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Introduction
On March 15, 2010 Sandia National Laboratories and the Massachusetts Institute of Technology (MIT) brought together roughly two dozen experts in the field of radioactive waste disposal to identify research needs for deep borehole disposal of nuclear waste. Following background presentations by the conveners and other participants, the attendees discussed research gaps and licensing and regulatory issues. The list of attendees, agenda, and presentations can be found below. A meeting summary follows.

Discussion
Discussion topics fell into 4 categories – Borehole Operations, Retrievability, Site Characterization, and Licensing. Discussion summaries for each category follow

*Borehole Operations*: Discussion focused on the need to understand drilling damage and extent and properties of the disturbed zone close to the borehole, and on the need for high integrity, low permeability seals to assure long-term isolation. Characteristics of the interface between the seals and the borehole wall will be particularly important. Fergus Gibb (Sheffield University) noted that using a “welded-rock” zone for part of the plug may be a promising approach. Several experts noted that it may be desirable to remove the steel liner in the zone above the waste before sealing. Others noted that wider boreholes become expensive rapidly. Estimated drilling outlays are very approximate because of fluid material costs, and the lack of extensive experience in the 30-50 cm diameter range.

Potential operational problems during emplacement, including damage to canisters and waste during the trip down the borehole, should be minimized, and it may be desirable to line the hole for its entire length with steel casing.
Some participants noted the value of establishing a reference design concept to provide a baseline for evaluating performance and impacts of alternative approaches.

**Retrievability:** Retrievability should be maintained through successful downhole insertion and up to the time the borehole is sealed. A slotted emplacement zone hole liner could be considered to facilitate grouting the liner to the hole wall and to the canisters. This would also provide support against crushing of bottom-most canisters and permit use of the simplest configuration: filling a single-branch vertical hole in stages, allowing the grout (cement) to dry before inserting the next upper set of canisters.

**Site Characterization:** Site, host rock, and hydrology characterization before, during and post-drilling and loading operations will be important for evaluating site viability and establishing the licensing basis. Examples of favorable site characteristics include tectonic stability, homogeneity of features such as permeability, high salinity of porewater at depth, and absence of overpressured zones. The use of natural analogues and evidence such as U-Pb indicators of transport can make major contributions to evaluating radionuclide mobility. Core samples will be useful sources of data. Both small and full-diameter boreholes can be used for acquiring key scientific information and for demonstrating key engineering and procedural features.

**Licensing:** The deep borehole approach could be difficult to license under regulations currently in effect in the US, which were written specifically for mined repositories.

Equally important were a number of engineering design and performance assessment principles recommended to guide future efforts:

a) It is important to separate those research needs that have a significant potential to impact the viability of the disposal concept from those that are less likely to do so.

b) It is important to focus on evaluating the viability of the concept at a generic level, considering a broad range of potential site conditions, and not narrow the siting search to a unique best-of-all sites.

c) Containment within the host formation (i.e., crystalline basement rock) should be the goal. Significant releases of radionuclides high-permeability into sedimentary overburden will make it more difficult to make a case for effective isolation.

d) The focus should be on the natural barriers and shaft seals, rather than on waste form and packaging. Unnecessary engineering enhancements could overly complicate the performance assurance effort. Simplicity is key.

e) Retrievability should not be allowed to compromise safety.
f) Information gained from the first hole in a disposal array should be used to simplify characterization of subsequent holes at the same site.

g) Surprises and a consequential evolution of requirements and features should be expected.

General research goals include:

I. To define a detailed reference base-case concept with as few variations as practicable but including: extent of casing, total depth, maximum diameter, lithology (with sedimentary cover or not), plugging/seals design, and perhaps minimum downhole standards;

II. To propose capabilities for pilot/prototypical holes to identify what is to be achieved and by when;

III. To identify what is needed for a compatible regulatory structure.

Table 1. Workshop Attendees

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
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<th>Institution</th>
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<tbody>
<tr>
<td>Bill Arnold</td>
<td>Sandia</td>
<td>Bill Murphy</td>
<td>NWTRB</td>
</tr>
<tr>
<td>Doug Blankenship</td>
<td>Sandia</td>
<td>Thomas Nicholson</td>
<td>NRC</td>
</tr>
<tr>
<td>Pat Brady</td>
<td>Sandia</td>
<td>Leonid Neymark</td>
<td>USGS</td>
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<tr>
<td>Dave Diodato</td>
<td>NWTRB</td>
<td>Mark Nutt</td>
<td>ANL</td>
</tr>
<tr>
<td>Mike Driscoll</td>
<td>MIT</td>
<td>Andrew Orrell</td>
<td>Sandia</td>
</tr>
<tr>
<td>Michael Fehler</td>
<td>MIT</td>
<td>Tom Peake</td>
<td>EPA</td>
</tr>
<tr>
<td>Fergus Gibb</td>
<td>U. Sheffield</td>
<td>Christine Pineda</td>
<td>NRC</td>
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<tr>
<td>Jim George</td>
<td>DOE</td>
<td>Dan Schultheisz</td>
<td>EPA</td>
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<tr>
<td>Jack Guttman</td>
<td>NRC</td>
<td>Andrew Sowder</td>
<td>EPRI</td>
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<tr>
<td>Bill Halsey</td>
<td>LLNL</td>
<td>John Stuckless</td>
<td>USGS (retired)</td>
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<tr>
<td>Kris Jensen</td>
<td>MIT</td>
<td>Johan Swahn</td>
<td>MKG, Sweden</td>
</tr>
<tr>
<td>Richard Lester</td>
<td>MIT</td>
<td>Peter Swift</td>
<td>Sandia</td>
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<tr>
<td>Allison Macfarlane</td>
<td>George Mason Univ.</td>
<td>John Ullo</td>
<td>Schlumberger</td>
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<tr>
<td>Christopher Markley</td>
<td>NRC</td>
<td>Roald Wigeland</td>
<td>INEL</td>
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</tbody>
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DOE = Department of Energy; EPA = Environmental Protection Agency; EPRI = Electric Power Research Institute; INL = Idaho National Laboratory; NRC = Nuclear Regulatory Commission; USGS = United States Geological Survey. Note: NRC and EPA attendees were present at the meeting as observers.
Workshop Agenda

When: March 15, 2010

Goals:

1. To develop and document a consensus on needed research for borehole disposal of nuclear waste.
2. To introduce the concept of borehole disposal to a broader range of interested observers, practitioners, and policy-makers in the nuclear waste field.
3. To engage knowledgeable people from outside the nuclear waste community with relevant technical expertise in developing insights into research needs for borehole disposal.

Schedule:

8.00-9.00 A.M. Overview, workshop goals (5 minute welcome: Andrew Orrell; 20 minute Engineering Overview Mike Driscoll; 20 minute Performance Overview – Peter Swift; 10 minute Workshop Plan - Pat Brady)
9.00-10.30 A.M. Panel 1: Criteria for siting and performance assessment (Lead: Bill Arnold; Kris Jensen)
10.30-12.00 P.M. Panel 2: Downhole engineering and design issues (Lead: Mike Driscoll; Doug Blankenship)
12.00-1.00 P.M. LUNCH
1.00-2.30 P.M. Panel 3: Regulatory and licensing issues (Lead: Peter Swift; Richard Lester)
2.30-3.30 P.M. General discussion; prioritization of research needs (Leads: Richard Lester; Pat Brady)
3.30 P.M. ADJOURN
Presentations

Peter Swift – Sandia

Goals for a Deep Borehole Disposal Workshop

Peter Swift
Sandia National Laboratories
SNL-MT Workshop on Deep Borehole Disposal
March 16, 2010
Washington DC

Outline

• Background
• Main conclusions from a recent SNL analysis of deep borehole disposal
• What we’re looking for today
  – Is deep borehole disposal a viable concept?
  – What are the research needs that will allow it to be fully evaluated?

Used Nuclear Fuel and High-Level Waste in the United States Today

Commercial Used Nuclear Fuel

DOE and Defense-Related Used Nuclear Fuel

Defence-Related and Commercial High-Level Radioactive Waste

Current Locations of Used Nuclear Fuel and High-Level Radioactive Waste in the United States

121 sites in 39 states

Commercial Used Nuclear Fuel

The US inventory of used fuel will increase in all scenarios

Existing power plants (above)
With new power plants (right)

Locations of NRC-Licensed Dry Storage Facilities for Used Fuel

• Currently 54 dry cask storage NRC-licensed Independent Spent Fuel Storage Installations (ISFSIs) in 23 states
• Orphaned Fuel. There are 14 shutdown reactors at 12 sites in 3 states with useable fuel in wet or dry storage
US Support for Research on Deep Borehole Disposal

- Historically, US evaluation of deep boreholes began in 1950s, extensive work in 1970s, again in 1990s.
- Early work established the basics of the concept; context has changed, but science remains sound.
- Current US activity:
  - MIT: ongoing work led by Mike Driscoll
  - Sandia: Lab-directed R&D beginning in 2009
  - DOE Office of Nuclear Energy reopens Federal consideration of the concept of deep borehole disposal in 2009.

New Observations from the Preliminary SNL Analysis

- All used fuel from the existing US LWR reactors could be placed in approximately 1000 deep boreholes.
  - SAND2009-4401 estimates that 159,300 MTHM of UO2 and HLW could be disposed of in ~550 boreholes.
- Total costs are competitive with mined repositories.
  - SAND2009-4401 estimates a very rough total program cost for the US of $71B.
- Long-term performance is likely to be excellent.
  - SAND2009-4401 estimates peak dose from a single disposal borehole containing 400 PWR assemblies to be 10^-9 mSv/yr, well below US and international standards.

Additional Observations from the Preliminary Sandia Analysis

- Further work is needed to test preliminary observations about long-term performance:
  - Scenario with other release pathways.
  - Thermal-hydrotologic-chemical-mechanical behavior of the borehole and surrounding rock should be modeled more accurately.
  - Seal design needs further basis.
  - Engineered materials that sequester iodine could increase confidence in near-zero releases.
  - Performance assessment analyses should address.

Additional Observations from the Preliminary Sandia Analysis (cont.)

- Detailed cost analysis would be beneficial.
- Consideration of changes in legal and regulatory requirements will be needed.
- Detailed analyses of engineering systems and operational practices for emplacement are needed.
- A full-scale pilot project should be undertaken.

Goals for the Workshop

- From the workshop agenda:
  - To develop and document a consensus on needed research for borehole disposal of nuclear waste.
  - To introduce the concept of borehole disposal to a broader range of interested observers, practitioners, and policy-makers in the nuclear waste field.
  - To engage knowledgeable people from outside the nuclear waste community with relevant technical expertise in developing insights into research needs for borehole disposal.
A Case for Disposal of Nuclear Waste in Deep Boreholes

Michael J. Driscoll
Massachusetts Institute of Technology
March, 2010

New Technical Factors Favoring Re-evaluation of Deep Boreholes

- Improved oil/gas/geothermal drilling technology especially for enhanced geothermal systems: same rock, same depth
- Successful Swedish & Finnish repository siting – same type of rock but in shallower (~500 m) mined repositories. Deep boreholes are slimmer, deeper (3 – 4 km) versions. Rock properties improve with depth (e.g., lower permeability)
- Improved host rock characterization methods: Again oil & gas developments. Both wide-field & downhole, e.g. seismic imaging, well logging

Favorable Aspects of Deep Boreholes

- Reducing chemistry: guarantees low solubility
- Extremely low rock permeability and water content/mobility
- Not heat load limited
- Inherently modular: Drill as needed, pay as you go
- Widespread applicability – can share international RD&D experience
- Simpler (but not trivial) to analyze: easier to understand case for safety assurance
- May be possible to separately license borehole technology and siting – analogous to process for standardized reactors
- Synergism with engineered geothermal systems (EGS)

Disadvantages of Deep Boreholes

- Harder to retrieve waste after final repository closure (but not impossible) (Advantageous for some waste classes)
- Cannot use for disposal of large intact contaminated components (not a pertinent goal?)
- Somewhat larger diameter than most other applications (i.e., 0.5 vs. 0.25 m); but can use smaller diameter for consolidated fuel or reprocessing waste forms
Worth mentioning is a possible factor inhibiting research in this area—the prohibition in the US Nuclear Waste Policy Act of 1982, as amended in 1987, of the evaluation of disposal into granite, to quote Sec. 161:

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

Target Downhole Properties

- **Salinity**
  - Unit volume
  - Salt-water interaction

- **Density**
  - Thickness
  - Density impact

- **Transmissivity**
  - Conductivity
  - Thermal conductivity

- **Porosity**
  - Permeability
  - Connectivity

- **Resistivity**
  - Thermal resistivity

MIT Findings over Past 20 Years

- Confirmation of work by others
- Prospects are good for a very effective sequestration
- The main escape threat is by transport in water
  - Most challenging radionuclide is I-131
  - Weakest link may be borehole plug
- The approach appears to be cost-effective: <100 $/kg HM for ready-to-use hole (1 mill/kWhr fee is equivalent to ~$400 $/kg HM)
- The thermal loading is quite tolerable – local max. rock temperature increase can be kept to 20° to 30°C

Summary/Conclusions/Recommendations

- Deep boreholes are worth reconsideration – especially as an alternative to transmutation
- Should exploit synergism with enhanced/engineered geothermal systems (EGS)

Some Priority Questions on Deep Borehole HLW Disposal

1. Is (near) all igneous continental bedrock (i.e., “granite”) similar with respect to key parameters (permeability, porosity, etc., salinity)?
2. Are self-filling methods currently adequate to measure these parameters in the range of interest for deep boreholes for HLW disposal?
3. Are current neutron methods (e.g., ground penetrating radar, geoelectricity, EM) adequate for borehole screening?
4. What is the practical current limit on borehole diameter (e.g., 0.5 m) and the cost of cementing/capping?
5. Can we do a borehole below in deep high-integrity granite?
6. Is it higher reliance on geology and geophysics and the lesser role of engineered defense in depth (e.g., canister materials) compared to shallower mind repositories, an acceptable strategy?
7. What must be emphasized should be placed on retrievability?
8. Is there significant commonality with boreholes drilled for enhanced geothermal systems?
9. Are there any unique socio-political licensing house factors to shallow mined repositories?
10. What factors would complicate deployment of these (e.g., of concrete, clay, and resins) that have long-term permeability comparable to the host rock?
11. What, in your opinion, is the biggest obstacle to putting deep boreholes a HLW disposal option?

Bibliography of MIT Work
Deep Borehole Disposal – Performance Assessment and Criteria for Site Selection

Bill W. Arnold, Peter N. Swift, and Patrick V. Brady
SNL-MIT Workshop on Deep Borehole Disposal
Washington, DC
March 15, 2010

Outline

• Deep borehole disposal concept
• Potential viability and safety of the concept
• Preliminary performance assessment (PA) analyses
• Research on unresolved technical issues
• Potential criteria for site selection

Deep Borehole Disposal Concept

• Vertical borehole drilled into crystalline basement to a depth of about 5 km
• Borehole is assessed for stress conditions, borehole stability, geochemistry, fluid pressures, permeability, etc.
• A string of waste containers with spent nuclear fuel assemblies or high-level radioactive waste glass is emplaced in the lower 2 km of borehole with approximately 45 cm diameter
• A borehole seal system consisting of compacted bentonite clay, asphalt, and concrete is used to seal the upper 3 km of the borehole

Disposal Concept Viability and Safety

• Crystalline basement rocks are relatively common at depths of 2 to 5 km
• Existing drilling technology permits construction of boreholes at a cost of about $50 million each
• Low permeability and high salinity in the deep continental crystalline basement suggest extremely limited interaction with shallow groundwater resources
• Geochemically reducing conditions limit the solubility and enhance the sequestration of many radionuclides
• Disposal could occur at multiple locations, reducing waste transportation costs and risks
• The deep borehole disposal concept is modular, with construction and operational costs scaling approximately linearly with waste inventory
• Disposal capacity would allow disposal of projected U.S. spent nuclear fuel inventory in about 350 boreholes

Preliminary Performance Assessment

• Define performance metric
• Identify relevant features, events, and processes (FEPs)
• Develop release scenario
• Define conceptual design and radionuclide inventory
• Develop conceptual and numerical models
• Representative parameter values used (probabilistic analyses not performed in preliminary PA)
• Compare PA analytical results to assumed performance metric
Preliminary Performance Assessment: Performance Metric

- Performance metrics are typically defined by regulations
- Given the lack of governing regulations for deep borehole disposal, the performance metric was assumed to be a risk-based dose standard
- The preliminary PA analysis was designed to estimate dose to a reasonably maximally exposed individual, similar in concept to the Yucca Mountain standard

Preliminary Performance Assessment: FEPs Analysis

- The list of 374 FEPs from the Yucca Mountain license application were considered for potential relevance to deep borehole disposal
- No new FEPs unique to deep borehole disposal were identified during the FEPs evaluation
- Preliminary screening of FEPs was based on several assumptions, such as the assumption that waste packages corrode quickly and are not significant barriers to flow and radionuclide transport
- Retrievability of waste assumed to be excluded as a position of policy
- Preliminary screening resulted in 119 FEPs that should be included in the PA analysis

Preliminary Performance Assessment: Release Scenario Selection

- A single release scenario that incorporates many of the most likely included FEPs was constructed for use in the PA
- This scenario includes the following:
  - Enhanced permeability in the disturbed zone and/or borehole
  - Thermally driven upward groundwater flow
  - Dissolution of radionuclides from the waste form and transport in the groundwater
  - Release of radionuclides into the shallower fresh groundwater system
  - Pumping of the contaminated groundwater and release to a receptor population

Preliminary Performance Assessment: Conceptual and Numerical Models

- Thermal conduction model used to simulate temperatures
- Results indicate a maximum temperature increase of about 30°C at the borehole wall
- Significant temperature increases do not persist beyond 100 to 200 years
- Results show a temperature increase of about 12.5°C for disposal of vitrified waste from reprocessing

Coupled Thermal-Hydrologic Model

- Grains was assigned a permeability of $1 \times 10^{-8} \text{ m}^2$
- Sealed borehole and disturbed hydrologic boundaries surrounding the borehole were assigned a value of $1 \times 10^{-8} \text{ m}^2$
- Results indicate upward vertical flow near the borehole driven primarily by thermal expansion, and not by free convection
- Upward flow (about 1.5 meter/year) persists for about 200 years at the top of the waste disposal zone
- Lesser upward flow (flux of up to 3.5 meter/year) occurs for about 50 years in the borehole at a location 1000 m above the waste
Groundwater Pumping and Dilution

- Radial 2.0 model of groundwater pumping and contaminant transport was constructed for the fresh water system in the upper 2000 m of the geosphere.
- Radionuclide mass would arrive more quickly to the higher-capacity pumping wells, but dilution would be greater.
- Quantitative estimates of delay and dilution were incorporated into the PA calculations.

Preliminary Performance Assessment: Conceptual and Numerical Models

- Dissolved solubility limits of radionuclides estimated for thermal—chemical conditions in the borahole and assuming solid oxide phases of radionuclides.
- Representative values of sorption coefficients under reducing conditions were based on literature.
- Decay and ingrowth of 31 radionuclides included.
- One-dimensional analytical solution for the advection–dispersion equation with sorption used for the analysis.
- Delay and dilution from pumping included in the analysis to calculate radionuclide concentrations released from the well.
- Biosphere dose conversion factors from the Yucca Mountain project used to calculate radiological dose.

Performance Assessment Results

- Peak radiological dose to an individual using contaminated groundwater from the hypothetical pumping well was calculated as 1.4 x 10^{-6} mSv/year (1.4 x 10^{-6} mSv/year).
- The only radionuclide contributing to the calculated dose is 90Sr, which has high solubility and is nonrecoiling.
- Peak dose was calculated to occur about 8,200 years following waste emplacement.
- For comparison, the regulatory limit for dose from the Yucca Mountain repository is 15 mSv/year (for the first 10,000 years) and 100 mSv/year (for up to 1,000,000 years).
- Preliminary analyses also indicate that nuclear criticality, molecular diffusion, and thermally induced hydrofracturing would not impact the safety of the disposal system.

Publication of Preliminary Results

Key Technical Issues

- Long-term behavior of borehole seals.
- Modeling of coupled thermal-hydrologic-chemical behavior near the borehole.
- Compounds that sorb/extract radionuclides (in particular, radioactive iodine) in the borehole or seals.
- More detailed performance assessment analyses:
  - Full consideration of features, events, and processes relevant to potential release pathways and scenarios.
  - Incorporation of more detailed modeling, including coupled processes, in particular:
  - Sealing up from single to multiple boreholes.
  - Criteria for site selection and borehole characterization.
  - Operational and engineering analysis of waste emplacement process.
  - More detailed cost analyses.

Potential Criteria for Site Selection

- Siting criteria should be based on potential impact to disposal performance.
- Discussion outlined here is limited to technical criteria for site selection—political/legal/economic considerations are clearly important, but outside the scope of this presentation.
- Criteria for site selection can be developed and applied at the scale of regional screening or at the scale of an individual borehole.
- For the screening level, criteria should be directed at improving the probability of success at any given location.
- Specific criteria for site suitability need to be defined at the level of an individual borehole.
Potential Criteria for Site Selection

- Preliminary list of siting criteria:
  - Depth to crystalline basement
  - Depth to saline groundwater
  - Anisotropy in horizontal stress
  - Fluid overpressure at depth
  - Geochemically reducing conditions at depth
  - Permeability of host rock
  - Tectonic stability
  - Volcanism
  - Geochemical gradients
  - Mineral resource potential
  - Topographic relief

Potential Criteria for Site Selection

- Potential Criterion: Depth to crystalline basement
  - Issues:
    - Crystalline basement should be less than 2 km deep
    - Overlying sedimentary strata with porous media-hosted fresh groundwater flow system may be desirable for isolation of the deeper fractured crystalline basement
    - Granite may be desirable type of crystalline basement
    - Can be evaluated at the screening level in many areas

Potential Criteria for Site Selection

- Potential Criterion: Depth to saline groundwater
  - Issues:
    - Saline groundwater indicates limited natural interaction with shallow fresh groundwater resources
    - Higher density of saline groundwater opposes upward groundwater movement via thermal convection
    - Saline groundwater in crystalline rock is not a target for pumping under most circumstances
    - Favorable geochemical conditions are generally associated with saline groundwater (e.g., reducing conditions)
    - Can be evaluated at the screening level in many areas, but requires confirmation by drilling

Potential Criteria for Site Selection

- Potential Criterion: Anisotropy in horizontal stress
  - Issues:
    - Borehole stability during drilling, emplacement operations, and post-closure development of borehole seals
    - Interaction with thermal stresses
    - May impact the effectiveness of borehole seals
    - Can be assessed using borehole geophysical methods
    - Can be evaluated at the screening level in some areas, but requires confirmation by drilling

Source: USGS Circular 1333
Potential Criteria for Site Selection

• Potential Criterion: Anisotropy in horizontal stress

  - Issues:
    - May be important to the stability and integrity of the repository
    - May affect the permeability and the ability to seal the repository

Potential Criteria for Site Selection

• Potential Criterion: Fluid overpressure at depth

  - Issues:
    - May provide a pathway for upward migration of groundwater in areas of disturbed zone
    - Can result from a number of hydrogeological conditions, including topographically driven flow, sediment compaction in active basins, bedrock faulting (e.g., fault), high thermal output in crystalline rocks (increasing convective flows), generation of gas, continental glaciation, and volcanism
    - May be difficult to assess within a borehole
    - Can be evaluated at the screening level in some areas, but requires confirmation by drilling

Potential Criteria for Site Selection

• Potential Criterion: Geochemical reducing conditions

  - Issues:
    - May affect the stability and integrity of the repository
    - Redox conditions can be determined from hydrochemistry and mineralogy of the host rock
    - May be related to the stability and integrity of the waste, grout, and any radionuclide 'trap' added to them
    - Expect geochemically reducing conditions at depth at all locations, but requires confirmation by drilling

Potential Criteria for Site Selection

• Potential Criterion: Permeability of host rock

  - Issues:
    - Low permeability of fractured crystalline host rock is expected, but experience indicates that some fracture zones with relatively high permeability can occur at great depth
    - Higher-permeability fracture zones not necessarily connected to shallower groundwater flow system
    - Fractures can be identified with geophysical logging or borecore
    - Fracture aperture can be estimated with geophysical logging
    - Higher-permeability zones within the disposal zone can be sealed and not used for emplacement of waste
    - Permeability generally decreases with depth, but requires confirmation by drilling

Potential Criteria for Site Selection

• Potential Criterion: Tectonic stability

  - Issues:
    - Important to the sealing and fault movement
    - Related to seismic hazard (probably not important to post-closure performance, but possibly important during operational phase)
    - May be relevant to overpressure (or underpressure) at depth
    - Can be evaluated at the screening level in all areas

Source: D'Agnessa et al. (1987)
Potential Criteria for Site Selection

- Potential Criterion: **Volcanism**
  - Issues:
    - Direct release pathway to the surface
  - Can be evaluated at the screening and site-specific levels in most areas

- Potential Criterion: **Geothermal gradient**
  - Issues:
    - High geothermal gradient may be indicative of upward groundwater flow (overpressures at depth), high thermal-output crustal basement, tectonically active regime, or volcanism
    - Very high geothermal gradient might be a target for geothermal resource development and lead to human intrusion
    - Very high geothermal gradient may lead to unacceptable high temperatures with the addition of decay heat from the waste
  - Can be evaluated at the screening level in some areas, but requires confirmation by drilling

- Potential Criterion: **Mineral resource potential**
  - Issues:
    - Presence of mineral resources in the disposal zone could lead to human intrusion
    - Very few mineral resources are targets for exploration or exploitation at depths of greater than 2 km in crystalline rock
  - Can be evaluated at the screening level in many areas, but requires confirmation by drilling

- Potential Criterion: **Topographic relief**
  - Issues:
    - High topography can result in regional groundwater flow that penetrates to great depths
    - Upward groundwater flow resulting from overpressure at depth occurs at some locations in deep regional groundwater flow systems
    - Topographically-driven regional groundwater flow can extend for hundreds of kilometers from some mountain fronts
  - Can be evaluated at the screening level in all areas
Criteria for Siting

- **Technical Siting Criteria**
  - Imperious crystalline rock – suitable basement rock must have extremely low permeability.
  - A good indicator for the isolating strength of basement rock is the age of groundwater.
  - Far from volcanic and seismic activity.
  - Cool rock: As a guideline, temperatures should be below 100°C at film depths to prevent overheating of waste assemblies and to make the site unsuitable for geothermal development.
  - Homogeneous horizontal geology free of vertical fractures.

Basement Rock Properties

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<th>Type</th>
<th>Value</th>
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<tbody>
<tr>
<td>Density, ( \rho )</td>
<td>2900 ( \text{kg/m}^3 )</td>
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<tr>
<td>Heat capacity, ( Q_i )</td>
<td>0.75 ( \text{kcal/kg} )</td>
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<tr>
<td>Thermal Conductivity, ( k ), ( \text{W/m} \cdot \text{K} )</td>
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</tr>
<tr>
<td>Thermal Diffusivity, ( a ), ( \text{m}^2/\text{sec} )</td>
<td>( \frac{k}{\rho C_p} )</td>
</tr>
<tr>
<td>Geothermal Gradient, ( \text{C/m} )</td>
<td>15</td>
</tr>
</tbody>
</table>
| Permeability, \( k \), \( \text{m}^2 \) | \( < 10^{-10} \) (\( \text{m}^2 \) sec)
| Lithostatic Pressure, \( \text{psi} \) | 250 |
| Unconfined Compressibility, \( \nu \) | 3 |
| Porosity, \( \phi \) | 0.3 |
| Young’s Modulus, \( E \), \( \text{MPa} \) | 50,000 |
| Mechanical Strength in Compression, \( R_c \) | 130 |
| Tensile Strength, \( R_t \) | 18 |
| Coefficient of linear thermal expansion, \( \alpha \), \( \text{m/}^\circ\text{C} \) | 8.0 \( \times 10^{-6} \) |

Useful Site Pre-Screening Maps

- **Preburnup Baseline Presence**
  - Shows where access to stable geologic rock is easiest.

- **Borehole Sites**
  - Provides geological information but needs to avoid vertical core conduits.

- **Geothermal Gradient**
  - Helps to limit the potential for evaporation and over print/alt retroflection.

- **Real Stress, Failing**
  - Regions to avoid.

- **Eruptive Activity**
  - Indicates the presence of fissures.

- **Proximity to Aquifer Locations**
  - Perforated regions.

- **Well Drilling**
  - May be preferable to scrub.

- **Fuel Rod, Waste Transportation**
  - Waste transport access to site for construction and deployment.

- **Source:**
  - USDOE, www.oepe.gov
  - EIA, NASA, GRACE Project
  - www.naturalisland.org

Borehole Wide-Area Survey Methods

<table>
<thead>
<tr>
<th>Author</th>
<th>Information</th>
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<tbody>
<tr>
<td>Geomorphology</td>
<td>Groundwater, geologic profiles</td>
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<tr>
<td>Geophysical</td>
<td>Location, size, shape of rock masses</td>
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<tr>
<td>Ground Penetrating Radar</td>
<td>Depth of sedimentary overburden, underground aquifers</td>
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<tr>
<td>Radiometric</td>
<td>Radioactive contamination helps in site delineation, assessment of uniformity</td>
</tr>
<tr>
<td>Seismic</td>
<td>Depth of sedimentary overburden, underground aquifers</td>
</tr>
<tr>
<td>Seismic Tomography</td>
<td>Depth of sedimentary overburden, underground aquifers</td>
</tr>
<tr>
<td>Petrophysical</td>
<td>Presence of water-potential, lack of atmosphere for tunnel drilling</td>
</tr>
<tr>
<td>Seismic Tomography</td>
<td>Rough estimate of subterranean topography</td>
</tr>
</tbody>
</table>
Some Observations on Deep Borehole Disposal of Spent Nuclear Fuel and High-level Nuclear Waste

William M. Murphy
David M. Diodato

Workshop on Research Needs for Borehole Disposal
Washington, DC
15 March 2010

General Observations

• Geologic disposal is the most technically viable approach to isolating high-level nuclear wastes and spent nuclear fuel for times approaching perpetuity
• Deep borehole disposal is a technically viable type of geologic disposal

Critical Aspects of Borehole Disposal

• Many potentially suitable lithologies
• Some geologic settings are more suitable than others for safe and reliable borehole disposal
• Engineered elements must function in harmony with natural system characteristics
• To reduce uncertainty and enhance confidence, sustained testing and analysis of geologic and engineered elements critical to system performance is required

Host Rock Selection

• Host rock selection should be based on rock characteristics (not simply lithology)
• Advantageous rock characteristics include:
  – Low permeability
  – High cation exchange capacity/sorption
  – Predictable fracture occurrence and properties

Geologic Setting

• Geologic setting is extremely important to safe and reliable isolation
• Advantageous geologic setting attributes:
  – No natural resources
  – Low heat flux
  – Stable in situ stress regime; geologic stability
  – Reducing geochemical environment
  – Characterized rock and water chemistry

Engineered Systems

• Boreholes should provide sufficient isolation without requiring engineering enhancements
• Engineered systems must operate in harmony with natural system
• Advantageous engineered system attributes:
  – No deleterious materials
  – Compatible with in situ geochemistry
  – Predictable degradation behavior
Fergus Gibb – Univ. of Sheffield

DEEP BOREHOLE DISPOSAL

1. The UK Position
2. The Advantages
3. The Concepts [Sheffield]
4. Towards Full-scale Demonstration

Advantages of Deep Boreholes

1. SAFETY
2. COST-EFFECTIVENESS
3. ENVIRONMENTAL IMPACT
4. SMALL ‘FOOTPRINT’
5. SITE AVAILABILITY
6. DISPERSED DISPOSAL
7. FLEXIBILITY
8. INSENSITIVE to COMPOSITION
9. LONGEVITY
10. EARLY IMPLEMENTATION
11. ACCEPTABILITY?
DEEP BOREHOLE DISPOSAL (DBD)
  a.k.a. VERY DEEP DISPOSAL (VDD)

- Low T° VDD
  1. Vitrified HLW
  2. SNF
  3. Pu
- High T° VDD
  Spent MOX
  High Burn-up SF

---

**Constructing the borehole:**
- Drill the first stage of the borehole
- Insert the casing
- Pour the cement base-plug
- Drill the next stage of the borehole
- Insert the casing
- Pour the cement base-plug
- Drill the next stage of the borehole
- And so on, down to > 4 km

Diameter: 0.5 - 0.8 m

**Low Temperature Very Deep Disposal**

**Vitrified waste:**
- Insert the final run of casing
- Emplace the first batch of HLW canisters
- Pump in the grout and allow it to set

**Sealing the borehole:**
- Pour in some backfill (crushed granite)
- Insert beacon and seal backfill & wall-rock to seal the borehole
- Pour in more backfill and seal the borehole again
- Repeat as often as required then fill the rest of the borehole with backfill
- 3 km deep (topmost canister)
Regulatory and Licensing Topics Relevant to Deep Borehole Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste in the United States

INL-MIT Workshop on Deep Borehole Disposal
March 15, 2010
Washington DC

The Nuclear Waste Policy Act

- No disposal options other than Yucca Mountain are possible without amending the NWPA
  - Sec. 112(c)(d): "If the Secretary at any time determines that the Yucca Mountain site is not suitable for development as a repository, the Secretary shall...
  - (F) report to Congress within 6 months with a recommendation for further action...
- If Yucca Mountain does not receive a construction license, no federal interim storage options are possible without amending the NWPA
  - Sec. 146(d)(1): "Construction of such facility may not begin until the Commission has issued a license for the construction of a repository under section 125(d)."

The Nuclear Waste Policy Act (cont.)

- Special provisions potentially relevant to deep boreholes
  - Sec. 161(d): Additional site criteria specific to crystalline rock should such site be considered at any time after enactment
    - "seasonal increase in population"
    - "proximity to public drinking water supplies, including those of metropolitan areas; and"
    - "impacts on tribal lands"

The Nuclear Waste Policy Act (cont.)

- Retrieval
  - Sec. 112: "Notwithstanding any other provision of this subchapter, any repository constructed on a site approved under this subchapter shall be designed and constructed to permit the retrieval of any spent nuclear fuel placed in such repository, during an appropriate period of operation of the facility, for any reason pertaining to the public health and safety, or the environment, or for the purpose of permitting the recovery of the economically valuable contents of such spent fuel. The Secretary shall specify the appropriate period of retrievability with respect to any repository at the time of design of such repository, and such aspect of such repository shall be subject to approval or disapproval by the Commission as part of the construction authorization process under subsections (b) through (d) of section 114..
" (emphasis added)
Regulations for Long-term Performance of Repositories

- Yucca Mountain regulations (40 CFR part 97 and 10 CFR Part 63) apply only to Yucca Mountain.
- Existing regulations that predate the 1987 NWPA amendments could, in principle, be applied to other disposal concepts for SNF/HW without revision.
  - EPA 40 CFR part 151 (Implemented for the Waste Isolation Pilot Plant [WIPP]).
  - NRC 10 CFR part 60 (never implemented).

Regulations for Long-term Performance of Repositories (cont.)

- 10,000-yr Containment Standard (cumulative release)
  - Requires consideration of human intrusion:
    - 10 boreholes/km²/10,000 yr for repositories
    - In proximity to sedimentary rock formations:
    - 3 boreholes/km²/10,000 yr for other locations.
- Release limits normalized to initial inventory.
- Cumulative limits remove uncertainty associated with exposure pathways and future human lifetimes.
- 10,000-yr Individual Protection Standard (15 mrem/yr).
- Undisturbed performance only (no intrusion).
- 10,000-yr Groundwater Protection Standard.
- Undisturbed performance only (no intrusion).

Regulations for Long-term Performance of Repositories (cont.)

- Requires compliance with EPA standards at 40 CFR 191.
- Also requires:
  - Substantially complete containment in waste packages for 500 years.
  - Release rate of each radionuclide from the engineered barrier system shall not exceed one part in 100,000 per year of the inventory of that nuclide at 1000 years.
  - Fasted path of likely radionuclide travel to the accessible environment shall be at least 1,000 years.

Implications of Existing US Regulations for Deep Borehole Disposal

- 40 CFR part 191
  - Normalized cumulative release standard could apply same standard to single boreholes or disposal arrays.
  - Half-effective release in large disposal arrays should be reduced.
  - Retroactivity is required to be possible.
  - No CSE on safety.
  - Disposal systems shall be selected so that removal of most of the waste is not precipitated for a reasonable period of time after disposal.
  - Any current concept for a mixed geologic repository means the repository shall be: 1. Integrated with the repository; 2. Providing a barrier to radionuclide migration; 3. Providing an active safety function; 4. Providing an active barrier to radionuclides.
  - Human intrusion specifications may be inappropriate for deep boreholes.
- 10 CFR part 60
  - Subsystem replacement for the waste package may be inappropriate for deep boreholes.
  - Allowing incompatibility with license amendment.
- US CSE stat: "an amendment shall be required... for any action which would make dispersed high level radioactive waste infeasible...

Implications of Existing US Regulations for Deep Borehole Disposal (cont.)

  - Regulations focus on subsurface injection of fluids, but may apply to deep borehole disposal.
- 40 CFR 140.5(a) defines Class 1, Type 3, injection wells as "Radioactive waste disposal wells which inject fluids below the lowermost formation containing an underground source of drinking water within one quarter mile of the well bore."
- Permitting authority varies from state to state.
- Compliance with 40 CFR part 144 was considered for WIPP: DOE concluded that evaluation in WIPP would not constitute "injection" (DOE/CA-1994-214, BEIR Section 2.1).

International Perspectives

- International Atomic Energy Agency
  - Section 1.14: "Geological disposal, as a concept, encompasses a range of options, including disposal in specially mined and engineered facilities, disposal in pre-existing mines and excavations, and disposal in deep boreholes."
  - Section 1.8: "The operational period... may include activities for waste retrieval, if considered necessary, prior to closure."

  - Section 1.14: "Geological disposal, as a concept, encompasses a range of options, including disposal in specially mined and engineered facilities, disposal in pre-existing mines and excavations, and disposal in deep boreholes."
  - Section 1.8: "The operational period... may include activities for waste retrieval, if considered necessary, prior to closure."
Perspectives on Retrievability

- Ethical, social, and political considerations are probably beyond the scope of this workshop
- Two quotes to consider
  - “The introduction of provisions for retrievability must not be detrimental to long-term safety. Thus, for example, locating a repository at a depth that is less than optimum from a long-term safety perspective in order to facilitate retrieval is unlikely to be acceptable…” (NEA 2001, Reversibility and Retrievability in Geologic Disposal of Radioactive Waste: Reflections at the International Level)
  - “...deep borehole systems may not be the best choice if permanent and irreversible disposal is not intended.” (Brady et al., 2000)

Dose vs. Cumulative Release Standards

- Dose
  - Emphasis on low annual dose or risk
  - Can be open-ended in time (or to peak dose)
  - Uncertainty in human behavior (e.g., water use and diet) is large
  - Encourages dilute and gradual release as well as isolation
  - Encourages smaller initial inventories

- Cumulative Release
  - Emphasis on location
  - Measurable only over specified time period
  - Allowable limit is a function of time
  - Focuses on uncertainty in barrier performance
  - No benefit for dilution
  - Normalization to initial inventory (as in 40 CFR 1911) removes incentive for smaller repositories

Implications for Deep Borehole Disposal (cont.)

- Any new standards are likely to be based on annual dose or risk
  - Consistent with IAEA guidelines and recommendation of the 1995 National Academies report on Yucca Mountain standards
- Any new standards are likely to extend to 1 million years
  - Consistent with recommendation of the 1995 National Academies report on Yucca Mountain standards
- It may be appropriate for new standards to reconsider
  - Human intrusion scenarios
  - Retrievability
Table 2. Long-term research questions developed and prioritized (1 being most important) by the workshop attendees.

<table>
<thead>
<tr>
<th>Order</th>
<th>Research Question</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><strong>Design of a Pilot:</strong> Shallow for testing emplacement engineering; Full depth to prove it can be done and recovered (Both actual diameter). Establish nature and role of field-scale pre-emplacement pilot testing.</td>
</tr>
<tr>
<td>2</td>
<td><strong>Borehole sealing/drilling:</strong> What happens if you can’t seal the borehole? How many holes will fail/be abandoned? Rock welding?</td>
</tr>
<tr>
<td>3</td>
<td><strong>Geochemistry:</strong> Uranium mobilization evidences, extent of coring and analysis? Paleohydrologic indicators; natural analogues. Note: this is a part of a larger groups of methods to interrogate hydrogeochemical stability. Fracture filling stability, heterogeneity, effect on performance, sensitivity to drilling (mud compatibility)</td>
</tr>
<tr>
<td>4</td>
<td><strong>Drilling:</strong> Assess the link between drilling and disturbed rock permeability. Show that borehole environment and performance is not deleteriously perturbed by drilling/emplacement.</td>
</tr>
<tr>
<td>5</td>
<td><strong>Reliability and Surveillance:</strong> How to demonstrate: bentonite in the annulus, bridge plug emplacement and performance, sensor performance and sensor parameter targets</td>
</tr>
<tr>
<td>6</td>
<td><strong>Hydrology:</strong> Establish lithologic heterogeneity controls over large-scale fluid convection in borehole disturbed zone.</td>
</tr>
<tr>
<td>7</td>
<td><strong>Waste Form:</strong> Ordinary casing?, high quality stainless steel? something else? Fuel consolidation (thermal load)</td>
</tr>
<tr>
<td>8</td>
<td><strong>Downhole Testing:</strong> What tools are missing? E.g. acoustic and electromagnetic techniques that allow continuous surveillance of vertical fluid motion.</td>
</tr>
<tr>
<td>9</td>
<td><strong>Geology:</strong> Geopressured zones at depth: How to detect/predict/pre-screen? How to show when/if it doesn’t matter.</td>
</tr>
<tr>
<td>10</td>
<td><strong>Drilling:</strong> Establish value of casing all the way down?</td>
</tr>
<tr>
<td>11</td>
<td><strong>Performance:</strong> Glacial effects</td>
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