SAND2011-8201P

Pilot Testing Deep Borehole Disposal of Nuclear Waste: October 26, 2011 Albuquerque, NM Workshop Report.

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October 27, 2011

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.

October 26, 2011 Borehole Workshop Attendees. Front Row left to right: Andrew Orrell – Sandia; Jack Tillman – Sandia; Bill Arnold – Sandia; Dennis Neilson – DOSECC; George Saulnier – AREVA; Bill Badger – CH2M-Hill; Jay Silberg - Pillsbury Winthrop Shaw Pittman LLP; Rod McCullum – NEI: Back Row left to right: Pat Brady – Sandia; Mike Driscoll – MIT; Tim Gunter – DOE-NE; Frank Hansen – Sandia; Rod Ewing – NWTRB/U. Michigan; Andrew Sowder – EPRI; Eric Knox – URS; Dave Jansen – Longenecker and Associates; Fergus Gibb – U. Sheffield; John Ullo – Schlumberger; Tito Bonano – Sandia; and John Kristofzski – CH2M-Hill.

Introduction

On October 26, 2011 Sandia National Laboratories 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. Andrew Orrell (Sandia) presented an overview of Deep Borehole Disposal followed by a discussion of borehole pilot testing at the Climax stock in Nevada in the early 1980's (Brady – Sandia), then a description of a recently issued base case reference borehole design (Arnold, Brady et al. 2011) from Bill Arnold (Sandia). Mike Driscoll (MIT) and Fergus Gibb (Sheffield) outlined alternative designs and novel rock-welding and sealing approaches (The individual presentations can be found below). A summary of the meeting discussions follows.

Discussion

Deep borehole disposal is calculated to be as safe as traditional mined geologic repositories (Brady, Arnold et al. 2009) but more flexible, less expensive (Arnold, Brady et al. 2011), and more rapidly implemented. Borehole disposal is estimated to cost about $158/kg HM (Arnold, Brady et al. 2011), substantially less than the cost estimated for Yucca Mountain.

A significant science and engineering literature of deep borehole disposal has accumulated (see Table 1 and the presentations at the end of this report) and important features of the approach have been pilot-tested (Patrick 1986).

Table 1. Partial listing of borehole technical articles

Subject	Article
Borehole Engineering analysis	(Juhlin and Sandstedt 1989; Juhlin and Sandstedt 1989; Nirex 2004; Beswick 2008)
Borehole geochemistry	(Anderson 2004; Brady, Arnold et al. 2009)
Rock welding for borehole plugging	(Gibb, Taylor et al. 2008)
Heat flow	(O'Brein, Cohen et al. 1979; Brady, Arnold et al. 2009)
Cannister design	(Hoag 2006)
Borehole support matrices	(Gibb, McTaggart et al. 2008)
Site selection for disposal of Pu in boreholes	(Heiken and al. 1996)
Pilot remote handling at the surface	(Patrick 1986)
Annealing of radiation-damaged waste forms in boreholes	(Weber, Ewing et al. 1996)

Questions central to the piloting and implementation of deep boreholes that were identified by the participants include the following.

- Who will pay for a demonstration?
- Where will the demonstration be?
- Why did Sweden examine, but not pursue, deep borehole disposal?
- How long does the "Journey of Discovery" need to be? Actual drilling will ultimately uncover unexpected features. Will their subsequent examination be lengthy (as at Yucca Mountain) and potentially crippling?
- What constitutes adequate characterization?
- How hard will it be to prove adequate downhole conditions e.g. "old" H_2O, high salinities, low permabilities.
- What is the role of engineered barriers?
- Is "The deeper you go the less you need to know" an accurate description of deep borehole site characterization?
- What are functional & operational requirements for a demonstration; what should be the balance between science and engineering?
- What waste types should be the basis of the demo (assemblies vs. rod consolidation, hot vs. cold, Cs/Sr)?
- What will future deep borehole regulations look like?
- What legislative /regulatory actions are needed for deep borehole disposal?
- How to address issue of retrievability?
- How to develop a champion for deep borehole demonstration and implementation?
- What will be the scope of a demonstration; for example, demonstrate drilling vs. demonstrate drilling at a potential disposal site vs. drilling near a reactor?
- What is the extent of characterization by pilot discovery holes vs. emplacement holes needed to demonstrate acceptable conditions?
- How much 'gilding' of a base reference design is needed?
- What are the mechanical properties of rock welds?
- How much logging should/will be done?
- How to garner approval to dispose (what is closure)? What is the regulatory framework?
- How/when do the utilities get involved? Where do they fit in? Same for DOE and/or FedCorp?
- What does the operational safety case look like?
- What is the narrative that will give the public an accurate picture of borehole safety and effectiveness? and that can be socialized with industry for making investments?
- How will we organize to tackle the above?

Other conclusions from the discussion were:

- Keep the design as simple as possible. Use the simple approach to guide the questions we ask about the site.
- As we pursue a demonstration, we will need to keep building the database and confidence that downhole conditions are what we assert. Likewise we need to articulate the case for DBH as 'faster cheaper better'.
- A cold demonstration (no hot fuel) would be effective and far easier to implement.
- A risk-informed approach might limit open-ended site discovery. Deciding ahead of time what a "bad borehole" is ahead of time focus site discovery.
- Industry not sold on additional cost savings gained by rod consolidation due to complexity and costs.
- Regulation might be done in two steps; initially qualifying a site followed by testing individual holes against previously established acceptability criteria.
- Deep borehole disposal of the Cs and Sr from Hanford (>30% of the activity) would be a useful first disposal target.
- Deep boreholes may not be the solution for all wastes.
- A new waste disposal paradigm is needed because the mine geologic repository model has features, such as engineered backfill systems, multi-barriers, and retrievability (?) that may not apply to deep boreholes. An analysis needs to be done to show that deep boreholes are better than mined geologic repositories (or CO_2 sequestration sites). Conference papers, peer-reviewed articles on deep boreholes would help.
- How defensible are basic geologic concepts that brine won't rise because of density stratification, seals will be effective and durable, host rock is suitably homogeneous?
- "The oil and gas industry routinely goes 5 km deep. A demonstration could be done with the technical/engineering understanding we have now. You're 99% done if you show no overpressuring and low permeabilities. "
- "There are no show-stoppers. Demonstrate that you can drill a hole this deep and wide, send a cold package up and down a few times and you're halfway there."
- Innovations will be developed in the course of a demo that might benefit carbon sequestration, engineered geothermal, oil and gas.
- Local advocacy is needed.

Coalition

The attendees collectively agreed that the technical concept is good, that a deep borehole demonstration pilot project is needed, and individually

expressed willingness to become part of a Deep Borehole Coalition to organize and implement the pilot. Splitting the coalition focus in three directions – engineering, science, and sociopolitical – might be wise. Details of the Deep Borehole Coalition will require time to be resolved.

References

Anderson, V. K. (2004). An evaluation of the feasibility of disposal of nuclear waste in very deep boreholes. Dept. of Nuclear Engineering. Cambridge, MA, MIT.

Arnold, B. W., P. V. Brady, et al. (2011). Reference Design and Operations for Deep Borehole Disposal of High-Level Radioactive Waste SANDIA REPORT SAND2011-6749.

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Heiken, G. and e. al. (1996). Disposition of excess weapon plutonium in deep boreholes – site selection handbook. Los Alamos, NM, Los Alamos National Laboratory.

Hoag, C. I. (2006). Canister design for deep borehole disposal of nuclear waste. Dept of Nuclear Engineering. Cambridge, MA, MIT. M.S.

Juhlin, C. and H. Sandstedt (1989). Storage of nuclear waste in very deep boreholes: Feasibility study and assessment of economic potential. Part I Geological considerations. Part II Overall facilities plan and cost analysis.

Juhlin, C. and H. Sandstedt (1989). Storage of nuclear waste in very deep boreholes: Feasibility study and assessment of economic potential. Part I: Geological considerations. Part II: Overall facility plan and cost analysis., Svensk Karnbranslehantering AB.

Nirex (2004). A Review of the Deep Borehole Disposal Concept for Radioactive Waste, Nirex-UK.

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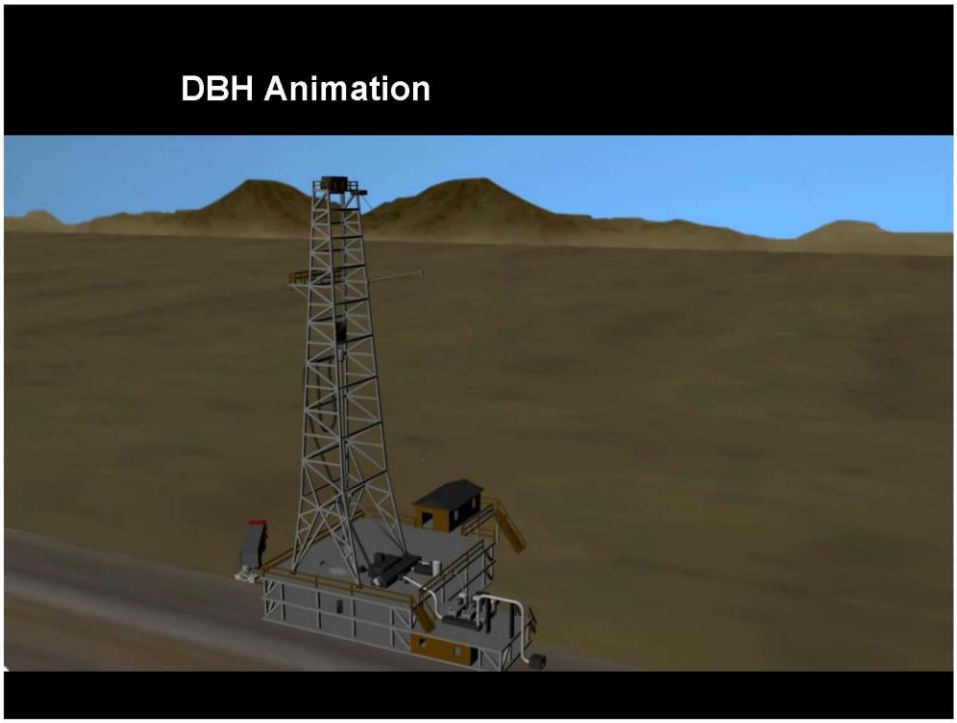
Patrick, W. C. (1986). "Spent Fuel Test-Climax: An Evaluation of the Technical Feasibility of Geologic Storage of Spent Nuclear Fuel in Granite. UCRL-53702.".

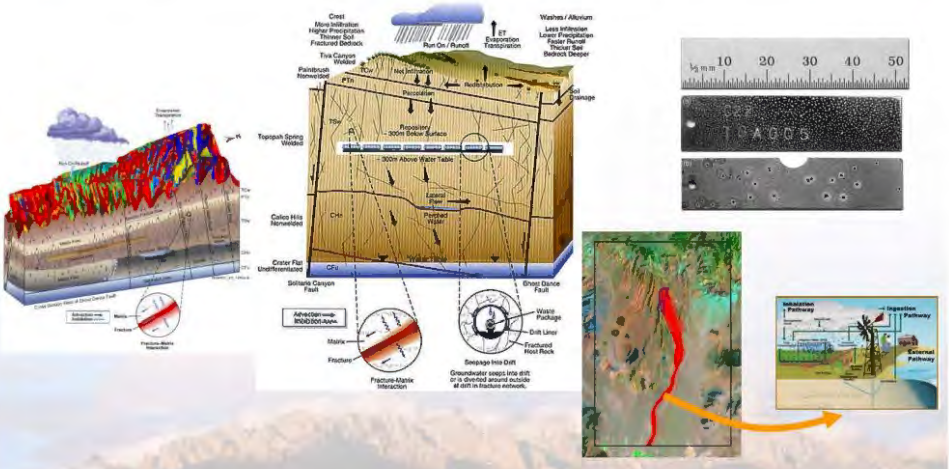
Weber, W. J., R. C. Ewing, et al. (1996). "Performance assessment of zircon as a waste form for excess plutonium under deep borehole burial conditions." Materials Research Society Symposium Proceedings 412: 25-32.

Andrew Orrell Presentation



Mined Repositories

- Coupling between the surface and near-field disposal environment



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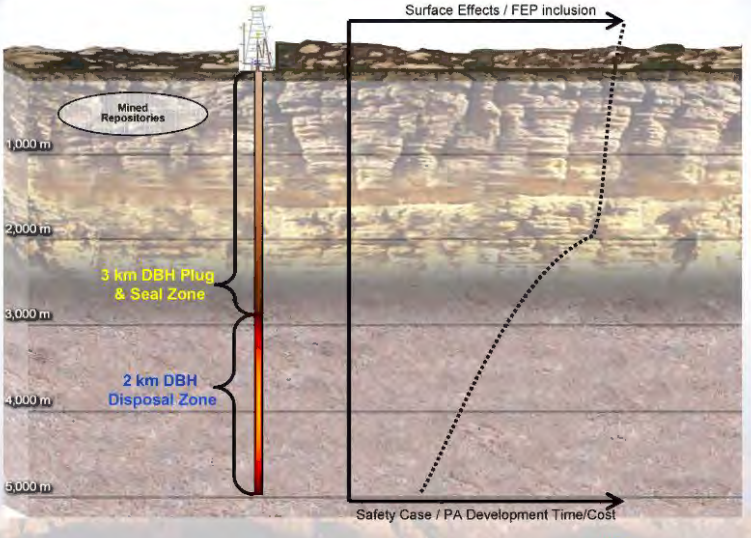
Deep Borehole Disposal Concept Drivers



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5 km Paths

Scale

Asserted Benefits of DBH 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 assurance isolation**
- **Thermal loading issues are minimized**
- **Geochemically reducing conditions limit solubility and enhance the sorption of many radionuclides**
- **Retrievability is difficult**
- **Compatible with multiple waste forms and types (e.g. CANDU bundles)**
- **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) could reduce this by ~1/2, or possibly further reduce costs for smaller hole bottom diameter
- **May be amenable to a COL approach (separate licensing for technology and siting)**

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)

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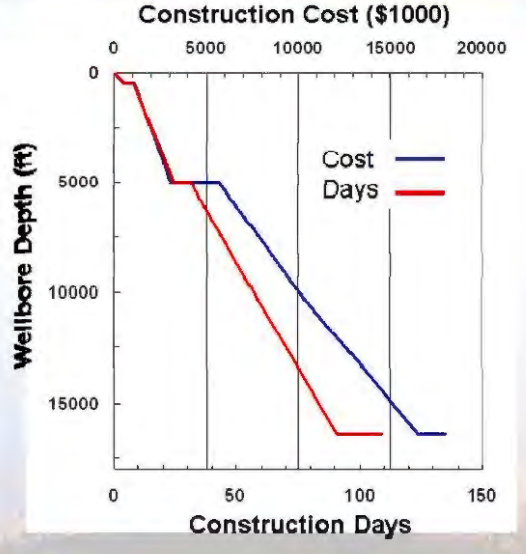
Feasibility



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

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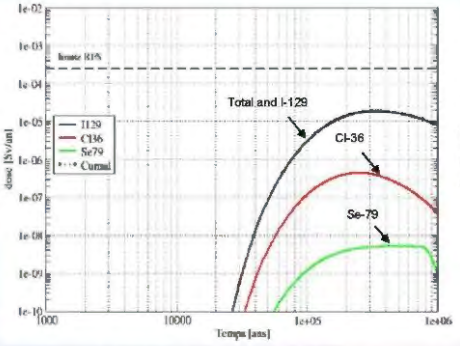
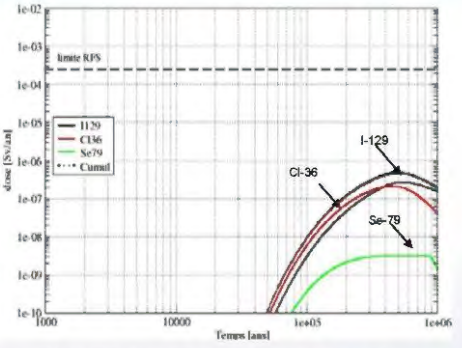
Two Repositories



ANDRA 2005, *Dossier 2005: Argile. Tome: Evaluation of the Feasibility of a Geological Repository in an Argillaceous Formation*, Figure 5.5-18, SEN million year model, CU1 spent nuclear fuel



ANDRA 2005, *Dossier 2005: Argile. Tome: Evaluation of the Feasibility of a Geological Repository in an Argillaceous Formation*, Figure 5.5-22, SEN million year model, C1+C2 vitrified waste

A Path to DBH Awareness

Even Bright HS Students Get It

Deep Boreholes as the Next-Generation Nuclear Waste Repository

Lisa Leung
Montgomery Blair High School
51 University Blvd. East
Silver Spring, MD 20901

under the direction of
Professor Emeritus Michael J. Driscoll
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139

January 29, 2003

Lisa Leung
Montgomery Blair High School
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Silver Spring, MD 20901

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Professor Emeritus Michael J. Driscoll
Massachusetts Institute of Technology
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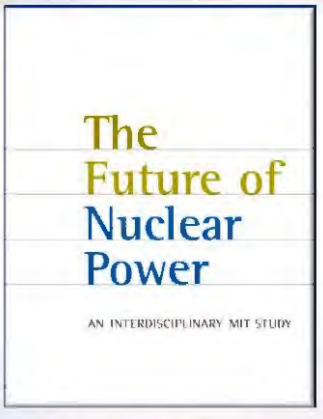
Cambridge, MA 02139

January 29, 2003

Deep Borehole Disposal



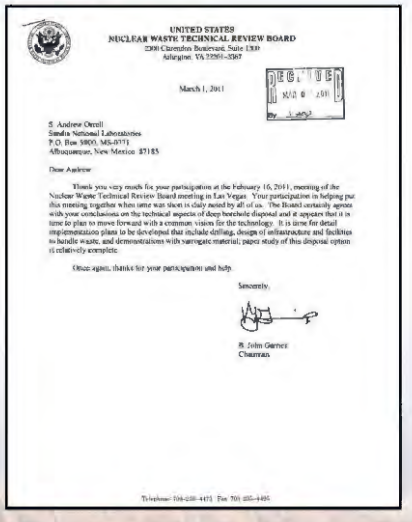
"We further conclude that waste management strategies in the once-through fuel cycle are potentially available that could yield long-term risk reductions at least as great as those claimed for waste partitioning and transmutation, with fewer short-term risks and lower development and deployment costs. *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)**

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

March 1, 2011

RECEIVED
MAR 0 2011
By

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,

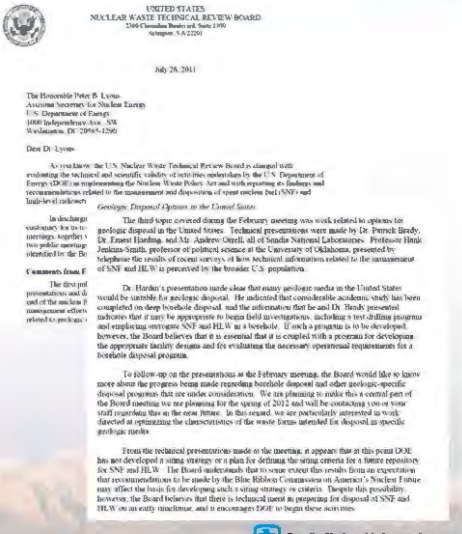
B. John Garrick
Chairman

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

Sandia National Laboratories

NWTRB Letter to Assistant Secretary for Nuclear Energy, July 26, 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 radiowaste.

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 Hardin, 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.

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Raising Visibility (2/2010)

NUCLEAR ENGINEERING INTERNATIONAL
FEBRUARY 2010
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RADWASTE MANAGEMENT: DEEP BOREHOLES

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 volumes of waste in deep boreholes. Conditions favorable 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 US 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 pressurized light [1]. The interesting 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. Waste in the deep borehole disposal system is seismically 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 in several factors. Crystalline basement rocks are relatively common at depths of 2000m-3000m 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 as 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. Given basically 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, shown schematically as a cross-section through the earth's crust, after Chapman & Gibb [10].

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 2009 NKS commissioned a feasibility study [11] into drilling the boreholes required for their VDH concept. The original well design was modified to give a deployment zone diameter of 0.8 km with a 0.5km outer diameter casing, using steel for the containers and casing in most of situations. 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 157 days to drill the hole and it would cost around EUR 16.5 - [illegible] million.

The most recent and comprehensive study of the status of drilling technology for DBD was carried out for the NDA in 2006 [12]. It was concluded that in an appropriate geology such as granite, a borehole with a clear, useable diameter of 0.3m, drilled and cased to a depth of 4km, is perfectly practicable using existing technology with some developments 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, 0.3m 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 build-in time of two years and cost about GBP20 EUC million, although savings on subsequent holes, especially on the same site, could approach 50%.

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 kilometer of 0.3m borehole can dispose of approximately 200m³ of packaged waste or 600 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 EVVER-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 about, this would effectively leave the pins surrounded by water. Such a situation would be analogous to the consolidated storage of used fuel pins as 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

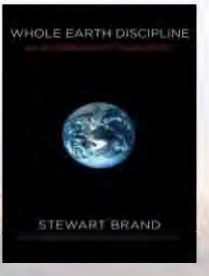
Demonstration, testing and development of several of the necessary technologies require a full scale 40 cm (inner diameter) cased borehole, but one that is shortened to a depth of a few hundred metres. The only other constraints are that it be in granite host rock and that its bottom end should be readily accessible from per-

Raising Visibility

- **Bulletin of the Atomic Scientists, Robert Alvarez, March 2010**
  - "More time will allow for other promising disposal options to be explored, such as burying waste in 2-3 mile-deep boreholes using existing drilling technology."
- **Energy and Water Development, FY2011 Appropriations, September 2010**
  - Much of the planned research on spent fuel management options will support the newly created Blue Ribbon Commission on America's Nuclear Future, which is to develop alternatives to the planned Yucca Mountain, NV, spent fuel repository, which President Obama wants to terminate. In addition to researching potential waste treatment technologies and approaches that may be considered by the Blue Ribbon Commission, the program will study "a variety of geologic disposal media such as granite, tuff, deep boreholes, clay, shale, salt, and basalt," according to the justification.

Whole Earth Discipline: An Ecopragmatist Manifesto…..by Stewart Brand

- "Nuclear has the most news. President Obama shut down Yucca Mountain and assigned a blue ribbon committee to come up with a practical nuclear waste storage policy for the US. One intriguing alternative being explored uses deep borehole technology developed by the oil and gas industry. At any reactor site you can drill a hole three miles deep, a foot and a half wide. Down there in the basement rock the water is heavily saline and never mixes with surface fresh water. You can drop spent fuel rods down the borehole, stack them up a mile deep, pour in some concrete, and forget about the whole thing."

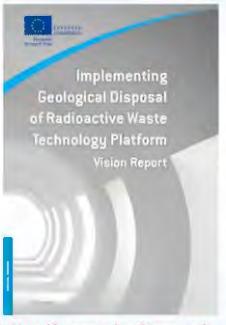


Conclusion

- The point here is not that Deep Borehole Disposal is the best or only solution for geologic disposal. The point is that 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.
- As the concept has such merit for the US, and potentially Mexico (small BWR inventory) and Canada (smaller diameter CANDU) as well, it may be worth considering a multinational collaborative effort similar to the EU technology platform for Implementing Geologic Disposal.
- Lastly, as a concept which could yield patentable technology that would have direct and indirect applications (e.g. enhanced geothermal), industry RD&D participation is conceivable, and could be a precursor to alternative waste management models such as FedCorp.

Using the IGD-TP as a Model for a DBH Consortium

Next Steps



http://www.igdtp.eu/

Stakeholders, led by industry, come together to **agree a common vision** for the technology.

Stakeholders **define a Strategic Research Agenda** setting out the necessary medium- to long-term objectives for the technology.

Stakeholders **implement the Strategic Research Agenda** with the mobilisation of significant human and financial resources.

"Our vision is that by 2025, the first geological disposal facilities for spent fuel, high-level waste, and other long-lived radioactive waste will be operating safely in Europe."

Sets the RD&D priorities for licencing and implementation

Deployment Plan expected 2011, to lay out forms of joint work and activities, leads, etc.

Can we create a DBH Disposal Technology Platform as a consortium of interested *implementers*, dedicated to resolving the remaining R&D needed for implementation of a pilot demonstration?

IGD-TP as a model

What is a TP?

"bring together R&D-relevant stakeholders with various backgrounds who would develop a long-term R&D strategy in areas of interest to Europe"

"industry lead is important to gain commitment and momentum".

http://cordis.europa.eu/technology-platforms/home_en.html

IGD-TP

IGD-TP: Membership based on commitment

How to join

- Joining a platform is not a simple decision. It is a commitment:
  - To participate to the work performed in the framework of the platform
  - To share views and works for the Vision
- Joining the IDG-TP platform is simple
  - To endorse the Vision
  - To send an application form to the Secretariat: www.igdtp.eu

IGD-TP

IGD-TP Vision Document

- To meet the overall vision of the IGD-TP in an efficient way, the activities to be performed within the technology platform need to be implementation-oriented.
- Mission: The platform will be a tool to support the confidence-building in the safety and implementation of deep geological disposal solutions. A strategic research agenda, means of working together and a detailed deployment plan will be developed. The platform will facilitate access to expertise and technology, interact with the stakeholders, and communicate the results to the benefit of all of Europe.
- Objective: to define, prioritise, initiate, and carry out European strategic initiatives that will facilitate the stepwise implementation of safe, deep geological disposal of spent fuel, high-level waste, and other long-lived radioactive waste by addressing the remaining scientific, technological and social challenges…

IGD-TP SRA

- The main objectives of the IGD-TP are to initiate and carry out collaborative actions in Europe to facilitate the stepwise implementation of safe, deep geological disposal of spent fuel, high-level waste, and other long-lived radioactive waste by solving the remaining scientific, technological and social challenges, and thereby to support the waste management programmes in the Member States. The platform intends to enhance confidence in the solutions and implementation of geological disposal, to reduce overlapping work, to produce savings in total costs of Research, Development and Demonstration (RD&D), and to make better use of existing competences and research infrastructures.
- It is also envisaged that the IGD-TP will enhance European co-operation in the areas where work still remains, optimise the solutions and move results from laboratories and pilot-facilities to the industrial scale.
- This document contains the SRA of the IGD-TP and outlines the remaining research, development and demonstration (RD&D) activities needed to reach the above-mentioned Vision 2025.

Consortium Conclusion

- **The IGD-TP could serve as a model to approach the BRC draft recommendation of "*DOE should develop an RD&D plan and roadmap for taking the borehole disposal concept to the point of a licensed demonstration*".**
  - It is implementation-oriented
  - Membership is based on a commitment to the vision (of DBH demonstration), and to participate in the work therein
  - Consortium members span the industry/academic/lab partners that can bring a demonstration to reality
  - The Strategic Research Agenda is a good mechanism to delineate the remaining "*remaining scientific, technological and social challenges,… facilitate stepwise implementation,…and to move results from laboratories and pilot-facilities to the industrial scale*" for DBH demonstration.
  - Key Question for the Workshop: can we create an enduring consortium that can uphold these ideals?

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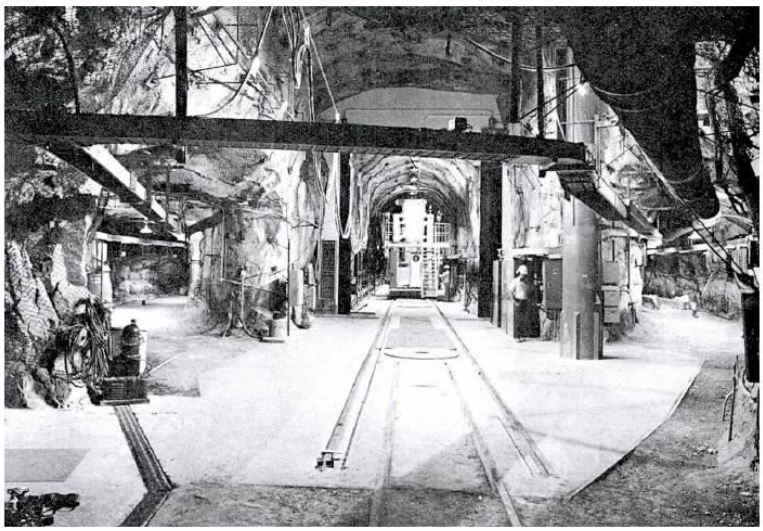
Pat Brady Presentation

Climax Spent Fuel test



W. C. Patrick (1986) Spent Fuel Test-Climax: An Evaluation of the Technical Feasibility of Geologic Storage of Spent Nuclear Fuel in Granite. UCRL-53702.

Bill Arnold Presentation

SAND2011-xxxx

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

Borehole Consortium Meeting
Albuquerque, New Mexico

October 26, 2011

Bill Arnold and Pat Brady

Sandia National Laboratories

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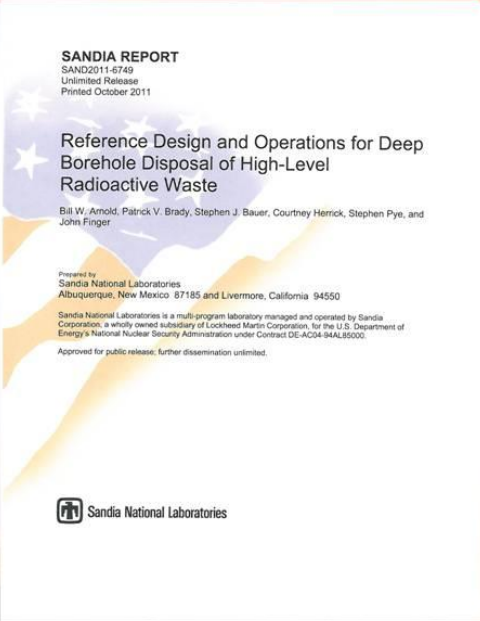
LOCKHEED MARTIN

Sandia National Laboratories

Reference Design SAND Report



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

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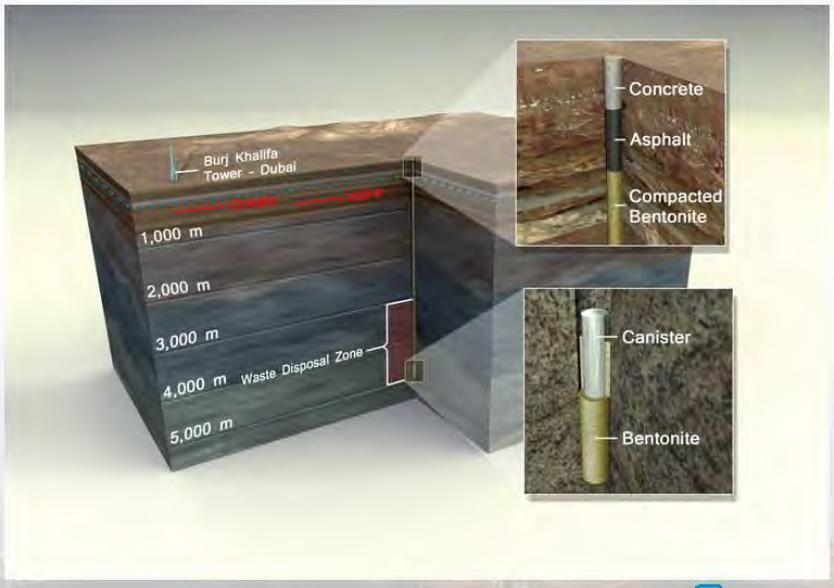
Outline

- Deep borehole disposal concept
- Reference design objectives
- Borehole construction
- Waste canisters
- Waste emplacement
- Borehole sealing and abandonment
- Cost and schedule analysis
- Conclusions

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
- 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 and cement
- Several factors suggest the disposal concept is viable and safe:
  - Crystalline basement rocks are common in many stable continental regions
  - Existing drilling technology permits dependable construction at reasonable cost
  - Low permeability and long residence time of high-salinity groundwater in deep continental crystalline basement at many locations suggests very limited interaction with shallow fresh groundwater resources
  - Geochemically reducing conditions at depth limit the solubility and enhance the sorption of many radionuclides in the waste
  - Density stratification of saline groundwater underlying fresh groundwater would oppose thermally induced groundwater convection

Deep Borehole Disposal Concept

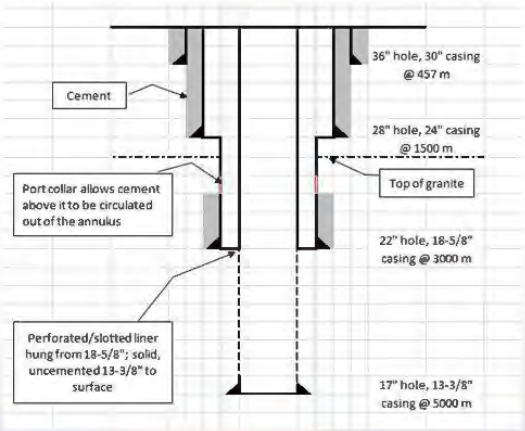


Reference Design Objectives

- Overarching objective: A simple and achievable, internally consistent system for waste disposal that meets regulatory requirements for operational and public safety.
- Update and refine the conceptual design presented in Brady et al. (2009)
- More completely evaluate the feasibility of all elements in the deep borehole disposal system, including operational plans
- Consider preliminary design alternatives
- Provide a reference design for performance assessment and risk analysis
- Provide a reference design for more accurate cost estimates

Borehole Construction

- Drilling to 5 km depth is not exceptional for geothermal development and 17 inches diameter should be feasible with current technology
- Anticipated testing and logging for the large diameters specified in the nested borehole design may be difficult to achieve, leading to consideration of alternatives, such as a pilot hole
- A liner casing will be in place for the emplacement of waste canisters to assure against stuck canisters
- The perforated liner will be left in place in the disposal zone, but will be removed in the seal zone, along with most of the intermediate casing



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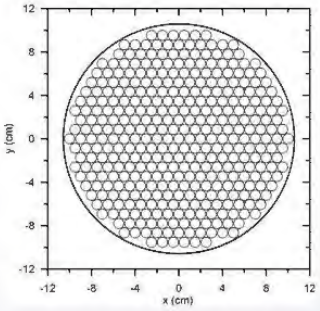
Waste Canisters

- Waste canisters consist of carbon steel tubing with welded plugs and threaded connections
- Canisters are designed to withstand projected hydrostatic pressure and mechanical load of overlying canisters for lower peak temperature (160 °C) and higher temperature (300 °C)
- Used PWR fuel assemblies would be dismantled and 367 fuel rods would be placed in the canister (lower-temperature design)
- Although not designed to withstand corrosion for long periods of time, waste canisters would retain their integrity until after the borehole is loaded and sealed



	Inside Diameter (inches)	Outside Diameter (inches)	Wall Thickness (inches)
Lower-Temperature Canister	8.33	10.75	1.21
Higher-Temperature Canister	8.05	10.75	1.35

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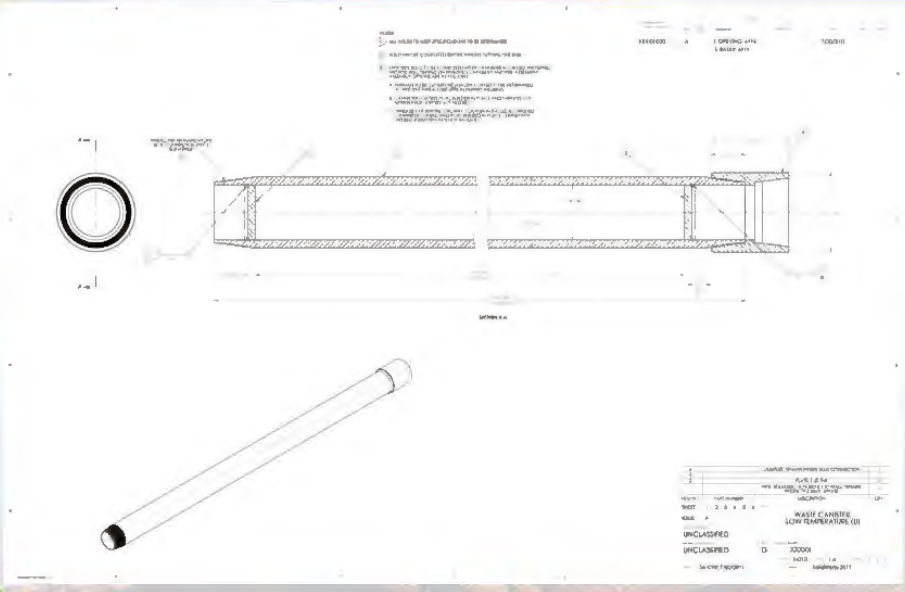
Waste Canisters



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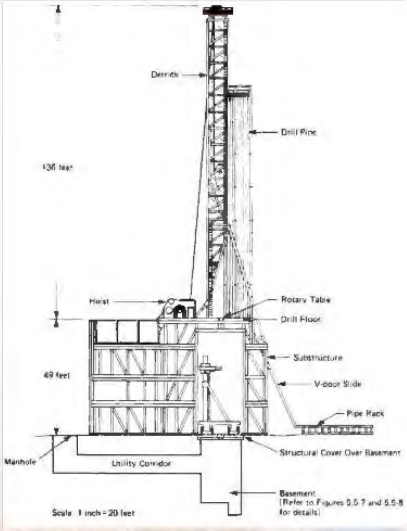
Waste Emplacement

- Loaded waste canisters would be transported to the site by tractor trailer using shipping casks
- Surface handling would rotate the shipping cask to a vertical position, move the cask by a short rail system over the borehole, attach the canister to the canister string and lower it into the borehole by remote operation
- Strings of 40 canisters (about 200 m) would be attached to the pipe string with a J-slot assembly and lowered to the disposal zone for disengagement
- A synthetic oil base mud with a high bentonite concentration would be present in the disposal zone, forming a grout around the waste canisters
- Each canister string would be separated from overlying canister strings by a bridge plug and cement plug



from Woodward-Clyde Consultants (1983)

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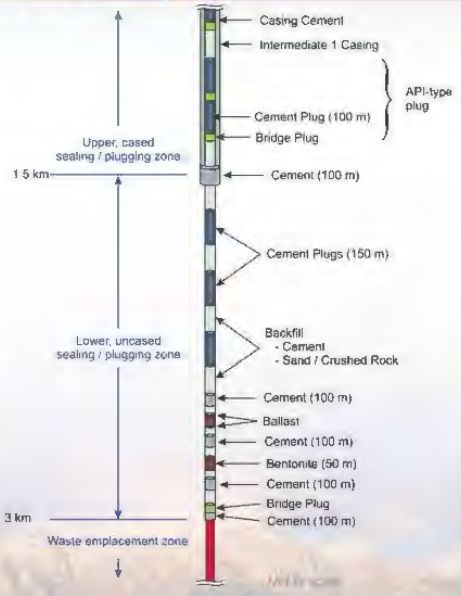
Borehole Sealing and Abandonment

- After the waste canisters have been emplaced and the overlying plugs have been set, the guide casing will be removed and the intermediate casing in the seal zone will be cut and removed
- Seals and plugs in the seal zone will be seated in contact with the rock of the borehole walls
- Compacted bentonite seals that swell by the uptake of water would be set by extrusion from a container or emplacement of a perforated tube
- Cement seals, alternating with sand/crushed rock/cement backfill, would fill the remainder of the seal zone
- Seals formed by "rock welding", as described by Dr. Gibb could be accommodated by the reference design



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Cost and Schedule Analysis

- Detailed, approximate cost analyses have been performed for each component of the deep borehole disposal system
- Borehole drilling and completion costs were analyzed for three cases: (A) a smaller-diameter (8.5 inch) pilot hole for coring, logging, and testing, (B) a full-diameter (17 inch) disposal borehole in which logging and testing is done, and (C) a full-diameter disposal borehole in which limited logging and testing is done
- Borehole costs are dominated by cost of rig time and casing

HOLE DESIGN	A	B	C
Interval costs			
Drilling time cost	$3,906,016	$7,421,582	$4,882,520
Tripping time cost	$2,446,664	$5,905,986	$3,058,330
Bit cost	$631,322	$3,861,709	$1,753,587
Other BHA	$315,661	$1,930,855	$876,793
Mud cost	$582,970	$1,732,607	$987,607
Casing cost	$1,183,200	$4,777,425	$4,777,425
Cementing time cost	$372,500	$790,625	$790,625
Cementing mat'l cost	$1,356,829	$2,339,904	$2,339,904
Trouble time	$0	$0	$0
Trouble cost	$0	$0	$0
Directional drilling	$467,850	$1,475,040	$951,165
Logging time	$645,000	$806,250	$806,250
Logging service	$200,000	$200,000	$200,000
Wellhead time	$120,000	$225,000	$225,000
Other costs	$1,612,500	$2,015,625	$0
Total interval costs	**$13,840,512**	**$33,482,609**	**$21,649,206**
Additional costs and time			
Mobilization/De-mob	$800,000	$1,000,000	$1,000,000
Site prep, cellar, conductor	$100,000	$100,000	$100,000
Pre-spud engineering	$300,000	$300,000	$300,000
Casing hangers, port collar, packers	$300,000	$500,000	$500,000
Wellhead equipment	$300,000	$500,000	$500,000
Contingency (15%)	$1,920,748	$5,022,391	$3,247,381
Total well cost	**$17,561260**	**$40,905,000**	**$27,296,587**
Total project time, days	**160.7**	**211.0**	**139.2**

Note: All costs are in 2011 $US and approximately for 2011 expenses.

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Conclusions

- The reference design meets the defined design criteria with available engineering technology
- Preliminary indications are that the reference design and operations meet anticipated regulatory requirements for safety and long-term risk, when implemented in an appropriate geological setting
- The estimated disposal cost (except transportation and storage costs) for used nuclear fuel is $158/kg heavy metal, which is less than the nuclear waste fee collected on electricity of about $400/kg heavy metal
- A large fraction of drilling costs for the initial borehole at a site are associated with logging and testing, suggesting that an initial, smaller-diameter pilot hole would be cost effective
- Dismantling fuel assemblies and consolidation of fuel rods in waste canisters constitutes an overall cost savings for the deep borehole disposal system

	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**

Note: All costs are in 2011 $US and approximately for 2011 expenses.

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Mike Driscoll Presentation

Other Variations on the Basic Borehole Option

- Reference version:
  - One vertical borehole per drill site. Field of holes on ~200m spacing.
- Design variations: optimize for
  - Retrievable service
  - Non-retrievable service
  - Intact spent fuel loading
  - Reconstituted spent fuel
  - Glass or ceramic reprocessing waste forms
  - Individual vs linked canisters
- Advanced/Less conventional versions
  - Multibranch boreholes (e.g. 10 branches per master hole)
  - High speed drilling – air in place of mud lube; laser, spallation, rotary + hammer, etc.
  - Caprock plugging methods
- Host geology
  - Ref:granitic
  - Salt – bedded or dome
  - Basalt

Two Special Applications

- (1) Enhanced Diversion Assurance
  - Incorporation of SiC sand in plug and liner cement can make recovery by re-drilling difficult and time consuming
  - Satellite surveillance can monitor for unusual top-of-hole post-closure activity, provide months of early warning.
  - Adoption is a good way to advertise non-proliferation bona fides.

Two Special Applications continued…

- (2) Minor Actinide Sequestration
  - Cost-effective alternative to transmutation using fast reactors/accelerators/fusion-fission hybrids.
  - Use of horizontal multibranch boreholes can increase thickness of caprock by factor of ten (4000m vs 400m) vs mined repository, decrease host rock permeability, increase downhole water salinity, insure reducing chemistry-which taken together can reduce probability of escape to biosphere by orders of magnitude.

Fergus Gibb Presentation

The University Of Sheffield.

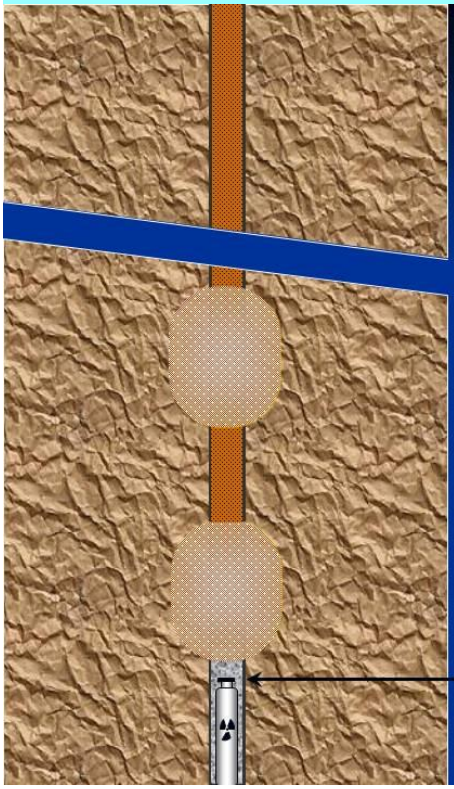
DEEP BOREHOLE DISPOSAL

BOREHOLE SEALING BY "ROCK WELDING"

Fergus G F Gibb

Department of Materials Science & Engineering, University of Sheffield, UK

Sandia NL – Oct. 2011

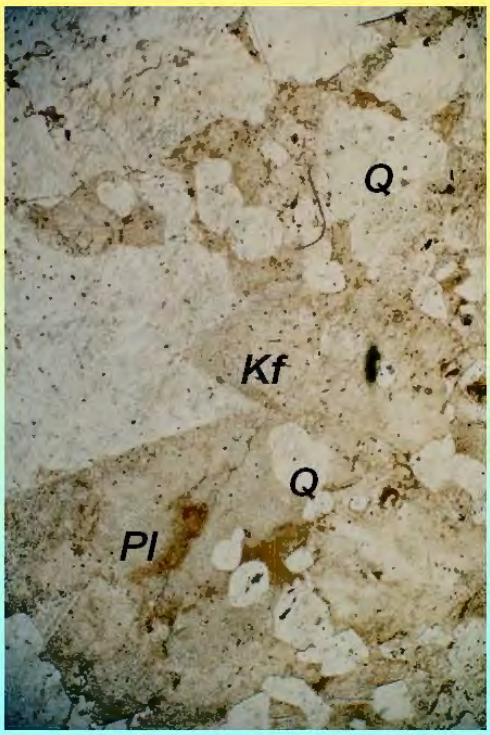


Sealing the borehole

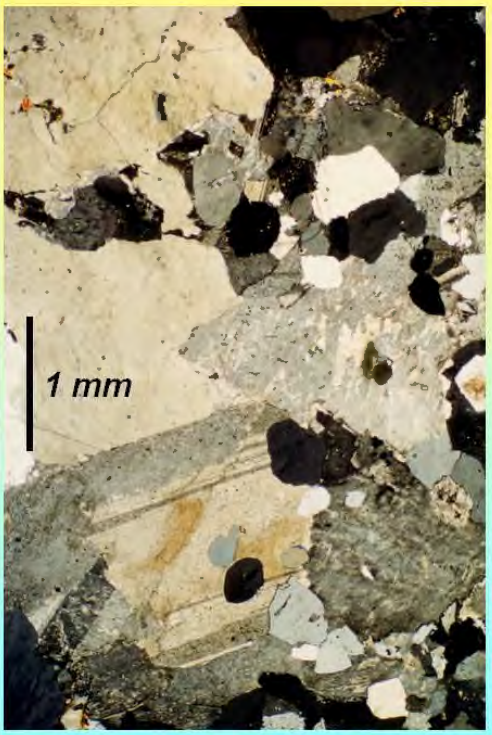
By "Rock-welding"

- *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*

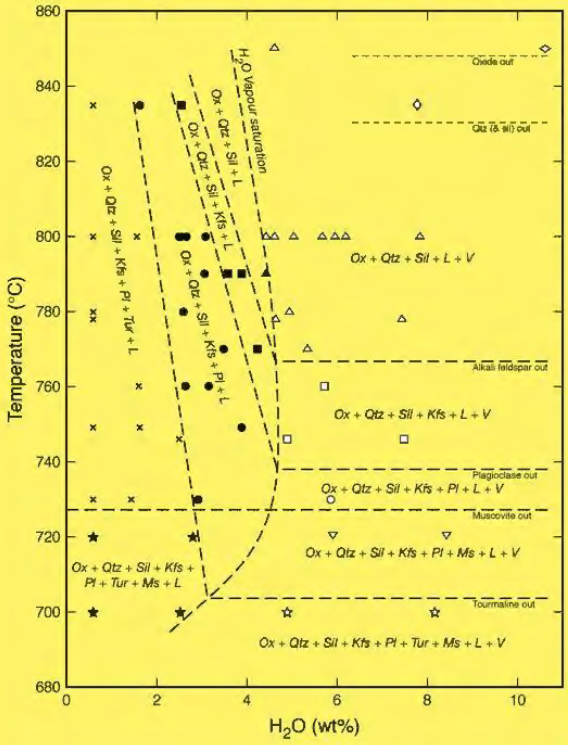
3 km deep (topmost canister)



Granite E93/7 (Plane polarised light)

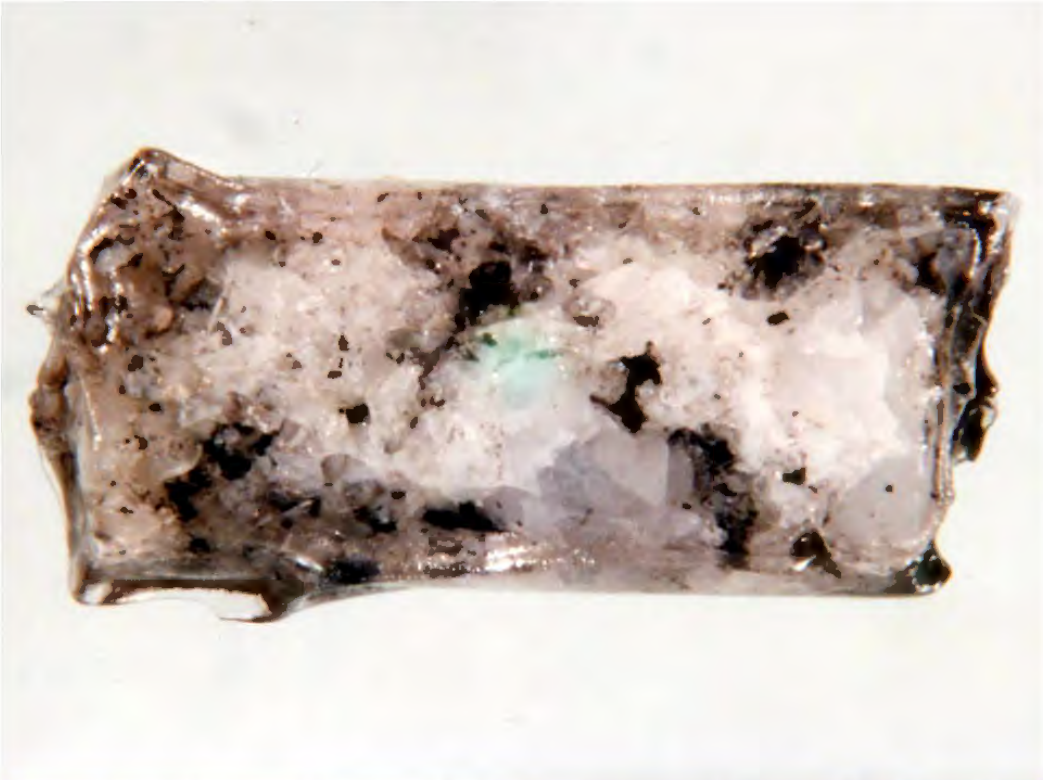


Granite E93/7 (Crossed polars)

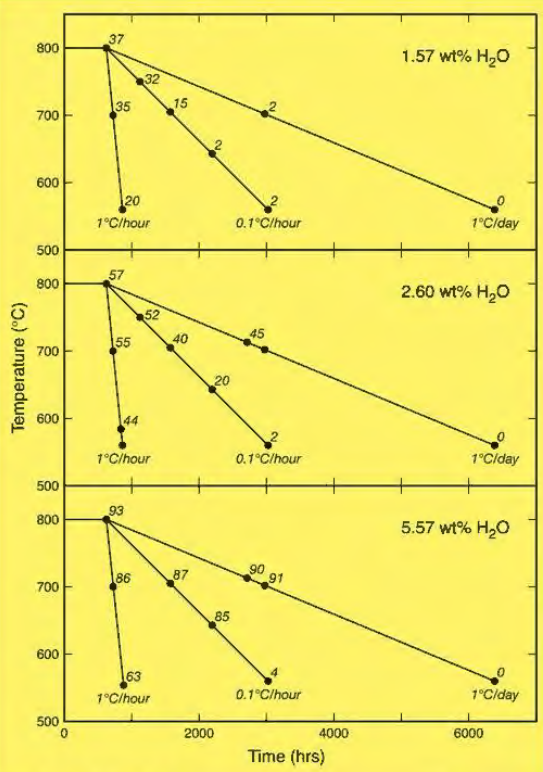


Phase Assemblage Diagram for Non-Equilibrium Partial Melting of Granite E93/7 at 0.15 GPa

[Attrill & Gibb (2003)]

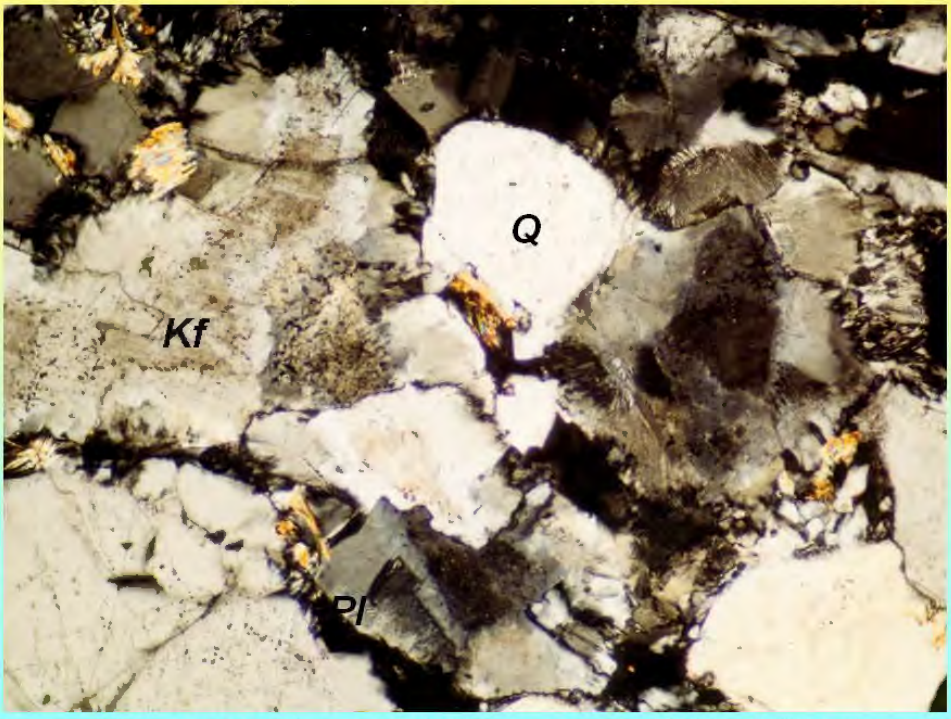


Granite E96/7 partially melted at 800ºC for 26 days (Plane polarised light)



Schematic of Recrystallisation Experiments on Granite E93/7 at 0.15 GPa

[Attrill & Gibb (2003)]



Granite E96/7 melted for 26 days at 800°C and cooled to 560°C at 0.1°C/hr (X-Polars)

The University Of Sheffield.

CONCLUSION

Using a sacrificial electric heater to melt the granite backfill and adjacent wall rock at ~800°C for 1 month then cooling to ~560°C at 0.1°C/hr (~100 days) will restore the backfill and wall rock to almost its original state and create a perfect seal.

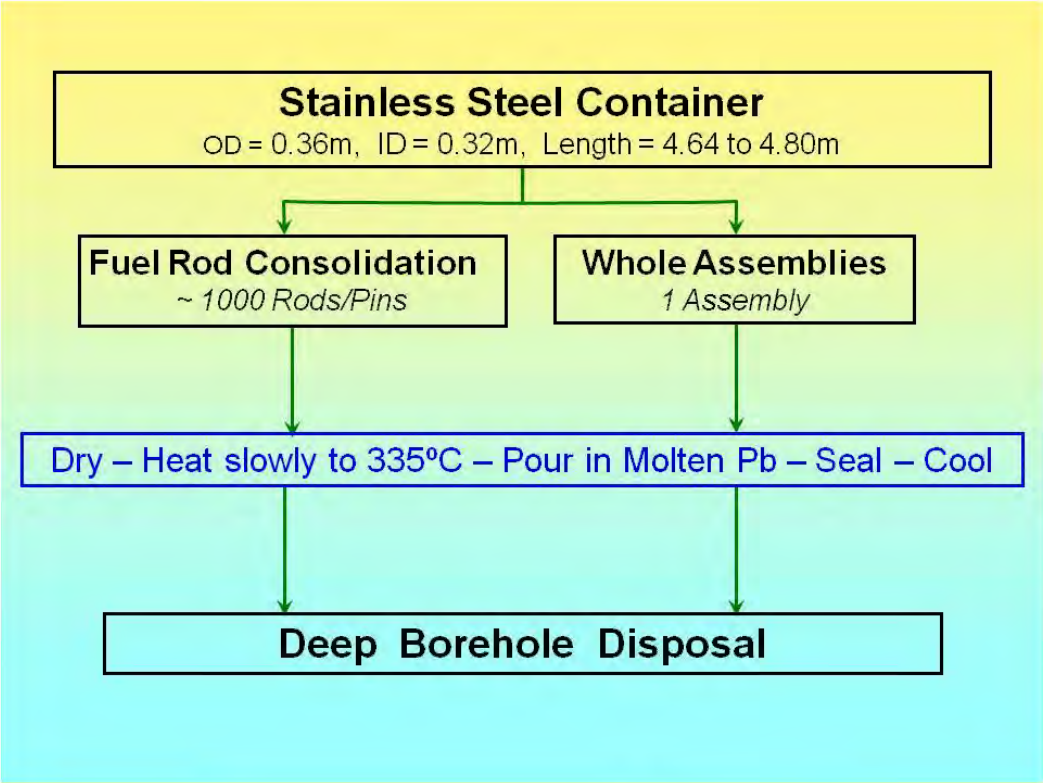
The University Of Sheffield.

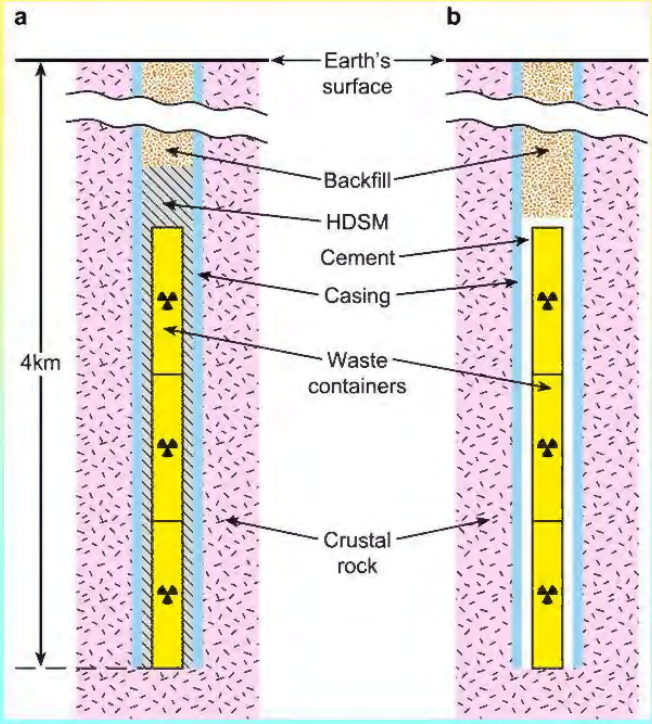
DEEP BOREHOLE DISPOSAL

Performance Enhancement Through the Use of **SUPPORT MATRICES**

Fergus G F Gibb & Karl P Travis

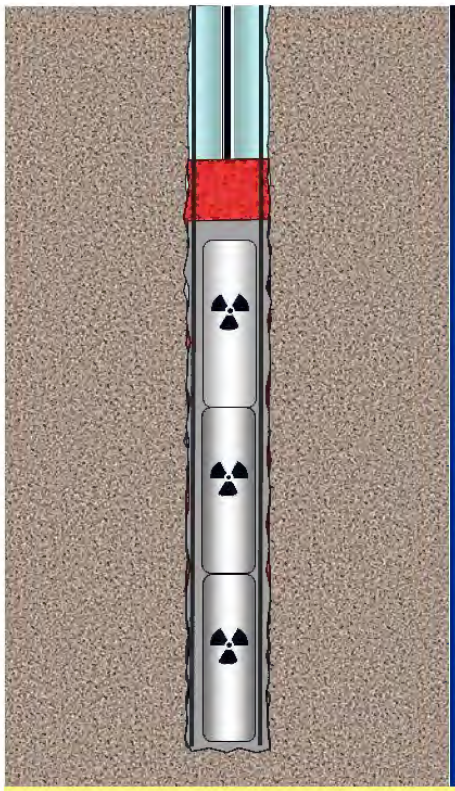
Department of Materials Science & Engineering, University of Sheffield, UK





Not to scale

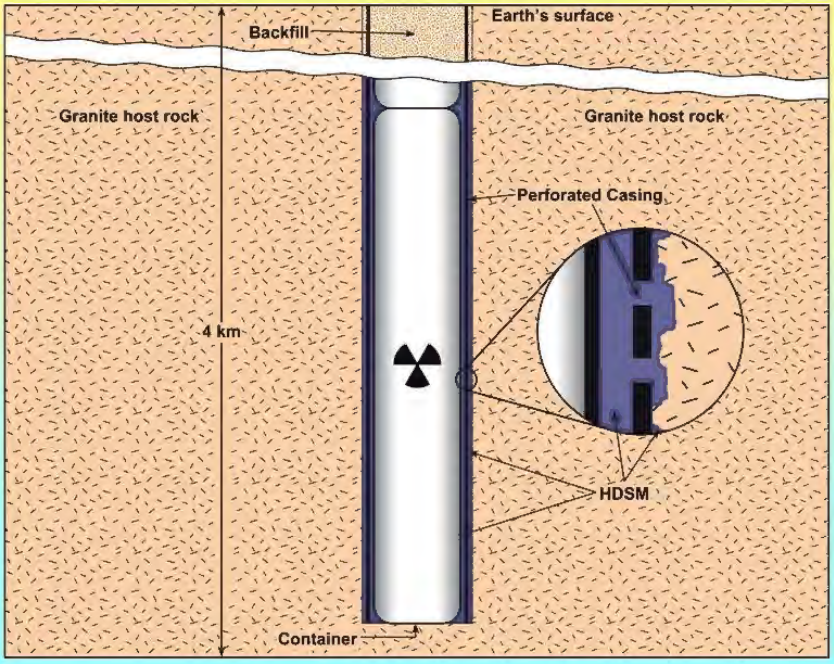
After Gibb et al. (2008)

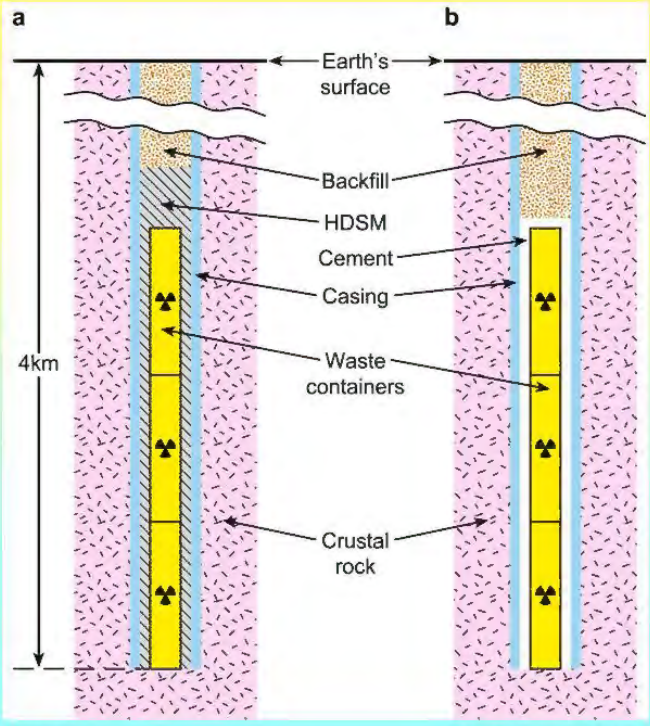


DEEP BOREHOLE DISPOSAL
(LTVDD-2a for Spent Fuel)

- 0.56 m Borehole cased to TD > 4km.
- Emplace first container using drill-string.
- Immediately followed by release of HDSM (Pb shot) to fill annulus.
- Insert rest of the containers at intervals with HDSM + "head".
- HDSM melts, settles into the annulus & eventually solidifies.

Schematic Cross Section of Borehole





Not to scale *After Gibb et al. (2008)*

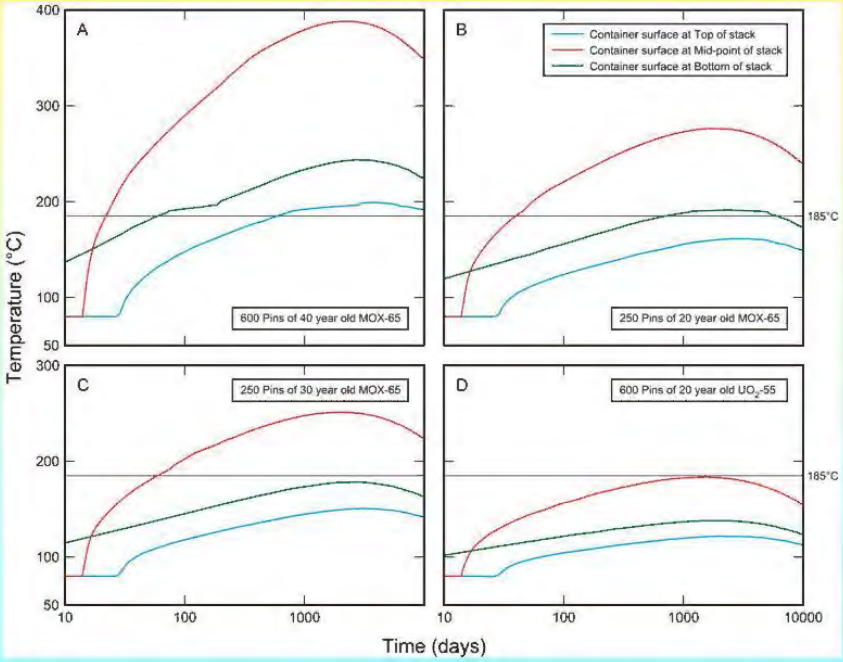
HEAT-FLOW MODELLING

Spent Fuel Type	=	**UO_2 & MOX**
Burn-ups	=	**55 & 65 GWd/t**
Fuel Assembly/Pins	=	**Westinghouse AP1000**
Packing Density	=	**< 80% of maximum**
Disposal Conditions	=	**80°C & 40 Mpa.**
HDSM Composition	=	**$Pb_{40}Sn_{60}$ shot** (SG = 8.4)
" **Solidus T°**	=	**185°C** (at 40 Mpa)
" **Liquidus T°**	=	**192°C** (at 40 Mpa)

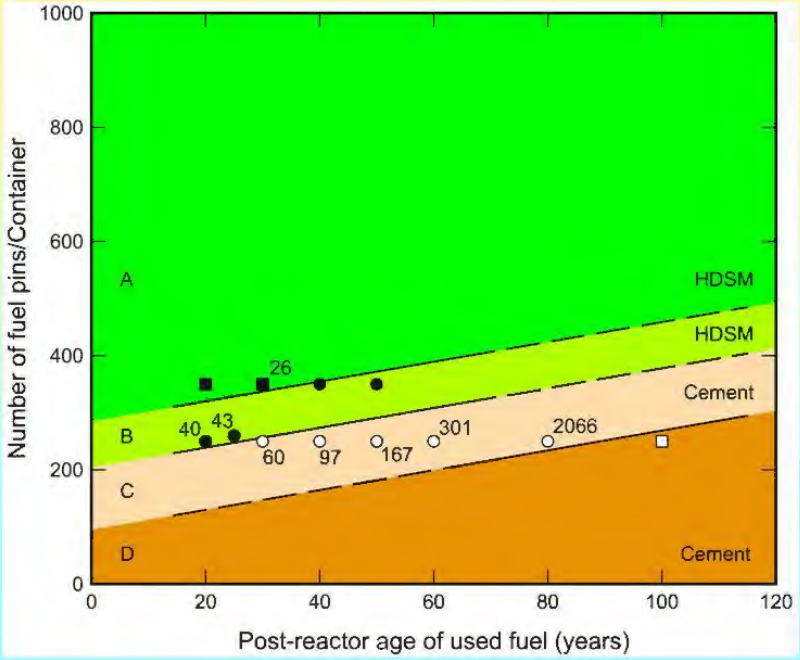
Finite Differences Model

Heat-source term reflects heat generating geometry of fuel rods;
Thermal properties of all materials temperature dependent.

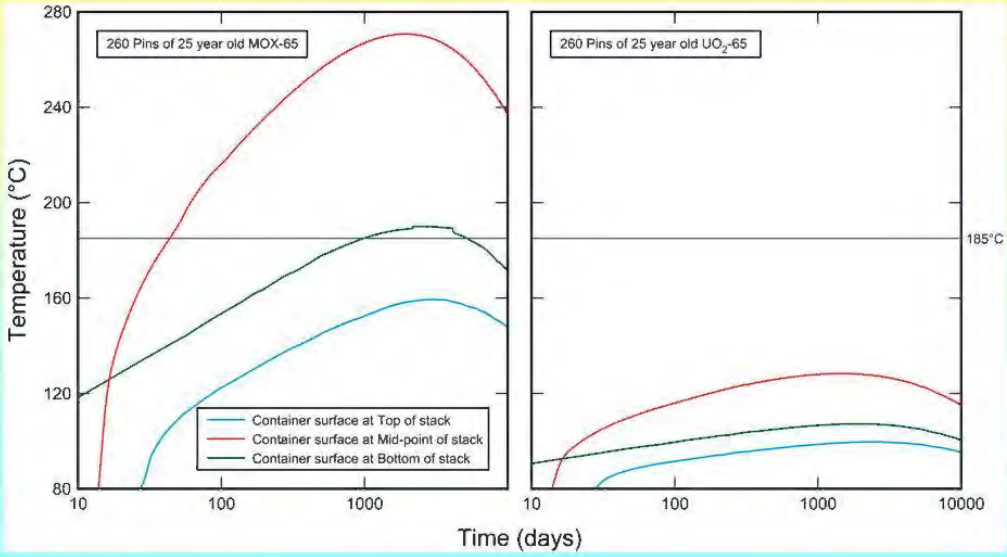
Temperature evolution "outcomes" for batches of 5 containers at 7-day intervals



Outcomes of temperature modelling for 5 containers of MOX-65



Temperature evolutions approximating to disposal of complete fuel assemblies (264 pins; 1 per container) in batches of 5 containers emplaced at 7-day intervals



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CONCLUSION

Although much research remains to be done, the use of solid dense materials as infill for spent fuel containers and as support matrices in the borehole appear to offer great promise, especially for enhancing the post-closure safety case.

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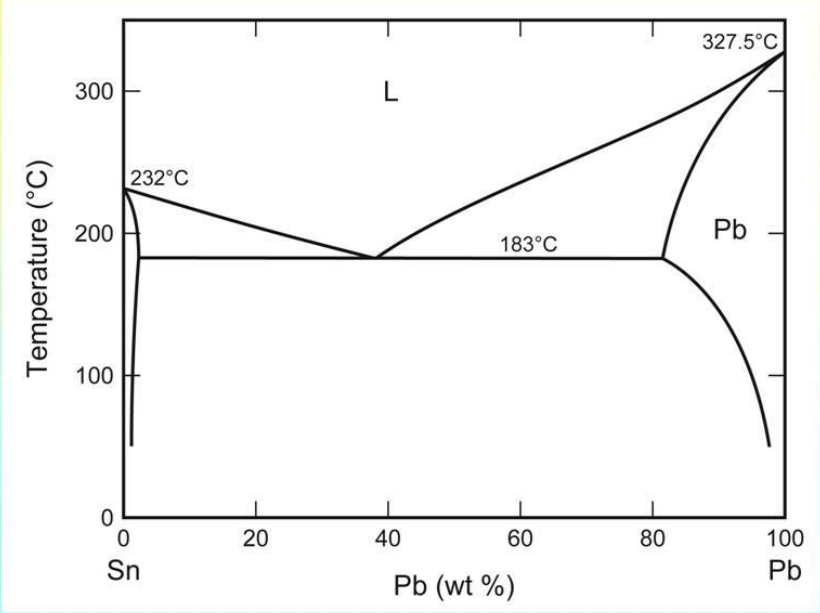
ISL

Thank you

Phase Diagram for the System Pb - Sn