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Deep Borehole Disposal of Nuclear Waste: Report from a Sandia-MIT Workshop on March 15, 2010 in Washington, DC.

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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. After a series of presentations by the conveners, Bill Murphy and Dave Diodato of the Nuclear Waste Technical Review Board (NWTRB), Fergus Gibb (U. Sheffield), Bill Halsey (Lawrence Livermore National Laboratory [LLNL]), and Johan Swahn (Swedish Office for Nuclear Waste Review [MKG]), 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

High priority issues that were discussed fall into 4 categories – Drilling, Retrievability, Site Characterization, and Licensing. Discussion summaries for each category follow

Drilling Special attention must be paid to drilling damage and the disturbed zone close to the borehole, and to the design of high integrity plugs, if the desired high assurance of sequestration is to be achieved. Plug/hole interfacing will be particularly important. A "welded-rock" zone for part of the plug may be a promising approach. The steel wall liner in the zone above the waste should be removed before sealing. 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. Damage to spent fuel on the trip down should be prevented at all cost.

Retrievability Retrievability should be maintained through successful downhole insertion and up to the time the the borehole is sealed. A slotted emplacement zone hole liner should be considered to facilitate grouting the liner to the hole wall and to the canisters. This will 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 and host rock and hydrology characterization before, during and post-drilling and loading operations is essential. Homogeneity and universality of features such as permeability, absence of geopressured zones and major faulting, will require explicit attention. The use of natural analogues and evidence such as U-Pb evidence of mobility can make major contributions. Core samples will be useful sources of data. There is a priority need for drilling both small and full-diameter boreholes for acquisition of key scientific information and also for demonstration of 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 out and relegate aspects to the "it does not matter category" and distinguish between "want to know" vs. "need to prove."
b) It is important to focus on and demonstrate generic applicability and not narrow the siting search to a unique best-of-all sites.
c) Should significant quantities of radionuclides escape from the crystalline basement rock into high-permeability sedimentary overburden it should be conceded that one has lost the case for confinement assurance.
d) The focus should be on the natural barriers, and not the harder to prove "artificial" barriers. Abnormal engineering enhancements will overly complicate the performance assurance effort. Simplicity is key.
e) Retrievability should not be allowed to compromise safety.
f) Avoid requiring full-scope re-affirmation on production holes.
g) Expect surprises and a consequential evolution of requirements and features.

General research goals include:

I. 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. Propose capabilities for pilot/prototypical holes to identify what is to be achieved and by when;

III. Identify what is needed for a compatible regulatory structure.

Table 1. Workshop Attendees

Bill Arnold	Sandia	Bill Murphy	NWTRB
Doug Blankenship	Sandia	Thomas Nicholson	NRC
Pat Brady	Sandia	Leonid Neymark	USGS
Dave Diodato	NWTRB	Mark Nutt	ANL
Mike Driscoll	MIT	Andrew Orrell	Sandia
Michael Fehler	MIT	Tom Peake	EPA
Fergus Gibb	U. Sheffield	Christine Pineda	NRC
Jim George	DOE	Dan Schultheis	EPA
Jack Guttman	NRC	Andrew Sowder	EPRI
Bill Halsey	LLNL	John Stuckless	USGS (retired)
Kris Jensen	MIT	Johan Swahn	MKG, Sweden
Richard Lester	MIT	Peter Swift	Sandia
Allison Macfarlane	George Mason Univ.	John Ullo	Schlumberger
Christopher Markley	NRC	Roald Wigeland	INEL

DOE = Department of Energy; EPA = Environmental Protection Agency; EPRI = Electric Power Research Institute; INEL = Idaho National Engineering 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

Where: The Mayflower® Renaissance Washington, DC Hotel, 1127 Connecticut Avenue NW, Washington, DC, 20036-4301, (202) 347-3000.

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

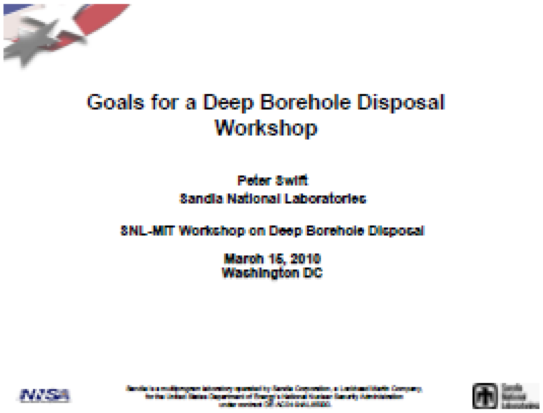
1.00-2.30 P.M. Panel 3: Regulatory and licensing issues (Lead: Peter Swift; Richard Lester)

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

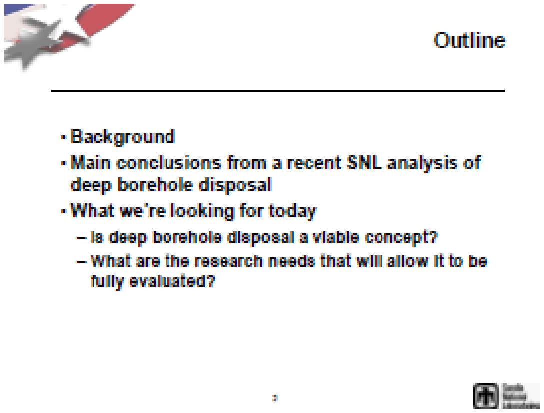


Goals for a Deep Borehole Disposal Workshop

Peter Swift
Sandia National Laboratories

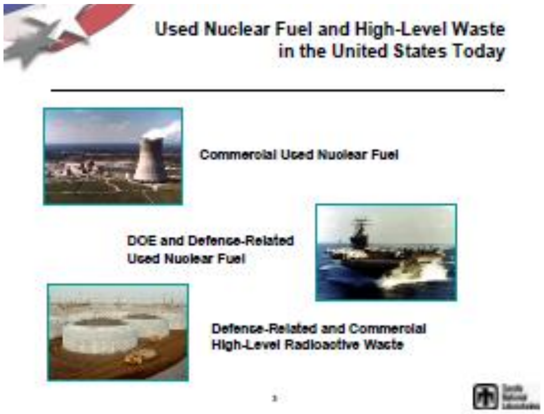
SNL-MIT Workshop on Deep Borehole Disposal

March 15, 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?

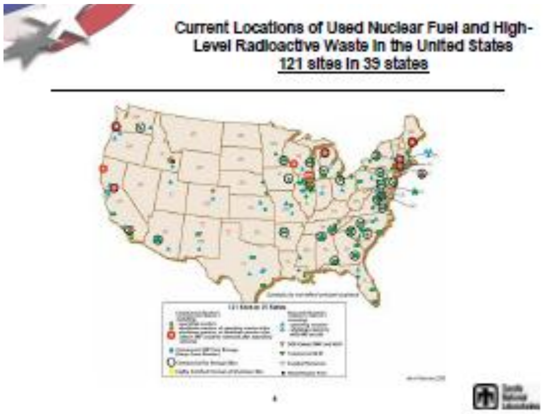


Used Nuclear Fuel and High-Level Waste in the United States Today

Commercial Used Nuclear Fuel

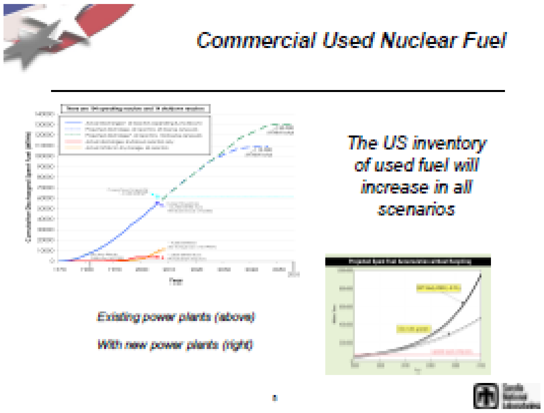
DOE and Defense-Related Used Nuclear Fuel

Defense-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 33 states
- Orphaned fuel: There are 14 shutdown reactors at 13 sites in 9 states with used 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 emplaced in approximately 1000 deep boreholes
  - SAND2009-4401 estimates that 109,300 MTHM of UNF and HLW could be disposed of in ~950 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^{-10} mrem/yr (10^{-12} 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
  - Scenarios with other release pathways
  - Thermal-hydrologic-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

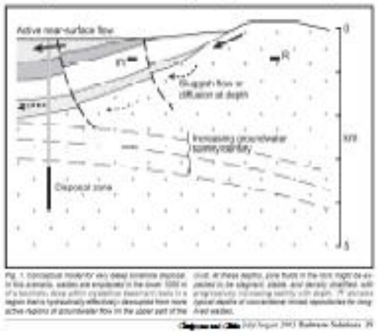
- From the workshop agenda
  - To develop and document a consensus on needed research for borehole disposal of nuclear waste
  - To introduce the concept of borehole disposal to a broader range of interested observers, practitioners, and policy-makers in the nuclear waste field
  - To engage knowledgeable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

Mike Driscoll – MIT

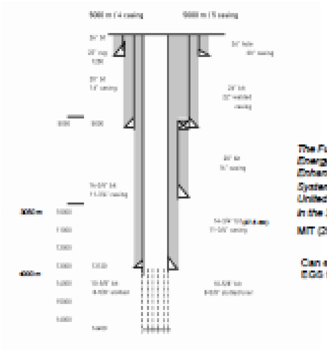
A Case for Disposal of Nuclear Waste in Deep Boreholes

Michael J. Driscoll
Massachusetts Institute of Technology
March, 2010

Conceptual Model for Very Deep Borehole Disposal



4- and 5-Interval 5,000 m Casing



The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century. MIT (2006), p. 6-47

Can easily adapt EGS technology

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.

Location of Surface Exposures of Crystalline Basement Rocks in the US

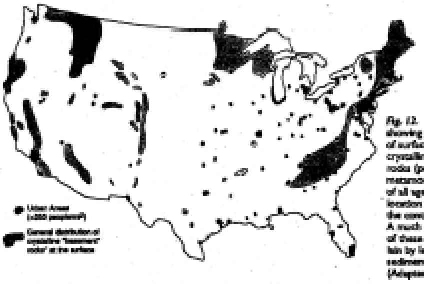


Fig. 12. General map showing the distribution of surface exposures of crystalline basement rocks (predominantly metamorphic and plutonic) of all ages as well as the location of urban areas in the conterminous US. A much larger distribution of these rock types is overlain by less than 1 km of sedimentary rocks. (Adapted from Flawn, 1967.)

Target Downhole Properties

An important goal is setting specifications for necessary and sufficient rock and water properties for deep borehole HLW disposal applications. They should be adequate to ensure the high level of sequestration required and at the same time be widely prevalent.

Candidate Properties Include:

Feature	Specification	Comment
Dominant Criterion: Permeability	$< 10^{-6}$ Darcy	To ensure low water movement velocity
Ancillary Goals: Porosity	< 1% by volume	% interconnected, and hydraulic diameter are also important, as contributors to low permeability
Water Content	< 1% by volume	Follows from low porosity
Downhole Pressure	Close to lithostatic or hydrostatic	To avoid excessive gradients
Salinity Density Increase	> 40 g/kg	Thwarts buoyant vertical convection in uppermost one km.
E_h (potential relative to hydrogen electrode)	< –0.1 volt	Characterizes reducing nature of environment; assures low solubility
pH (acid/base characterization)	> 6; < 9	Also helps reduce corrosion and maintain low solubility
Retardation Factor	> 100 for most species	Adsorption on rock reduces rate of transport by this factor

MIT Findings over Past 20 Years

- Confirmative of work by others
- Prospects are good for very effective sequestration
- The main escape threat is by transport in water
  - Most challenging radionuclide is I-129
  - Weakest link may be borehole plug
- The approach appears to be cost-effective: <100 $/kg HM for ready-to-use hole (1 mill/kWhre 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)

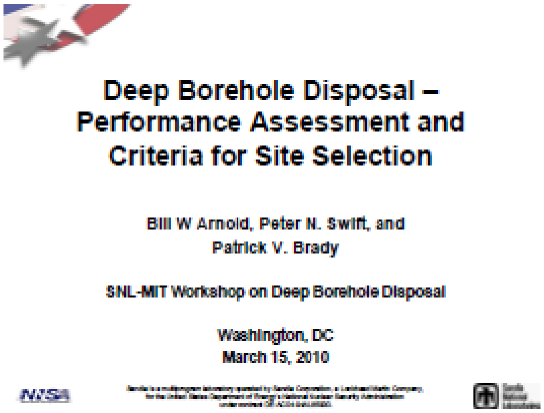
Some Priority Questions on Deep Borehole HLW Disposal

1) Is (nearly) all igneous continental bedrock (i.e., "granite") similar with respect to key parameters (permeability, porosity, E_h, pH, salinity)?
2) Are oil well logging methods currently adequate to measure these parameters in the range of interest of deep boreholes for HLW disposal?
3) Are current remote survey methods (seismic, ground penetrating radar, gravimetric, EM) adequate for initial site screening?
4) What is the practical current limit on borehole diameter (e.g. ~ 0.5m?) and the cost vs. diameter dependence?
5) Can we do without borehole liners in deep high-integrity granite?
6) Is the higher reliance on geology and geochemistry and the lesser role of engineered defense in depth (e.g. canister materials), compared to shallower mind repositories, an acceptable strategy?
7) How much emphasis 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 issues compared to shallower mined repositories?
10) What factors could complicate emplacement of seals (e.g. of concrete, clay, and asphalt) that have long-term permeability comparable to the host rock?
11) What, in your opinion, is the biggest obstacle to pursuing deep boreholes as a HLW disposal option?

Bibliography of MIT Work

- W.-S. Kuo, M. J. Driscoll, J. W. Tester, "Re-evaluation of the Deep Drillhole Concept for Disposing of High-Level Nuclear Wastes," Nuclear Science Journal, Vol. 32, No. 3, June 1995
- W.-S. Kuo, "Evaluation of Deep Drillholes for High Level Nuclear Waste Disposal," Nucl. Eng./SM Thesis, MIT Nuclear Engineering Dept., 1991
- C. R. Sizer, C. I. Hoag, S. Shaikh, M. J. Driscoll, "Partitioning and Interment of Selected High Level Wastes," Trans. Am. Nucl. Soc., Vol. 96, June 2007
- C. R. Sizer, "Minor Actinide Waste Disposal in Deep Geological Boreholes," SB Thesis, MIT Dept. of Nuclear Science and Engineering, May 2006
- C. I. Hoag, "Canister Design for Deep Borehole Disposal of Nuclear Waste," SM Thesis, MIT Dept. of Nuclear Science and Engineering, Sept. 2006
- V. K. Anderson, "An Evaluation of the Feasibility of Disposal of Nuclear Waste in Very Deep Boreholes," SM Thesis, MIT Dept. of Nuclear Science and Engineering, Sept. 2004
- S. Shaikh, "Effective Thermal Conductivity Measurements Relevant to Deep Borehole Nuclear Waste Disposal," SM Thesis, MIT Dept. of Nuclear Science and Engineering, Jan. 2007
- T. A. Moulton, "Parametric Study of the Total System Life Cycle Cost of an Alternate Nuclear Waste Management Strategy Using Deep Boreholes," SM Thesis, MIT Dept. of Nuclear Science and Engineering, Sept. 2008
- B. Sapiie and M. J. Driscoll, "A Review of Geology-Related Aspects of Deep Borehole Disposal of Nuclear Wastes," MIT-NFC-TR-109, Aug. 2009
- B. Sapiie, M. J. Driscoll and K. G. Jensen, "Regional Examples of Geological Settings for Nuclear Waste Disposal in Deep Boreholes," MIT-NFC-TR-113, Jan. 2010
- K. G. Jensen and M. J. Driscoll, "A Framework for Performance Assessment and Licensing of Deep Borehole Repositories," MIT-NFC-PR-112, Jan. 2010

Bill Arnold – Sandia

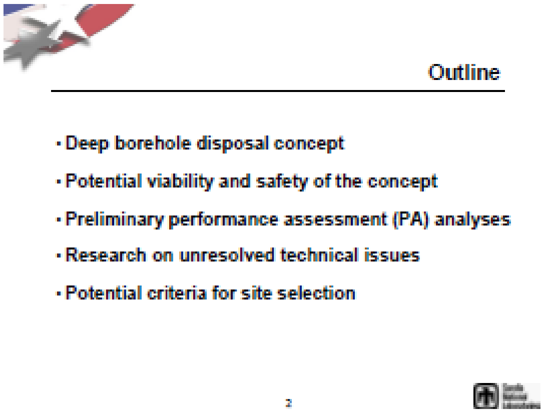


Deep Borehole Disposal – Performance Assessment and Criteria for Site Selection

Bill W Arnold, Peter N. Swift, and
Patrick V. Brady

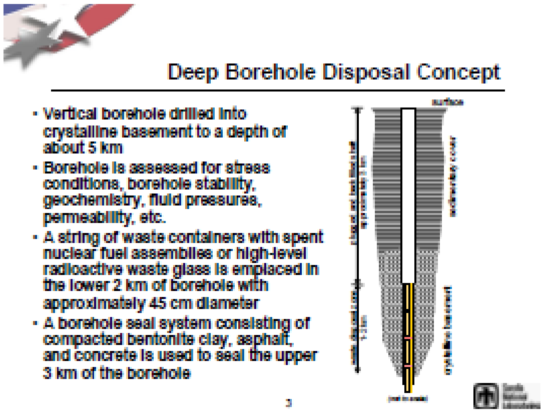
SNL-MIT Workshop on Deep Borehole Disposal

Washington, DC
March 15, 2010



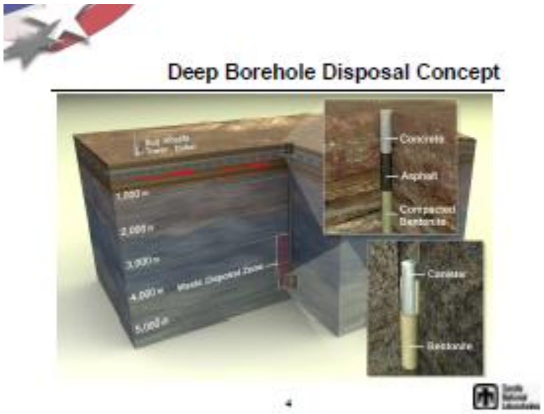
Outline

- 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

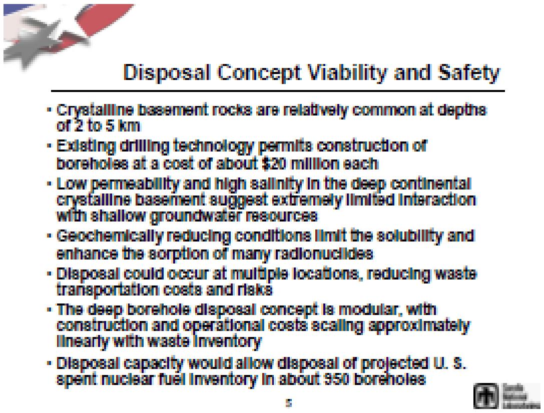


Deep Borehole Disposal Concept

- 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

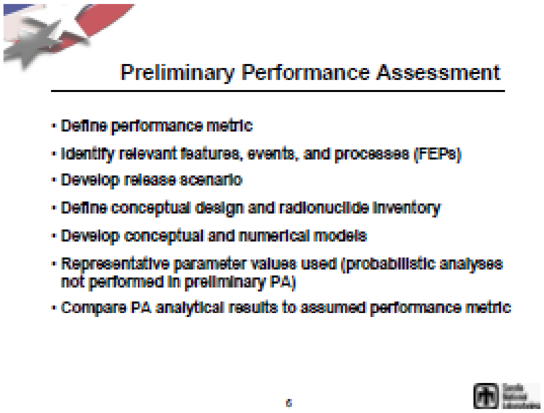


Deep Borehole Disposal Concept



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 $20 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 sorption 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 950 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 110 FEPs that should be included in the PA analysis

Preliminary Performance Assessment: Release Scenario Selection

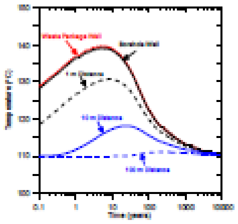
- A single release scenario that incorporates many of the most likely included FEPs was constructed for use in the PA
- This scenario includes the following:
  - Enhanced permeability in the disturbed zone and/or borehole
  - Thermally driven upward groundwater flow
  - Dissolution of radionuclides from 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 Design and Inventory

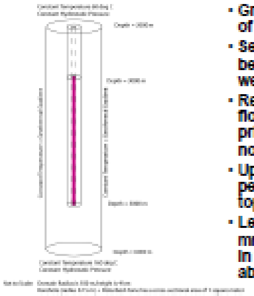
- Assume 400 used pressurized water reactor (PWR) fuel assemblies are stacked in a single borehole
- Radionuclide inventory and thermal output is based on average used PWR fuel that has been aged for 25 years
- Although fuel assemblies are sealed in waste canisters, assume rapid corrosion and degradation of canisters

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 125 °C for disposal of vitrified waste from reprocessing



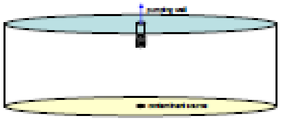
Coupled Thermal-Hydrologic Model



- Granite was assigned a permeability of 1 X 10^{-19} m^2
- Sealed borehole and disturbed bedrock surrounding the borehole were assigned a value of 1 X 10^{-16} 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 cm/year) persists for about 200 years at the top of the waste disposal zone
- Lesser upward flow (flux of up to 3.5 mm/year) occurs for about 600 years in the borehole at a location 1000 m above the waste

Groundwater Pumping and Dilution

- Radial 2-D 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 well, but dilution would be greater
- Quantitative estimates of delay and dilution were incorporated into the PA calculations



Not to Scale. Model domain has a radius of 10 km and depth of 2 km. Contaminant source has a cross-sectional area of approximately 1 m².

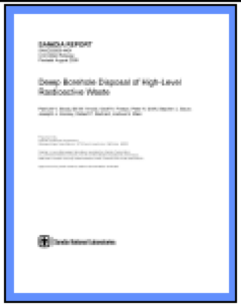
Preliminary Performance Assessment: Conceptual and Numerical Models

- Dissolved solubility limits of radionuclides estimated for thermal – chemical conditions in the borehole 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^{-10} mrem/year (1.4 x 10^{-12} mSv/year)
- The only radionuclide contributing to the calculated dose is ^{129}I, which has high solubility and is nonsorbing
- 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 mrem/year (for the first 10,000 years) and 100 mrem/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



SANDIA REPORT

Deep Borehole Disposal of High-Level Radioactive Waste

Key Technical Issues

- Long-term behavior of borehole seals
- Modeling of coupled thermal-hydrologic-mechanical-chemical behavior near the borehole
- Compounds that sorb/sequester 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
  - Scaling 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

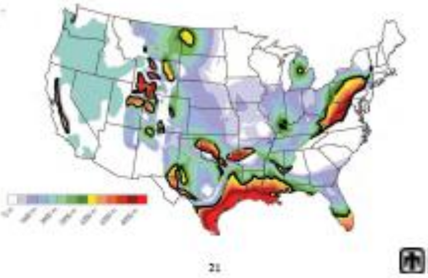
- Preliminary list of siting criteria:
  - Depth to crystalline basement
  - Depth to saline groundwater
  - Anisotropy in horizontal stress
  - Fluid overpressure at depth
  - Geochemically reducing conditions at depth
  - Permeability of host rock
  - Tectonic stability
  - Volcanism
  - Geothermal gradient
  - 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 crystalline basement



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: Depth to saline groundwater

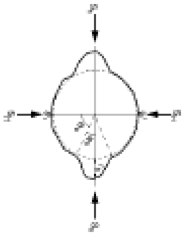
Source: USGS Circular 1323

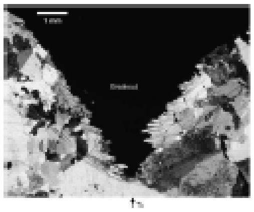
Potential Criteria for Site Selection

- Potential Criterion: Anisotropy in horizontal stress
- Issues:
  - Borehole stability during drilling, emplacement operations, and post-closure (development of borehole breakout)
  - 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

Potential Criteria for Site Selection

- Potential Criterion: <u>Anisotropy in horizontal stress</u>





Potential Criteria for Site Selection

- Potential Criterion: <u>Fluid overpressure at depth</u>
- Issues:
  - Provides fluid potential for upward advection of groundwater in borehole or disturbed zone around borehole
  - Can result from a number of hydrogeological conditions, including topographically driven flow, sediment compaction in active basins, tectonic loading (e.g., faults), high thermal output in crystalline rocks (creating convective flow), 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

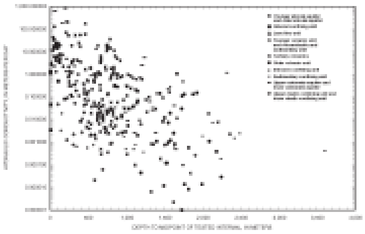
- Potential Criterion: <u>Geochemically reducing conditions</u>
- Issues:
  - Highly important to solubility and mobility of many radionuclides
  - In situ redox state can be determined from hydrochemistry and mineralogy of host rock
  - May be relevant to the stability and durability of seals, grouts, and any radionuclide "getters" added to them
- Expect geochemically reducing conditions at depth at all locations, but requires confirmation by drilling

Potential Criteria for Site Selection

- Potential Criterion: <u>Permeability of host rock</u>
- 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 depths
  - Higher-permeability fracture zones not necessarily connected to shallower groundwater flow system
  - Fractures can be identified with geophysical logging of borehole
  - Fracture apertures 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: <u>Permeability of host rock</u>



Source: D'Agnese et al. (1997)

Potential Criteria for Site Selection

- Potential Criterion: <u>Tectonic stability</u>
- Issues:
  - Relevant to the faulting 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

Potential Criteria for Site Selection

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

---

Potential Criteria for Site Selection

- Potential Criterion: <u>Geothermal gradient</u>
- Issues:
  - High geothermal gradient may be indicative of upward groundwater flow (overpressures at depth), high thermal-output crystalline 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 unacceptably 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 Criteria for Site Selection

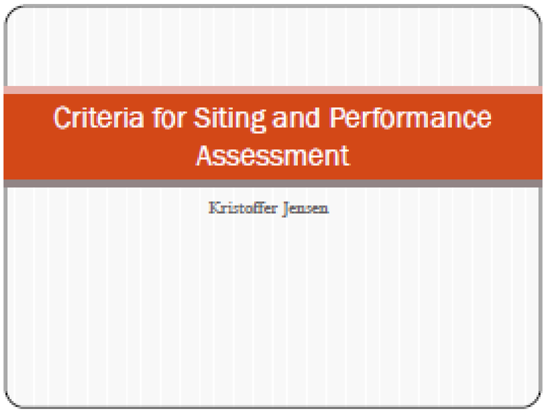
- Potential Criterion: <u>Mineral resource potential</u>
- Issues:
  - Presence of mineral resources in the disposal zone could lead to human intrusion
  - Very few mineral resources are targets for exploration or exploitation at depths of greater than 2 km in crystalline rock
- Can be evaluated at the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

---

Potential Criteria for Site Selection

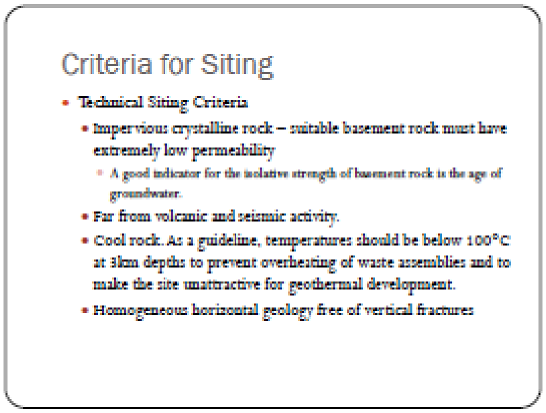
- Potential Criterion: <u>Topographic relief</u>
- Issues:
  - High topographic relief can result in regional groundwater flow that penetrates to great depths
  - Upward groundwater flow resulting from overpressure at depth occurs at some locations in deep regional groundwater flow systems
  - Topographically-driven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

Kristoffer Jensen – MIT



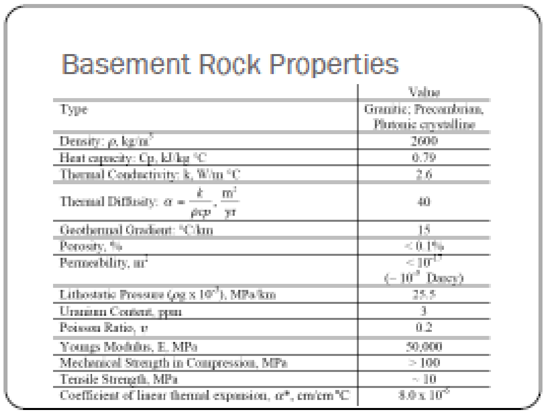
Criteria for Siting and Performance Assessment

Kristoffer Jensen



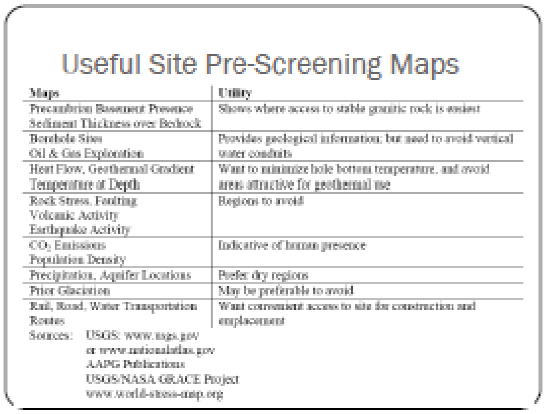
Criteria for Siting

- Technical Siting Criteria
  - Impervious crystalline rock – suitable basement rock must have extremely low permeability
    - A good indicator for the isolative 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 3km depths to prevent overheating of waste assemblies and to make the site unattractive for geothermal development.
  - Homogeneous horizontal geology free of vertical fractures



Basement Rock Properties

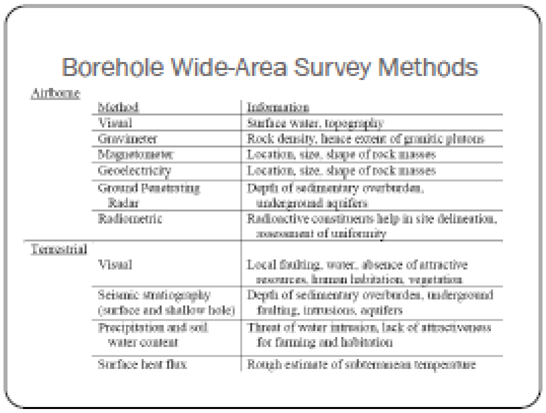
	Value
Type	Granitic; Precambrian, Plutonic crystalline
Density: ρ, kg/m^3	2600
Heat capacity: Cp, kJ/kg °C	0.79
Thermal Conductivity: k, W/m °C	2.6
Thermal Diffusity: $\alpha = \frac{k}{\rho c p}, \frac{m^2}{yr}$	40
Geothermal Gradient: °C/km	15
Porosity, %	< 0.1%
Permeability, m^2	$< 10^{-17}$ ($\sim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



Useful Site Pre-Screening Maps

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

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

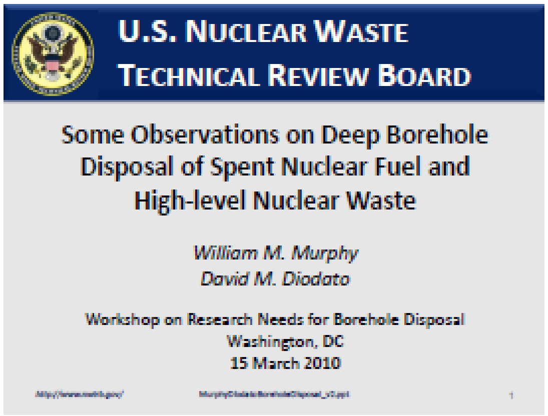


Borehole Wide-Area Survey Methods

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

William Murphy and David Diodato – NWTRB

Except where otherwise indicated, the views expressed are those of the authors and should not be construed as findings or recommendations of the U.S. Nuclear Waste Technical Review Board.

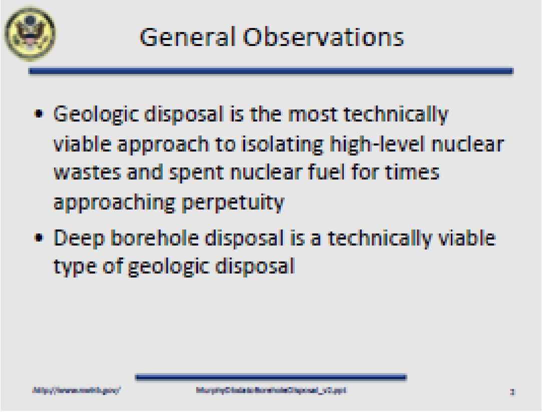


U.S. NUCLEAR WASTE
TECHNICAL REVIEW BOARD

Some Observations on Deep Borehole Disposal of Spent Nuclear Fuel and High-level Nuclear Waste

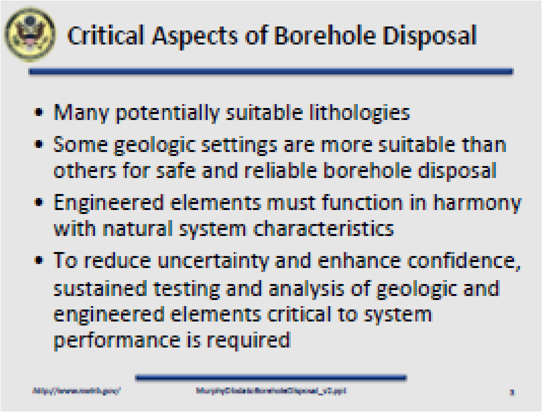
William M. Murphy
David M. Diodato

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



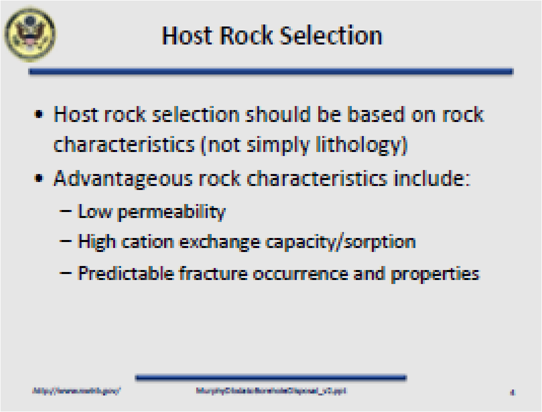
General Observations

- 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



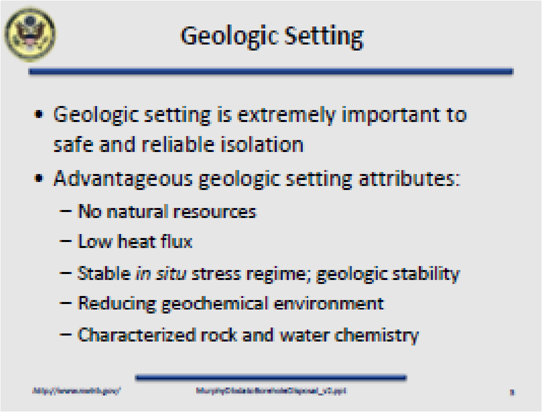
Critical Aspects of Borehole Disposal

- 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



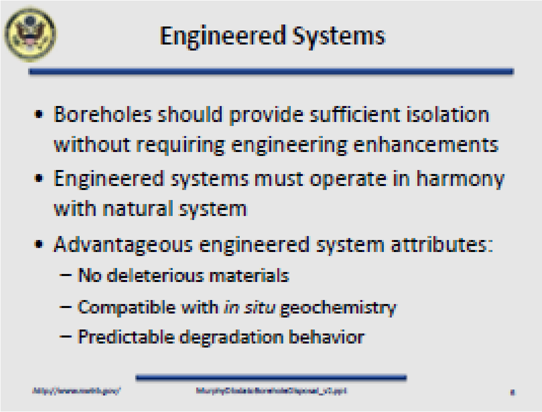
Host Rock Selection

- 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



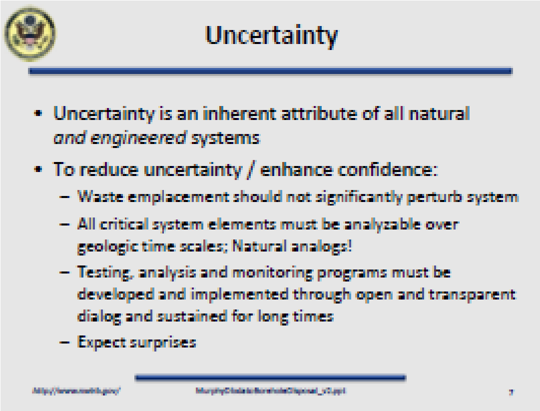
Geologic Setting

- 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

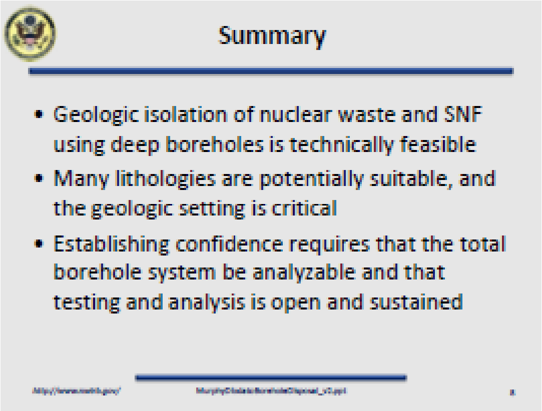
- Boreholes should provide sufficient isolation without requiring engineering enhancements
- Engineered systems must operate in harmony with natural system
- Advantageous engineered system attributes:
  - No deleterious materials
  - Compatible with *in situ* geochemistry
  - Predictable degradation behavior



Uncertainty

- Uncertainty is an inherent attribute of all natural *and engineered* systems
- To reduce uncertainty / enhance confidence:
  - Waste emplacement should not significantly perturb system
  - All critical system elements must be analyzable over geologic time scales; Natural analogs!
  - Testing, analysis and monitoring programs must be developed and implemented through open and transparent dialog and sustained for long times
  - Expect surprises

http://www.nwtrb.gov/ MurphyGlobalBoreholeDisposal_v2.ppt 7



Summary

- Geologic isolation of nuclear waste and SNF using deep boreholes is technically feasible
- Many lithologies are potentially suitable, and the geologic setting is critical
- Establishing confidence requires that the total borehole system be analyzable and that testing and analysis is open and sustained

http://www.nwtrb.gov/ MurphyGlobalBoreholeDisposal_v2.ppt 8

Fergus Gibb – Univ. of Sheffield

The University Of Sheffield.

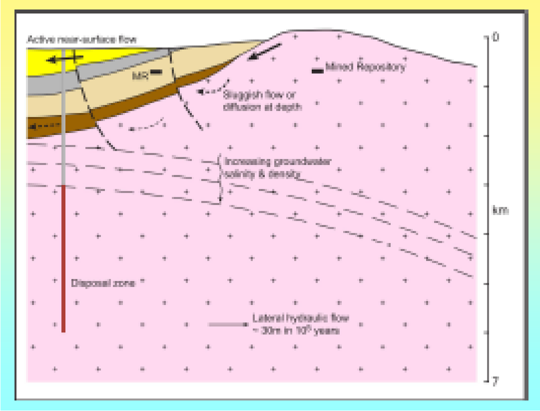
ISL

DEEP BOREHOLE DISPOSAL

Fergus Gibb

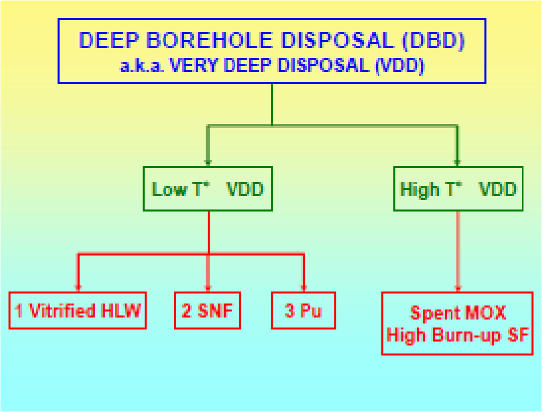
1. \- The UK Position
2. \- The Advantages
3. \- The Concepts [Sheffield]
4. \- Towards Full-scale Demonstration

UK Government/NDA Reference Repository Concept – (Co-Location)



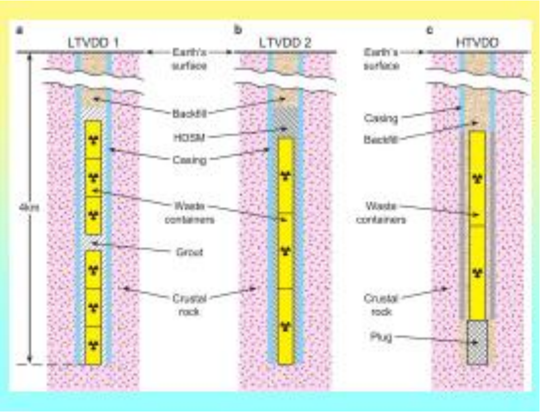
Advantages of Deep Boreholes

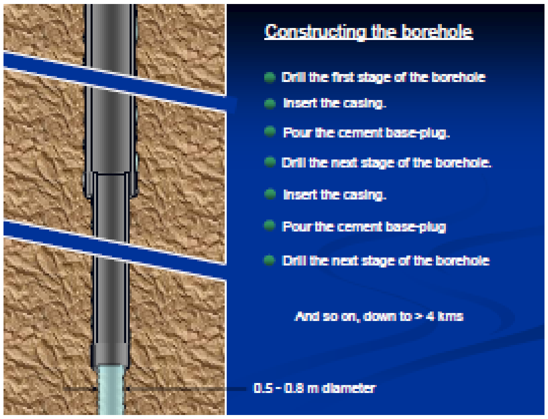
1. SAFETY
2. COST-EFFECTIVENESS
3. ENVIRONMENTAL IMPACT
4. SMALL 'FOOTPRINT'
5. SITE AVAILABILITY
6. DISPERSED DISPOSAL
7. FLEXIBILITY
8. INSENSITIVE to COMPOSITION
9. LONGEVITY
10. EARLY IMPLEMENTATION
11. ACCEPTABILITY ?



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 kms

0.5 - 0.8 m diameter

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

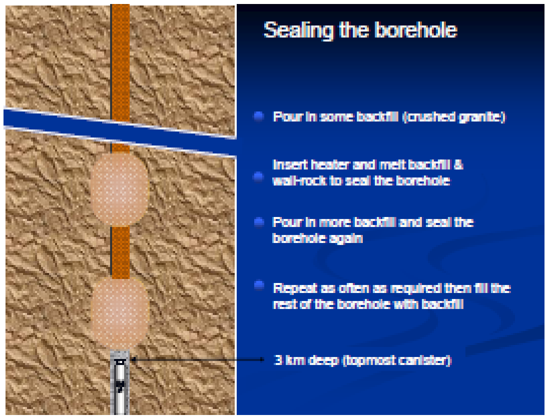
Low Temperature
Very Deep Disposal

Vitrified waste

- Insert Bentonite clay (Optional)
- Insert another batch of canisters, pour grout & allow to set

Repeat until the bottom km of the borehole is filled

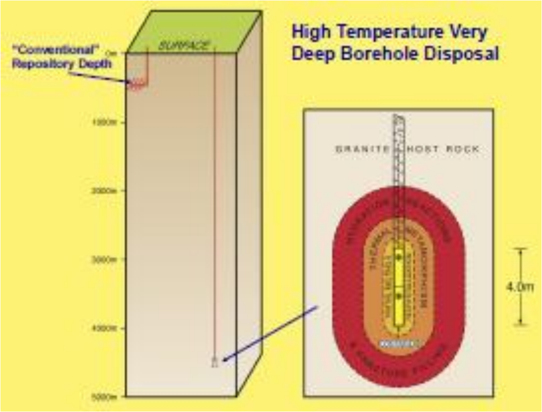
4 kms

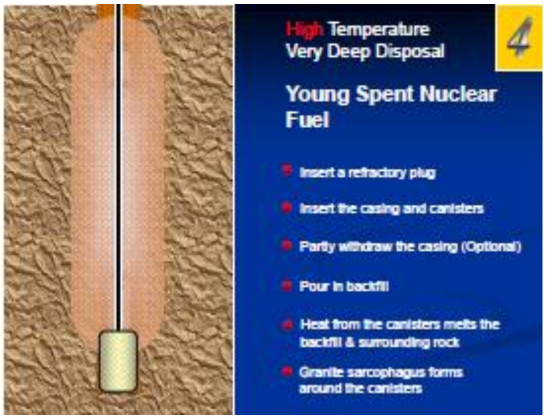


Sealing the borehole

- Pour in some backfill (crushed granite)
- Insert heater and melt 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)


High Temperature Very Deep Borehole Disposal

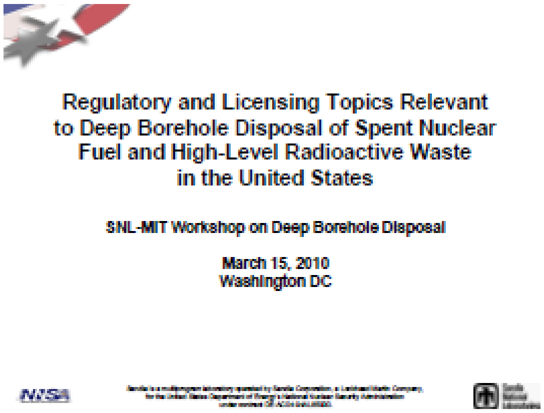


High Temperature Very Deep Disposal

Young Spent Nuclear Fuel

- Insert a refractory plug
- Insert the casing and canisters
- Partly withdraw the casing (Optional)
- Pour in backfill
- Heat from the canisters melts the backfill & surrounding rock
- Granite sarcophagus forms around the canisters

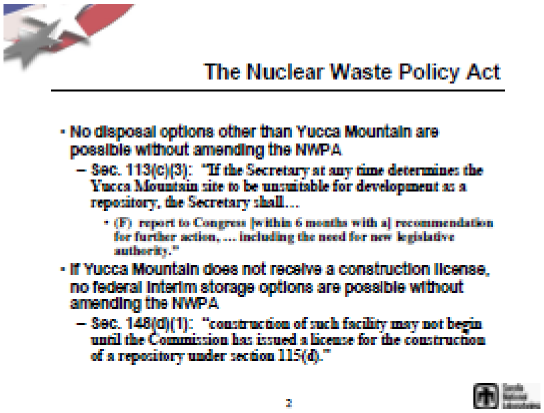
Peter Swift – Sandia



Regulatory and Licensing Topics Relevant to Deep Borehole Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste in the United States

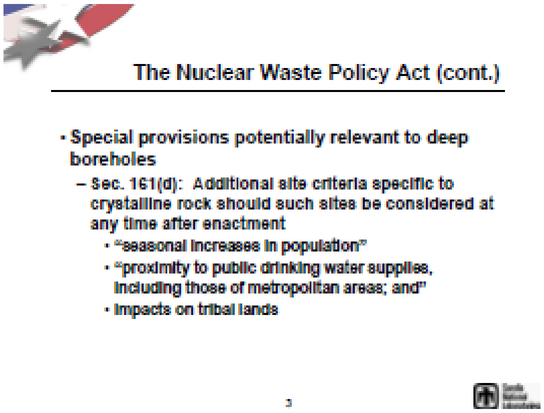
SNL-MIT Workshop on Deep Borehole Disposal

March 15, 2010
Washington DC



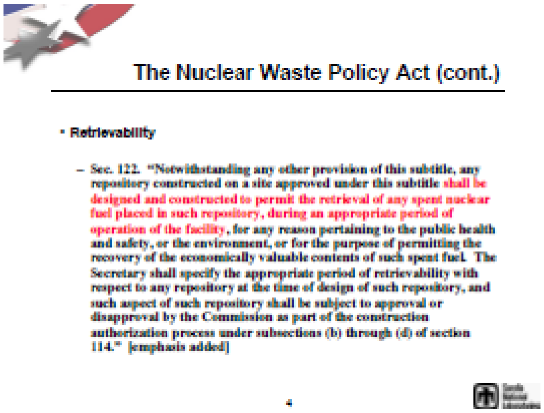
The Nuclear Waste Policy Act

- No disposal options other than Yucca Mountain are possible without amending the NWPA
  - Sec. 113(c)(3): "If the Secretary at any time determines the Yucca Mountain site to be unsuitable for development as a repository, the Secretary shall…
    - (F) report to Congress [within 6 months with a] recommendation for further action, … including the need for new legislative authority."
- If Yucca Mountain does not receive a construction license, no federal interim storage options are possible without amending the NWPA
  - Sec. 148(d)(1): "construction of such facility may not begin until the Commission has issued a license for the construction of a repository under section 115(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 sites be considered at any time after enactment
    - "seasonal increases in population"
    - "proximity to public drinking water supplies, including those of metropolitan areas; and"
    - impacts on tribal lands



The Nuclear Waste Policy Act (cont.)

- Retrievability
  - Sec. 122. "Notwithstanding any other provision of this subtitle, any repository constructed on a site approved under this subtitle 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 197 and 10 CFR Part 63) apply only to Yucca Mountain
- Existing regulations that predate the 1987 NWPA amendment could, in principle, be applied to other disposal concepts for SNF/HLW without revision
  - EPA 40 CFR part 191 (implemented for the Waste Isolation Pilot Plant [WIPP])
  - NRC 10 CFR part 60 (never implemented)

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

1985 EPA Standard 40 CFR part 191 (revised 1994)

- 10,000-yr Containment Standard (cumulative release)
  - Requires consideration of human intrusion
    - 30 boreholes/sq km/10,000 yr for repositories "in proximity to sedimentary rock formations," 3 boreholes/sq km/10,000 yr for other locations
  - Release limits normalized to initial inventory
  - Cumulative limits remove uncertainty associated with exposure pathways and future human lifestyles
- 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.)

- 1983 NRC Standard 10 CFR part 60 (revised 1985-1996)
  - Requires compliance with EPA standards at 40 CFR 191
  - Also requires
    - Substantially complete containment in waste packages for 300 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
    - Fastest 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

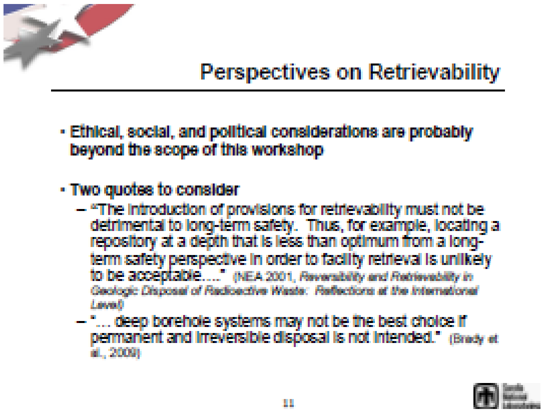
- 40 CFR part 191
  - Normalized cumulative release standard could apply same standard to single boreholes or disposal arrays
    - Total allowable release for large disposal arrays could be relatively large
  - Retrievability is required to be possible
    - 40 CFR 191.14(f): "Disposal systems shall be selected so that removal of most of the wastes is not precluded for a reasonable period of time after disposal."
    - "...any current concept for a mined geologic repository meets this requirement..." "Rather, it is intended to call into question any other disposal concept that might not be so reversible..." (EPA 1985, 38082 FR 50)
  - Human intrusion specifications may be inappropriate for deep boreholes
- 10 CFR part 60
  - Subsystem requirement for the waste package may be inappropriate for deep boreholes
  - Allows irretrievability with license amendment
    - 10 CFR 60.46(a)(1) "an amendment shall be required ... [for] any action which would make emplaced high-level radioactive waste irretrievable..."

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

- Regulation of Underground Injection Wells under the Safe Drinking Water Act of 1974
  - 40 CFR parts 144-148 set requirements for Federal Underground Injection Control Program
  - Regulations focus on subsurface injection of fluids, but may apply to deep borehole disposal
  - 40 CFR 146.5(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 emplacement in WIPP did not constitute "injection" (DOE/CAO-1996-2184, BECR Section 8.1)

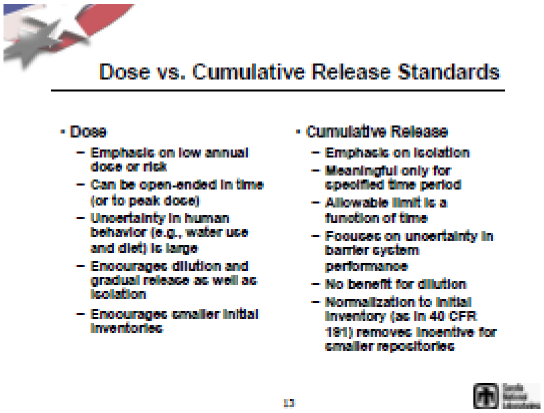
International Perspectives

- International Atomic Energy Agency
  - *Geological Disposal of Radioactive Waste*, Safety Requirements No. WS-R-4 (2006)
    - 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..."



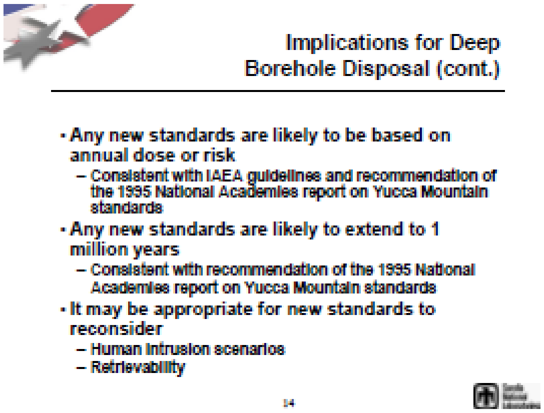
Perspectives on Retrievability

- 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 facility 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., 2009)



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 dilution and gradual release as well as isolation
  - Encourages smaller initial inventories
- Cumulative Release
  - Emphasis on isolation
  - Meaningful only for specified time period
  - Allowable limit is a function of time
  - Focuses on uncertainty in barrier system performance
  - No benefit for dilution
  - Normalization to initial inventory (as in 40 CFR 191) 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.

Order	Research Question
1	**Design of a Pilot:** 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.
2	**Borehole sealing/drilling:** What happens if you can't seal the borehole? How many holes will fail/be abandoned? Rock welding?
3	**Geochemistry**: 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)
4	**Drilling**: Assess the link between drilling and disturbed rock permeability. Show that borehole environment and performance is not deleteriously perturbed by drilling/emplacement.
5	**Reliability and Surveillance:** How to demonstrate: bentonite in the annulus, bridge plug emplacement and performance, sensor performance and sensor parameter targets
6	**Hydrology**: Establish lithologic heterogeneity controls over large-scale fluid convection in borehole disturbed zone.
7	**Waste Form:** Ordinary casing?, high quality stainless steel? something else? Fuel consolidation (thermal load)
8	**Downhole Testing**: What tools are missing? E.g. acoustic and electromagnetic techniques that allow continuous surveillance of vertical fluid motion.
9	**Geology:** Geopressured zones at depth: How to detect/predict/pre-screen? How to show when/if it doesn't matter.
10	**Drilling**: Establish value of casing all the way down?
11	**Performance**: Glacial effects