Events, and Processes for Deep Borehole Waste Disposal**

| Category | | Comments |
|---|---|---|
| **Dominant FEPs identified to date** | | |
| | Waste Form Corrosion and Solubilization | • minimized by reducing environment in deep rock<br>• can mitigate by choice of canister materials and fill |
| | Escape via Water Transport | • thwarted by low permeability in deep granitic rock and retardation by adsorption<br>• increase of water salinity with depth offsets buoyancy due to increased local temperature, destabilizes colloids |
| | Borehole Plug Failure | • requires diverse, multilayer design<br>• most vulnerable at plug-hole wall interface, and drilling-disturbed layer of host rock |
| **Hitherto Less-Investigated** | | |
| | Post Closure Criticality | • very low probability but not absolutely impossible<br>• less likely than mined repository due to wider spatial dispersion |
| | Seismic, Vulcanism | • can initially eliminate by careful site selection<br>• consequences lower than for shallower mined repositories |
| | Human Intrusion | • low likelihood, requires advanced technology<br>• small consequences<br>• more difficult than for shallower mined repositories<br>• could include abrasive sand in cement plugs to make intrusion more difficult |

## *3.8 References for Chapter 3*

(3-1) US Nuclear Regulatory Commission, “Feasibility Study for a Risk-Informed and Performance-Based Regulatory Structure for Future Plant Licensing,” NUREG-1860, Dec. 2007

(3-2) DOE/EIS-0250 F-SI, “Final Supplemental Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada,” 2008

(3-3) Total System Performance Assessment Model/Analysis for the License Application,” MDL-WIS-PA-000005 Rev 00 AD 01 (2008)

(3-4) P. V. Brady et al., “Deep Borehole Disposal of High-Level Radioactive Waste,” SAND2009-4401, Aug. 2009

(3-5) B. Sapiie, M. J. Driscoll, K. G. Jensen, “Regional Examples of Geological Settings for Nuclear Waste Disposal in Deep Boreholes,” MIT-NFC-TR-113, Jan. 2010

(3-6) “Geological Disposal of Radioactive Waste: Safety Requirements,” IAEA Safety Standards Series No. WS-R-4, IAEA, OECD/NEA, 2006
(3-7) “Storage of Nuclear Waste in Very Deep Boreholes: Feasibility Study and Assessment of Economic Potential,” SKB Technical Report 89-39, Dec. 1989
(3-8) Report 2007: 6e “Deep Boreholes: An Alternative for Final Disposal of Spent Nuclear Fuel?” KASAM, Swedish National Council for Nuclear Waste, March 2007
(3-9) N. Marsic, B. Grundfelt, M. Wiborg, “Very Deep Hole Concept: Thermal Effects on Groundwater Flow,” SKB Report R-06-59, Sept. 2006
(3-10) Project on Alternative Systems Study (PASS), Final Report, SKB TR-93-04, 1992
(3-11) F. G. F. Gibb et al., “A Model for Heat Flow in Deep Borehole Disposals of High-Level Nuclear Waste,” *Journal of Geophysical Research,* Vol. 113, 2008

# Chapter 4 Post-Closure Considerations

## 4.1 Chapter Introduction

There are two aspects of borehole performance in the post-closure phase. Most of the attention has been paid to scenarios which would lead to escape of radionuclides back to the biosphere over a time horizon as long as a million years. This focus will, understandably, continue to be the case. However, environmental remediation shortly after closure also deserves attention. Hence this topic is the first one addressed in the present Chapter.

## 4.2 Environmental Remediation

Upon initial consideration, site restoration post-closure may appear to be a trivial topic since the boreholes are, by definition, completely underground. However, there are two above-ground legacy issues: the mud pits constructed in support of drilling operations, and the rock cutting spoils removed during drilling. Other items – for example equipment – are either mobile or semi-portable, and are moved from hole to hole, and then can be carried off when the field is officially closed. The only other intrusive element is the receiving/repackaging station building, which will no doubt remain and be repurposed as a post-closure monitoring headquarters.

### 4.2.1 Drilling Mud

It is common practice in the oil/gas well drilling industry to employ drilling mud in the borehole to increase wall stability, lubricate and cool drill bits, and to sweep out cuttings. (4-1)(4-2)(4-3) While granitic bedrock may prove to be sufficiently stable to eventually do otherwise, it appears prudent at this point to assume mud will be used in drilling of boreholes for HLW disposal. The Swedish studies of this option (4-4)(4-5) specified this to be the case, and, in fact, loaded their waste canisters into mud-filled holes, using a deployment mud which was thicker than drilling mud. The mud formulation consisted of a bentonite slurry and conferred additional protection against radionuclide escape in the long term. Our initial review, however, does not identify an analysis of the effects of radiolysis on long term behavior. Because of the complex nature of the several phenomena involved, an experimental approach is suggested. This might be possible using a tube inserted in the MIT Reactor spent fuel pool, for example. Based on studies in cement, the net effects are anticipated to be tolerable. (4-6)

Bentonite is the most common mud-thickening additive. Bentonite is a montmorillonite clay, principally made up of alternating alumina and silica layers. Representative muds are 10 to 50% denser than pure water. Bentonite is non-hazardous: its other applications include use as cat litter and as a laxative. As an aside, bentonite is readily available. The US, mainly in Wyoming and Colorado, supplies about one-third of the world demand.

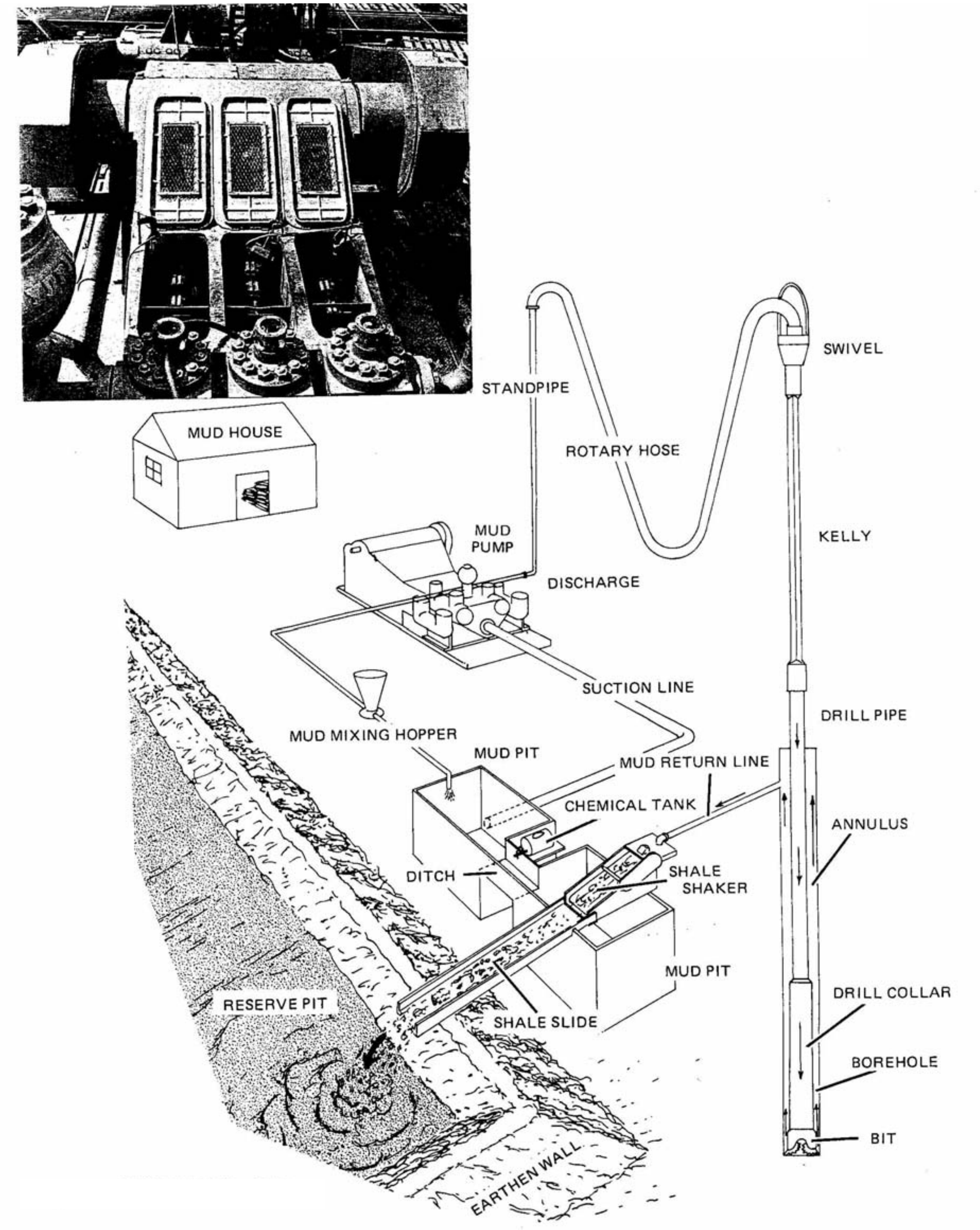

Figure 4.1 Features of Mud-Assisted Drilling (from Ref[4-7])

The use of bentonite is a highly synergistic feature for deep boreholes to be used for HLW disposal, because bentonite is highly effective in retarding radionuclide transport. But one should also note some diametrically opposing requirements. For oil and gas wells it is important not to seal off porosity and fractures around the hole, which will interfere with hydrocarbon recovery. For HLW boreholes such plugging is a significant benefit. Thus it may even be of interest to employ "poor" oil/gas well practice, and re-optimize to emphasize such residual effects.

Figure 4.1 shows the features associated with the use of mud at a drilling site.

A rule of thumb is that mud pit volumes should be about three times hole volume. Hence 4 km of a borehole having a 0.2 $m^2$ cross-sectional area has a volume of 800 $m^3$, leading to a mud pit volume of 2400 $m^3$ (e.g. 2 m deep and 35 m on a side) – which is quite large. Fortunately most of the mud should be recoverable for use on the next borehole in the sequence. A significant portion of the remainder might be suitable for use in the bentonite segment of the borehole plug. The residual could be excavated and removed, or even left in place. However, as noted in the section which follows, the best practice may be to remove all mud-associated residue and employ it to cap an in-fill or berm which sequesters drillhole cuttings.

### 4.2.2 Drill Cuttings

Section 3.2 addresses the physical impact of drilled-out rock, which need not be visually obtrusive if spread out uniformly over the site to a depth of several centimeters. However, the rock contains uranium in equilibrium with its decay products. Based on information in Refs (4-8) and (4-9), granite containing 4 ppm uranium will also contain about 1.7 p Ci/g of radon. Hence 600 $m^3$ of cuttings will contain around 2700 μCi of embedded radon gas. The average emission rate of radon from the earth's surface into the atmosphere worldwide is on the order of 540 p $Ci/m^2$ s. Hence a 200 x 200 m plot would emit 220 μCi/sec. Thus it is not entirely out of the question that the cuttings would add a detectable amount to this background. This is another reason for hauling them away. In addition to increasing general background for post-closure monitoring, and exposure for the hypothesized future residents, the taint of all things radioactive would be incurred. Table 4.1 reproduces a newspaper article reporting on radioactivity due to drilling oil wells. Since our host rocks are much drier, the impact should be far less.

**Table 4.1 Radionuclide Release Due to Well Drilling (4-10)**
***Boston Globe*, Tues. Dec. 4, 1990**

### High Radiation Reported in US Oil Fields

Associated Press
NEW YORK – Decades of oil drilling have brought so much radium to the surface that radioactive contamination in oil fields sometimes exceeds by five to 30 times the level permitted at nuclear plants, The New York Times said yesterday.

Environmental officials have found radium, a naturally occurring radioactive material, in every oil-producing region in the country from Alaska to the Gulf of Mexico, the newspaper reported.

The officials found low levels of radiation in pumps, pipes and storage tanks from radium that leaches from mineral deposits into water that comes to the surface with oil, the Times said.

For years, oil companies have poured billions of gallons of contaminated water into thousands of unlined ponds in the South before pumping it back into the ground or releasing it into wetlands, the newspaper said.

The contamination is worst in the South and along the Gulf Coast, where radium concentrations in the water are much higher than in other regions.

The extent of the health risk to oil workers who handle drilling equipment contaminated by radium or to people exposed to radium-contaminated water and soil is unknown. But health officials worry that exposure may raise the risk of cancer and other illnesses, the report said.

Oil industry representatives say the risk is minimal or nonexistent, the paper said.

The federal government has no regulations to deal with oil field radiation, the paper said.

## *4.3 Post-Closure Criticality*

Although an extremely remote possibility, a modest amount of analysis must be invested to confirm that there are no credible scenarios in which downhole fissile material can reconfigure in such a way as to go critical, i.e. create a man-made “Oklo.” At a later date some state-of-the-art computer codes will be exercised to provide quantitative assurance. But at this point a qualitative review must suffice.

A kilometer long stack of spent PWR fuel assemblies will contain about 100 MT of heavy metal. About 1% of this is plutonium: hence 1000 kg, or roughly 100 times that needed to construct a weapon. If dissolved in pure water, about 50 g/l represents a minimum critical concentration for a thermalized spectrum. Hence the origins of concern based on superficial thinking.

We know from fuel storage pool analyses that a single isolated PWR assembly will not go critical. Moreover, in a borehole there is insufficient space for a thick external water reflector, and voids inside canisters will in all likelihood be filled with grout or sand to improve crush resistance. Hence only scenarios which dissolve, separate and re-concentrate plutonium are left for consideration.

Gaps between the canister string, liner, and rock wall will be on the order of 1 or 2 cm thick, and may also be filled with grout. If not, an "infinitely" long thin annulus of radius ~30 cm containing plutonium dissolved in water can be postulated. This is one of the configurations that can be calculated. A more drastic scenario would occur if an empty fuel assembly were to collapse into sludge and leave room for a 30 cm cylinder of plutonium solution. Since one assembly contains about 5 kg plutonium, one can probably concoct a critical situation by piling on additional assumptions, such as the absence of other dissolved species (uranium and fission products) in solution. To avoid such open-ended speculation it is probably preferable to consider filling assembly void space with borosilicate glass (i.e. Pyrex) beads as the crush-proofing medium.

Finally, if plutonium diffuses into the surrounding host rock, its concentration is limited to the available void space – considerably less than 1 vol. % in deep crystalline bedrock. This suggests a second calculation to find the maximum multiplication factor of a plutonium/water/granite mixture of infinite extent.

### *4.4 Host Rock Heatup: Quasi-Steady-State Limit*

Host rock temperature is of interest for two reasons: the potential effect on rock and seal integrity, and as the heat sink temperature on which to superimpose internal waste canister temperature rise.

While a transient analysis is needed to determine the actual history of the temperature profile in space and time, a steady-state limiting case can provide useful insights.

Consider a one-meter segment of a <u>horizontal</u> borehole, 2 km deep in granitic rock, and 200 m transversely from neighboring boreholes.

A representative fuel assembly will, after 40 years post-discharge cooling, have a linear power of approximately 100 W/m, likewise for a 1 assembly/canister borehole.

Consider the vertical slab of rock 2000 m x 200 m x 1 m, above the borehole (very conservatively neglecting that beneath it). One then has

$q''(o) = 0.5$ W/m$^2$ initial areal loading at the bottom of the rock slab (about ten times the earth's natural vertical heat flux).

The rock mass of $10^9$ kg has a heat capacity of about 25 kW year per °C.

The temporal decay of linear power has the approximate dependence as a function of time since emplacement, t, in years:

$$q'(t) = \frac{q'(o)}{(1 + t/40)^{3/4}}$$

The integrated energy release is just:

$$E = 8.8\left[t^{1/4} - 40^{1/4}\right], \text{ kW yr/m}$$

The above data and prescriptions can be used to generate the following table:

| ***t***, yrs since emplacement | $q'$, W/m | $E$ kWyr/m | rock $\overline{\Delta T}$ |
|---|---|---|---|
| 0 | 100 | 0 | 0 |
| 100 | 39 | 5.8 | 0.23 |
| **1000** | 8.7 | 27.5 | 1.1 |
| **10,000** | 1.6 | 66 | 2.6 |
| **100,000** | 0.28 | 135 | 5.4 |

Thus, after about 1000 years the decay power has fallen to a value roughly equivalent to the earth's natural value. At this juncture it could be removed by conduction vertically driven by a gradient of roughly 15°C/km, and a further increase in temperature avoided.

As also evident, for these low areal loadings the mean increase in rock temperature never becomes significant.

The reason, of course, is the low areal loading arising from the assumed wide spacing between boreholes. In a more practical configuration holes would be staggered in depth and criss-cross in horizontal planes. An areal loading equivalent to that encountered in a vertical borehole field appears appropriate.

Consider <u>vertical</u> holes having a 2 km emplacement zone and a checkerboard array spacing of 200 m. Then the initial areal heat flux vertically is:

$$q''(o) = \frac{(2000\,\text{m})(100\,\text{W/m})}{(200\text{ m})^2} = 5\text{ W/m}^2$$

which is ten times the value in the widely dispersed horizontal case. But even then the rock mass adiabatic heatup would only be some tens of degrees centigrade, and a steady state with removal by areal conduction equaling power input will be achieved a few tens of thousands of years.

## 4.5 Chapter Summary

This chapter has dealt with several post-closure considerations. The first is environmental remediation. It was concluded that the drilling mud, and granite drill cuttings should best be removed from the immediate environs of the holes and consolidated and covered over near the borehole field periphery – somewhat along the lines of mine tailings sequestration. The small amounts of uranium decay chain radionuclides are not especially hazardous, but it is preferable to have as low as practicable an immediate background for post-closure monitoring.

A second topic – post closure nuclear criticality – is raised principally in the interests of completeness, and it is expected that future calculations will justify relegating it to the status of a very minor concern.

Finally, a basis has been established for eliminating undue concern over long-term far-field rock temperature increases above pre-emplacement ambient values. This will allow concentrating on the near-field in subsequent computer modeling.

## 4.6 References for Chapter 4

(4-1) R. O. Anderson, *Fundamentals of the Petroleum Industry,* Univ. of Oklahoma Press, 1984
(4-2) A. D. K. Brehm, C. D. Ward, "Pre-Drill Planning Saves Money," E&P, May 2005, Hart Energy Publishing, www.eandpnet.com
(4-3) C. Madge, J. Zhang, W. Standefird, "Predict Predrill Pressure and Stress," E&P, May 2006, Hart Energy Publishing, www.eandpnet.com
(4-4) T. Harrison, "Very Deep Borehole: Deutag's Opinion on Boring, Canister Emplacement and Retrievability," SKB Report R-00-35, May 2000
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(4-6) P. Offermann, "Calculation of the Radiolytic Gas Production in Cemented Waste," in *Scientific Basis for Nuclear Waste Management XII,* W. Lutze and R. C. Ewing, Eds., MRS Proceedings, Vol. 127, 1988
(4-7) "Fundamentals of Petroleum," Petroleum Extension Service, Univ. of Texas at Austin, 1979
(4-8) M. Eisenbud, *Environmental Radioactivity from Natural, Industrial and Military Sources,* 3rd Edition, Academic Press, 1987
(4-9) J. Hala, J. D. Navratol, *Radioactivity, Ionizing Radiation and Nuclear Energy,* 2nd Edition, Konvoy, Czech Republic, 2003
(4-10) "High Radiation Reported in US Oil Fields," *Boston Globe,* Tues. Dec. 4, 1990

# Chapter 5 Summary, Conclusions and Recommendations

## *5.1 Summary and Conclusions*

Project efforts during the period covered by this report were concentrated in two complementary areas: a review of both generic and site-specific criteria developed for mined repository assessment; and prior designs for, and evaluations of, deep borehole repositories, mainly by Swedish and UK investigators. Table 5.1 summarizes the top dozen reference documents which informed our review. Each in turn is based upon a broad edifice of earlier supporting evidence and analyses: thus more recent references are favored.

The broadest top-level geosciences related conclusion arrived at in the course of this review is that ubiquitous continental deep igneous (granitic) bedrock inherently possesses properties favoring assurance of highly effective waste sequestration: very low permeability and porosity, a reducing, buffered chemical environment, and mild beneficial salinity in the small amount of water that is present (due to colloid and buoyancy suppression). Accordingly, a significant component of future efforts should be devoted to marshalling further evidence and analyses of the pros and cons of this assertion.

In addition to the scientific aspects represented by the above findings, an ongoing technological effort is being pursued to converge on a preferred approach to engineering implementation. Section 5.2 suggests an attractive next iteration, which is in part based on other thesis work currently underway, which although not sponsored by the present project, is closely coordinated: work by J. Gibbs on multibranch drilling and by E Bates on emplacement.

**Table 5.1 Consensus Most-Useful Reference Material**

| | Resource | Contributions | (Ref) |
|---|---|---|---|
| **1** | Y.M. TSPA 2008 | Provides a roadmap for performance analysis starting with features, events and processes, proceeding through scenario modeling and consequence evaluation | (5-1) |
| **2** | YM EIS | Provides a comprehensive table of impacts which can be emulated, translated and applied to deep boreholes | (5-2) |
| **3** | IAEA Stds. 2006 | A high-level international consensus on requirements; mentions deep boreholes | (5-3) |
| **4** | KASAM (Sweden) 2007 Report | A summary of an information seminar developed to inform stakeholders of the nature of the deep borehole alternative | (5-4) |
| **5** | SKB (Sweden Technical Report 89-39, 1989) | Comprehensive, detailed systems analysis; establishes a benchmark for all future work; rock type (granite) is highly relevant | (5-5) |
| **6** | NIREX Report 2004 | Review from UK perspective; acknowledges debt to SKB program | (5-6) |
| **7** | Chapman & Gibb article, 2003 | Good generic description of concept in terms informative for both the layman and experts | (5-7) |
| **8** | Ahall MKG Report 2, Dec. 2006 | Focuses on bedrock characteristics and hydrogeology at great depths as related to deep boreholes | (5-8) |
| **9** | UCRL Report 1996 | Chief concern is with Pu disposition, but presents a wide ranging, transferable, total systems analysis | (5-9) |
| **10** | Sandia Review Aug. 2009 | Independent assessment by an expert group having vast Yucca Mtn. experience | (5-10) |
| **11** | Los Alamos Handbook, 1996 | While aimed at plutonium disposition, the properties and locations of suitable host rock are thoroughly reviewed | (5-11) |
| **12** | Lawrence Berkeley Report, 1979 | An early review of geotechnical considerations by earth scientists | (5-12) |

## 5.2 Recommendations

Based upon the review summarized in this report, several tasks have been identified for priority attention during the first quarter of 2010. A longer range (3 year) program plan is outlined in the NEUP Pre-Proposal reproduced in Appendix D.

Near term objectives:

(a) Make a more thorough case that igneous bedrock (granite) at depths beyond two kilometers has suitable physical and geochemical properties for the task at hand, which are, furthermore, sufficiently similar continent-wide to justify generic assessment prior to focusing on specific sites.

(b) Provide a quantitative demonstration that post-closure criticality is so unlikely as to justify its dismissal from further consideration.

(c) Permit downselection between vertical and slant-path boreholes, for example, by evaluating how one can engineer anti-crushing measures for the vertical option.

Another recommendation is that a multibranch borehole configuration be evaluated – one which combines the best features of the vertical and slant-path arrangements. As shown in Fig. 5.1, it would consist of a multibranch emplacement zone of four 500 m holes drilled at a small splay angle (~10°) from the vertical from a single parent hole. This would avoid bottom canister crushing, while requiring sealing of only a single vertical shaft. The reduced total depth would reduce cost and allow for a larger diameter hole in the emplacement zone. At only ten degrees from vertical, gravity would still simplify canister emplacement.

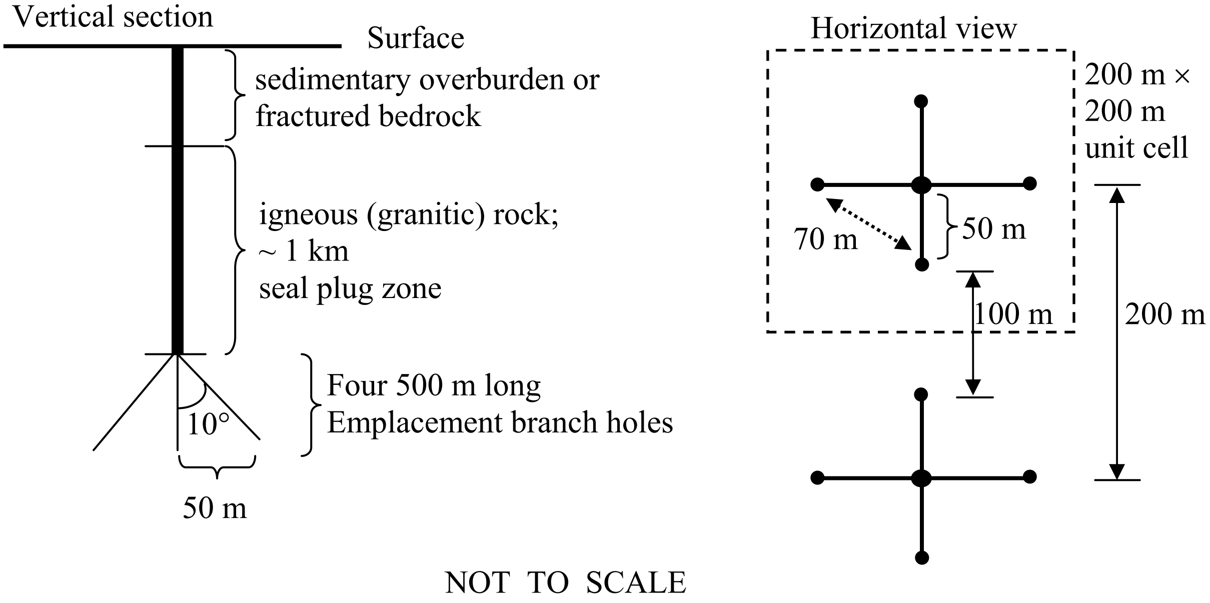

**Fig. 5.1 Multibranch Alternative Borehole Layout**

## 5.3 References for Chapter 5

(5-1) “Total System Performance Assessment Model/Analysis for the License Application,” MDL-WIS-PA-000005 Rev 00 AD 01 (2008)

(5-2) DOE/EIS-0250 F-SI, “Final Supplemental Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada,” 2008

(5-3) “Geological Disposal of Radioactive Waste: Safety Requirements,” IAEA Safety Standards Series Series No. WS-R-4, IAEA/OECD/NEA, 2006

(5-4) KASAM Report 2007: 6e "Deep Boreholes: An Alternative for Final Disposal of Spent Nuclear Fuel?", 2007
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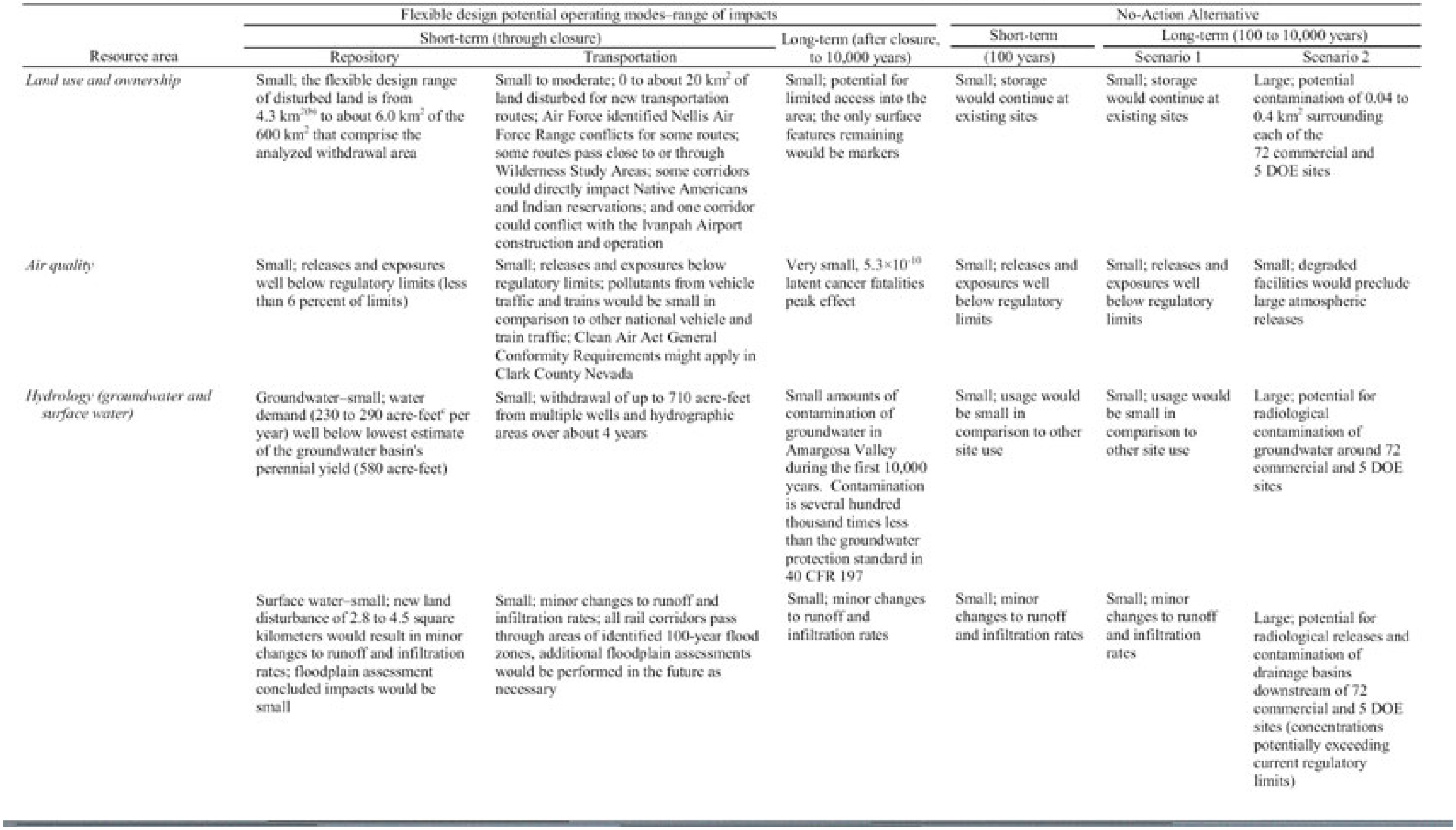
(5-7) N. Chapman and F. Gibb, "A Truly Final Waste Management Solution," Radwaste Solutions, Vol. 10, No. 4, July/Aug., 2003
(5-8) K. I. Ahall, "Final Disposition of High Level Nuclear Waste in Very Deep Boreholes," MKG Report 2, Dec. 2006
(5-9) A. M. Wijesinghe, "Alternative Technical Summary Report for Immobilized Disposition in Deep Boreholes," UCRL-LR-121736, Aug. 23, 1996
(5-10) P. V. Brady et al., "Deep Borehole Disposal of High-Level Radioactive Waste," SAND 2009-4401, Aug. 2009
(5-11) G. Heiken et al., "Disposition of Excess Weapons Plutonium in Deep Boreholes – Site Selection Handbook," LA-13168-MS, Sept. 1996
(5-12) M. T. O'Brien et al., "The Very Deep Hole Concept: Evaluation of an Alternative for Nuclear Waste Disposal," LBL-7089, 1979

# Appendix A

## Yucca Mountain EIS Summary

Table “S-1” which follows is taken directly from Ref (A-1). As noted in the main text, it provides a good framework for reviewing either generic or specific sites for deep borehole fields.

## Table S-1. Impacts associated with the Proposed Action and No-Action Alternative (page 1 of 4)



| | Flexible design potential operating modes–range of impacts | | | No-Action Alternative | | |
|---|---|---|---|---|---|---|
| | Short-term (through closure) | | Long-term (after closure, to 10,000 years) | Short-term | Long-term (100 to 10,000 years) | |
| Resource area | Repository | Transportation | | (100 years) | Scenario 1 | Scenario 2 |
| *Land use and ownership* | Small; the flexible design range of disturbed land is from 4.3 km$^{2(b)}$ to about 6.0 km$^2$ of the 600 km$^2$ that comprise the analyzed withdrawal area | Small to moderate; 0 to about 20 km$^2$ of land disturbed for new transportation routes; Air Force identified Nellis Air Force Range conflicts for some routes; some routes pass close to or through Wilderness Study Areas; some corridors could directly impact Native Americans and Indian reservations; and one corridor could conflict with the Ivanpah Airport construction and operation | Small; potential for limited access into the area; the only surface features remaining would be markers | Small; storage would continue at existing sites | Small; storage would continue at existing sites | Large; potential contamination of 0.04 to 0.4 km$^2$ surrounding each of the 72 commercial and 5 DOE sites |
| *Air quality* | Small; releases and exposures well below regulatory limits (less than 6 percent of limits) | Small; releases and exposures below regulatory limits; pollutants from vehicle traffic and trains would be small in comparison to other national vehicle and train traffic; Clean Air Act General Conformity Requirements might apply in Clark County Nevada | Very small, $5.3\times10^{-10}$ latent cancer fatalities peak effect | Small; releases and exposures well below regulatory limits | Small; releases and exposures well below regulatory limits | Small; degraded facilities would preclude large atmospheric releases |
| *Hydrology (groundwater and surface water)* | Groundwater–small; water demand (230 to 290 acre-feet$^c$ per year) well below lowest estimate of the groundwater basin's perennial yield (580 acre-feet) | Small; withdrawal of up to 710 acre-feet from multiple wells and hydrographic areas over about 4 years | Small amounts of contamination of groundwater in Amargosa Valley during the first 10,000 years. Contamination is several hundred thousand times less than the groundwater protection standard in 40 CFR 197 | Small; usage would be small in comparison to other site use | Small; usage would be small in comparison to other site use | Large; potential for radiological contamination of groundwater around 72 commercial and 5 DOE sites |
| | Surface water–small; new land disturbance of 2.8 to 4.5 square kilometers would result in minor changes to runoff and infiltration rates; floodplain assessment concluded impacts would be small | Small; minor changes to runoff and infiltration rates; all rail corridors pass through areas of identified 100-year flood zones, additional floodplain assessments would be performed in the future as necessary | Small; minor changes to runoff and infiltration rates | Small; minor changes to runoff and infiltration rates | Small; minor changes to runoff and infiltration rates | Large; potential for radiological releases and contamination of drainage basins downstream of 72 commercial and 5 DOE sites (concentrations potentially exceeding current regulatory limits) |

**Table S-1.** Impacts associated with the Proposed Action and No-Action Alternative.[a] (page 2 of 4).

| | Flexible design potential operating modes–range of impacts | | | No-Action Alternative | | |
|---|---|---|---|---|---|---|
| | Short-term (through closure) | | Long-term (after closure, to 10,000 years) | Short-term (100 years) | Long-term (100 to 10,000 years) | |
| Resource area | Repository | Transportation | | | Scenario 1 | Scenario 2 |
| *Biological resources and soils* | Small to moderate; loss of about 4.3 $km^2$ to 6.0 $km^2$ of desert soil, habitat, and vegetation; adverse impacts to individual threatened desert tortoises (not the species as a whole); reasonable and prudent measures to minimize impacts; impacts to other plants and animals and habitat small; wetlands assessment concluded impacts would be small | Small to moderate; loss of 0 to 20 $km^2$ of desert soil, habitat, and vegetation for heavy-haul routes and rail corridors; adverse impacts to individual threatened desert tortoises (not the species as a whole); reasonable and prudent measures to minimize impacts; impacts to other plants and animals and habitat small; additional wetlands assessments would be performed in the future as necessary prior to any construction | Small; slight increase in temperature of surface soil directly over the repository for 10,000 years resulting in a potential temporary shift in plant and animal communities in this small area (about 8 $km^2$) | Small; storage would continue at existing sites | Small; storage would continue at existing sites | Large; potential adverse impacts at each of the 77 sites from subsurface contamination of 0.04 to 0.4 $km^2$ |
| *Cultural resources* | Small to moderate; repository development would disturb up to about 4.5 $km^2$ of previously undisturbed land; mitigation measures would avoid or minimize damage to and illicit collecting at archaeological sites; programs in place to minimize impacts; opposing Native American viewpoint | Small to moderate; loss of 0 to 20 $km^2$ of land disturbed for new transportation routes; mitigation measures would avoid or minimize damage to and illicit collecting at archaeological sites; programs in place to minimize impacts; opposing Native American viewpoint | Small; potential for limited access into the area; opposing Native American viewpoint | Small; storage would continue at existing sites; limited potential of disturbing sites | Small; storage would continue at existing sites; limited potential of disturbing sites | Small; no construction or operation activities; no impacts |
| *Socioeconomics* | Small; estimated peak total employment of 3,400 occurring in 2006 would result in less than a 1 percent increase in composite regional employment; therefore, impacts would be small. Estimated peak direct employment for the repository during construction would be approximately 1,900 in 2006. | Small; employment increases would range from less than 1 percent to 4.9 percent (use of intermodal transfer station in Lincoln County) of employment in affected counties | Small; no workers, no impact | Small; population and employment changes would be small compared to totals in the regions | Small; population and employment changes would be small compared to totals in the regions | Small; no workers; no impacts |
| *Occupational and public health and safety* | | | | | | |
| Public | | | | | | |
| Radiological[d] | | | | | | |
| MEI (probability of an LCF) | $1.6\times10^{-5}$ to $3.1\times10^{-5}$ | $1.4\times10^{-4}$ to $1.2\times10^{-3}$ | $4\times10^{-10}$ to $4\times10^{-8}$ at the boundary of the controlled area (approximately 18 km south of the repository) | $4.3\times10^{-4}$ | $1.3\times10^{-6}$ | (e) |
| Population (LCFs) | 0.46 to 2.0 | 0.61 to 2.5 | $2\times10^{-6}$ to $3\times10^{-4}$ | 0.41 | 3 | 3,300[f] |
| Nonradiological (fatalities due to emissions) | Small; exposures well below regulatory limits | 1.6 to 2.8[g] | Small; exposures well below regulatory limits or guidelines | Small; exposures well below regulatory limits or guidelines | Small; exposures well below regulatory limits or guidelines | Moderate to large; substantial increases in releases of hazardous substances in the spent nuclear fuel and high-level radioactive waste and exposures to the public |

**Table S-1.** Impacts associated with the Proposed Action and No-Action Alternative.[a] (page 3 of 4).

| | Flexible design potential operating modes–range of impacts | | | No-Action Alternative | | |
|---|---|---|---|---|---|---|
| | Short-term (through closure) | | Long-term (after closure, to 10,000 years) | Short-term (100 years) | Long-term (100 to 10,000 years) | |
| Resource area | Repository | Transportation | | | Scenario 1 | Scenario 2 |
| *Occupational and public health and safety (continued)* | | | | | | |
| Workers (involved and noninvolved) | | | | | | |
| Radiological (LCFs) | 4.0 to 6.8 | 3.2 to 11.7 | No workers, no impacts | 16 | 10 | No workers, no impacts |
| Nonradiological fatalities (includes commuting traffic fatalities) | 2.0 to 3.3 | 12 to 23[b] | No workers, no impacts | 9 | 1,080 | No workers, no impacts |
| *Accidents* | | | | | | |
| Public | | | | | | |
| Radiological | | | | | | |
| MEI (probability of an LCF) | $2.9\times10^{-13}$ to $1.9\times10^{-5}$ | 0.0015 to 0.015 | Not applicable | No impacts | No impacts | Not applicable |
| Population (LCFs) | $1.4\times10^{-11}$ to $1.1\times10^{-2}$ | 0.55 to 5 | Not applicable | No impacts | No impacts | 3 to 13 |
| Workers | Large; for some unlikely accident scenarios workers would likely be severely injured or killed | Large; for some unlikely accident scenarios workers would likely be severely injured or killed | No workers, no impacts | Large; for some unlikely accident scenarios workers would likely be severely injured or killed | Large; for some unlikely accident scenarios workers would likely be severely injured or killed | Small; no workers; no impacts |
| *Noise/Ground Vibration* | Small; impacts to public would be low due to large distances to residences; workers exposed to elevated noise levels–controls and protection used as necessary | Small to moderate; transient and not excessive, less noise than 90 dBA[c]; ground vibration infrequent and less than 88 dBV at 25 m | Small; no activities, therefore, no noise or ground vibration | Small; transient and not excessive, less than 90 dBA | Small; transient and not excessive, less than 90 dBA | Small; no activities, therefore, no noise |
| *Aesthetics* | Small; low adverse impacts to aesthetic or visual resources in the area. There may be increase in lighting impacts due to lighting associated with the ventilation system | Small; possible temporary and transient; conflict with visual resource management goals for Wilson Pass Option of the Jean rail corridor; and discernible impacts from the Caliente Intermodal transfer facility near Kershaw-Ryan State Park. | Small; only surface features remaining would be markers | Small; storage would continue at existing sites; expansion as needed | Small; storage would continue at existing sites; expansion as needed | Small; aesthetic value decreases as facilities degrade |
| *Utilities, energy, materials, and site services* | Small; use of materials would be very small in comparison to amounts used in the region; electric power delivery system to the Yucca Mountain site would have to be enhanced | Small; use of materials and energy would be small in comparison to amounts used nationally | Small; no use of materials or energy | Small; materials and energy use would be small compared to total site use | Small; materials and energy use would be small compared to total site use | Small; no use of materials or energy |
| *Management of site-generated waste and hazardous materials* | Small; radioactive and hazardous waste generated would be a few percent of existing offsite capacity; other wastes would be managed onsite | Small; waste generated would be a fraction of existing offsite capacity | Small; no waste generated or hazardous materials used | Small; waste generated and materials used would be small compared to total site generation and use | Small; waste generated and materials used would be small compared to total site generation and use | Small; no waste generated or hazardous materials used |

**Table S-1.** Impacts associated with the Proposed Action and No-Action Alternative.[a] (page 4 of 4).

| | Flexible design potential operating modes – range of impacts | | | No-Action Alternative | | |
|---|---|---|---|---|---|---|
| | Short-term (through closure) | | Long-term (after closure, to 10,000 years) | Short-term (100 years) | Long-term (100 to 10,000 years) | |
| Resource area | Repository | Transportation | | | Scenario 1 | Scenario 2 |
| *Environmental justice* | Small; no disproportionately high and adverse impacts to minority or low-income populations; opposing Native American viewpoint | Small; no disproportionately high and adverse impacts to minority or low-income populations; opposing Native American viewpoint | Small; no disproportionately high and adverse impacts to minority or low-income populations; opposing Native American viewpoint | Small; no disproportionately high and adverse impacts to minority or low-income populations | Small; no disproportionately high and adverse impacts to minority or low-income populations | Large; potential for disproportionately high and adverse impacts to minority or low-income populations |

a. Ranges might differ from simple addition of the minimum and maximum values listed for the constituent phases because these values might not correspond between different phases. For example, a scenario that maximizes impacts during construction could result in minimal impacts during operations.

b. $km^2$ = square kilometers; to convert to acres, multiply by 247.1.

c. To convert acre-feet to cubic meters, multiply by 1233.49.

d. LCF = latent cancer fatality; MEI = maximally exposed individual.

e. With no effective institutional controls, the maximally exposed individual could receive a fatal dose of radiation within a few weeks to months. Death would be caused by acute direct radiation exposure.

f. Downstream exposed population of approximately 3.9 billion over 10,000 years.

g. Nonradiological fatalities due to exhaust emissions health effects from spent nuclear fuel and high-level radioactive waste transportation, including loadout; exhaust emissions health effects from commuter and materials transportation for repository construction, operation, and closure; and rail line or heavy-haul truck/intermodal transfer station construction, maintenance, and operation.

h. Nonradiological traffic fatalities from spent nuclear fuel and high-level radioactive waste transportation and commuter traffic fatalities. As many as 10 to 17 of these fatalities could be members of the public.

i. dBA = *A-weighted decibels*, a common sound measurement. A-weighting accounts for the fact that the human ear responds more effectively to some pitches than to others. Higher pitches receive less weighting than lower ones.

**References for Appendix A**

(A-1) *Final Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada.* DOE/EIS-0250, Feb. 2002.

(A-2) *Final Supplemental Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada: Summary.* DOE/EIS-0250 F-SI, June 2008

# Appendix B Miscellaneous Technical Notes

## B.1 Purview of This Appendix

Back-of-the-envelope calculations are particularly useful for deep borehole performance assessment, since it is often possible to bound effects without resorting to complicated, hence more obscure, and more tedious computer simulations. In addition, insight can be gained to help structure such higher order models. What follows are a series of technical notes documenting a variety of short parametric studies in support of the topics addressed in the body of this report.

## B.2 Justification for Quasi Steady-State Viewpoint[2]

Following temperature histories over the canonical million year time horizon using a transient computer code is far too time consuming. Fortunately asymptotic limits are approached far sooner.

The characteristic time constant for temperature field decay in a cylinder is just:

$$t_c = \frac{R^2}{(2.405)^2 \alpha}\text{; and for granitic rock } \alpha \sim 40 \text{ m}^2/\text{yr.}$$

Thus:

| ***R*,m** | ***t*$_c$, yrs** |
|---|---|
| **10** | 0.43 |
| **100** | 43 |
| **1000** | 4300 |

---

[2] Y. A. Cengel, R. H. Turner, *Fundamentals of Thermal-Fluid Sciences,* Second Edition, McGraw-Hill, 2005, p. 818.

which shows that in a few hundred to a few thousand years a temperature pulse can smear out to fill any reasonable volume of rock surrounding a borehole heat source.

## B.3 Equality of Water and Rock Temperatures

Water oozing through narrow capillary and fracture conduits will rapidly dissipate any energy generated internally due to radionuclide decay or gamma heating, and thus have the same temperature as the host rock.

The thermal diffusivity of water at 100°C is approximately:

$$\alpha = 1.7 \times 10^{-3}\ \text{cm}^2/\text{s}$$

The characteristic time constant for conductive heat transfer in a cylindrical tube is:

$$\tau = \frac{R^2}{(2.4048)^2 \alpha}, \text{ sec}$$

Thus for R = $50\mu$, $\tau$ = 2.5 milliseconds, which makes heat dissipation virtually instantaneous.

Another way of looking at the situation is to calculate the steady state temperature rise in a cylinder having a uniform internal volumetric heat source:

$$\Delta\hat{}T = \frac{q''' R^2}{4k}$$

where $q'''$ = power density, W/m$^3$

For an (inordinately high) concentration of 1 Curie/cc of a radionuclide having a decay energy of 1 Mev/disintegration, hence $q''' = 6000$ W/m$^3$, $\Delta\hat{}T$ is a miniscule $5.5 \times 10^{-6}$ °C for $R = 50\mu$.

## B.4 Derivation of Darcy Relations[3]

In view of its central role in estimation of borehole repository performance, it is worthwhile to sketch out a derivation of the equation embodying what is commonly known as Darcy's Law.

---

[3] Y. Gueguen and V. Palciauskas, *Introduction to the Physics of Rocks,* Princeton Univ. Press, 1994

Pressure drop in a filament of water worming its way through rock is expressed in conventional form as:

$$\Delta P = f\left(\frac{L}{d}\right)\frac{\rho\upsilon^2}{2}$$

where the extremely slow flow is clearly laminar, so that the friction factor is given by (for an equivalent cylindrical tube):

$$f = 64/\mathrm{Re} = 64\Big/\left(\frac{d\upsilon\rho}{\mu}\right)$$

so that one arrives at Poiseuille's Law:

$$\upsilon = \left(\frac{d^2}{32\mu}\right)\left(\frac{\Delta P}{L}\right) = \left(\frac{d^2}{32\mu}\right)\left(\frac{dP}{dx}\right)$$

But note that the path followed is zig-zag; hence $L$ is longer by the factor $\tau$, the "tortuosity," and the projected transverse $\Delta P$ is lower than along the true path. We also want superficial velocity (i.e., smeared over the entire frontal area), which is capillary velocity times porosity, $\varepsilon$.

Thus the superficial velocity becomes:

$$\bar{\upsilon}_1 = \left(\frac{d^2\varepsilon}{32\tau^2\mu}\right)\left(\frac{dP}{dL}\right)$$

Hence $k = \left(\frac{d^2\varepsilon}{32\tau^2}\right)$, Darcy's permeability coefficient.

Thus for

$d = 1\mu = 10^{-6}$ m

$\varepsilon = 0.001$ (i.e., 0.1%)

$\tau = 4$

we have

$k = 2 \times 10^{-18}\ \mathrm{m}^2$

$\equiv 2 \times 10^{-6}$ Darcy

which is about that of granite/crystalline rock – which can vary by several orders of magnitude.

It is also important to note the following:

(a) $k$ decreases with depth because lithostatic pressure squeezes passages closer together
(b) a similar analysis can be applied to yield equivalent results for planar crack conduits

With respect to the latter remark, it is also clear that large faults, especially vertical, can significantly increase escape rates. Thus quantitative confirmation of deep rock integrity must be a top goal of repository qualification measurements, as must be assurance of low future seismic impact.

## B.5 Water and Rock Expansion and Compression

In our range of interest (~ 200 bar, 100°C) one has for water:

$$\frac{\Delta\rho}{\rho} \cong 5.0 \times 10^{-5} \cdot \Delta P_{Bar}$$

$$\frac{\Delta\rho}{\rho} = -7.0 \times 10^{-4} \cdot \Delta T_{^\circ\mathrm{C}}$$

Thus a mere 7°C rise in temperature can offset a 1 km increase in depth (hence hydrostatic pressure of ~ 100 Bar) for which $\frac{\Delta\rho}{\rho} = 0.005$. This explains why the pressure effect is commonly neglected.

Water density is also a function of salinity. In terms of NaCl equivalence:

$$\frac{\Delta\rho}{\rho} \approx 0.058 \cdot M$$

where $M$ = molality = number of formula weights per kilogram.

For granite, linear expansion and compression are approximately given by:

$$\frac{\Delta Z}{Z} \approx 8 \times 10^{-6} \text{ per}\,^\circ\mathrm{C}$$

$$\frac{\Delta Z}{Z} \approx 2 \times 10^{-6} \text{ per Bar}$$

Hence such effects can usually be neglected relative to water in rock.

Given these properties, an unconstrained one kilometer column of rock subjected to an increase in temperature of 50°C would expand by

$$\Delta Z = (8 \times 10^{-6})(50)(1000\,\mathrm{m})$$
$$= 0.4\,\mathrm{m} = 40\,\mathrm{cm}$$

Under constraint by cooler adjacent rock the column would undergo local compression, while its surroundings would be subjected to a tensional component.

Note that the stress-strain curve in compression differs from that in tension[4]

$$\left(\frac{\Delta Z}{Z}\right)_{COMP} = \ell n\left[1 + \left(\frac{\Delta Z}{Z}\right)_{TEN}\right]$$

But for small strains $\ell n(1 + x) = x,$ so that this distinction is not that important.

## B.6 Buoyancy-Assisted Escapes

As described in Ref(1), the areal average flow velocity of water in a porous medium is given by

$$\upsilon = \left(\frac{k}{\eta}\right)\left(\frac{\Delta P}{\Delta Z}\right), \text{ cm/s}$$

with appropriate parameter dimensions and representative values for deep-down granite of

$k$ = permeability ($10^{-7}$ Darcy)
$\eta$ = water viscosity (~ 0.5 centipoise)
$\frac{\Delta P}{\Delta Z}$ = pressure gradient, bar/cm

In the present instance the gradient is provided by the decrease in water density due to thermal expansion. The coefficient has the approximate value

$$\alpha = 6.7 \times 10^{-4}, \ \Delta\rho/\rho \text{ per °C}$$

Converting units, since water hydrostatic head is $10^{-3}$ bar/cm, one has

$$\frac{\Delta P}{\Delta Z} = 10^{-3} \cdot \alpha\,\Delta T = 6.7 \times 10^{-7}\ \Delta T, \text{ bar/cm}$$

Next assume $\Delta T = 100°\text{C}$, difference in radial temperature between near and far field, at all elevations and for all time (very conservative). Then one finds for the superficial velocity:

$$\upsilon = 13.4 \times 10^{-12} \text{ cm/s} = 0.425 \times 10^{-8} \text{ km/yr}$$

Since velocity in the interstices is larger by the reciprocal of the porosity, the water oozes up at a rate of $0.425 \times 10^{-6}$ km/yr – hence it takes 2.4 million years to ascend one kilometer: about one half life of Np-237. This emphasizes the need to also invoke retardation and the effect of salinity in offsetting the buoyancy gradient.

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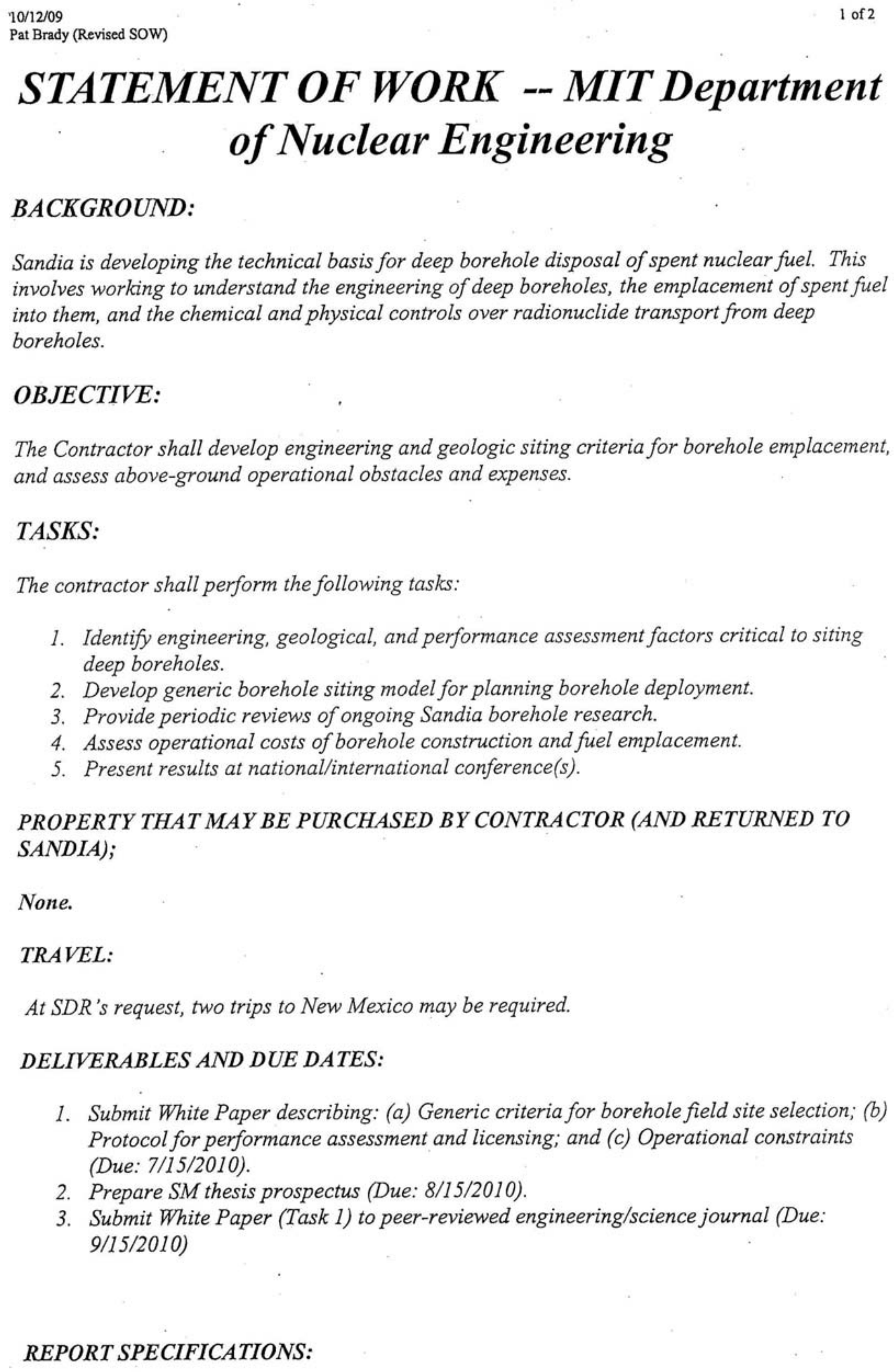
[4] W. F. Hiesford, *Mechanical Behavior of Materials,* Cambridge Univ. Press, 2005

# Appendix C



10/12/09
Pat Brady (Revised SOW)

1 of 2

# *STATEMENT OF WORK -- MIT Department of Nuclear Engineering*

## *BACKGROUND:*

*Sandia is developing the technical basis for deep borehole disposal of spent nuclear fuel. This involves working to understand the engineering of deep boreholes, the emplacement of spent fuel into them, and the chemical and physical controls over radionuclide transport from deep boreholes.*

## *OBJECTIVE:*

*The Contractor shall develop engineering and geologic siting criteria for borehole emplacement, and assess above-ground operational obstacles and expenses.*

## *TASKS:*

*The contractor shall perform the following tasks:*

1. *Identify engineering, geological, and performance assessment factors critical to siting deep boreholes.*
2. *Develop generic borehole siting model for planning borehole deployment.*
3. *Provide periodic reviews of ongoing Sandia borehole research.*
4. *Assess operational costs of borehole construction and fuel emplacement.*
5. *Present results at national/international conference(s).*

## *PROPERTY THAT MAY BE PURCHASED BY CONTRACTOR (AND RETURNED TO SANDIA);*

*None.*

## *TRAVEL:*

*At SDR's request, two trips to New Mexico may be required.*

## *DELIVERABLES AND DUE DATES:*

1. *Submit White Paper describing: (a) Generic criteria for borehole field site selection; (b) Protocol for performance assessment and licensing; and (c) Operational constraints (Due: 7/15/2010).*
2. *Prepare SM thesis prospectus (Due: 8/15/2010).*
3. *Submit White Paper (Task 1) to peer-reviewed engineering/science journal (Due: 9/15/2010)*

## *REPORT SPECIFICATIONS:*

***White Paper:***

*This report shall be written in the form sufficient for subsequent submittal to a peer-reviewed technical journal and must reference the contract number and Sandia support. The format will depend on the journal that is ultimately chosen. The journal article that is submitted may contain only a portion of the results described in the White Paper, but must also acknowledge Sandia support.*

***SM Thesis:***

*This report shall be written to MIT SM formatting requirements.*

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***MIT PI:*** *Prof. Michael Driscoll, Professor Emeritus of Nuclear Engineering*

***Email:*** *mickeyd@mit.edu*

***Phone:*** *617-253-4219 Fax: 617-258-8863*

***SDR/Technical POC:*** *Peter N. Swift, 505/284-4817, Org. 6780*

***SLODR:*** *J. Delene Cox, 505/284-3871, Org. 10666*

***P/T:*** *106866/08.07.02*

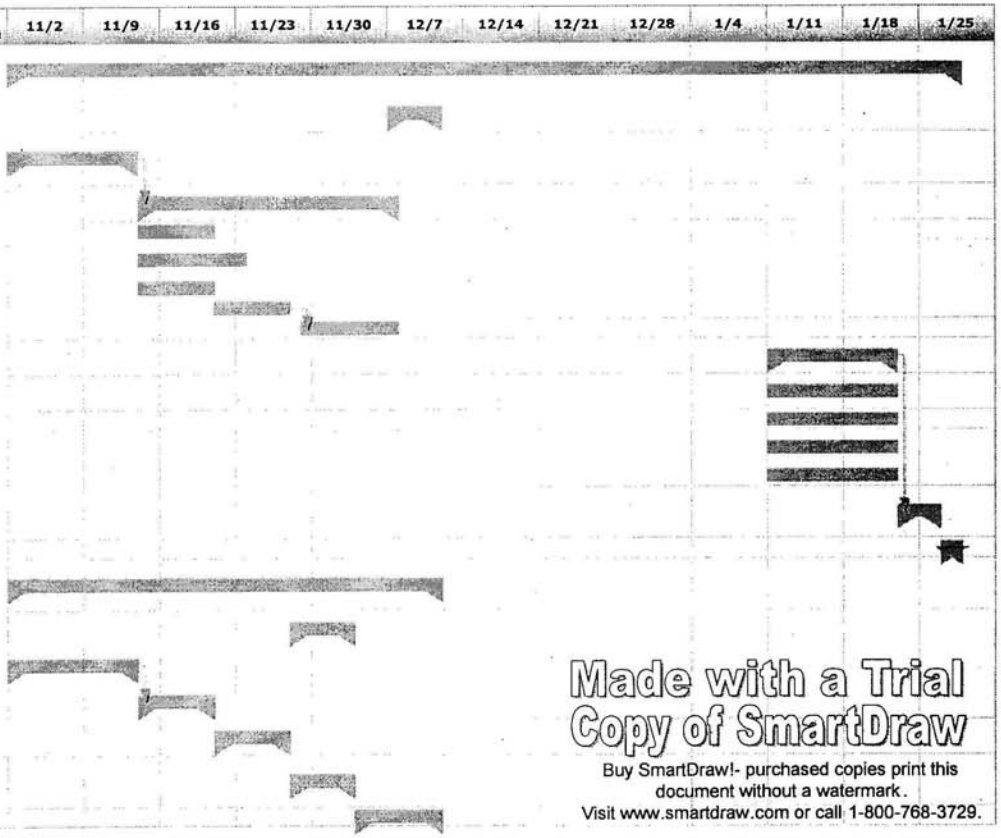
***Budget:*** *$100K*

***LO:*** *$10K*

***Start date:*** *Earliest date possible*

***Duration:*** *1 yr with an option to renew*

| Number | Task | Start | End | Duration | % Complete |
|---|---|---|---|---|---|
| 1 | Framework Report<br>FRAMEWORK FOR PERFORMANCE ASSESSMENT AND LICENSING | 11/2/2009 | 1/28/2010 | 64 | |
| 1.1 | Chapter 1<br>Introduction | 12/7/2009 | 12/11/2009 | 5 | |
| 1.2 | Chapter 2<br>Reference/Ideal Borehole Sites and Technologies | 11/2/2009 | 11/13/2009 | 10 | |
| 1.3 | Chapter 3<br>Assessment Methods Review | 11/14/2009 | 12/7/2009 | 16 | |
| 1.3.1 | Construct Bibliography | 11/14/2009 | 11/20/2009 | 5 | |
| 1.3.2 | Contact Peter Swift and Other Experts | 11/14/2009 | 11/23/2009 | 6 | |
| 1.3.3 | Review EIS | 11/14/2009 | 11/20/2009 | 5 | |
| 1.3.4 | Review TSPA | 11/21/2009 | 11/27/2009 | 5 | |
| 1.3.5 | Write | 11/29/2009 | 12/7/2009 | 6 | |
| 1.4 | Chapter 4<br>A Proposed Framework | 1/11/2010 | 1/22/2010 | 10 | |
| 1.4.1 | Review de Neufville Work on Siting Frameworks | 1/11/2010 | 1/22/2010 | 10 | |
| 1.4.2 | Review Literature | 1/11/2010 | 1/22/2010 | 10 | |
| 1.4.3 | Identify Key Parameters and Probabilistic Characterization | 1/11/2010 | 1/22/2010 | 10 | |
| 1.4.4 | Write | 1/11/2010 | 1/22/2010 | 10 | |
| 1.5 | Chapter 5<br>Summary, Conclusions, and Recommendations | 1/23/2010 | 1/26/2010 | 2 | |
| 1.6 | Editing and Finishing | 1/27/2010 | 1/28/2010 | 2 | |
| 2 | Examples Report<br>REGIONAL EXAMPLES OF GEOLOGICAL SETTINGS | 11/2/2009 | 12/11/2009 | 30 | |
| 2.1 | Chapter 1<br>Introduction | 11/28/2009 | 12/3/2009 | 4 | |
| 2.2 | Chapter 2<br>Generic Site Characteristics | 11/2/2009 | 11/13/2009 | 10 | |
| 2.3 | Chapter 3<br>European Small Users | 11/14/2009 | 11/20/2009 | 5 | |
| 2.4 | Chapter 4<br>Middle Eastern New Users | 11/21/2009 | 11/27/2009 | 5 | |
| 2.5 | Chapter 5<br>Summary, Conclusions, and Recommendations | 11/28/2009 | 12/3/2009 | 4 | |
| 2.6 | Editing and Finishing | 12/4/2009 | 12/11/2009 | 6 | |



# Appendix D

## Pre-Application Submission in Response to NEUP-001-10

**Title of Project: Resolution of Key Technical Issues for Deep Borehole Waste Disposal**
**Work Scope ID No.: FCD-2 Advanced Methods for Evaluation of Geologic Repository Performance**
**Alternatives: MR-IIR Investigator Initiated**
**: FCS-4 Waste Form Stability**
**Principal Investigator: M. J. Driscoll, MIT**
**Collaborating Organization: Sandia National Laboratories**

### Summary of Contributions

The safe disposal of high-level nuclear waste in the form of spent fuel and/or its separated constituents is a problem of critical international importance. We propose to evaluate geological and geochemical aspects of waste form/waste package interactions in deep boreholes drilled into geologically old crystalline rocks that have little or no natural permeability. The result will be the quantification of key performance metrics and their uncertainty, as needed to qualify this approach.

### Description of Project

The US has recently committed to re-assessment of high level nuclear waste disposal alternatives to Yucca Mountain. Deep boreholes, drilled 3 – 5 km into basement crystalline igneous granitic rock are a promising approach, based on earlier studies in the US, and ongoing work at MIT, Sheffield University in the UK, Sweden, and Sandia National Laboratories. Sufficient work has been done to identify the key factors needing elucidation before current predictions of exceptional waste sequestration capability can be supported with the extremely high degree of assurance that is required. This proposal focuses on aspects identified during the past two decades of work at MIT and elsewhere, organized under three Tasks, as follows:

(1) Formulation of Top-level Criteria and Methods for Siting and Performance Assessment

The viability of the deep borehole approach must be evaluated consistent with precedent (i.e., Yucca Mountain experience) and risk-informed quantification of performance. For example, one preliminary suggestion is to structure the process around a probabilistic estimation of the dose to a hypothetical future individual situated 24/7 atop the sealed borehole.

Since transport by water is the only credible escape mechanism for a well-chosen site, it must be shown that a variety of sites are available having the requisite low deep rock permeability essential to ensure the integrity of the natural granite sarcophagus. Available geological information, and the known capability of seismic and other survey methods, both wide-field and downhole, will be reviewed as part of this subtask.

A key performance assessment task is provision for long-term post-emplacement monitoring – for example, in collocated instrumented wells – to confirm that regulatory commitments are fully met.

Another obvious top-level criterion is cost, principally that of borehole preparation, but including a complete life-cycle overview.

Finally, philosophical and socio-political considerations in the context of alternatives, such as retrievability and proliferation safeguards, must be addressed.

### (2) Resolution of Specific Thermal/Hydraulic/Chemical/Mechanical Performance Issues

#### (a) *Avoidance of borehole breakout and canister crushing*

Somewhere beyond several kilometers of lithostatic pressure a borehole wall can spall (breakout) due to shear stress. Hence significant work must be done on the geomechanics of granitic rocks with particular attention to borehole stability for both vertical and high-angle wells. A better computation of tolerable depths based on rock properties, local stress state and pore pressure is needed as well as confirmation that a borehole liner can ward off canister jamming.

A second mechanical design issue is the tolerable weight of a canister stack before the bottom-most are crushed. Also relevant is whether intermediate plugs or horizontal drilling can protect against such stresses and similarly, use of a filler for in-canister void space to protect against radial crushing.

#### (b) *Canister thermal design and host rock thermal transport*

Waste temperature is a principal determinant of concept acceptability. Because of the smaller canister diameter and lower radial resistance, temperatures should be lower than in mined repositories. Aspects requiring quantification include:

- post emplacement thermal fields for both intact assemblies (PWR and BWR) and for special post-reprocessing waste forms (e.g., glasses or ceramics containing fission products and/or minor actinides).
- evaluation of the need for grouting between the borehole wall and its liner, and the liner and the waste canisters, to increase thermal conductivity (and simultaneously protect against crushing, water ingress, and radionuclide transport).
- Thermal analysis of host rock response and how this influences water-rock interaction in the vicinity of the repository.

#### (c) *Coping with water radiolysis*

While the host rock environment contains little water, flooding with water cannot be ruled out over the course of millennia. Cements and grout are also a potential source of water. It must be shown that radiolytic production of $H_2$ and $O_2$ cannot create downhole pressures which would threaten host rock and borehole plug integrity. This can be done by showing that these gases will diffuse away into the host rock at sufficiently low pressure gradients.

(d) *Borehole plug design and performance assessment*

The borehole plug is by all indications the most vulnerable path for loss of confinement. Hence its design and transport performance are an essential topic. Issues include the advantage achieved by removal of borehole liner casing in the plug zone, as well as choice of plug materials – most likely as a sequence of diverse barriers: e.g., cement, asphalt, bentonite clay, or perhaps even molten granite.

(3) Refinement of Emplacement Procedures

Surface handling and downhole lowering of unshielded single assembly canisters can add significantly to operational complexity and hence cost. Hence a thorough evaluation will be made of such operations, including detailed design of a reference technology and a step-by-step procedure. Scoping calculations have indicated that the simple, but unorthodox, alternative of canister free fall through a lined borehole flooded with water may be feasible. Detailed fluid mechanics computations and a scale mock-up experiment can confirm this, if only as a fallback option.

Other aspects include seamless interfacing with the currently planned mode for transportation to a repository site. For example, it may be possible to simply remove TAD cask single-assembly box-like trays and slide them into a borehole emplacement canister, which could be a standard half-length oil/gas-well drillstring section.

Deliverables: In addition to routine quarterly and annual reports, as required, student theses and topical reports in each of the three task areas enumerated above will be issued as completed; likewise journal and conference papers.

Collaboration: In carrying out this work the MIT team, which involves contributors from both the Department of Nuclear Science and Engineering and the Department of Earth, Atmospheric and Planetary Sciences, will also work in collaboration with investigators at Sandia National Laboratories, and advisory contributions by a consultant formerly associated with Schlumberger.

Personnel involved will be
Prof. M. J. Driscoll, MIT Nuclear Science and Engineering Dept.
Prof. J. Buongiorno, MIT Nuclear Science and Engineering Dept. (early career researcher)
Prof. R. K. Lester, MIT Nuclear Science and Engineering Dept.
Dr. P. V. Brady, Sandia National Laboratories
Dr. P. N. Swift, Sandia National Laboratories
Dr. M. Fehler, MIT Earth, Atmospheric and Planetary Sciences Dept.
Dr. J. Ullo, Private Consultant, ex-Schlumberger (retired)

Budget: The proposed effort will involve a total of three graduate research assistants and their supervisory faculty, and is projected to require 400K \$/year for three years, with 20% budgeted for Sandia support. Sandia will contribute across the board, but be of special help on Task 1.