Final Disposal in Deep Boreholes Using Multiple Geologic Barriers: Digging Deeper for Safety

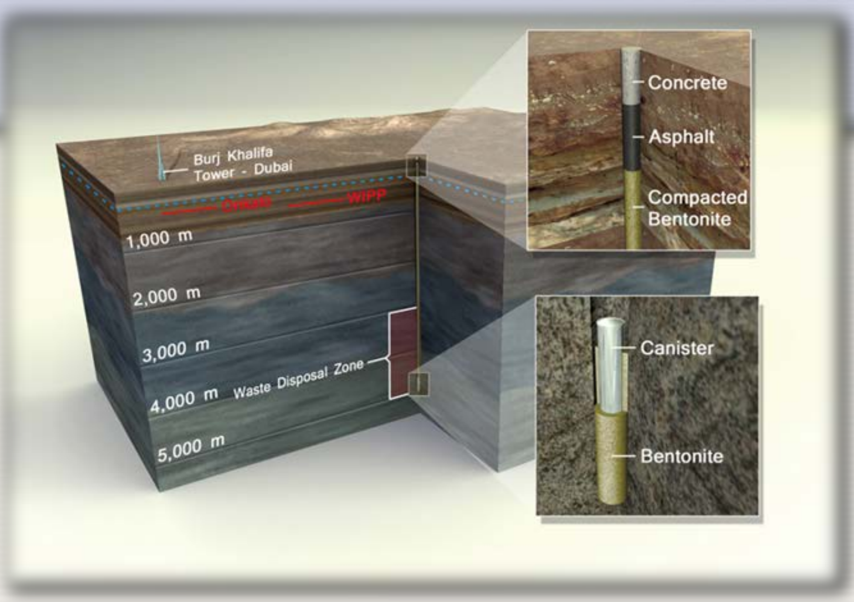
Genesis of the US R&D Program for Deep Borehole Disposal

Andrew Orrell

International Expert-Workshop on June 5 and June 6, 2015

IAEA
International Atomic Energy Agency

Outline



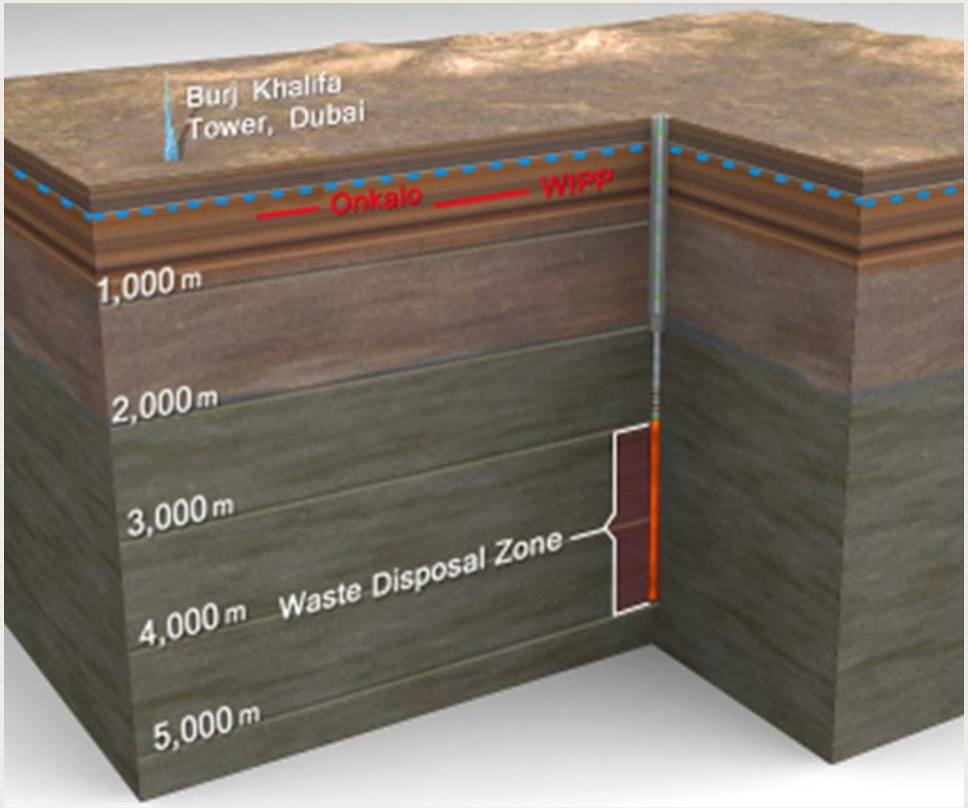
- Objective
- Concept
- History
- Recent U.S. Developments
  - Motivations for a Renewed Consideration
  - 2008-2013
- Final Thoughts

Objective

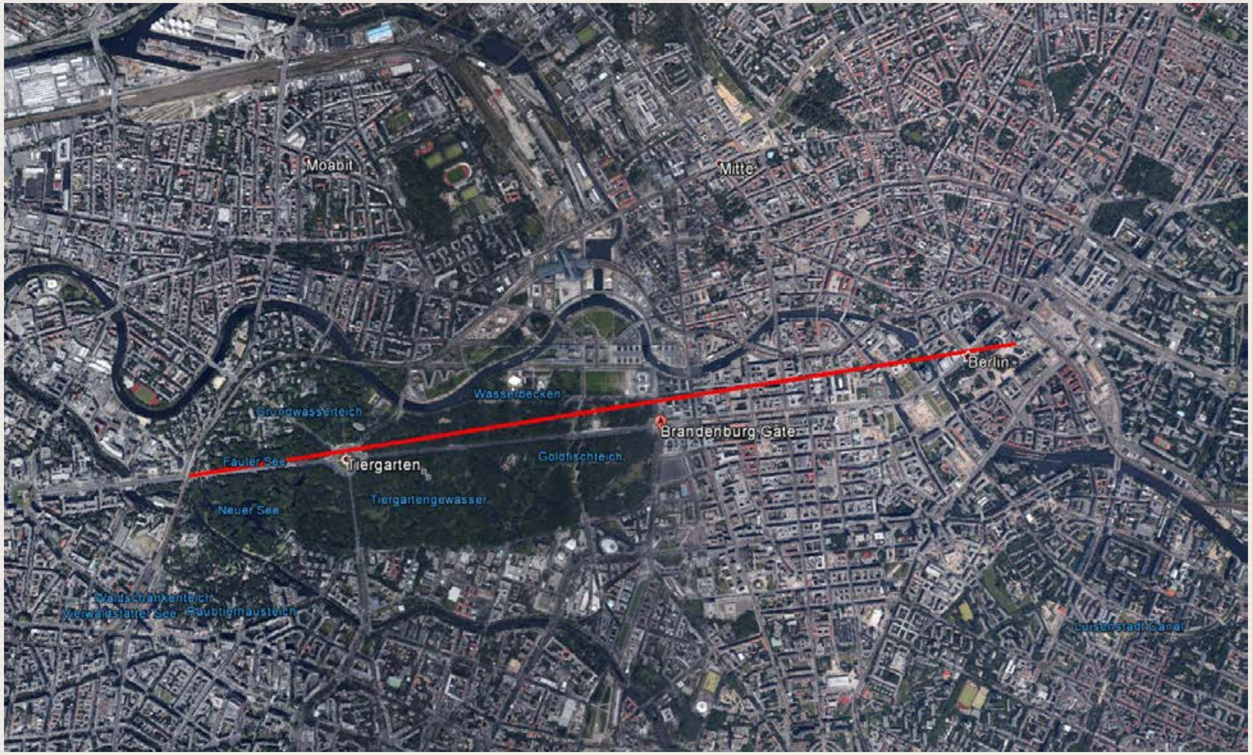
- To understand the context of what led to the current momentum to develop deep borehole disposal concept
- To accelerate and contribute to your own deliberations on whether to pursue

Deep Borehole Disposal Concept

- Disposal concept consists of drilling a borehole or array of boreholes into crystalline basement rock to about 5,000 m depth to ~45 cm diameter
  - Bottom hole diameter
    - 17 in. for bulk waste forms or SNF/HLW
    - 8.5 in. for smaller DOE-managed waste forms
- Borehole casing or liner assures unrestricted emplacement of waste canisters
- Waste would consist of spent nuclear fuel and/or high-level radioactive waste
- Approximately 400 waste canisters would be emplaced in the lower 2,000 m of the borehole
- Upper borehole would be sealed with compacted bentonite clay, cement plugs, and cemented backfill



5 Km Paths



368m

x 13.5 = 5 KM.

Tallest structure in Germany, Berliner Fernsehturm

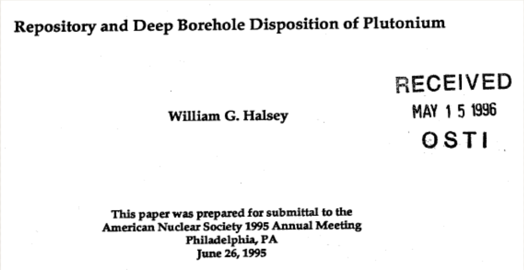
Asserted Benefits of Deep Borehole Disposal Concepts

- Crystalline basement rocks are relatively common at depths of 2 km to 5km
- Disposal could occur at multiple locations, reducing waste transportation costs and risks
  - Greater potential for site to site performance comparability, possibly avoiding 'best site' contentions, fostering equity and fairness issues.
- Low permeability and high salinity in the deep crystalline basement suggest extremely limited interaction with shallow groundwater resources; high confidence isolation
- Thermal loading issues are minimized
- Geochemically reducing conditions limit solubility and enhance the sorption of many radionuclides
- Retrievability is difficult, but not impossible
- Compatible with multiple waste forms and types (e.g. CANDU bundles, PWR w/ or w/o rod consolidation)
- The deep borehole disposal concept is modular, with construction and operational costs scaling approximately linearly with waste inventory
- Existing drilling technology permits construction of boreholes at a cost of about $20 million each
  - Low cost facilitates abandonment of emplacement-ready holes that fail to meet minimum criteria, limits 'make it work' perceptions
- Disposal capacity of ~950 boreholes would allow disposal of projected US SNF inventory
  - Dry Rod Consolidation (demonstrated at INL in the 80's and at present in Germany, Sweden) could reduce this by ~1/2, or possibly further reduce costs for smaller hole bottom diameter

Source: Brady, P.V., B.W. Arnold, G.A. Freeze, P.N. Swift, S.J. Bauer, J.L. Kanney, R.P. Rechard, J.S. Stein, 2009, *Deep Borehole Disposal of High-Level Radioactive Waste*, SAND2009-4401, Sandia National Laboratories, Albuquerque, NM, and
Technology and Policy Aspects of Deep Borehole Nuclear Waste Disposal, M. J. Driscoll, R. K. Lester, K. G. Jensen (MIT), B. W. Arnold, P. N. Swift, and P. V. Brady (SNL)

History of Deep Borehole Disposal

- **Deep borehole disposal of high-level waste (HLW) has been considered in the US since 1950s**
- **Deep borehole disposal of spent nuclear fuel and HLW has been studied in increasing detail periodically since the 1970s to the present (mostly in paper studies), usually in relation to various pressures**
  - **Disposal of surplus weapons Pu**
  - **Disposal of vitrified or cemented wastes**
  - **Disposal of fuel assemblies (with or without rod consolidation)**
  - **Melting of host rock to encapsulate waste**


Repository and Deep Borehole Disposition of Plutonium

William G. Halsey

RECEIVED
MAY 1 5 1996
OSTI

This paper was prepared for submittal to the American Nuclear Society 1995 Annual Meeting
Philadelphia, PA
June 26, 1995

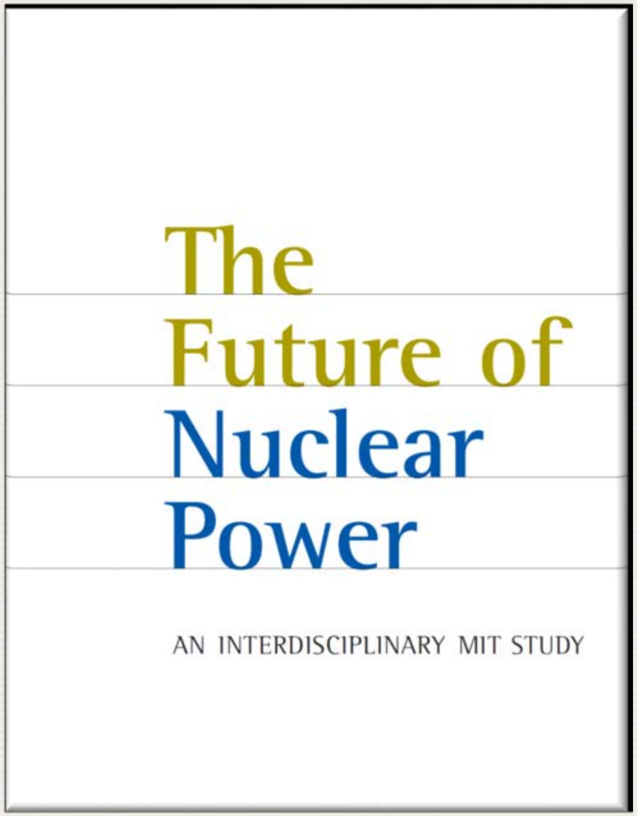
- **Time was not ripe**
  - **Technological risks lower with u/g mining**
  - **Technical capability absent**
- **What has Changed?**
  - **Drilling technology capability has greatly increased**
  - **Experience with mined disposal repositories**
  - **New pressures for disposal**

Recent U.S. Developments

MOTIVATIONS FOR A RENEWED CONSIDERATION

Deep Borehole Disposal

MIT July 2003



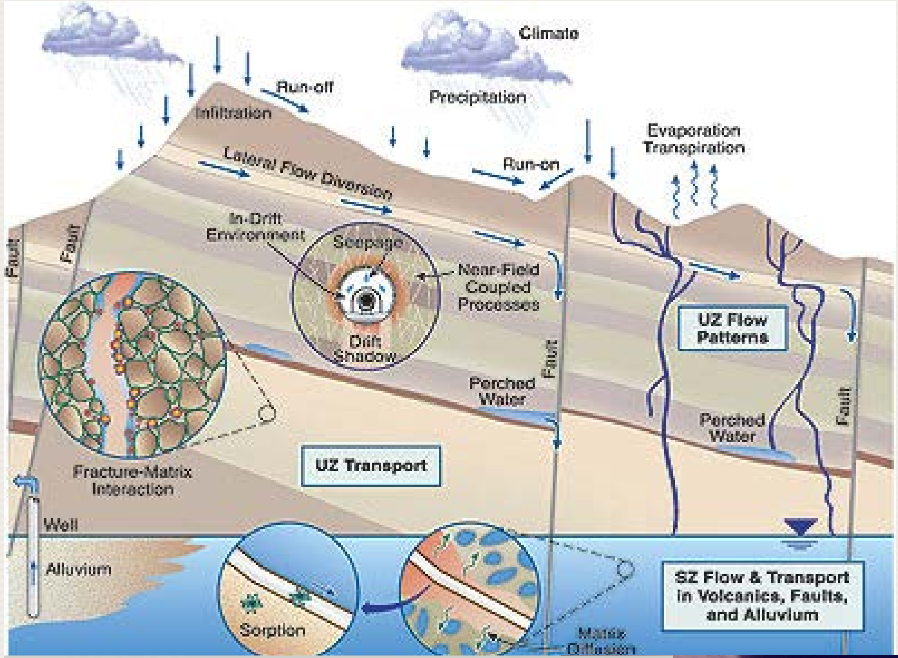
"We further conclude that waste management strategies in the once-through fuel cycle are potentially available that could yield long-term risk reductions at least as great as those claimed for waste partitioning and transmutation, with fewer short-term risks and lower development and deployment costs. *These include both incremental improvements to the current mainstream mined repositories approach and more far-reaching innovations such as deep borehole disposal*. "

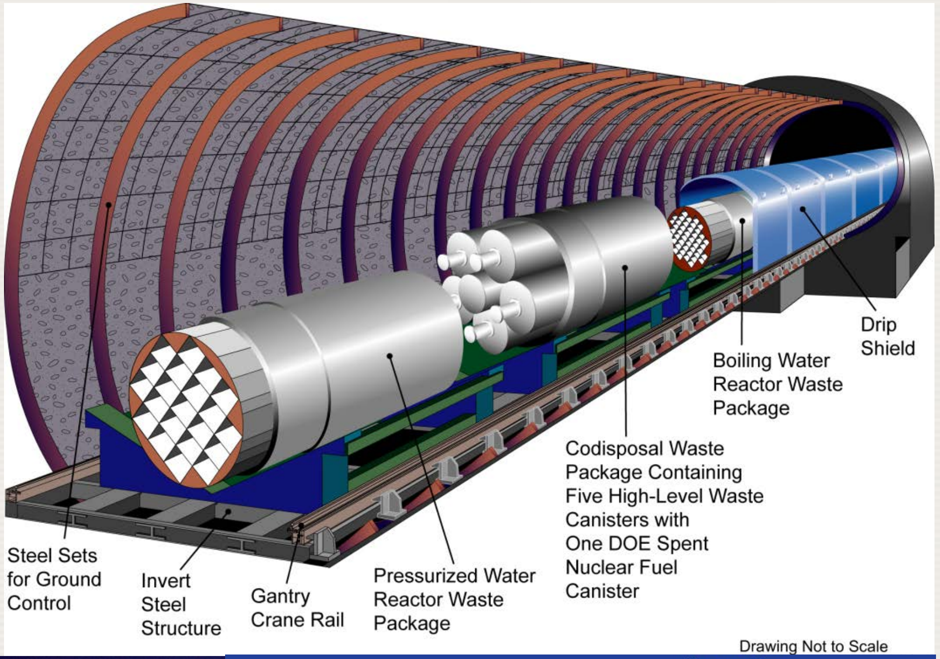
"More attention needs to be given to the characterization of waste forms and engineered barriers, followed by development and testing of engineered barrier systems. *We believe deep boreholes, as an alternative to mined repositories, should be aggressively pursued.* These issues are inherently of international interest in the growth scenario and should be pursed in such a context.

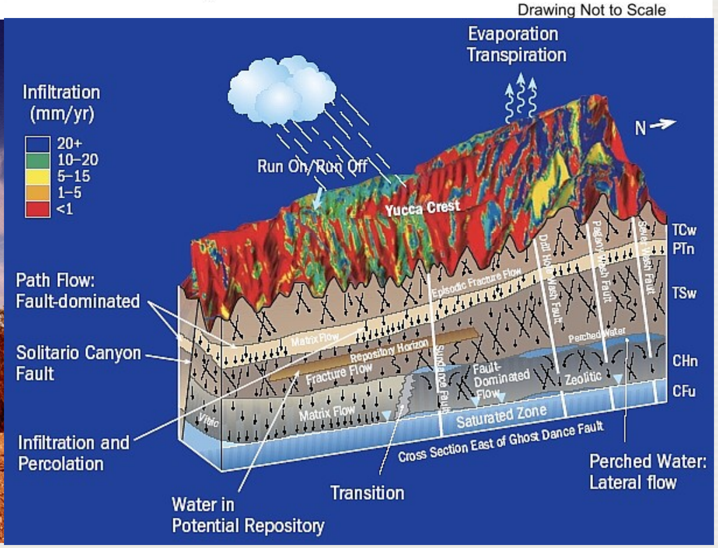
***"A research program should be launched to determine the viability of geologic disposal in deep boreholes within a decade. "* (Listed as one of the principle recommendations on waste management – July 2003)**

Professors John Deutch and Ernest Moniz Chaired Effort to Identify Barriers and Solutions for Nuclear Option in Reducing Greenhouse Gases

Perspectives from a Mined Repository

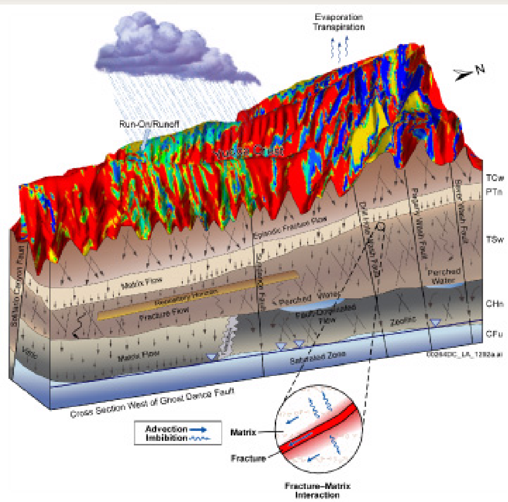


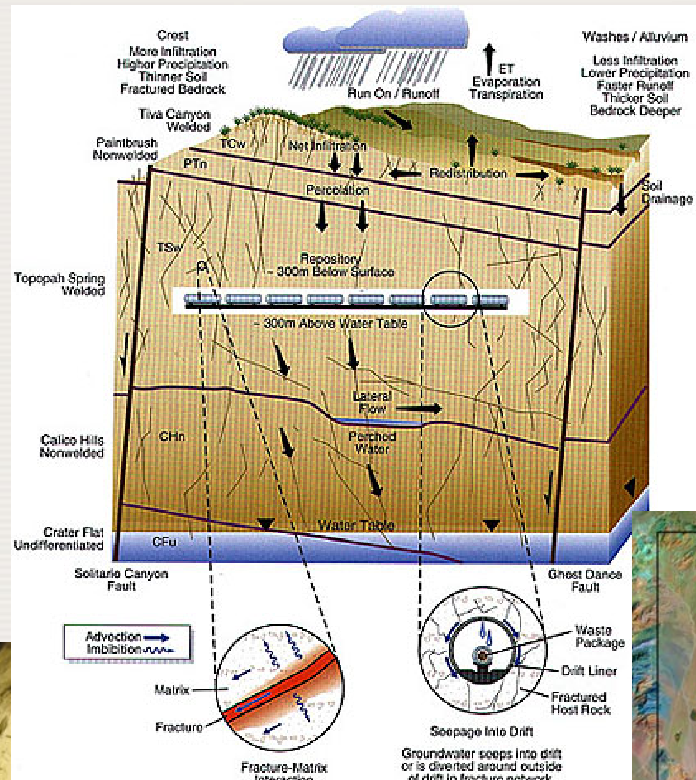


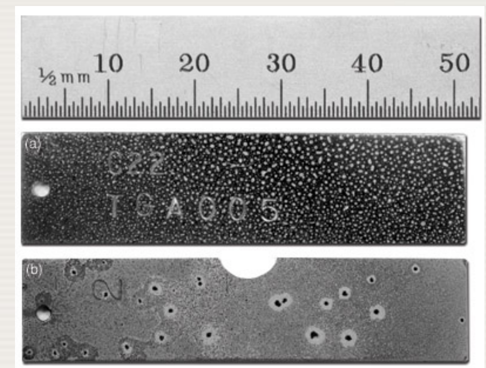


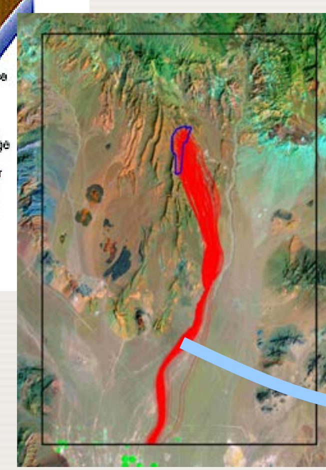
Mined Repositories

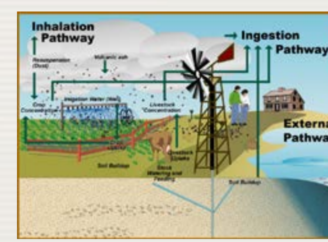
- Coupling between the surface and near-field disposal environment





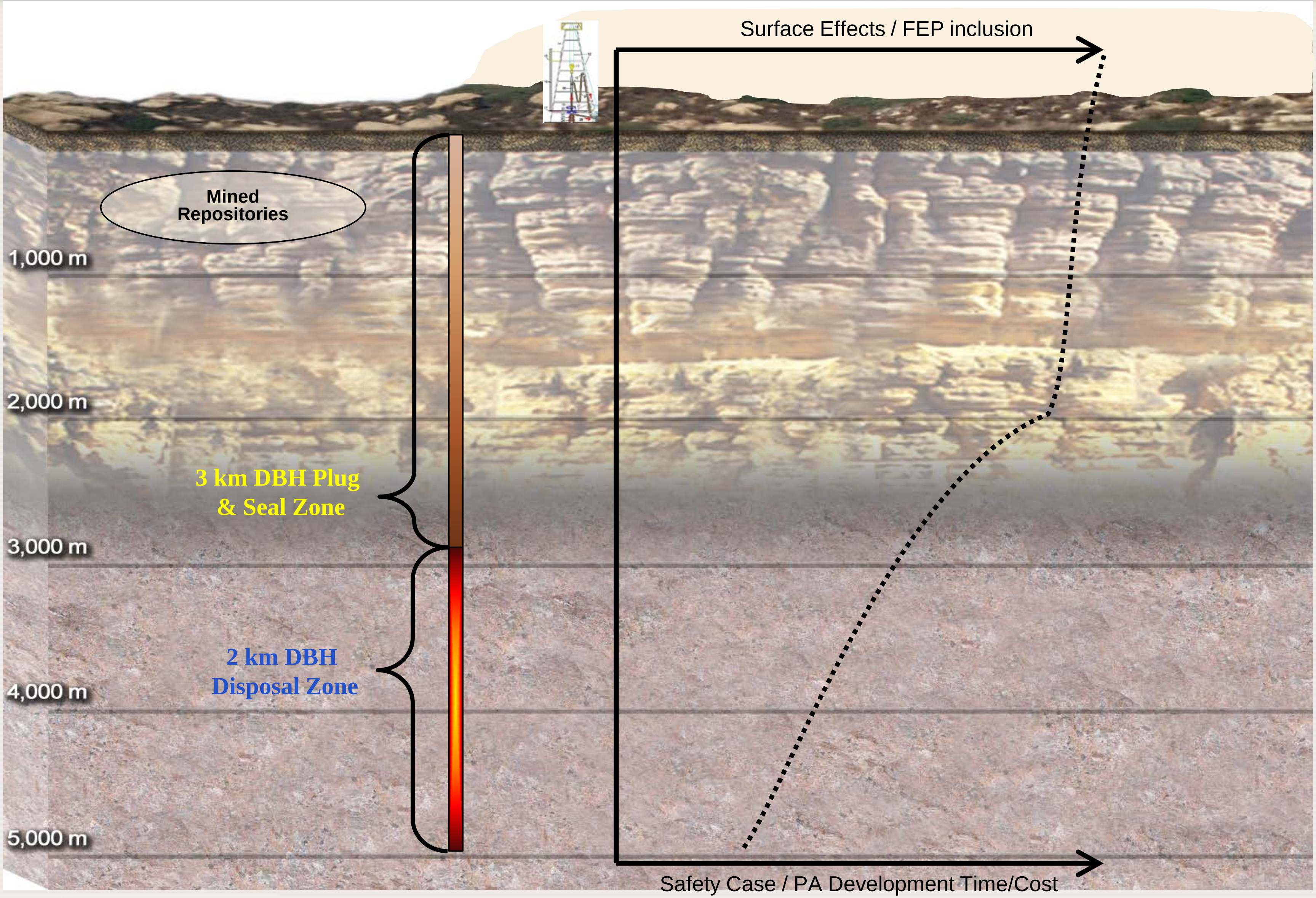






Deep Borehole Disposal Concept

Faster, Cheaper, Better Drivers



Performance Assessment
August 2009

SANDIA REPORT
SAND2009-4401
Unlimited Release
Printed August 2009

Deep Borehole Disposal of High-Level Radioactive Waste

Patrick V. Brady, Bill W. Arnold, Geoff A. Freeze, Peter N. Swift, Stephen J. Bauer, Joseph L. Kanney, Robert P. Rechard, Joshua S. Stein

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

Sandia National Laboratories

Preliminary analysis suggests excellent long-term performance

- Conservative estimate of deep borehole peak dose to a hypothetical human withdrawing groundwater above the disposal hole is
- 1.4 x 10-10 mrem/yr (1.4 x 10-12 mSv/yr)
- YMP standard is 15 mrem/yr (< 10,000 yrs) and 100 mrem/yr (peak dose to 1M yrs)

Source: Brady, P.V., B.W. Arnold, G.A. Freeze, P.N. Swift, S.J. Bauer, J.L. Kanney, R.P. Rechard, J.S. Stein, 2009, *Deep Borehole Disposal of High-Level Radioactive Waste,* SAND2009-4401, Sandia National Laboratories, Albuquerque, NM

Raising Visibility (2/2010)

NUCLEAR ENGINEERING INTERNATIONAL
FEBRUARY 2010
www.neimagazine.com

Into the deep

The lower reaches of a borehole drilled 5km (3mi) into the earth's crust represents an interesting alternative location for high-level radioactive waste compared to mined repositories at much lesser depths. The first deep borehole performance assessment and dose estimate has been carried out. By Bill W. Arnold, Peter N. Swift, Patrick V. Brady, S. Andrew Orrell, and Geoff A. Freeze

The potential technical and cost advantages of deep borehole disposal have become more apparent over time. Drilling technology for petroleum and geothermal production has improved, resulting in lower costs and greater reliability for the construction of deep boreholes. Deep borehole disposal, characterization and excavation costs should scale approximately linearly with waste inventory: small inventories require fewer boreholes; large inventories require more boreholes. Characterization of near-surface geology and hydrology required for deep borehole disposal should be less extensive and costly than for shallower mined repositories because of the greater isolation of waste in deep boreholes. Conditions favourable for deep borehole disposal exist at many locations, particularly on geologically stable continental cratons. A system of regional deep borehole disposal sites could possibly help address waste management equity issues and perhaps transportation concerns.

In 1957 the U.S. National Academy of Sciences Committee on Waste Disposal considered both deep borehole disposal of radioactive waste (in liquid form) and mined storage of radioactive waste in a positive light [1]. The intervening half-century has seen high-level waste and spent nuclear fuel disposal efforts in the United States and other nations focus primarily on mined repositories. Nonetheless, evaluations of the deep borehole disposal concept have periodically continued in several countries (for example, [2-7]).

The deep borehole disposal concept consists of drilling a borehole into crystalline basement rock (typically granite) to a depth of about 5000m, emplacing waste canisters containing spent nuclear fuel or vitrified radioactive waste from reprocessing in the lower 2000m of the borehole, and sealing the upper 3000m of the borehole. The concept is illustrated in Figure 1, showing the borehole disposal depth relative to the typical depth for mined repositories of several hundred meters. Waster in the deep borehole disposal system is several times deeper than for typical mined repositories, resulting in greater natural isolation from the surface and near-surface environment.

The viability and safety of the deep borehole disposal concept are supported by several factors. Crystalline basement rocks are relatively common at depths of 2000 to 5000m in the United States and many other countries, suggesting that numerous appropriate sites exist. Low permeability and high salinity in the deep continental crystalline basement at many locations suggest extremely limited interaction with shallow fresh groundwater resources, which is the most likely pathway for human exposure. The density stratification of groundwater would also oppose thermally induced groundwater convection from the waste to the shallow subsurface, as shown in Figure 1. Geochemically reducing conditions in the deep subsurface limit the solubility and enhance the sorption of many radionuclides in the waste, leading to limited mobility.

Preliminary estimates for deep borehole disposal of the entire projected waste inventory through 2030 from the current U. S. fleet of nuclear reactors suggest a need for a total of about 950 boreholes, with a total cost that could be less than a mined repository disposal system at Yucca Mountain [8].

The legal and regulatory framework governing the disposal of high-level radioactive waste in the U.S. and other countries is oriented toward mined geological disposal and likely would need to be revised to implement deep borehole disposal. In particular, regulations specific to the potential retrieval of waste would need to be modified to reflect the more permanent disposal nature of a deep borehole disposal system. Although retrievability would be maintained during emplacement operations, waste may not be fully

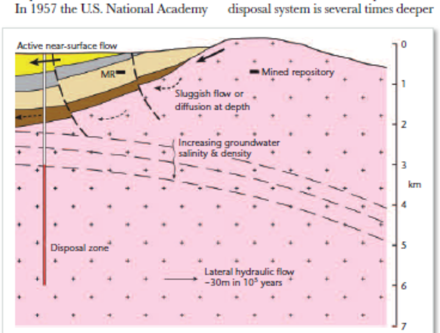


Fig. 1: The general deep borehole concept, drawn schematically as a cross-section through the earth's crust, after Chapman & Gibb [18].

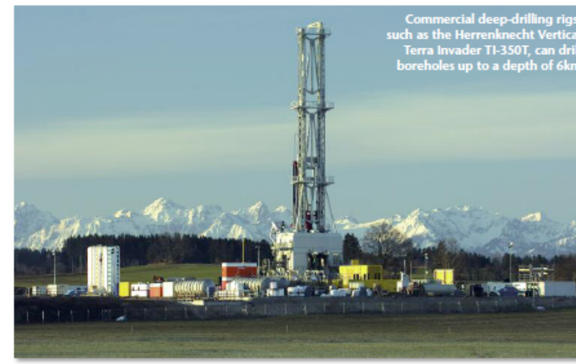
Looking down the bore

Deep borehole waste disposition research has not progressed to demonstration. ***Fergus Gibb*** *reviews the steps necessary before drilling can begin.*

Historically, reluctance to pursue deep borehole disposition centred on the fact that, while boreholes a few metres in diameter were possible and holes could be drilled to depths in excess of 10 km, the combination of a hole several tens of cm in diameter to a depth of 4 km or more has never been attempted (largely because the hydrocarbon, geothermal energy and other industries have had no need for it.) This gave rise to allegations of "immature technology" and concerns that to develop the necessary capability could take many years and prove prohibitively expensive or even impossible.

In 2000 SKB commissioned a feasibility study [14] into drilling the boreholes required for their VDH concept. The original well design was modified to give a deployment zone diameter of 0.83m with a 0.76m outer diameter casing, using steel for the containers and casing instead of titanium. In addition to well design, this report also gave engineering details of canister design, emplacement technology and retrieval mechanisms. It was concluded that it was possible to drill the borehole with the-then existing technology but that it represented one of the biggest challenges to the drilling industry. It was estimated that it would take around 137 days to drill the hole and it would cost around EUR4.65 ($6.8) million.

The most recent and comprehensive study of the status of drilling technology for DBD was carried out for the NDA in 2008 [17]. It was concluded that in an appropriate geology such as granite, a borehole with a clear, useable diameter of 0.5m, drilled and cased to a depth of 4km, is perfectly practicable using existing technology with some development of tools and systems. Larger holes, diameter up to 0.75m, would be difficult to implement beyond 3km, while 1.0m holes are considered impractical at the present time. Among the other outcomes of this study were that it would take around nine months to drill and case a 4km deep, 0.5m borehole and between 6 months and 2 years to emplace the waste packages, depending on size, number and method used. The first such borehole would require a lead-in time of two years and cost about GBP20 ($32) million, although savings on subsequent holes, especially on the same site, could approach 50%.



Commercial deep-drilling rigs, such as the Herrenknecht Vertical Terra Invader TI-350T, can drill boreholes up to a depth of 6km

The maximum size and depth of practical boreholes restricts the types of wastes for which DBD would be appropriate to those with small to moderate volumes, mainly high-level wastes, including spent fuel. A kilometre of 0.5m borehole can dispose of approximately 200m³ of packaged waste or 690 vitrified HLW containers.

THEORETICAL STUDIES

A criticality analysis will be important for concepts in which large amounts of potentially fissile material are disposed of, such as LTVDD-2 [see p17], in which spent fuel pins are closely packed in the containers. Taking this as an example, the first stage to consider is when water gains access to the container, and might form thin films between the fuel pins and the enclosing lead. However under these conditions there is no possibility of criticality. At the other extreme is the post-closure situation when the container has failed completely and aqueous fluids have leached out most of the lead matrix around the fuel pins.

Notwithstanding the facts that fluid flow rates at the depths in question are too low for this to happen and that there are no foreseeable hydrogeochemical processes that could bring it about, this would effectively leave the pins surrounded by water. Such a situation would be analogous to the consolidated storage of used fuel pins in metal boxes in ponds – where again there is no question of criticality arising. Nevertheless, a full criticality analysis of the disposal that takes account of predictable changes in the isotopic composition of the spent fuel over long periods must be undertaken.

Then, after this criticality analysis, and following a successful performance assessment [see p18], the next step would require practical tests.

DEMONSTRATION

Demonstration, testing and development of several of the necessary technologies require a full sized (0.5m inner diameter) cased borehole, but one that is shortened to a depth of a few hundred metres. The only other constraints are that it be in granitic host rock and that its bottom end should be readily accessible from pre-

Blue Ribbon Commission

January 2010- January 2012

- DBD mentioned in first open meeting opening remarks March 2010

The Blue Ribbon Commission on America's Nuclear Future (BRC) was formed by the Secretary of Energy at the request of the President to conduct a comprehensive review of policies for managing the back end of the nuclear fuel cycle and recommend a new strategy. It was co-chaired by Rep. Lee H. Hamilton and Gen. Brent Scowcroft. Other Commissioners are Mr. Mark H. Ayers, the Hon. Vicky A. Bailey, Dr. Albert Carnesale, Sen. Pete Domenici, Ms. Susan Eisenhower, Sen. Chuck Hagel, Mr. Jonathan Lash, Dr. Allison M. Macfarlane, Dr. Richard A. Meserve, Dr. Ernest J. Moniz, Dr. Per Peterson, Mr. John Rowe, and Rep. Phil Sharp.

The Commission and its subcommittees met more than two dozen times between March 2010 and January 2012 to hear testimony from experts and stakeholders, to visit nuclear waste management facilities in the United States and abroad, and to discuss the issues identified in its Charter. Additionally, in September and October 2011, the Commission held five public meetings, in different regions of the country, to hear feedback on its draft

- Note participants subsequent career positions

Nuclear Waste Technical Review Board Meeting
Las Vegas, NV - February 16, 2011

- "The Board certainly agrees with your conclusions on the technical aspects of deep borehole disposal and it appears that it is time to plan to move forward with a common vision for the technology."
- "It is time for detail implementation plans to be developed that include drilling, design of infrastructure and facilities to handle waste, and demonstrations with surrogate material; paper study of this disposal option is relatively complete."

UNITED STATES
NUCLEAR WASTE TECHNICAL REVIEW BOARD
2300 Clarendon Boulevard, Suite 1300
Arlington, VA 22201-3367

RECEIVED
MAR 0 2011
By

March 1, 2011

S. Andrew Orrell
Sandia National Laboratories
P.O. Box 5800, MS-0771
Albuquerque, New Mexico 87185

Dear Andrew:

Thank you very much for your participation at the February 16, 2011, meeting of the Nuclear Waste Technical Review Board meeting in Las Vegas. Your participation in helping put this meeting together when time was short is duly noted by all of us. The Board certainly agrees with your conclusions on the technical aspects of deep borehole disposal and it appears that it is time to plan to move forward with a common vision for the technology. It is time for detail implementation plans to be developed that include drilling, design of infrastructure and facilities to handle waste, and demonstrations with surrogate material; paper study of this disposal option is relatively complete.

Once again, thanks for your participation and help.

Sincerely,

B. John Garrick
Chairman

Telephone: 703-235-4473 Fax: 703-235-4495

NWTRB Letter to Assistant Secretary for Nuclear Energy, July 2011

- To follow-up on the presentations at the February meeting, the Board would like to know more about the progress being made regarding borehole disposal and other geologic-specific disposal programs that are under consideration. We are planning to make this a central part of the Board meeting we are planning for the spring of 2012 and will be contacting you or your staff regarding this in the near future. In this regard, we are particularly interested in work directed at optimizing the characteristics of the waste forms intended for disposal in specific geologic media.

UNITED STATES
NUCLEAR WASTE TECHNICAL REVIEW BOARD
2300 Clarendon Boulevard, Suite 1300
Arlington, VA 22201

July 26, 2011

The Honorable Peter B. Lyons
Assistant Secretary for Nuclear Energy
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20585-1290

Dear Dr. Lyons:

As you know, the U.S. Nuclear Waste Technical Review Board is charged with evaluating the technical and scientific validity of activities undertaken by the U.S. Department of Energy (DOE) in implementing the Nuclear Waste Policy Act and with reporting its findings and recommendations related to the management and disposition of spent nuclear fuel (SNF) and high-level radioacti

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Geologic Disposal Options in the United States

The third topic covered during the February meeting was work related to options for geologic disposal in the United States. Technical presentations were made by Dr. Patrick Brady, Dr. Ernest Harding, and Mr. Andrew Orrell, all of Sandia National Laboratories. Professor Hank Jenkins-Smith, professor of political science at the University of Oklahoma, presented by telephone the results of recent surveys of how technical information related to the management of SNF and HLW is perceived by the broader U.S. population.

Dr. Hardin's presentation made clear that many geologic media in the United States would be suitable for geologic disposal. He indicated that considerable academic study has been completed on deep borehole disposal, and the information that he and Dr. Brady presented indicates that it may be appropriate to begin field investigations, including a test drilling program and emplacing surrogate SNF and HLW in a borehole. If such a program is to be developed, however, the Board believes that it is essential that it is coupled with a program for developing the appropriate facility designs and for evaluating the necessary operational requirements for a borehole disposal program.

To follow-up on the presentations at the February meeting, the Board would like to know more about the progress being made regarding borehole disposal and other geologic-specific disposal programs that are under consideration. We are planning to make this a central part of the Board meeting we are planning for the spring of 2012 and will be contacting you or your staff regarding this in the near future. In this regard, we are particularly interested in work directed at optimizing the characteristics of the waste forms intended for disposal in specific geologic media.

From the technical presentations made at the meeting, it appears that at this point DOE has not developed a siting strategy or a plan for defining the siting criteria for a future repository for SNF and HLW. The Board understands that to some extent this results from an expectation that recommendations to be made by the Blue Ribbon Commission on America's Nuclear Future may affect the basis for developing such a siting strategy or criteria. Despite this possibility, however, the Board believes that there is technical merit in preparing for disposal of SNF and HLW on an early timeframe, and it encourages DOE to begin these activities.

Sandia Progress

Workshop: Pilot Testing Deep Borehole Disposal of Nuclear Waste, October 2011

SANDIA REPORT
SAND2011-6749
Unlimited Release
Printed October 2011

Reference Design and Operations for Deep Borehole Disposal of High-Level Radioactive Waste

Bill W. Arnold, Patrick V. Brady, Stephen J. Bauer, Courtney Herrick, Stephen Pye, and John Finger

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

Approved for public release; further dissemination unlimited.

Sandia National Laboratories

In October, 2011 Sandia brought together twenty representatives from the fields of radioactive waste disposal and drilling to:

- review the state of deep borehole science and engineering;
- identify the necessary features of a deep borehole pilot demonstration; and,
- consider organizational approaches to implementing a deep borehole pilot.

Blue Ribbon Commission on America’s Nuclear Future
Report to the Secretary of Energy, January 2012

- “In its deliberations, the Commission focused chiefly on two deep geologic disposal options: disposal in a mined geological formation and disposal in deep boreholes. The former has been the front-running disposal strategy in the United States for more than 50 years; it is also the approach being taken in other countries with spent fuel or HLW disposal programs. By contrast, disposal in deep boreholes may hold promise but this option is less well understood and the development of an appropriate safety standard, along with further RD&D is needed to fully assess its potential advantages and disadvantages.
- A number of possible advantages have been cited that support further efforts to investigate the deep borehole option. These include the potential to achieve (compared to mined geologic repositories) reduced mobility of radionuclides and greater isolation of waste, greater tolerance for waste heat generation, modularity and flexibility in terms of expanding disposal capacity, and compatibility with a larger number and variety of possible sites. On the other hand, deep boreholes may also have some disadvantages in terms of the difficulty and cost of retrieving waste (if retrievability is desired) after a borehole is sealed, relatively high costs per volume of waste capacity, and constraints on the form or packaging of the waste to be emplaced.

Blue Ribbon Commission on America's Nuclear Future
U. S. Department of Energy

Blue Ribbon Commission on America's Nuclear Future
Report to the Secretary of Energy, January 2012

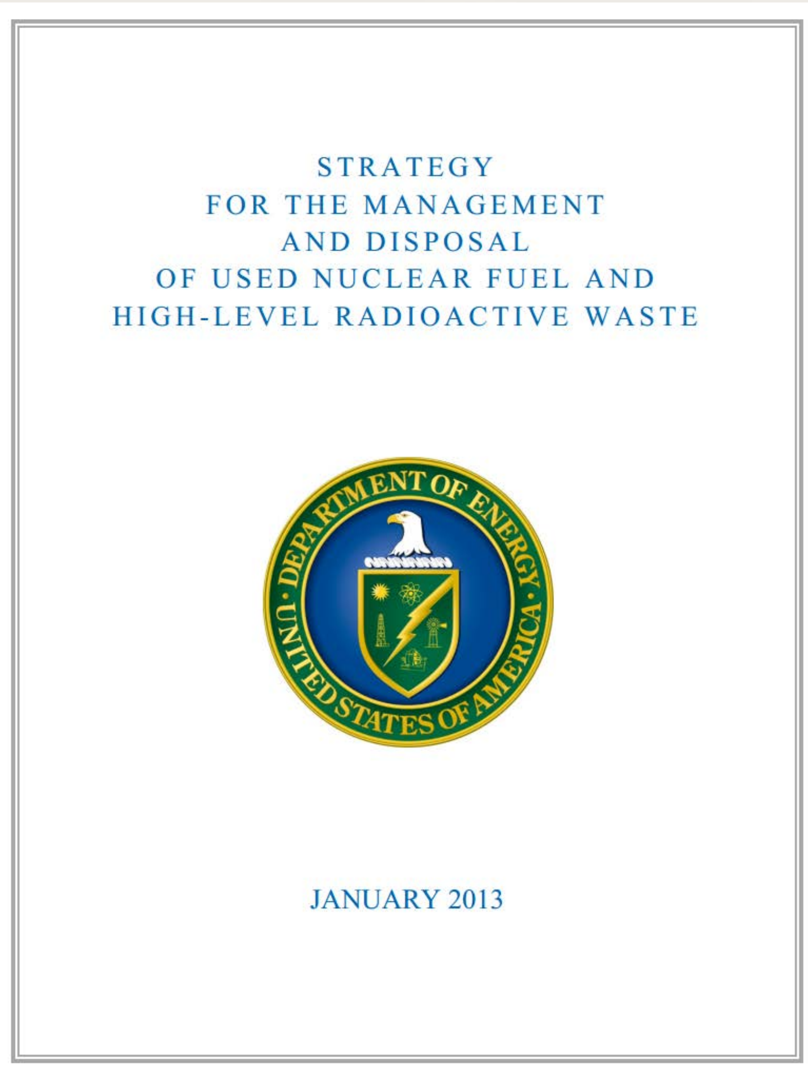
- Overall, the Commission recommends further RD&D to help resolve some of the current uncertainties about deep borehole disposal and to allow for a more comprehensive (and conclusive) evaluation of the potential practicality of licensing and deploying this approach, particularly as a disposal alternative for certain forms of waste that have essentially no potential for re-use.
- 9.3 Recommendations for Developing Future Disposal Facility Standards—
  - *7. EPA and NRC should also develop a regulatory framework and standards for deep borehole disposal facilities (p. 105).*
  - The Commission has identified deep boreholes as a potentially promising technology for geologic disposal that could increase the flexibility of the overall waste management system and therefore merits further research, development, and demonstration. While a regulatory framework and safety standards for deep boreholes would have much in common with those for mined geologic repositories, the technologies also have key differences. For this reason the Commission recommends that EPA and NRC develop a regulatory framework and safety standard for deep boreholes as a way to support further RD&D efforts aimed at developing a licensed demonstration project (*though we also note that this effort should not detract in any way from the expeditious development of revised generic regulations for mined geologic repositories).*

Blue Ribbon Commission on America's Nuclear Future

U. S. Department of Energy

- 12. Near Term Actions
  - Disposal
    - DOE should develop an RD&D plan and roadmap for taking the borehole disposal concept to the point of a licensed demonstration (p. 134).
  - Regulatory Actions
    - The Administration should identify an agency to take the lead in defining an appropriate process (with opportunity for public input) for developing a generic safety standard for geologic disposal sites. The same lead agency should coordinate the implementation of this standard-setting process with the aim of developing draft regulations for mined repositories and deep borehole facilities (p. 135).

Administration Response to BRC January 2013



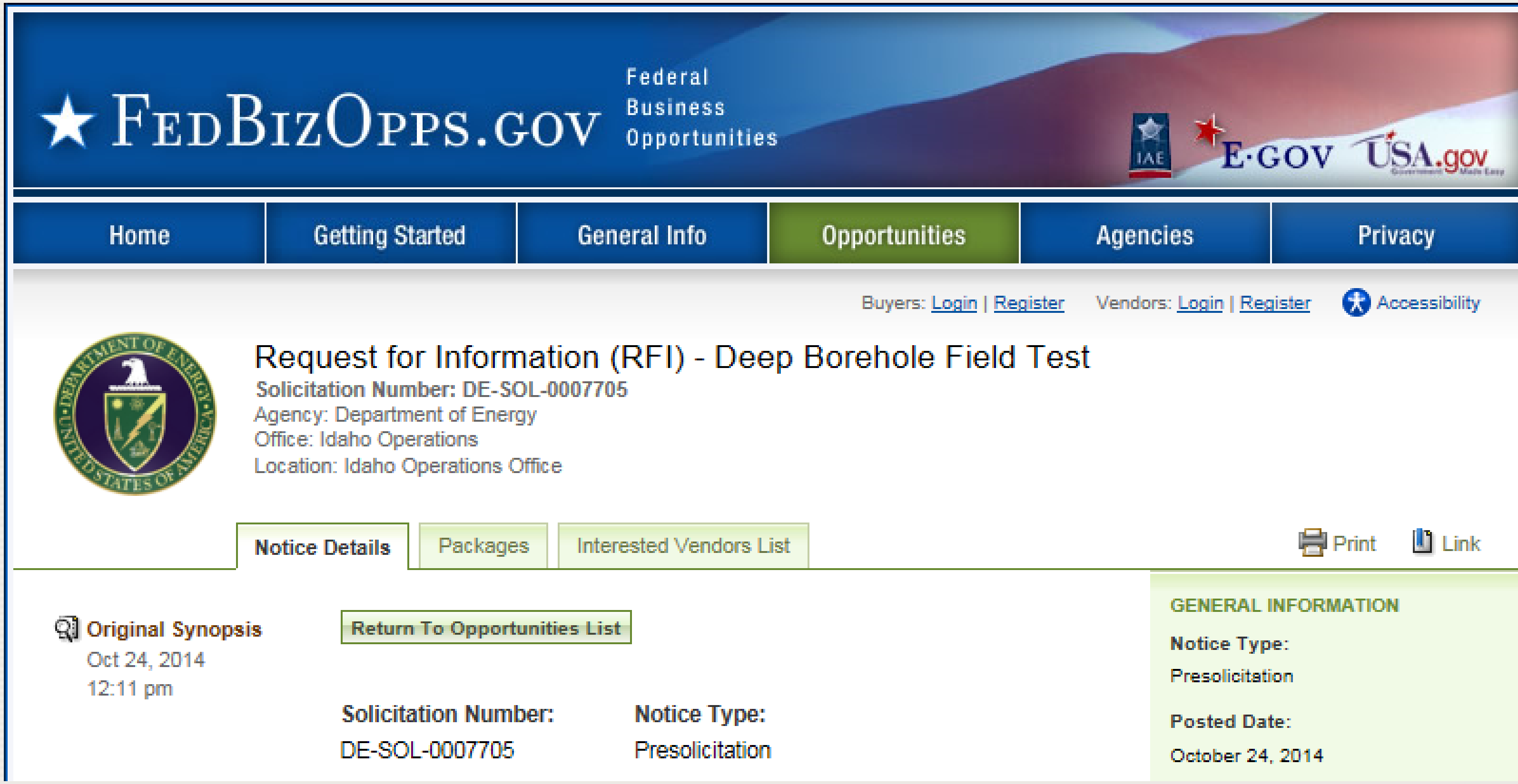
"The ability to retrieve used nuclear fuel and high-level radioactive waste from a geologic repository for safety purposes or future reuse has been a subject of repository design debate for many years. A recently completed technical review by Oak Ridge National Laboratory found that approximately 98 percent of the total current inventory of commercial used nuclear fuel by mass can proceed to permanent disposal without the need to ensure post-closure recovery for reuse based on consideration of the viability of economic recovery of nuclear materials, research and development (R&D) needs, time frames in which recycling might be deployed, the wide diversity of types of used nuclear fuel from past operations, and possible uses to support national security interests. This assessment does not preclude any decision about future fuel cycle options, but does indicate that retrievability it is not necessary for purposes of future reuse."

- **this is open recognition of support for direct disposal AND no need for retrievability for reuse**

"In FY 2013, the Department is undertaking disposal-related research and development work in the following areas: an evaluation of whether direct disposal of existing storage containers used at utility sites can be accomplished in various geologic media; an evaluation of various types and design features of back-filled engineered barriers systems and materials; evaluating geologic media for their impacts on waste isolation; evaluating thermal management options for various geologic media; establishing cooperative agreements with international programs; and developing a research and development plan for deep borehole disposal, consistent with BRC recommendations."

- **explicit recognition of deep borehole development as on the R&D agenda**

October 2014



Other countries have also begun to explore DBD: Germany, China, Korea, Ukraine…

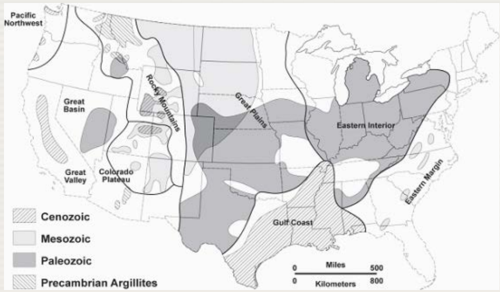
Final Thoughts

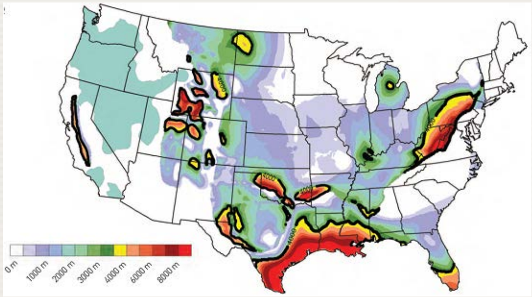
CAN DBD BE ‘FASTER, CHEAPER, BETTER’?

Potential Repository Host Rocks

Property	Salt	Shale	Granite	Deep boreholes
Thermal conductivity	High	Low	Medium	Medium
Permeability	Practically impermeable	Very low to low	Very low (unfractured) to permeable (fractured)	Very low
Strength	Medium	Low to medium	High	High
Deformation behavior	Visco-plastic (creep)	Plastic to brittle	Brittle	Brittle
Stability of cavities	Self-supporting on decade scale	Artificial reinforcement required	High (unfractured) to low (highly fractured)	Medium at great depth
In situ stress	Isotropic	Anisotropic	Anisotropic	Anisotropic
Dissolution behavior	High	Very low	Very low	Very low
Sorption behavior	Very low	Very high	Medium to high	Medium to high
Chemical	Reducing	Reducing	Reducing	Reducing
Heat resistance	High	Low	High	High
Mining experience	High	Low	High	Low
Available geology*	Wide	Wide	Medium	Wide
Geologic stability	High	High	High	High
Engineered barriers	Minimal	Minimal	Needed	Minimal

Favorable property — Average — Unfavorable property

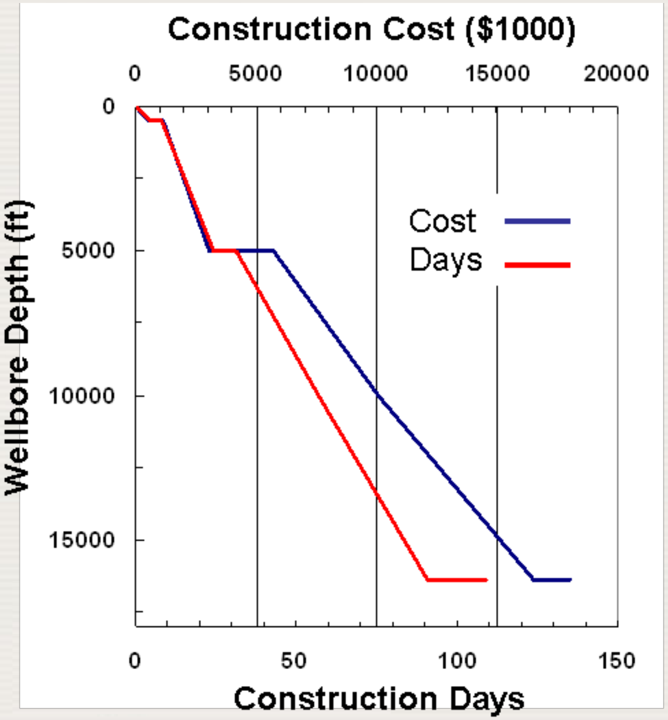




Feasibility

Note: All costs are in 2011 $US and approximately for 2011 expenses.	**Cost per Borehole**
Drilling, Casing, and Borehole Completion	$27,296,587
Waste Canisters and Loading	$7,629,600
Waste Canister Emplacement	$2,775,000
Borehole Sealing	$2,450,146
Total	**$40,151,333**

from Arnold et al. (2011)



- Faster
  - estimated time for drilling, borehole completion, waste emplacement, and sealing is about 186 days (not decades)
- Cheaper
  - low initial costs
  - low investment risk
  - scaled costs
  - estimated disposal costs are $158/kg heavy metal (compared to nuclear waste fund fee of roughly $400/kg, Gibbs, 2010)
- Better
  - extremely low peak dose assessments

Source: Polsky, Y., L. Capuano, et al. (2008). *Enhanced Geothermal Systems (EGS) Well Construction Technology Evaluation Report,* SAND2008-7866, Sandia National Laboratories, Albuquerque, NM

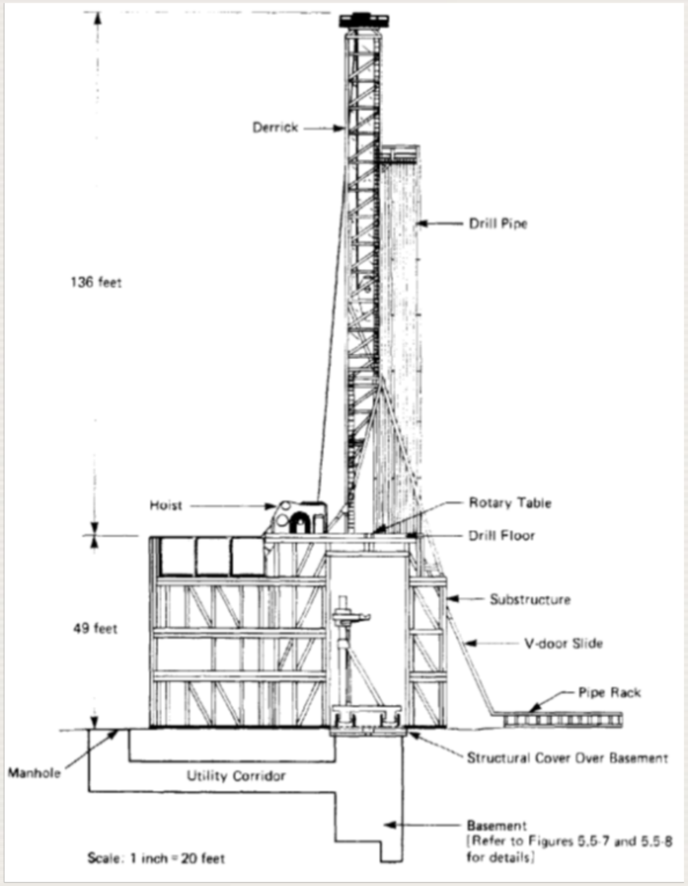
However…

- Like ‘paper reactors*’ the same should be said of ‘paper repositories’; things always look good on paper.
  - Thus, the desire to implement a field-scale demonstration
- The point is <u>not</u> that Deep Borehole Disposal is the best or only solution for geologic disposal.
- The point is the concept holds such significant promise that it warrants consideration of an effort to accelerate its pilot demonstration, and to vet its true feasibility and viability.
- The concept has merit for programs with both large and small waste burdens; it may be worth considering a multinational collaborative effort.

* Admiral H.G. Rickover, "Paper Reactors, Real Reactors" (5 June 1953)

Thank You

- Sit down before fact with an open mind. Be prepared to give up every preconceived notion. Follow humbly wherever and to whatever abyss Nature leads or you learn nothing. Don't push out figures when facts are going in the opposite direction. (Admiral Rickover)



from Woodward-Clyde Consultants (1983)