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Deep Borehole Disposal (DBD) of Radioactive Waste

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Managing Radioactive Waste and Spent Nuclear Fuel
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Outline

- **Deep Borehole Disposal (DBD) Concept**
- **U.S. Department of Energy (DOE), Office of Nuclear Energy (NE) DBD Activities**
  - Participants
  - DBFT
  - DBD Safety Case
- **Potential Applicability of DBD in South Australia**
- **Summary**

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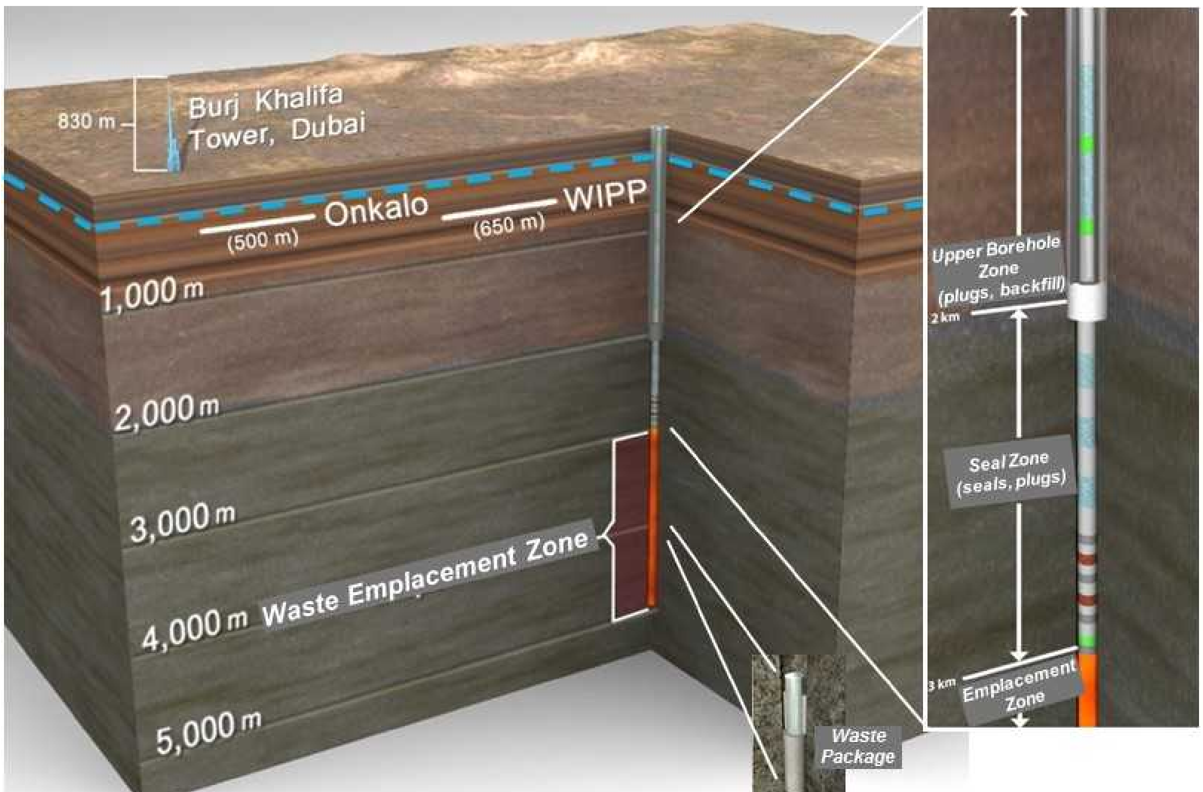
Deep Borehole Disposal Concept

- **5,000 m deep borehole(s) in crystalline basement rock**
- **Waste packages in lower 2,000 m**
  - well below depth of fresh groundwater resources (– –) and mined repositories
- **Seals in upper 3,000 m**
  - compacted bentonite clay, cement plugs, and sand/crushed rock backfill



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Deep Borehole Disposal – Historical Research

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NAS (1957) Publication 519
The Disposal of Radioactive Waste on Land, Appendix C: Committee on Deep Disposal

O'Brien et al. (1979) LBL-7089
The Very Deep Hole Concept: Evaluation of an Alternative for Nuclear Waste Disposal

Woodward-Clyde (1983) ONWI-226
Very Deep Hole Systems Engineering Studies

Juhlin and Sandstedt (1989) SKB 89-39
Storage of Nuclear Waste in Very Deep Boreholes

Ferguson (1994) WSRC-TR-94-0266
Excess Plutonium Disposition: The Deep Borehole Option

Heiken et al. (1996) LANL LA-13168-MS
Disposition of Excess Weapon Plutonium in Deep Borehole: Site Selection Handbook

Gibb (1999) Univ. of Sheffield
High-temperature, very deep, geological disposal: a safer alternative for high-level radioactive waste

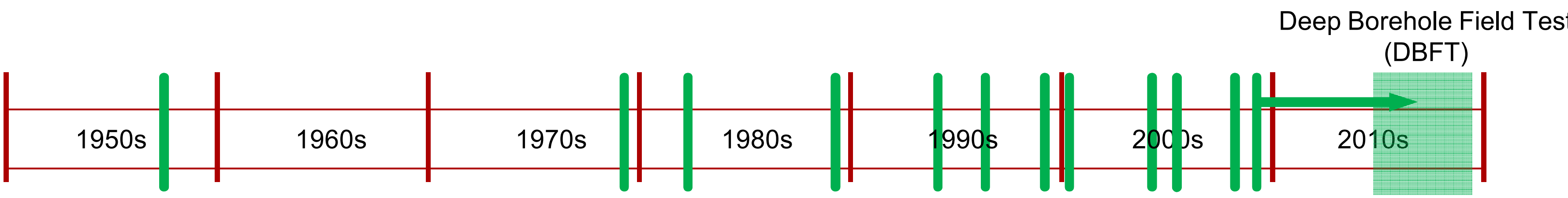
Harrison (2000) SKB R-00-35
Very Deep Borehole: Deutag's Opinion on Boring, Canister Emplacement and Retrievability

Nirex (2004) N/108
A Review of the Deep Borehole Disposal Concept for Radioactive Waste

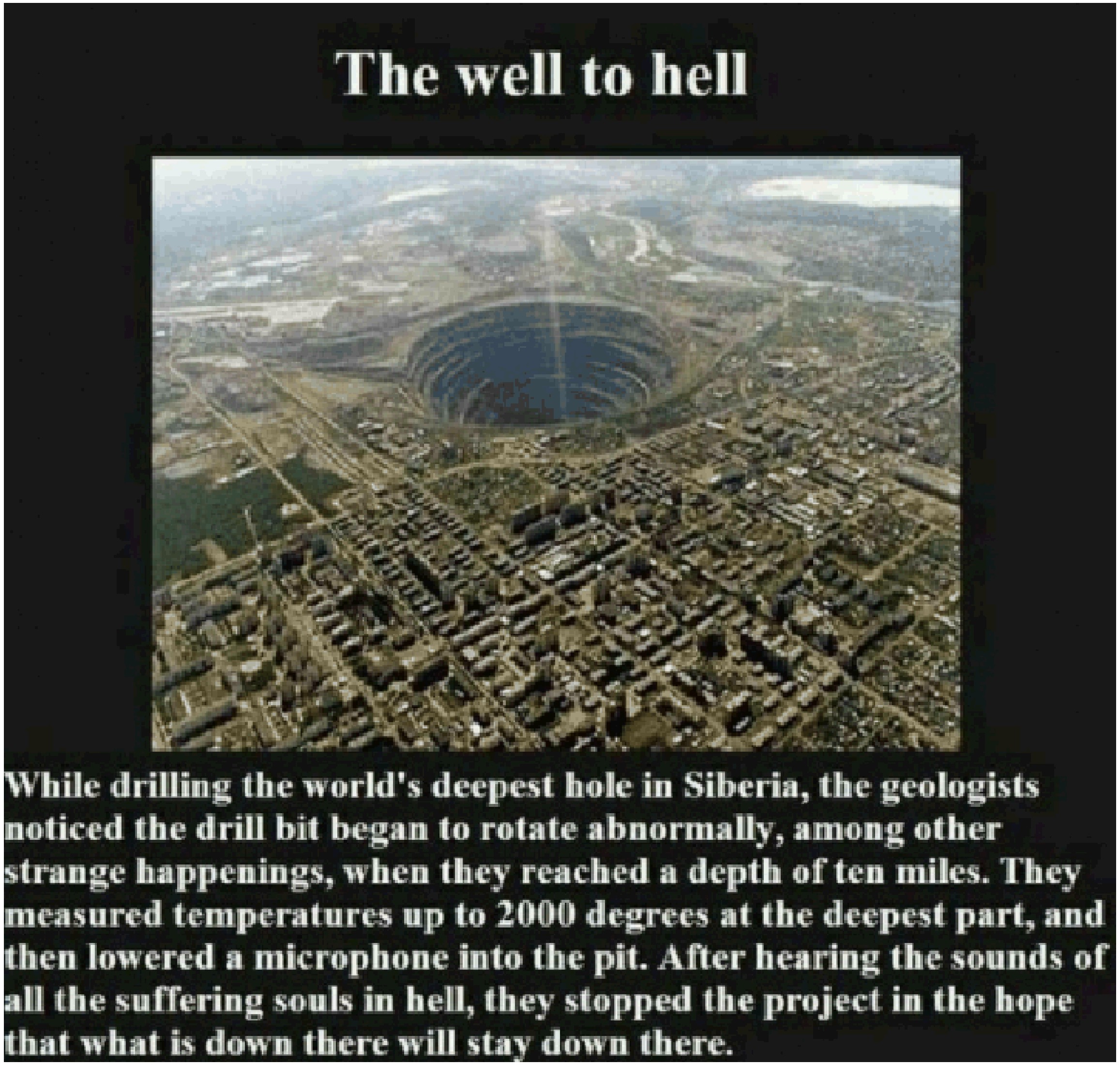
Driscoll (2005 - Present) MIT
Multiple theses and publications

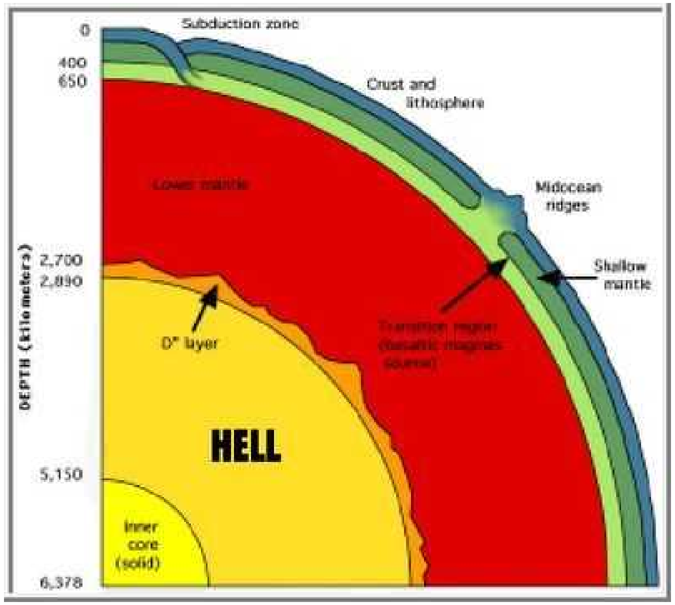
Beswick (2008) Report for the NDA
Status of Technology for Deep Borehole Disposal

Sandia National Laboratories (SNL) (2009 – Present)
Multiple reports – internal and DOE-NE sponsored



Deep Borehole Disposal – Internet Research

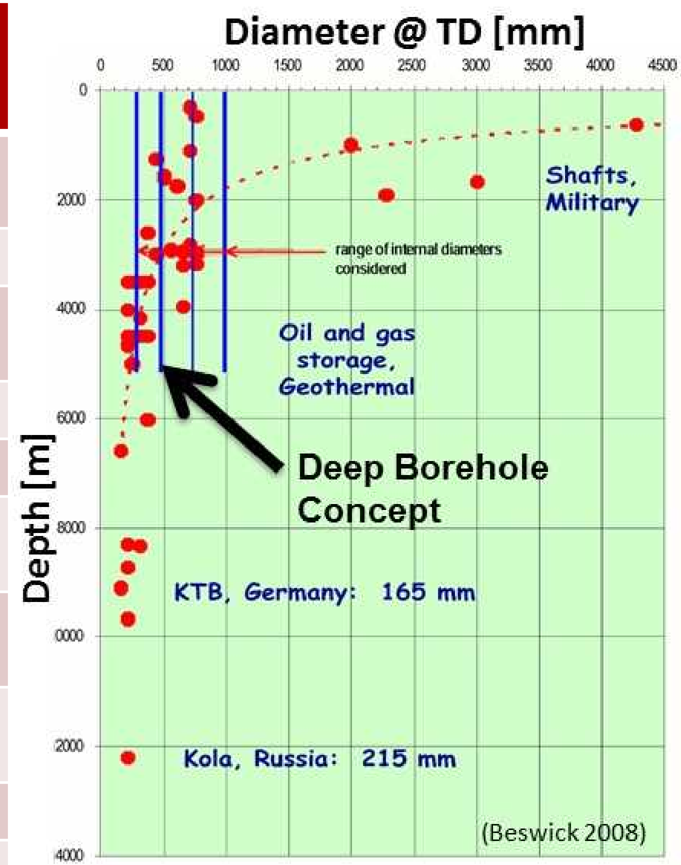


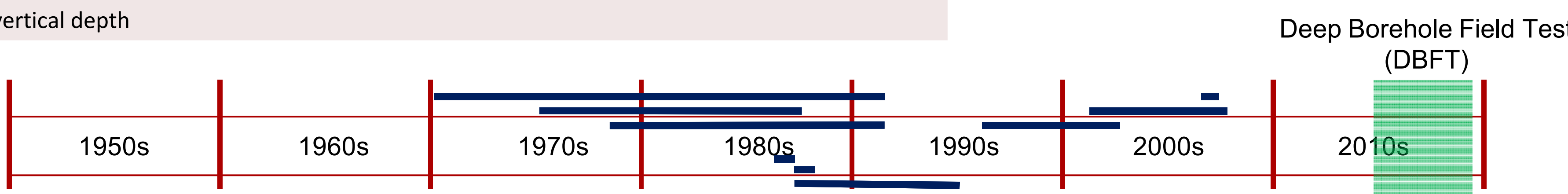


Deep Drilling Experience

Site	Location	Years	Depth [km]	Diam. * [in]	Purpose
Kola SG-3	NW USSR	1970-1992	12.2	8½	Geologic Exploration + Tech. Development
Fenton Hill	New Mexico	1975-1987	4.6	9⅞	Enhanced Geothermal
Urach-3	SW Germany	1978-1992	4.4	5½	Enhanced Geothermal
Gravberg	Sweden	1986-1987	6.6	6½	Gas Wildcat
Cajon Pass	S California	1987-1988	3.5	6¼	Geologic Exploration
KTB	SE Germany	1987-1994	9.1	6½	Geologic Exploration + Tech. Development
Soultz-sous-Forêts GPK	NE France	1995-2003	5.3	9⅝	Enhanced Geothermal
SAFOD	Central California	2002-2007	4 (3)#	8¾	Geology Exploration
Basel-1	Switzerland	2006	5	8½	Enhanced Geothermal

* borehole diameter at total depth
# true vertical depth

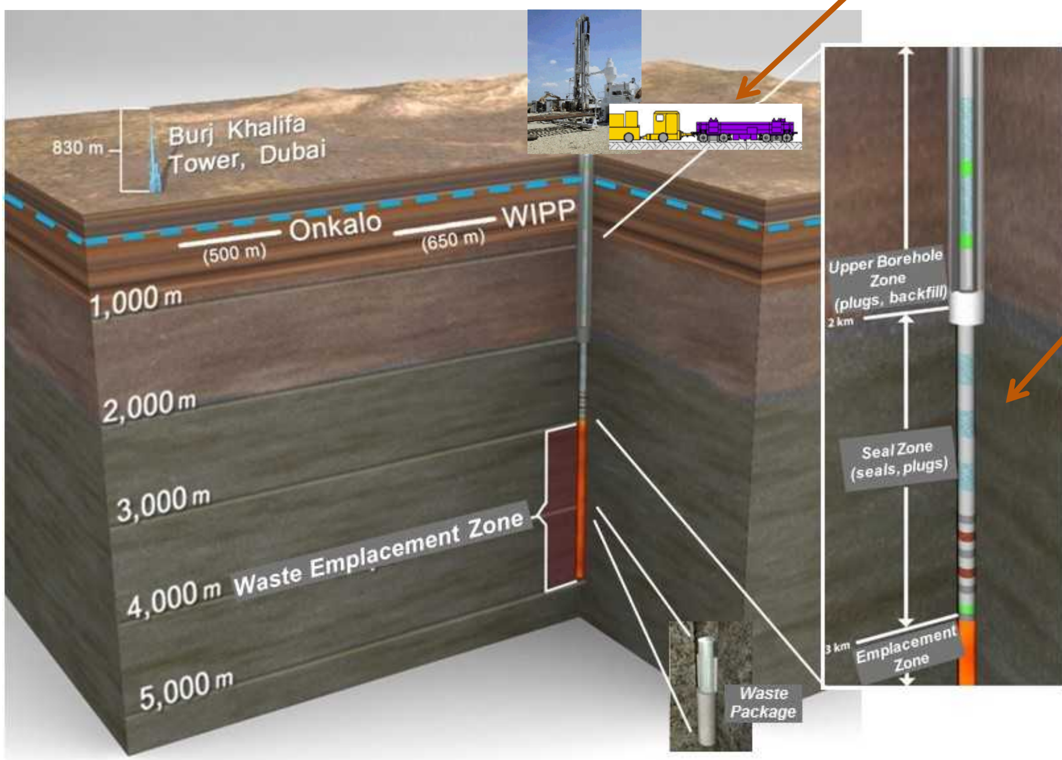




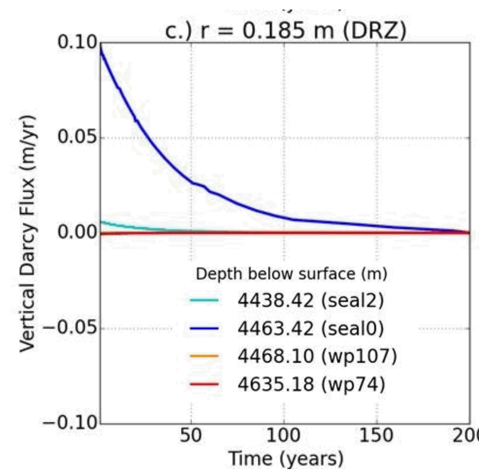
Deep Borehole Disposal Concept – Operational Feasibility and Safety

Existing drilling technology should permit dependable construction at acceptable cost

Waste package emplacement system can be engineered to maintain structural integrity and operational safety during surface handling and downhole emplacement



Borehole seals can be engineered and emplaced adjacent to the disturbed rock zone (DRZ) to maintain a low-permeability barrier over the period of thermally-induced upward flow

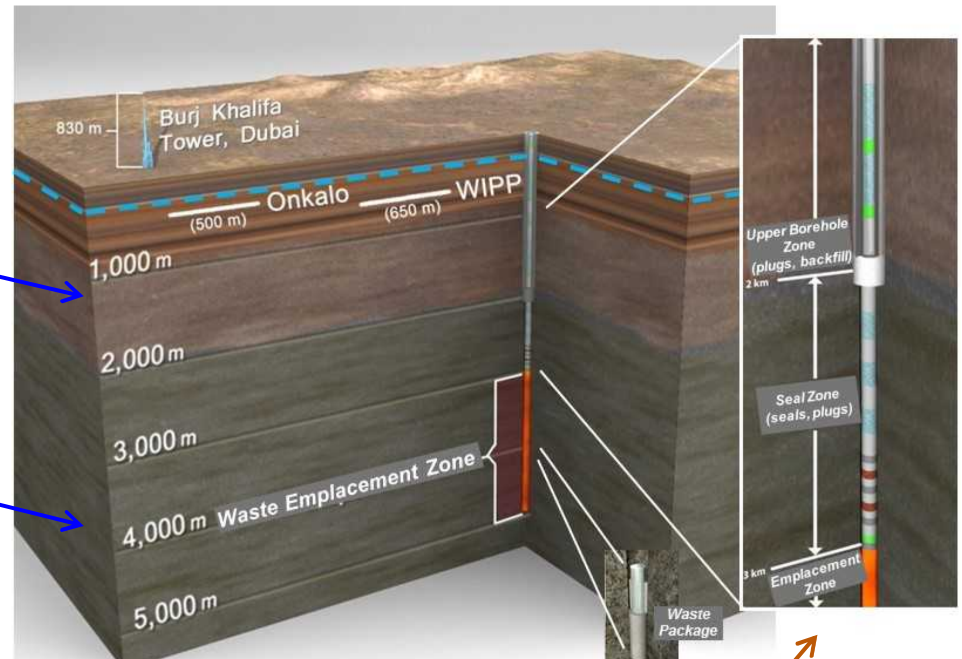


(Freeze et al. 2016)

Deep Borehole Disposal Concept – Post-Closure Performance and Safety

Robust Multiple-Barrier Isolation of Waste from the Biosphere
- Waste disposal is deep in crystalline basement rock
- Crystalline basement within 2,000 m of the surface is common in many stable geologic regions
- At least 1,000 m of crystalline rock (seal zone) overlying the waste emplacement zone

Natural Barriers
- Overlying Sediments
- Crystalline Basement
  - Hydrologically isolated from shallow groundwater (typically low permeability and long groundwater residence time in deep crystalline rocks)
  - Deep groundwater typically exhibits density stratification (saline groundwater underlying fresh groundwater) that opposes upward convection
  - Geochemically reducing conditions limit the solubility and enhance the sorption of many radionuclides



Engineered Barriers
- Waste Forms
- Waste Packages
- Borehole Seals

Deep Borehole Disposal Concept – Research and Development

- **Additional research and development (R&D) is necessary in several important areas for further consideration of deep borehole disposal of radioactive waste, including:**
  - Evaluation of drilling technology and borehole construction to 5,000 m depth with sufficient diameter for cost effective waste disposal
  - Development and testing of engineering methods for waste package loading, shielded surface operations, waste package handling and emplacement, and borehole seals deployment
  - Evaluation of waste, packaging, and sealing materials at representative temperature, pressure, salinity, and geochemical conditions
  - Verification of deep geological, geochemical, and hydrological conditions at a representative location

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Deep Borehole Disposal – DOE-NE Scope

- **DOE-NE is performing R&D to provide a sound technical basis for multiple viable radioactive waste disposal options in the U.S.**
  - Mined geologic repositories in crystalline, argillite, and salt rocks
  - Deep borehole disposal in deep crystalline rock
- **Deep Borehole Disposal R&D**
  - DOE-NE Assessment of Disposal Options (DOE 2014) recommended consideration of deep borehole disposal of smaller DOE-managed waste forms, such as cesium (Cs) and strontium (Sr) capsules
  - DOE-NE is conducting a planned 5-year Deep Borehole Field Test (DBFT) (DOE 2016) to evaluate the feasibility of siting and operating a deep borehole disposal facility
    - *DBFT will use surrogate waste packages (no radioactive waste)*
    - *DBFT Site Geoscience Guidelines and Data Evaluation (Sassani et al. 2016)*
    - *DBFT Conceptual Design (SNL 2016a)*
    - *DBFT Laboratory and Borehole Testing Strategy (SNL 2016b)*
    - *DBD Safety Case and Safety Assessment model analyses (Freeze et al. 2016)*

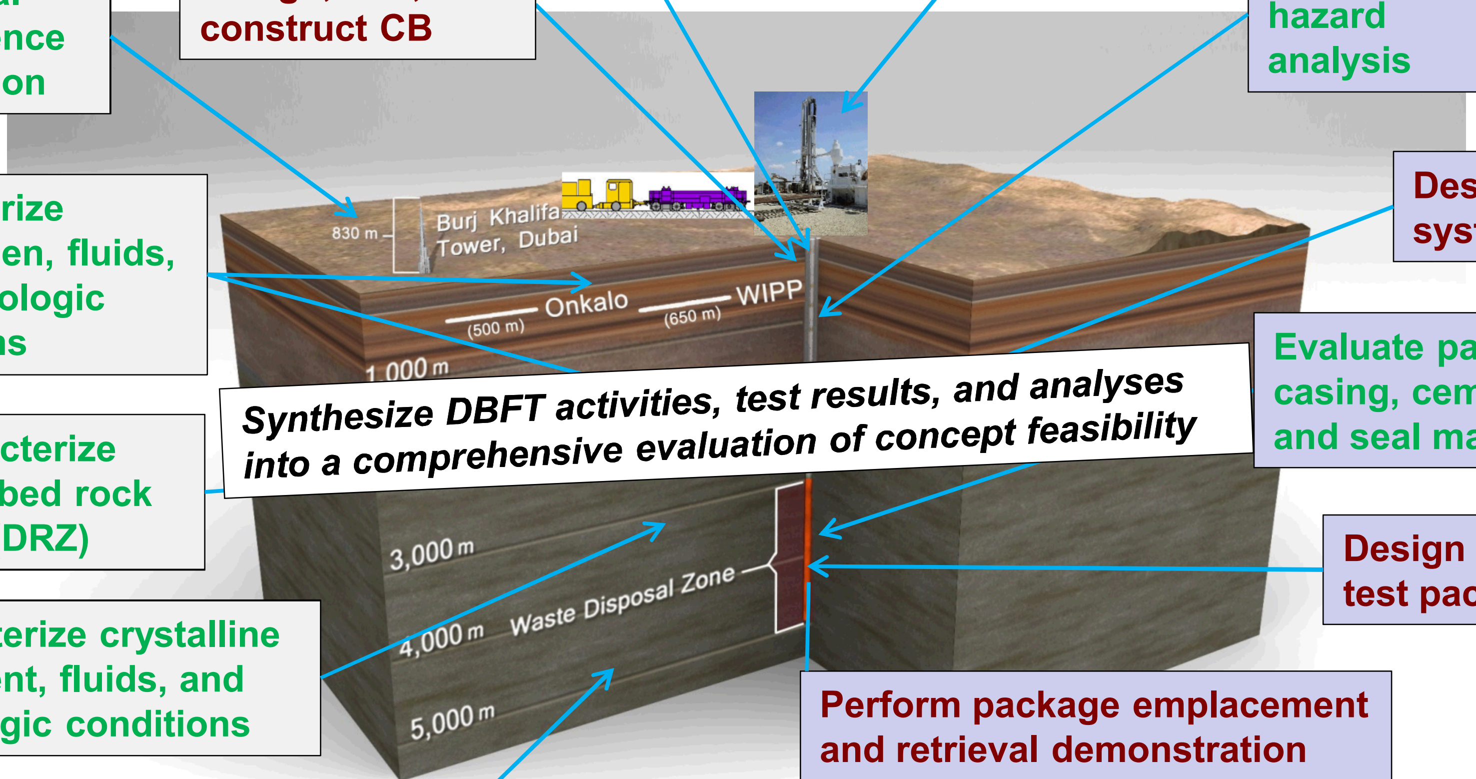
Deep Borehole Field Test – Program Participants

- **DOE-NE**
  - Andrew Griffith, Deputy Assistant Secretary, Spent Fuel and Waste Disposition (SFWD)
  - William Boyle, Director, Spent Fuel and Waste Science and Technology (SFWST)
  - Tim Gunter, Federal Program Manager, Disposal R&D, SFWST
- **Sandia National Laboratories (Project Technical Lead)**
  - Robert MacKinnon, Geoff Freeze, Ernest Hardin, Dave Sassani, Kris Kuhlman, Patrick V. Brady, Bill Arnold (retired), Frank Perry (LANL)
- **Collaborating National Labs**
  - LANL, LBNL, ORNL, PNNL, INL
- **University Partners**
  - MIT, University of Sheffield

Deep Borehole Field Test

- **To address the R&D objectives for DBD, the DBFT includes (DOE 2016, SNL 2016a, SNL 2016b):**
  - A site with technically acceptable geologic and hydrologic characteristics
  - Two ~ 5,000 m deep boreholes into crystalline basement rock
    - *Characterization Borehole (CB) ~8.5-in (0.22 m) bottom-hole diameter*
      - to identify and demonstrate downhole scientific testing methods that can be used at an actual DBD site to characterize crystalline basement rock and groundwater conditions favorable to long-term isolation of waste
    - *Field Test Borehole (FTB) ~17-in (0.43 m) bottom-hole diameter*
      - to design and demonstrate proof-of-concept engineering activities using surrogate test packages (borehole drilling and construction, package surface handling and downhole emplacement, and package retrieval during emplacement)
  - Laboratory testing of borehole sealing materials and methods
  - Modeling and analyses supporting DBD concept evaluation

Deep Borehole Field Test



Design, drill, and construct FTB

Develop systems for handling, emplacing, and retrieving packages

Regional geoscience evaluation

Design, drill, and construct CB

Emplacement hazard analysis

Characterize overburden, fluids, and hydrologic conditions

Design seal system

Evaluate package, casing, cement, and seal materials

Synthesize DBFT activities, test results, and analyses into a comprehensive evaluation of concept feasibility

Characterize disturbed rock zone (DRZ)

Design and test packages

Characterize crystalline basement, fluids, and hydrologic conditions

Perform package emplacement and retrieval demonstration

Develop site-specific geologic framework model

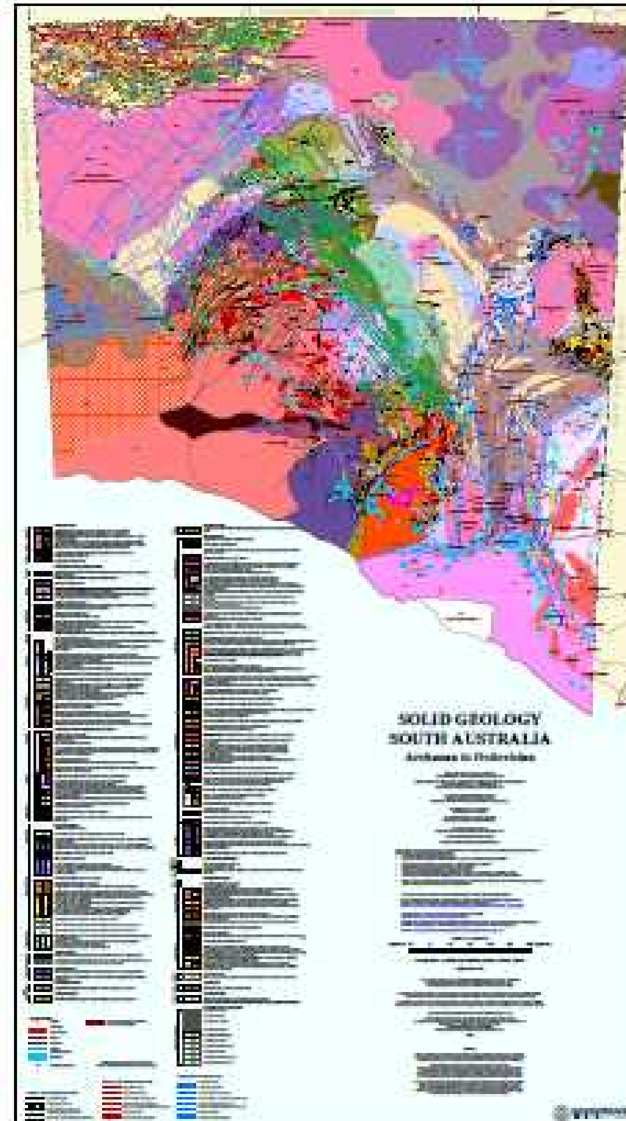
Assess post-closure safety

Assess pre-closure safety

In no case will the US Government place or otherwise have nuclear material, waste, or other waste disposal material on the property [DOE 2015]

Potential Applicability of DBD in South Australia

- **Preferred Site Geologic/Hydrologic Characteristics (DOE 2016, Freeze et al. 2016):**
  - Depth to crystalline basement ≤ 2,000 m
  - Lack of steeply dipping foliation/layering and low horizontal differential stress in crystalline basement
  - Absence of major regional structures, crystalline basement shear zones, or other tectonic features
  - Lack of fresh groundwater flow at depth
  - High-salinity (increasing with depth) and geochemically-reducing conditions
  - Geothermal heat flux ≤ 75 mW/m^2
  - Low probability of seismic/tectonic/volcanic activity
  - Absence of potential natural resources



Potential Applicability of DBD in South Australia

- **Potential Waste Streams**
  - SNF (e.g., 1 PWR assembly fits in a 17-in. borehole)
  - HLW (e.g., smaller U.S. DOE waste forms fit in 8.5-in and 12.25-in boreholes)
  - ILW / LLW
- **Potential Implementation**
  - DBD offers flexibility and a capital cost advantage over a mined repository in that it can be developed incrementally, one borehole at a time, and each borehole can be designed for a specific waste stream

Summary and Conclusions

- **Recent studies have identified no fundamental flaws regarding safety or implementation of the DBD concept**
  - Preliminary DBD safety case analyses suggest:
    - *Pre-closure – low probability of operational failures*
    - *Post-closure – robust waste isolation for 1,000,000 years*
  - DOE has made no decision to dispose of any waste in deep boreholes
- **Additional R&D is necessary in several important areas**
  - The DBFT will provide further insights into the feasibility of the DBD concept
- **Open issues (Freeze et al. 2016, NWTRB 2016):**
  - Drilling feasibility and borehole breakout
  - Operational feasibility
  - Waste form and waste package longevity
  - Seal (and DRZ) characteristics and evolution
  - Deep subsurface characterization
  - Effects of gas generation (from metal corrosion), microbes, and radiolysis
- **The DBD concept could have applicability in South Australia**

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References

- Arnold, B.W., P.V. Brady, S.J. Bauer, C. Herrick, S. Pye, and J. Finger 2011. *Reference Design and Operations for Deep Borehole Disposal of High-Level Radioactive Waste*. SAND2011-6749. Sandia National Laboratories, Albuquerque, NM.
- Arnold, B.W., P. Brady, S. Altman, P. Vaughn, D. Nielson, J. Lee, F. Gibb, P. Mariner, K. Travis, W. Halsey, J. Beswick, and J. Tillman 2012. *Research, Development, and Demonstration Roadmap for Deep Borehole Disposal*. FCRD-USED-2012-000269, SAND2012-8527P. Sandia National Laboratories, Albuquerque, NM.
- Arnold, B.W, P. Brady, S. Altman, P. Vaughn, D. Nielson, J. Lee, F,. Gibb, P. Mariner, K. Travis, W. Halsey, J. Beswick, and J. Tillman 2013. *Deep Borehole Disposal Research: Demonstration Site Selection Guidelines, Borehole Seals Design, and RD&D Needs.* FCRD-USED-2013-000409, SAND2013-9490P. U.S. Department of Energy, Office of Used Nuclear Fuel Disposition, Washington, DC.
- Arnold, B.W., P. Brady, M. Sutton, K. Travis, R. MacKinnon, F. Gibb, and H. Greenberg 2014. Deep Borehole Disposal Research: Geological Data Evaluation, Alternative Waste Forms, and Borehole Seals. FCRD-USED-2014-000332, SAND2014-17430R. U.S. Department of Energy, Office of Used Nuclear Fuel Disposition, Washington, DC.
- Beswick, J. 2008. *Status of Technology for Deep Borehole Disposal.* Report for the Nuclear Decommissioning Authority by EPS International Contract No. NP01185.
- 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.
- DOE (U.S. Department of Energy) 2014. *Assessment of Disposal Options for DOE-Managed High-Level Radioactive Waste and Spent Nuclear Fuel* . October 2014, U.S. Department of Energy, Washington, DC.
- DOE (U.S. Department of Energy) 2016. *Request for Proposal (RFP) – Deep Borehole Field Test: Characterization Borehole Investigations*. Solicitation Number DE-SOL-0010181, US Department of Energy Idaho Operations Office, Idaho Falls, ID.
- Ferguson, K.L. 1994. *Excess Plutonium Disposition: The Deep Borehole Option (U)*. WSRC-TR-94-0266, Westinghouse Savannah River Company, Aiken, SC.
- Freeze, G., E. Stein, L. Price, R. MacKinnon, and J. Tillman 2016. *Deep Borehole Disposal Safety Analysis.* FCRD-UFD-2016-000075, SAND2016-10949R. Sandia National Laboratories, Albuquerque, NM.
- Gibb, F.G.F. 1999. High-temperature, very deep, geological disposal: a safer alternative for high-level radioactive waste? in *Waste Management 19*: 207-211.
- Harrison, T. 2000. *Very Deep Borehole: Deutag's Opinion on Boring, Canister Emplacement and Retrievability*. R-00-35. Svensk Karnbranslehantering AB (SKB), Stockholm, Sweden.

References

- Heiken, G., G. Woldegabriel, R. Morley, H. Plannerer, and J. Rowley 1996. *Disposition of Excess Weapon Plutonium in Deep Boreholes – Site Selection Handbook*. LA-13168-MS, Los Alamos National Laboratory, Los Alamos, NM.
- Juhlin, C. and H. Sandstedt. 1989. *Storage of Nuclear Waste in Very Deep Boreholes: Feasibility Study and Assessment of Economic Potential*. SKB Technical Report 89-39. Svensk Karnbranslehantering AB (SKB), Stockholm, Sweden.
- NAS (National Academy of Sciences) 1957. *The Disposal of Radioactive Waste on Land.* Publication 519. National Academy of Sciences.
- Nirex 2004. *A Review of the Deep Borehole Disposal Concept for Radioactive Waste*. Nirex Report N/108. Prepared by Safety Assessment Management Ltd. for United Kingdom Nirex.
- NWTRB (U.S. Nuclear Waste Technical Review Board) 2016. *Technical Evaluation of the U.S. Department of Energy Deep Borehole Disposal Research and Development Program*. Report to the U.S. Congress and the Secretary of Energy. U.S. Nuclear Waste Technical Review Board, January 2016.
- O'Brien, M.T, L.H. Cohen, T.N. Narasimhan, T.L. Simkin, H.A. Wollenberg, W.F. Brace, S. Green, and H.P. Platt 1979. *The Very Deep Hole Concept: Evaluation of an Alternative for Nuclear Waste Disposal*. LBL-7089, Lawrence Berkeley National Laboratory, Berkeley, CA.
- Sassani, D., G. Freeze, E. Hardin, K. Kuhlman, R. MacKinnon, F. Perry, and R. Kelley 2016. *Site Geoscience Guidelines and Data Evaluation for Deep Borehole Field Test.* FCRD-UFD-2016-000073. Sandia National Laboratories, Albuquerque, NM.
- SNL (Sandia National Laboratories) 2016a. *Deep Borehole Field Test Conceptual Design Report*. FCRD-UFD-2016-000070, Rev. 1, SAND2016-10246R. Sandia National Laboratories, Albuquerque, NM.
- SNL (Sandia National Laboratories) 2016b. *Deep Borehole Field Test Laboratory and Borehole Testing Strategy*. FCRD-UFD-2016-000072, SAND2016-9235R. Sandia National Laboratories, Albuquerque, NM.
- Woodward-Clyde Consultants 1983. *Very Deep Hole Systems Engineering Studies*. ONWI-226, prepared for Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH.

Backup Slides

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DOE-NE Disposal R&D

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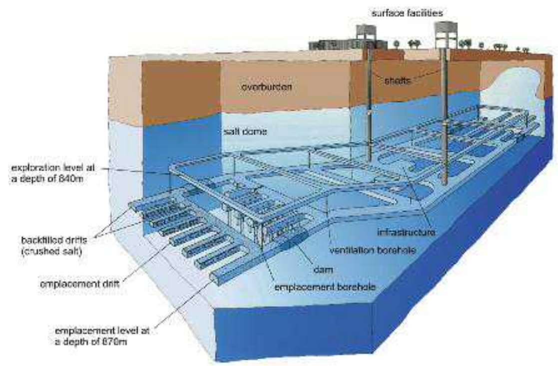
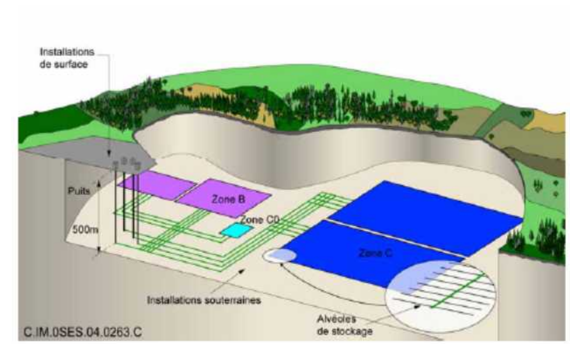
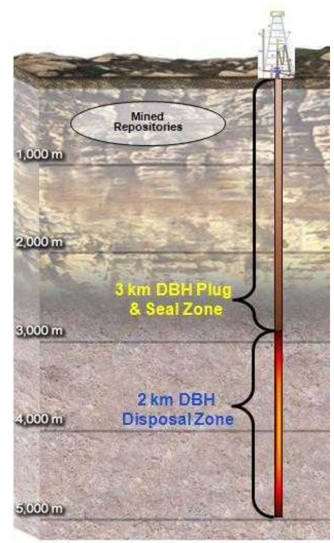
- Provide a sound technical basis for multiple viable disposal options in the US
- Increase confidence in the robustness of generic disposal concepts
- Develop the science and engineering tools needed to support disposal concept implementation
- Leverage international collaborations



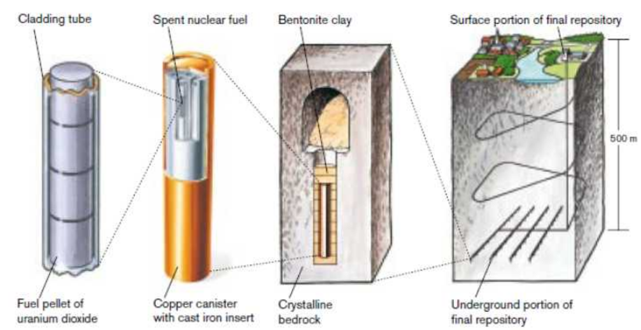
Mined repositories in salt



Mined repositories in clay/shale



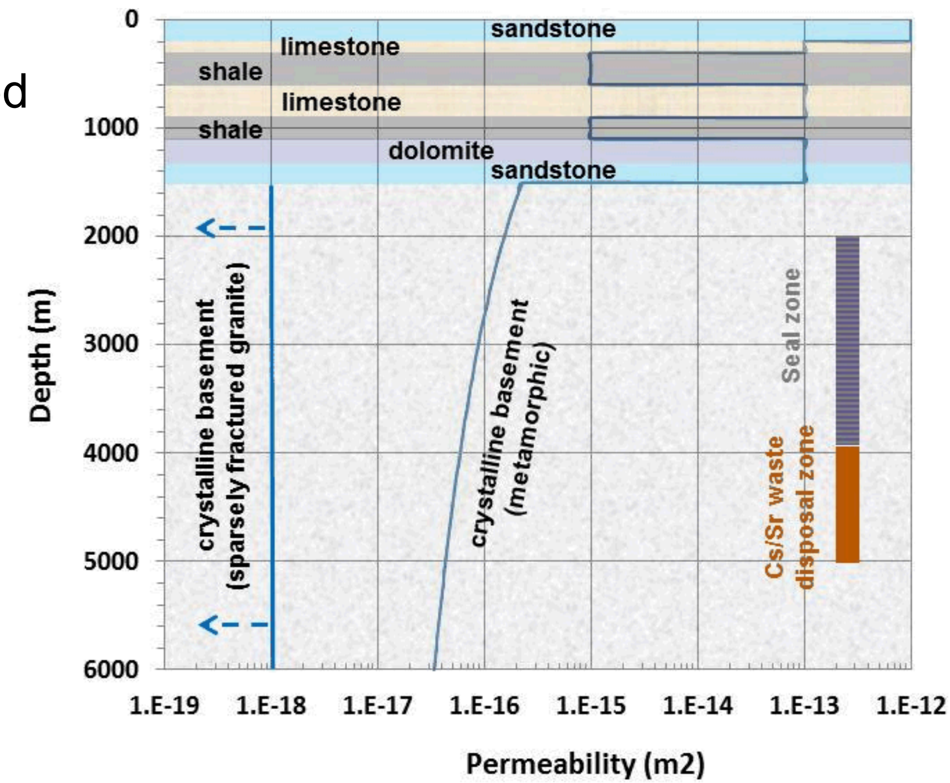
Deep boreholes in crystalline rock



Mined repositories in crystalline rock

DBD Conceptual Model – Undisturbed Scenario

- **Sediments**
  - Hypothetical alternating units assumed above seal zone
- **Crystalline Basement**
  - Low permeability (k) and porosity (Φ)
    - *$k = 1\times10^{-19}$ to 1×10^{-16} m^2*
    - *$\Phi = 0.01$*
  - Thermal gradient = 25°C/km
    - *Ambient temperature*
      - *10°C at surface*
      - *~120°C at center of disposal zone*
    - *Thermal conductivity = 3.0 W/m°K*
    - *Specific heat = 880 J/kg°K*



  - Ambient reducing geochemical conditions at depth
  - Salinity and density gradients
    - *Salinity ~ 300 g/L TDS at center of disposal zone*
    - *Density ~ 1.2 kg/m3 at center of disposal zone*