TECHNOLOGY AND POLICY ASPECTS OF DEEP BOREHOLE NUCLEAR WASTE DISPOSAL

RADIOACTIVE WASTE MANAGEMENT AND DISPOSAL

KEYWORDS: *nuclear waste disposal, deep boreholes, repository licensing*

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The use of deep boreholes for the disposal of high-level radioactive waste is reassessed, emphasizing key enabling technical features and their strong linkage to national and international fuel cycle policy. Emplacement 2 to 4 km deep in widely available granitic continental bedrock, under a 1-km caprock layer of high-integrity bedrock, is shown in this analysis to have the potential to provide sufficiently low host rock permeability to prevent radionuclide escape by transport in water—the only plausible release mechanism. The modular nature of the concept enables multiregion siting in large user countries and is especially well-suited for small-user nations. Irretrievability can be built-in to better meet safeguards objectives, and the exceptionally high assurance of confinement makes the disposal of minor actinides (and troublesome fission products) an attractive alternative to their destruction by transmutation.

I. INTRODUCTION

Consideration of deep boreholes drilled into continental bedrock for permanent disposition of the high-level radioactive waste (HLW) in used nuclear reactor fuel has a long history.[1] While to date, shallower mined repositories have been accorded preference, reassessment is merited in view of an accumulation of technical advances and international developments relevant to the deep borehole option[2–4] and the recent setback for the Yucca Mountain site.[5] A range of borehole concepts is feasible, including deeper or shallower holes, holes with slanted or even horizontal disposal zones, and holes with multiple disposal zones diverging from a single emplacement hole.[2,6] For the purposes of the following discussion, consider a single generic borehole 4 km deep and ~500 mm in diameter, with the bottom 2 km filled vertically with waste canisters. Section III provides details.

In the United States, boreholes were considered for irretrievable plutonium weapon pit entombment as late as the 1990s (Ref. 3). The policy decision to burn plutonium in reactors instead led to project abandonment. This and other historical investigations are summarized in Ref. 1.

Since then, the highest-profile assessment of long standing took place in Sweden,[7] as a backup alternative to the Swedish mined repository initiative, whose successful siting process effectively ended Sweden's borehole work in mid-2009. Otherwise, sustained and still extant investigations appear confined to Sheffield University in the United Kingdom,[8] and a more modest in-house effort at Massachusetts Institute of Technology (MIT) over the past two decades.[4] This state of affairs changed in 2009 with the expansion of related work at Sandia National Laboratories[9] (SNL) to include cosponsorship of workshops at MIT in August 2009 and in Washington, D.C. in March 2010 (Ref. 10). The review presented in this paper has been supported by the U.S. Department of Energy (DOE) through a contract between SNL and MIT.

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In what follows, several themes are addressed:

1. a focus on essential host rock attributes: permeability and susceptibility to water-borne transport
2. a reference borehole and repository field concept in response to these requirements
3. a review of technical advantages and issues, including the effect of evolutionary changes in prospects, and some plausible future trends
4. programmatic and sociopolitical factors favorable to deep borehole development and deployment.

In this review, it is assumed that existing shipping casks will be loaded at reactor sites and transported to the borehole field by rail and/or truck, using technology and procedures already licensed and exercised in the U.S. HLW program and abroad. Upon receipt, unloading and transfer into the smaller emplacement canisters and their temporary shield casks, followed by truck transport to the borehole wellhead, will merely replicate such tried-and-true procedures. Hence, these facilities and procedures are not expected to be any more contentious than those associated with shallower mined repositories such as Yucca Mountain or at-reactor operations. Accordingly, this subtopic is not further addressed since the focus is on attributes unique to the borehole concept.

II. ESSENTIAL ATTRIBUTES

II.A. Host Rock Permeability

The work at MIT over the past 20 yr summarized in Ref. 4 and, more importantly, the larger efforts mounted in Sweden[7] and elsewhere[8] all come down to host rock and borehole seal permeabilities as the controlling parameter. In the analyses described here, seals are implicitly assigned material properties equivalent to those of the host rock, consistent with an assumption that borehole seals can be designed and constructed to have a permeability as low as, or lower than, the surrounding host rock. As discussed further in Sec. III, qualitative consideration of seal designs using currently available materials and technologies supports this assumption.

As embodied in Darcy's relation, permeability characterizes the velocity at which water (hence waterborne species) can move vertically through the geologic environment. The effective granite permeability value accounts for both interconnected pores and fractures on microscales and macroscales; these latter are squeezed almost shut by high lithostatic pressure at depth. The following prescription results:

$$\frac{k}{\eta R} = 10^{-4}\left(\frac{H\varepsilon}{t}\right)\left(\frac{dP}{dZ}\right)^{-1} , \tag{1}$$

where

k = permeability (m^2) (1 darcy = $0.987 \times 10^{-12} \cdot$ m^2)

η = dynamic viscosity of fluid (kg/m·s) (1 centipoise = 10^{-3} kg/m·s)

R = retardation factor due to sorption

H = caprock thickness (cm)

ε = rock porosity

t = transit time (s)

P = overpressure, difference between fluid pressure and hydrostatic pressure (Pa) (1 bar = 10 197 kg/m^2 = 10^5 Pa)

Z = vertical distance (cm)

Equation (1) is plotted in Fig. 1 for various transit times. In what follows, only the portion of the granite above the repository zone, here termed "caprock," is credited with retarding radionuclide transport, ignoring potential contributions in the entombment zone and by any sedimentary overburden, if present. Again, because of high overburden pressure, no continuous fractures are expected.

Note that for a reference case of $R = 1$ (no retardation) and $\eta = 10^{-3}$ kg/m·s (pure water at 25°C), the vertical axis is just k, the permeability in square meters. Typical temperatures immediately above the disposal zone for deep borehole disposal (2000- to 3000-m depth) will be somewhat higher, 60°C to 80°C, and the viscosity will be a factor of 2 to 3 lower.

The performance map clearly shows the need to choose rock having low permeability and weak upward potential gradients (i.e., no overpressuring) if long confinement times are to be achieved. The benefit of a large retardation factor R, hence, compatible chemistry, is also evident.

As can be seen, confinement times of up to 1 million yr (by which time most radionuclides will have decayed away) are predicted if the permeability and hydraulic pressure gradient are sufficiently small. High natural vertical pressure gradients can be avoided in the site selection process, and the maximum buoyancy associated with decay heat from the waste will dissipate by thermal conduction over timescales much shorter than fluid transit times. Moreover, most species will be further delayed by retardation due to adsorption on rock water channel surfaces: The retardation factor R can easily be a factor of 100 or more. This leaves soluble long-lived radionuclides, notably ^{129}I (15.7-million-yr half-life), as the likely limiting case.

While small, both the permeability and hydraulic pressure gradient are measurable parameters in principle, although the true gradient is not easily characterized in the very low porosity of a candidate borehole.

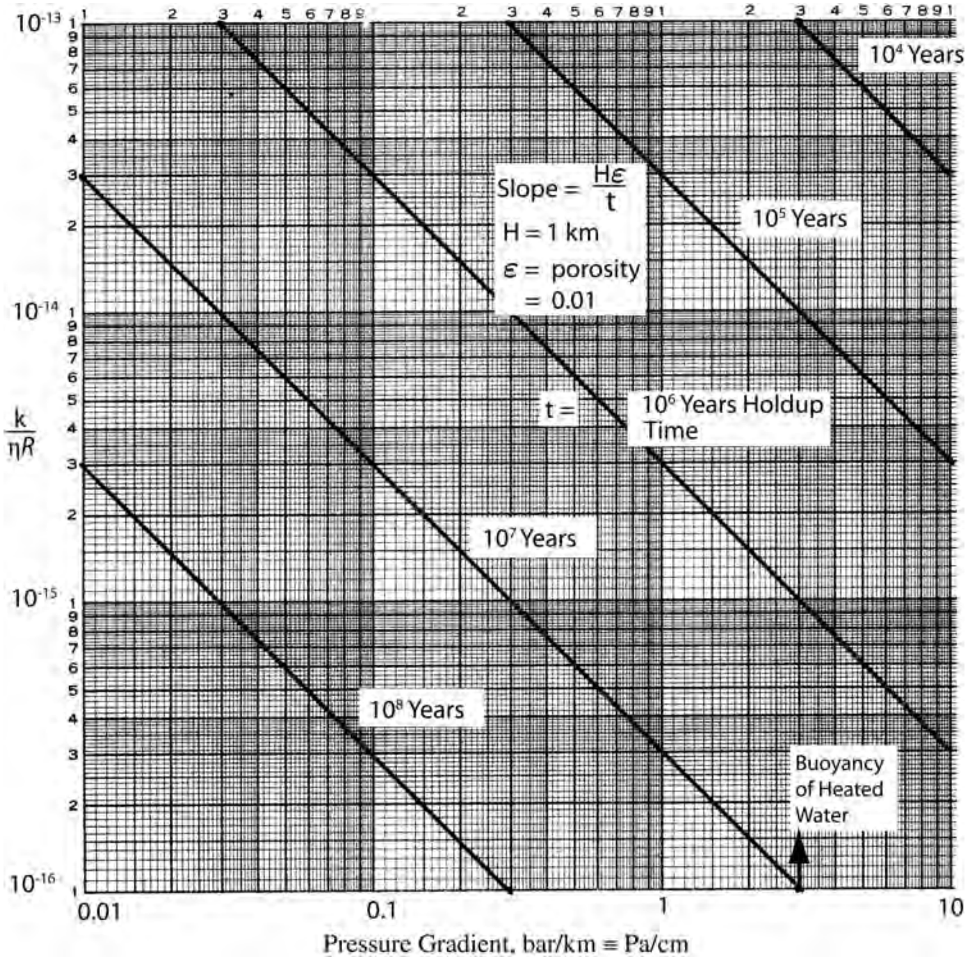

Fig. 1. Transport delay provided by 1 km of caprock.

II.B. Inhibition of Vertical Convection by Salinity

Vertical movement of water due to thermally induced buoyancy in sediment and bedrock is a well-studied geological phenomenon.[11]

A simple analysis can roughly estimate the vertical total dissolved solid (TDS) (i.e., "salinity") gradient that can offset the thermal buoyancy.

Consider a large-diameter tube of host rock surrounding a borehole. Figure 2 shows the approximate linearized near- and far-field vertical temperature and TDS profiles.

Assuming that the near-field water moves upward without cooling or dilution of salinity, the following mass density balance can be struck between top-to-bottom averages:

$$\overline{\Delta S} = S_h/2 \geq -\bar{\beta}\bar{\rho}\overline{\Delta T}$$

$$= -\beta\rho \cdot \tfrac{1}{2}[(T_h - T_o + \Delta T) + \Delta T] \qquad (2)$$

so that

$$S_h \geq -\bar{\beta}\bar{\rho}[T_h - T_0 + 2\Delta T] \ , \qquad (3)$$

where

$$\bar{\beta} = \frac{1}{\bar{\rho}}\left(\frac{d\bar{\rho}}{dT}\right) \ , \qquad (4)$$

volumetric coefficient of thermal expansion; for upwelling water at a mean temperature of 100°C, $\bar{\beta} = -7.5 \times 10^{-4}$/°C (smaller magnitude for lower T)

T_h = 100°C for a geothermal gradient of 25°C/km, 3-km depth, and 25°C surface temperature (T_o)

ΔT = 30°C, peak near-field rock temperature rise (hence pore water ΔT)

$\bar{\rho} \approx$ 1000 g/kg, normalized fluid mass density

$S_h \geq$ 100 g/kg, downhole TDS requirement; this value of S_h is about four times that of seawater but is not uncommon in deep formations. It (i.e., 10% salinity) is also the reference value selected by analysts in Sweden for its groundwater thermal buoyancy simulations.[11]

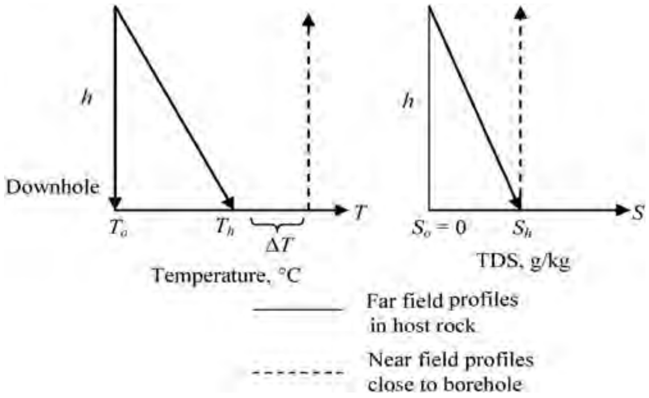

Fig. 2. Linearized near- and far-field temperature and TDS profiles.

Note that we have omitted the smaller increase in density due to the compressibility of water, i.e., $\Delta\rho/\rho \approx 0.004/\text{km}$ of hydrostatic pressure because it is essentially the same in both the near- and far-field water columns, to first order.

The above criterion is very conservative for several reasons.

Assume, for example, a plume of water in rock at 100°C surrounded by host rock and water at 50°C. The resulting 3% density reduction creates a net upward pressure gradient of ~3 bars/km. The Darcy relation then predicts that vertical transport upward through caprock 1 km thick, having a permeability of 1 microdarcy, takes on the order of 1 million yr (see Fig. 1). This by itself should assuage concern. Moreover, it will not be possible to sustain the hypothesized temperature difference, hence buoyancy.

Caprock thermal diffusivity, $\alpha = k/\rho c_p$, is ~40 m^2/yr, and the characteristic time for heat diffusion outward radially from a line source is $\tau = r^2/4\alpha$. For $r =$ 100 m (midway to the next borehole in an array), τ is then ~60 yr, which is much shorter than the vertical rise time. This also means that the radial temperature profile will flatten out long before plume water rises very far into the caprock. In addition, at the start of the hypothesized upwelling, the heat capacity of the caprock will reduce the temperature of the rising water for a protracted period. Furthermore, in the long term, the waste heat warming the water in the entombment zone decays with time: by a factor ~10 in 800 yr (Ref. 6).

There will, however, also be slow mixing with upper-level water, which will reduce salinity and hence margin. This motivates more detailed modeling. Reference 11 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 and helps put to rest the hypothetical buoyancy-driven phenomenon raised at the outset of this discussion.

II.C. Heatup due to Waterborne Radionuclide Decay

One could postulate that a rising plume's temperature-driven buoyancy will be replenished by the energy emitted by decaying radionuclides.

Purely for the sake of argument, assume, *very* conservatively, that the water in question contains HLW at a concentration roughly that of its natural salinity, e.g., 0.1 g/cm^3.[a] Further, assume that the energy release rate is the same as spent fuel after 100 yr cooling, e.g., 0.7×10^{-3} W/g. This results in a volumetric heat source strength of 7×10^{-5} W/cm^3 in water. However, the water is present in small pores and, thus, promptly shares this energy with the surrounding rock. At 1% porosity, then, the volumetric heat source is only 7×10^{-7} W/cm^3.

The volumetric heat capacity of granitic bedrock is ~2 W·s/cm^3·°C. Hence, the above heat source could cause an adiabatic heatup rate of only 3.5×10^{-7}°C/s, or ~10°C/yr. For a more realistic radionuclide concentration of 0.1 mg/cm^3 [for example, estimated radionuclide levels under similar low E_h conditions are not expected to greatly exceed $10^{-4} M$ (Ref. 12)], the calculated adiabatic heatup would be ~0.1°C/yr.

However, in 1 yr, a pulse of energy will move a nominal distance:

$$r = 2\sqrt{\alpha t} \ , \tag{5}$$

where α = thermal diffusivity of granite ≈ 40 m^2/yr, in which case $r = 13$ m in 1 yr.

In other words, self-generated "hot brine balloon" heatup is not a credible mechanism: What does occur is small and readily dissipated.

A simple quantitative demonstration of the relative decay rates of forces promoting and opposing plume rise follows.

The fraction of a line source pulse diffusing beyond the distance r at time t can be obtained by integrating the diffusion kernel[13] from r to ∞ and is just

$$F = e^{-(r^2/4\alpha t)} \quad \text{for heat} \tag{6}$$

and

$$F = e^{-(r^2/4Dt)} \quad \text{for ionic diffusion} \ , \tag{7}$$

where α and D are the thermal diffusivity and diffusion coefficient, respectively.

Hence, the ratio α/D is a good measure of the relative rates of dissipation. For granite, $\alpha \approx 1.3 \times 10^{-2}$ cm^2/s.

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[a] Note that the added water density would further inhibit temperature-induced plume rise.

For ions diffusing in tortuous passages via water in the rock, the effective diffusion coefficient is[14]

$$D_{eff} = D_o \frac{\varepsilon}{\tau} \ , \tag{8}$$

where

D_o = diffusion coefficient in water, which here is $\sim 1.6 \times 10^{-5}$ cm^2/s (using NaCl as the salt)

ε = interconnected porosity; assume 0.01

τ = tortuosity of path; take as 4.

Hence,

$$D_{eff} = 4 \times 10^{-8} \text{ cm}^2/\text{s}$$

in which case

$$\frac{\alpha}{D} = 3.2 \times 10^7$$

so that heat losses dominate a salinity decrease by a very large margin for the hypothetical hot brine balloon scenario.

III. ATTRIBUTES OF A FAVORABLE REPOSITORY SITE

Because of the high degree of reliance on basement rock geophysical and geological properties as the principal guarantors of effective confinement, limits on certain key parameter values may need to be met. Chief among them is the permeability for flow of water, as noted in Table I. Because water flow rates are so low (<10 mm/yr) under projected downhole host rock conditions,[4] we are assured of local chemical and radiolytic equilibrium, which decouples flow rate effects from waste solubilization rates, but the resulting near-equilibrium conditions can affect radionuclide dissolution rates.

Limiting the transport of radionuclides is critical to their isolation. Hence, rock with very low permeability and porosity is a prime candidate. Fortunately, continental basement rock with such properties in the form of crystalline igneous and metamorphic rocks is pervasive at accessible depths of a few kilometers or less.

The parameters listed in Table I are a compromise between what is needed and what is available. For example, rock properties become more favorable to waste isolation with depth—e.g., permeability decreases—depth also increases the thickness of the caprock zone above the entombment zone, through which water-borne species must penetrate, which increases holdup times (allowing for radionuclide decay). Also relevant is the ability to measure the subject parameter values with adequate accuracy. One caveat worth emphasizing is that when permeability measurements are done in the laboratory, they must be done under simulated downhole pressures since all rock has microcracks and macrocracks that are effectively sealed by lithostatic pressure.

Throughout, one should keep in mind that the chosen site(s) will, by selection, initially be essentially free from flowing water at the emplacement depth. However, we conservatively choose to analyze a scenario in which an emplacement borehole is filled with water, with the possibility of a sufficient upward gradient to lead to radionuclide releases from the borehole.

IV. REFERENCE DESIGN

IV.A. Description

It is important to be precise about proposed borehole features since several variations have been explored in the literature.[1–3,6] Figure 3 shows the reference design version: a simple vertical borehole, lined in its upper reaches and in the emplacement zone with standard cemented casing but only temporarily with uncemented casing in the caprock region that hosts the plug. The larger-diameter surface zone casing facilitates removal of the caprock zone casing. Figure 4 gives additional specifications. The reference design canister is constructed of cast iron—similarly to the Swedish and Finnish versions[16] but without external cladding. It is readily adapted to accommodate other loadings such as consolidated fuel bundles, and glass or ceramic reprocessing waste forms. In the downhole geochemical environment, corrosion rates should be less than several microns per year (Ref. 16, p. 391).

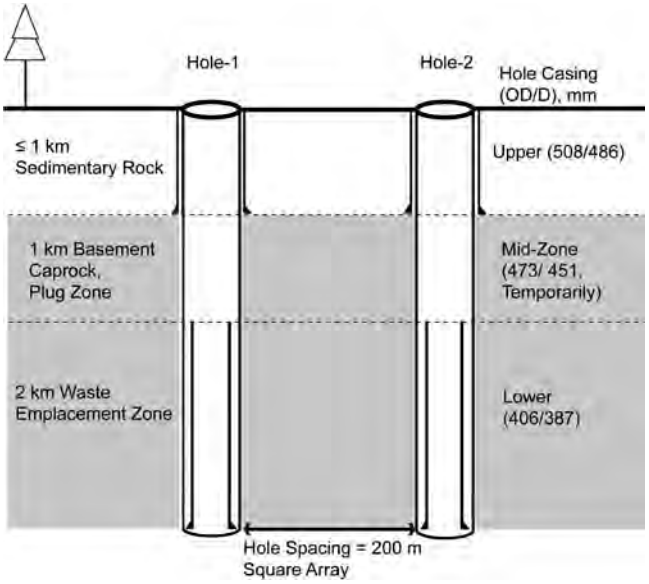


Fig. 3. Deep borehole HLW disposal concept.

TABLE I

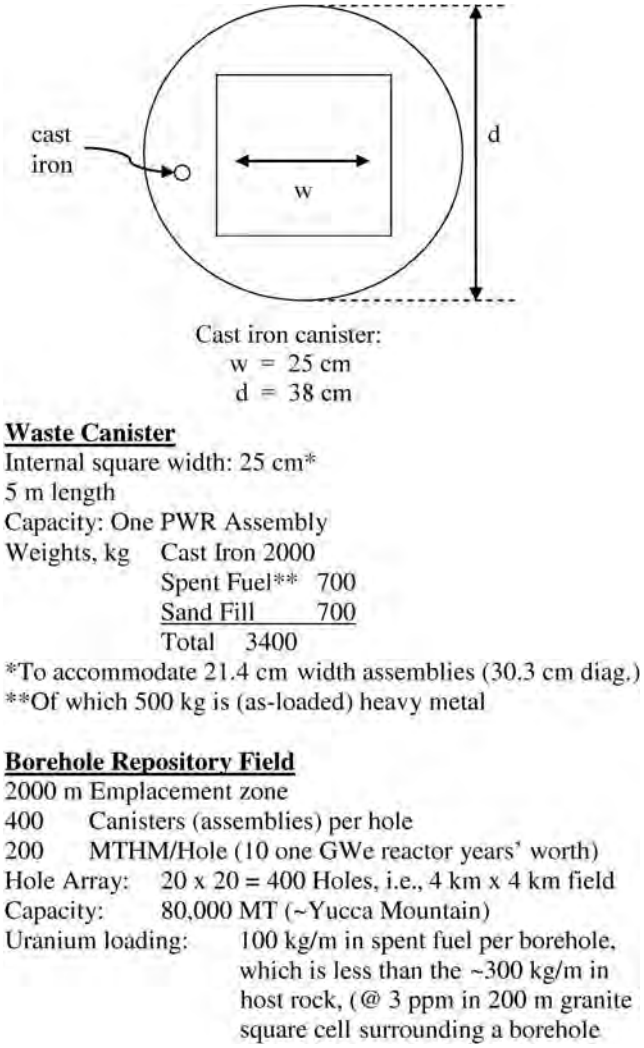
Target Downhole Host Rock and Borehole Field Properties

Feature	Goal	Comment
Dominant Criterion: Permeability	<100 microdarcy	To ensure low water movement velocity, as low as 0.1 microdarcy *may* be available.
Ancillary goals		
Porosity	<1 vol%	Percent interconnected, and hydraulic diameter are also important, as contributors to low permeability. Deep rock values $<0.1\%$ are prevalent.
Water content	<1 vol%	Follows from low porosity; some is connate (trapped)
Downhole pressure	Close to hydrostatic	To avoid excessive gradients
Salinity density increase	Ideally, 100 g/kg	Thwarts buoyant vertical convection in uppermost 1 km; prevents colloid formation
E_h (potential relative to hydrogen electrode)	<-0.1 V	Characterizes reducing nature of environment; assures low solubility of many radionuclides
pH: acid/base characteristics	>6; <9	Also helps reduce corrosion and maintain low solubility
Retardation factor	>100 for most species (principal exception is ^{129}I)	Adsorption on rock reduces rate of transport by this factor
Desirable near-field attributes		To reduce threat of major disruptive events (applies to all repository concepts; e.g., see Ref. 15)
Low seismicity, volcanism, and large-scale faulting	Same or better than shallow mined repositories	
Evidence of permanence	A history longer than confinement time horizon	Increases confidence in future projections (can confirm by measurement of radionuclide decay products in host rock)
Absence of valuable mineral resources	For example, Cu, Fe, Au, U, coal, oil, gas, etc.	Reduces risk of future human intrusion (universally applicable requirement)
Low geothermal gradient	<30°C/km	Reduces waste temperature, chemical reaction rates, water density gradient (<20°C/km widely available)
Optional preferences		
Inhospitable surface environs	Lack of water: surficial and aquifer	To discourage adjacent human habitation and farming, reduce potential for future radiation exposure
Low sedimentary overburden	0 to 1 km	Can reduce drilling depth to reach high-integrity caprock, hence cost

Figure 5 illustrates the multilayer plug of asphalt/bentonite clay/expanding concrete. This provides the classical "defense in depth," but one should also note that each layer is grossly overdesigned [much longer than needed based on its anticipated $<10^{-20}$-m^2 (10-nanodarcy)] permeability. This was considered desirable in view of the extreme variability in the physicochemical properties of both clay and asphalt—which makes predictive characterization a problematical and highly probabilistic challenge. Also, note that the layers are in a different sequence than proposed by earlier Swedish and Russian workers.[17,18] Our bentonite layer is up-hole of the concrete because of concern that highly saline deep water could degrade its retentive properties over eons.

IV.B. Cost

The cost of HLW disposal in deep boreholes appears competitive. Finished, ready-to-load boreholes to the depth required (4 km) for oil, gas, and enhanced geothermal system (EGS)–type applications are documented to be on the order of $10 million (Refs. 19 and 20). They are, however, of smaller diameter than required for intact pressurized water reactor (PWR) assembly disposal (but



Cast iron canister:
w = 25 cm
d = 38 cm

Waste Canister
Internal square width: 25 cm*
5 m length
Capacity: One PWR Assembly
Weights, kg Cast Iron 2000
Spent Fuel** 700
Sand Fill 700
Total 3400
*To accommodate 21.4 cm width assemblies (30.3 cm diag.)
**Of which 500 kg is (as-loaded) heavy metal

Borehole Repository Field
2000 m Emplacement zone
400 Canisters (assemblies) per hole
200 MTHM/Hole (10 one GWe reactor years' worth)
Hole Array: 20 x 20 = 400 Holes, i.e., 4 km x 4 km field
Capacity: 80,000 MT (~Yucca Mountain)
Uranium loading: 100 kg/m in spent fuel per borehole, which is less than the ~300 kg/m in host rock, (@ 3 ppm in 200 m granite square cell surrounding a borehole

Fig. 4. Summary of borehole waste disposal system features (MT = metric ton; MTHM = tonne HM).

not reconstituted assemblies or waste forms from reprocessing operations). One comprehensive estimate for a larger EGS hole suggests \$20 million as a more relevant figure.[9] This would hold a stack of 400 PWR assembly canisters, containing 200 tonnes of heavy metal, which works out to 100 \$/kg, not including emplacement and plugging costs. Nevertheless, since the U.S. waste fee of 1 mill/kW·h(electric) corresponds to ~400 \$/kg, this borehole-only cost should be tolerable. As noted, it will be less for smaller-diameter reprocessing waste forms where multibranch drilling can also be employed.[21]

V. SOCIOPOLITICAL CONSIDERATIONS

V.A. Overview

Many believe that it is not the available technology that is the principal impediment to solving the waste disposal problem.[22] However, it is possible that exploitation of borehole technology could facilitate acceptance because of the demonstrable improvement in containment capability.

The broad availability of equally well-qualified disposal sites and the low cost per borehole permit employing more than one location. This should foster stakeholder perceptions of fairly shared burdens.

Small-user nations worldwide can readily accommodate their own needs in a cost-effective manner by exploiting the modularity of deep boreholes for waste disposal, while providing assurance of benign intent to their neighbors and the world at large, by promptly and securely sequestering potentially weapons-usable materials.

A standardized international design will assist in the development of uniform performance assessment methods and quality control measures, thereby enhancing assurance of effectiveness.

The ultimate goal, preferred by some, of a collaborative centralized multiuser facility would be facilitated.

Shared research, development, and demonstration (RD&D) costs will make the nuclear option less costly and will reduce the user fees collected from the consumers of electric energy.

If a hole fails final ready-to-use acceptance criteria despite all pre-emplacement vetting, the cost of abandonment is sufficiently modest that pressures to pursue expensive, ad hoc work-arounds to preserve the hole location should be low.

V.B. Unresolved Legislative and Regulatory Issues

The Nuclear Waste Policy Act of 1982, as amended in 1987, called for the phaseout of research on the disposal in granite and set added requirements should the U.S. Secretary of Energy reinstitute work in this area, namely, the consideration of such potentially disqualifying factors as

1. seasonal increases in population
2. proximity to public drinking water supplies, including those of metropolitan areas
3. the impact that characterization or siting decisions would have on lands owned or placed in trust by the United States for Native American tribes.

While none of the latter appear particularly onerous, the net result of the initial cutoff has been a two-decade hiatus in U.S. RD&D on both shallower mined and deep borehole repositories in granite.

Until resolved by subsequent executive and/or legislative action, one must therefore resort to speculative extrapolation from the experience base accumulated in the performance assessment of the Waste Isolation Pilot Project, Yucca Mountain, and Hanford.[22,23] This attempt

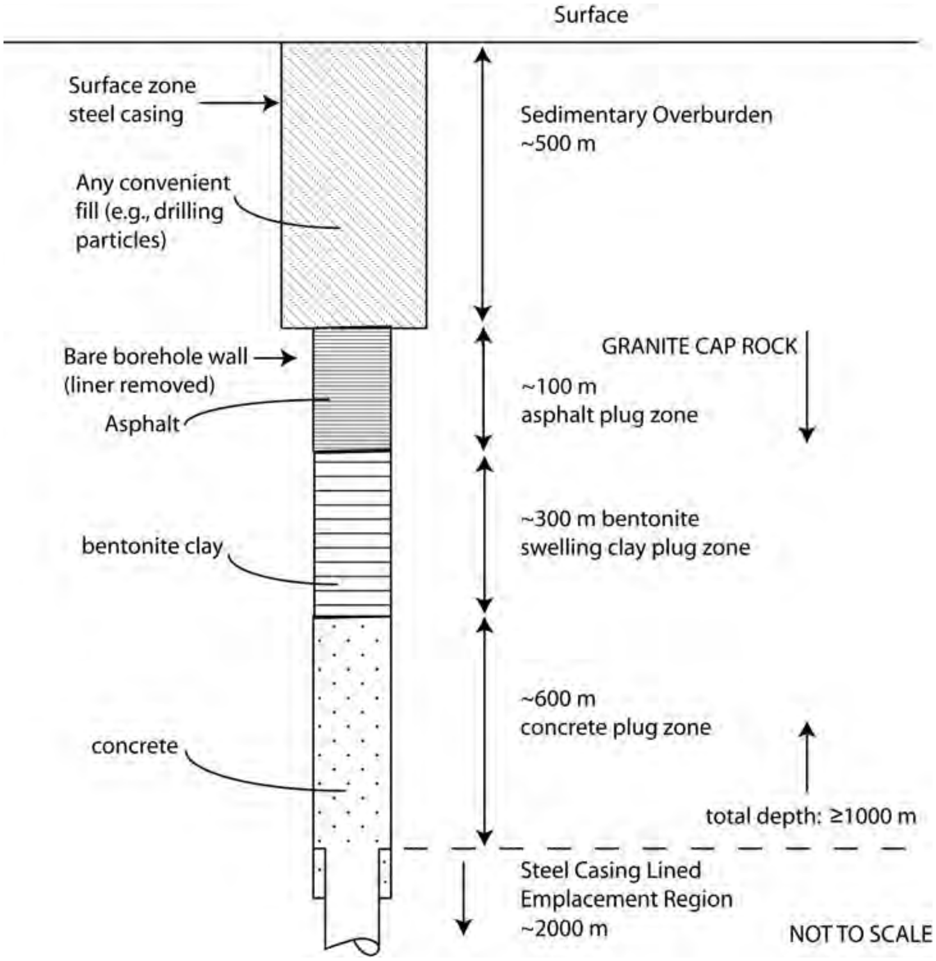


Fig. 5. Schematic of borehole plug design features.

is further clouded by the uncertain fate of the Yucca Mountain licensing application submitted by the DOE to the U.S. Nuclear Regulatory Commission in mid-2008 and the report of the program of the Blue Ribbon Commission on America's Nuclear Future established by President Obama, issued in January 2012 (Refs. 24 and 25).

At present, available precedent and codified federal regulations (e.g., 40 CFR 191, 40 CFR 197, 40 CFR 144 through 40 CFR 148, 10 CFR 60, and 10 CFR 63) (Ref. 26) identify few issues other than retrievability in which deep boreholes are potentially less suitable than shallower mined repositories. Otherwise, they have the potential for superior performance based on their geophysical and geochemical attributes.

Speculative future developments applicable to all repository types include an increased emphasis on risk-informed, performance-based regulation, a performance metric of annual risk and dose, 1-million-yr time horizon, and a continuing struggle to reduce uncertainty (Ref. 10 and Chap. 15 of Ref. 16).

VI. SUMMARY AND CONCLUSIONS

This brief review can hardly do justice to all of the aspects of such a broad topic. Hence, it has focused on the principal technical rationale for pursuing deep borehole emplacement of HLW, namely, the high degree of assurance of confinement resulting from very low host rock permeability. Quite satisfactory performance is predicted for permeabilities on the order of 10^{-18} m^2 (1 microdarcy), which is reassuring when premium local sites could have values as low as 10^{-20} m^2 (10 nanodarcy) at depths of a few kilometers. This would mean escape delay time on the order of 10^8 yr.

As experience has taught, however, it is also very important to consider nontechnical factors in waste management strategies. Fortunately, the deep borehole option has many desirable attributes from this perspective too, summarized as follows:

1. Better geophysical and geochemical environment than shallower mined repositories

   a. lower rock permeability, porosity, water content; increased lithostatic pressure seals ubiquitous microcracks
   b. ensures presence and stability of reducing chemistry (negative E_h), which reduces the solubility of most key species and increases the sorption of some species
   c. small hole diameter leads to low waste and host rock temperatures
2. Wide applicability
   a. intact used fuel assemblies: one PWR per canister or three boiling water reactors per canister
   b. reprocessed waste forms
      i. can reduce diameter to exploit most prevalent commercial drilling practice
      ii. can employ multibranch well technology: one main vertical hole for 6 to 12 side branches; horizontal emplacement increases caprock thickness
      iii. an ideal alternative to transmutation
   c. suitable as weapon pit disposal option
3. Programmatic advantages
   a. modularity of construction and expenditures: Drill as needed; pay as you go
   b. exceptional flexibility: can move rapidly to test, demonstrate, and implement; easy to switch sites, abandon individual holes; can vary hole spacing and depth depending on waste subcategory
   c. widespread site availability in United States and abroad; amenable to shared RD&D
   d. synergism with enhanced/engineered geothermal systems: similar rock and depths. Again eligible for shared RD&D
4. Disadvantages
   a. more difficult to ensure easy retrievability (but not impossible)
   b. limited commercial experience at hole diameters needed
   c. concerns over effects on local seismicity
   d. potential contamination of local groundwater due to confinement failure
   e. cannot accommodate oversize components
5. Future prospects
   a. research and development underway by several organizations on faster, hence less costly, drilling: factors of 2 to 5 claimed
   b. ideally suited for growing roster of small-user nations.

To cite but one feature: the widespread accessibility to continental bedrock should greatly facilitate the search for volunteer sites.

VII. RECOMMENDATIONS

The most productive next step in the development of deep borehole technology would be to begin field testing for scientific research purposes: for example, a small-diameter hole drilled to full depth, to confirm the ability to locate and qualify high-quality host rock; a shallower full-diameter hole for thermal tests using an electrically heated canister mock-up; and possibly in situ rock and seal tests in existing deep mines to confirm flow and radionuclide transport properties.

In parallel, a more comprehensive performance assessment model should be assembled, capable of both deterministic and probabilistic performance assessment of key metrics such as peak long-term dose to the reasonably maximally exposed individual. Reference 9 documents preliminary estimates.

Another priority area worth exploring is the potential role of deep boreholes for disposal of minor actinides and troublesome fission products as an alternative to their transmutation using reactors or accelerators. A comprehensive comparative cost/risk/benefit analysis could help inform decisions about future deployment of nuclear fuel cycle options.

Other, more circumscribed initiatives include the following:

1. *establishing a collaborative working agreement with those pursuing engineered/enhanced geothermal applications, who target similar (but more permeable) rock at comparable depths*: This can provide rock samples for permeability measurements (under simulated high downhole lithostatic pressures).

2. *tapping into oil/gas prospecting expertise to obtain a more quantitative assessment of how well deep rock properties can be inferred from surface and pilot hole measurements*: This includes techniques such as seismic propagation and the use of ground-penetrating radar. The ability to measure very low permeability downhole is a particular problem since oil and gas well developers work primarily with high-permeability (e.g., 10^{-12} m^2 = 1 darcy) rocks. Exercising this technology, including siting and creation of a test hole, would be of inestimable value. Such a hole or holes could also be used to

demonstrate downhole decay heat propagation and the performance of special measurements such as reducing chemistry (E_h). This measurement is difficult but possible on carefully acquired rock drillcore samples, and by inference from comparisons of measured rock chemical composition to equilibrium thermochemical E_h-pH calculations.

3. *Proceeding to further develop an implementation path based on the following overall guiding principles*:

   a. surface storage until a decision is made to proceed with nonretrievable disposition
   b. allowing primary reliance on geological and geochemical characteristics rather than only on special engineered waste package features
   c. perhaps separate consideration of a generic borehole configuration and specific site characteristics.

4. *Carrying out a comprehensive independent assessment of RD&D currently underway on advanced drilling technology in view of the fact that the emplacement-related costs of the deep borehole option are essentially inversely proportional to the drilling rate, and potential improvements by factors of 3 to 5 are being touted.*

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