RESEARCH NEEDS FOR DEEP BOREHOLES

Patrick V. Brady[1], Bill W. Arnold, Robert J. MacKinnon, Ernest L. Hardin, David C. Sassani, Kristopher L. Kuhlman, and Geoff A. Freeze

[1]*Sandia National Laboratories, Albuquerque, New Mexico, USA 87185; pvbrady@sandia.gov*

While deep borehole disposal of nuclear waste should rely primarily on off-the-shelf technologies pioneered by the oil and gas and geothermal industries, the development of new science and technology will remain important. Key knowledge gaps have been outlined in the research roadmap for deep boreholes (B. Arnold et al., 2012, Research, Development, and Demonstration Roadmap for Deep Borehole Disposal, Sandia National Laboratories, SAND2012-8527P) and in a recent Deep Borehole Science Needs Workshop. Characterizing deep crystalline basement, understanding the nature and role of deep fractures, more precisely age-dating deep groundwaters, and demonstrating long-term performance of seals are all important topics of interest. Overlapping deep borehole and enhanced geothermal technology needs include: quantification of seal material performance/failure, stress measurement beyond the borehole, advanced drilling and completion tools, and better subsurface sensors. A deep borehole demonstration has the potential to trigger more focused study of deep hydrology, high temperature brine-rock interaction, and thermomechanical behavior.

I. INTRODUCTION

Disposal of radioactive waste in a deep borehole requires demonstration of several key technical features:

1 - Groundwater in the deep crystalline basement at disposal zone depths is very old and has been isolated from the surface for very long times.
2 - Ambient fluid potential does not have a significant upward gradient between the disposal zone and the shallow subsurface (i.e., overpressured conditions are not present).
3 - Deep groundwater has high salinity, well known chemical composition, and is chemically reducing.
4 - Bulk permeability of host rock and the borehole disturbed rock zone (DRZ) are acceptably low.
5 - Borehole seals, plugs, and grout have sufficient integrity and durability to meet safety requirements.
6 – Basic parameter values chemical, thermal, hydrology
7 – Equipment and approaches for monitoring post-closure data

While many of the questions above can be resolved with existing tools, additional technical analysis might provide greater resolution to predictions of borehole performance. The analyses that might do the most good were identified in the course of a Deep Borehole Science Needs Workshop held in Albuquerque, New Mexico on November 12, 2014. Participants included DOE, national laboratories, and academia (see attendee list in Figure 1 caption). Each of the preceding 7 elements was expanded

Figure 1. Attendees at the Deep Borehole Science Needs Workshop, Albuquerque, New Mexico November 12, 2014. Participants from left to right: Paul Johnson/LANL, Pat Brady/Sandia, Bill Arnold/Sandia, Kris Kuhlman/Sandia, Hari Viswanathan/LANL, Andrew Manning/USGS, John Cochran/Sandia, Dave Sassani/Sandia, Ernie Hardin/Sandia, Teklu Hadgu/Sandia, Frank Perry/LANL, Tom Daley/LBNL, Florie Caporuscio/LANL, Jim Houseworth/LBNL, Bob MacKinnon/Sandia, Dave Sevougian/Sandia, Dan King/DOE, Geoff Freeze/Sandia, Mark Freshley/PNNL, Tim Gunter/DOE, Lance Roberts/SD School of Mines, Mark Everett/Texas A&M, Jason Heath/Sandia, Mary Lou Zoback/NWTRB, Jack Tilman/Sandia, Paul Reimus/LANL. Not shown: Peter Davies/Sandia, Marianne Walck/Sandia, Erik Webb/Sandia, Fergus Gibb/Sheffield, Karl Travis/Sheffield, Frank Hansen/Sandia, Susan Altman/Sandia.

into several key technical targets and the targets were then prioritized in order of importance: primary research targets are in bold; secondary research targets are italicized. The technical targets were left in their unedited form to give a more accurate flavor of the discussions.

II. RESULTS

Element 1. Groundwater in the deep crystalline basement at disposal zone depths is very old and has been isolated from the surface for very long times.

- **Dating the water using isotopic tracers** and best tools – history/provenance; which isotopes, which tracers? What mixtures?
- *Identification of the fluid source, profiling*
- Fluid inclusions vs. fracture fluids
- Mineral equilibria in fractures
- Disequilibria between rocks and waters; can we reproduce water compositions theoretically?
- Multiple source water mixing(?)
- **How to get GOOD samples (consistent data from multiple methods).**

Element 2. Ambient fluid potential does not have a significant upward gradient between the disposal zone and the shallow subsurface (i.e., over-pressured conditions are not present).

- **How to get GOOD data (e.g. pressures) at great depth in relatively impermeable formations?**
- What scales (time, distance) are the measurements interrogating?
- *How will it all change once temperature changes, corrosion occurs, etc.?*
- Determine fracture pressure; how close to ambient pressure?
- How to use flow survey to integrate pressure? What tools?
- Salinity profile links to pressure.
- Long-term monitoring of microseismicity to infer shear state and evolution.
- How to model time-dependent rock mechanics and hydrology.
- **Are we causing/will we cause over-pressured conditions?**

Element 3. Deep groundwater has high salinity, well known chemical composition, and is chemically reducing.

- **Quality of sampling methodologies; how much will drilling perturb situation? "Tag" the drilling fluids? Use small well results to inform big well analyses.**
- Sorption coefficients and solubilities in high TDS brines at $T > 100^oC$, especially anions. Pitzer coefficients available?
- Reactive transport modeling approaches
- Fracture mineralogy and whole rock mineralogy; isotopic analysis of fracture mineralogy
- Tailored backfills
- *Redox disequilibria/reducing conditions*
- Microbial activity? Colloids?
- Use high value characterization targets to choose drilling fluids (if we can)
- What will corrosion do to geochemical behavior?
- **Surface-based geophysics for e.g. salinity/fracture determination (Seismic/EM/Gravity/Aeromagnetic)**

Element 4. Bulk permeability of host rock and the borehole DRZ are acceptably low.

- **Characterization of fractures, how they might change, which ones are conductive.**
- Borehole televiewer to provide 3D fracture imaging.
- Packer bleedoff measurements
- *Vertical dipole pump test/tracer tests*
- Time-phased sampling of groundwater to track DRZ reactivity.
- Cross-well and surface-borehole hydrogeologic/geophysical analysis
- 4d seismic, passive imaging tracked through time
- Reaction-transport analysis of long pump time geochemical results.
- Standard borehole fractured rock permeability testing
- Multi-method distinguishing of scale-dependent permeabilities

Element 5. Borehole seals, plugs, and grout have sufficient integrity and durability to meet safety requirements.

- **Long-term monitoring (using new materials? – e.g. self-monitoring fibers); seals that communicate their performance. New techniques – e.g. that sense seals wall rock bonding, fracture densities.**
- Keep track of international URL's (Canadian)
- Alternative sealing materials – e.g. tailored epoxies
- *Evolving seals mineralogy over T, P, time.*
- *Gas generation/movement past seals.*
- How to demonstrate better seals performance
- Seals sensitivity to heat/pressure from waste.
- Seals cross-interaction
- Better waste forms; resistant to corrosion, etc.
- Sealing the borehole above the waste
- Rock welding
- Sealing and support matrices
- High density support (HDSM)
- Class G cement formulation
- Fluid mechanics and package deployment

- Thermal modeling
- Thermal hydrologic modeling
- **Formation and behavior (fluid mechanics) of disturbed rock zone**
- Larger diameter borehole/canisters

Element 6. Basic parameter values chemical, thermal, hydrology. Equipment and approaches for monitoring post-closure data.

- **Geomechanical predictors of borehole stability = in situ stress measurements,**
- Thermodynamic gaps = e.g. Green rust, radionuclide sulfides.
- High T, P, high salinity, sensors
- Data collection while drilling

Primary and secondary research targets are listed below preceded by the element they map to.

Primary Research Targets

- (3) Surface-based geophysics for e.g. salinity/fracture determination (Seismic/EM/Gravity/Aeromagnetic)
- (1) Dating the water using isotopic tracers; Identification of the fluid source, profiling
- (1) How to get GOOD samples (consistent data from multiple methods).
- (2) How to get GOOD data (e.g. pressures) at great depth in relatively impermeable formations?
- (2) Are we causing/will we cause over-pressured conditions?
- (3) Quality of sampling methodologies; how much will drilling perturb situation? "Tag" the drilling fluids? Use small well results to inform big well analyses.
- (4) Characterization of fractures, how they might change, which ones are conductive.
- (5) Long-term monitoring (using new materials? – e.g. self-monitoring fibers); seals that communicate their performance. New techniques – e.g. that sense seals wall rock bonding, fracture densities.
- (6) Geomechanical predictors of borehole stability = in situ stress measurements
- (5) Formation and behavior (fluid mechanics) of disturbed rock zone

Secondary Research Targets

- (4) Vertical dipole pump test/tracer tests
- (2) How will it all change once temperature changes, corrosion occurs, etc.?
- (3) Redox disequilibria/reducing conditions
- (5) Evolving seals mineralogy over T, P, time.
- (5) Gas generation/movement past seals.

To the gas generation/movement past seals research target immediately above might be added H_2 generation from anoxic corrosion of casing/canisters, and hydrogen sinks at depth.

III. SUMMARY

The listed science needs provide a set of clearly directed priorities for ongoing deep borehole research and will also be used to inform the technical strategy of the deep borehole field test started in late 2014.

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