Key Observations from Seven Discussion Panels at the U.S. Nuclear Waste Technical Review Board's International Technical Workshop on Deep Borehole Disposal of Radioactive Waste

Presented by panel representatives

Panel 1-Experience in Deep Drilling in Crystalline Rocks: Key Points

1. Drilling of wells is technically feasible, no new technology needs to be developed:
   - Stick to industry drilling standard practice and dimensions.
   - Use state-of-the-art technology – e.g., directional control, minimizing vibration, downhole motors, automated drilling systems, PDC drill bits (Chimera bits may be available).
   - Design drilling mud program for borehole stability and hole cleaning in crystalline rock.

2. Plan for the unforeseen - develop drilling, completion and sealing plan based upon real downhole conditions:
   - Idealized homogeneous granitic basement under low differential stress does not exist.
   - Anticipate high differential stresses, leading to formation of extensive breakouts and tensile fractures.
   - Likely to experience fracture zones with heavy fluid influx or loss. Must plan for that – including consequences for drilling, completion, emplacement and sealing.
   - Stress and permeability measurements should be an integral part of the drilling program (logging, minifracs, drill-stem tests – stress profile needed).
   - Blowouts happen, plan accordingly (cannot safely assume hydrostatic pressures - high fluid pressures might be encountered).

Panel 1 Key Points (cont.)

3. Integrated approach is needed for drilling/completion in relation to rest of project:
   - Project leaders need to “own” entire process and set expectations for drilling, completion, emplacement, sealing, sampling and testing program.
   - Regulatory requirements for retrievability and time period required for isolation need to be clarified. Design of all aspects of the project accordingly.
   - Peer review of the drilling program is recommended, including comprehensive risk analyses.

4. Field Test site needs detailed 3-D site characterization, combining surface-based and downhole methods:
   - Select location for Field Test site to be most likely representative for potential disposal sites in the U.S. (maximize transfer value).
   - Each waste disposal site will also need one or more characterization holes.
   - Use adaptive well design based on site-specific geologic information to guide drilling, completion, emplacement and seals.

Panel 1 Key Points (cont.)

5. Many questions remain about seal design and implementation:
   - What is the impact of breakouts and tensile fractures as well as associated near-borehole damage zones on seal integrity?
   - What role might time-dependent failure and thermal stresses play in damage zone evolution?
   - How do we test integrity of the seals over long time scales at in-situ conditions?
   - What is the sensitivity of cement to chemical, biologic and thermal degradation?

6. Increase engagement in geomechanical and geological aspects of the project:
   - Expand effort to characterize geologic and geomechanical risks, which could be more severe (and less well known) than engineering risks.
   - Better involve experimental rock mechanics, fracture/fault characterization, hydrology and geophysical imaging communities (surface and borehole).
   - Grimsel lab in Switzerland is working on seals between casing, bentonite and crystalline rock at depth.

7. Long-term downhole monitoring is needed to ensure containment at relevant (disposal) time scales.

Panel 2 (Emplacement): Key Observations

- Design and execute the Deep Borehole Field Test consistent with existing and anticipated EPA and NRC regulations
    - Best: Base on dialogue with regulators
    - Fallback: Use r<u>ealistic</u> expectations of what might be
- Place design, operational, and science objectives on an equal footing
- Simulate <u>all</u> aspects of deep borehole disposal implementation as if it were using radioactive wastes
    – Normal operations
    – Maintenance
    – Off-normal events
- Emphasize engineering controls, not administrative controls

Panel 2 (Emplacement): Key Observations

- Solidify emplacement mode recommendation
  - Current preference for 1-package wireline emplacement over 40-package drill pipe seems appropriate based on
    - Near-surface operational complexity
    - Material at risk
    - Initial event tree analyses
  - Provide rationale for selecting the emplacement mode
    - Wireline
    - Drill pipe
    - Gravity/freefall
    - Conveyance liner
    - Coiled tubing

Panel 2 (Emplacement): Key Observations

- Consider measures to mitigate risks during emplacement, e.g.,
  - Directional drilling to reduce potential descent rate
  - Descent rate monitoring
  - Detection/mitigation of retrieved package over-pressurization
- Develop an organizational structure to establish and demonstrate a culture of safety
- Develop strategy to integrate conventional borehole operations and remote handling of highly radioactive materials
- Plan for contingencies
  - Anticipate governmental schedule and budget pressures
  - Include provisions to recover from minor and major events remotely
  - Recognize that little things can lead to big – and bad -- things

Panel 3 (Seals): Key Observations

- Current DOE concept proposes hole sealing above the disposal zone.
  - *RECOMMEND*. Fill well with compacted solid material. Use cementing techniques including squeezing and verify cement seals outside of casing.
- Current DOE concept sealing around the waste packages is provided by drilling mud.
  - *RECOMMEND*. Assessment of using other materials is recommended; lead-based alloys, cement grout, compacted bentonite.
- FURTHER RECOMMENDATIONS
  - Other advanced borehole sealing concepts should be considered; rock-welding, compacted bentonite systems, thermite ceramics, *etc*.

Panel 3 (Seals): Key Observations

- FURTHER RECOMMENDATIONS
  - Detailed seal development and testing programs are recommended.
    - Long-term testing; accelerated testing methods?
  - Modelling.
    - For assessment of long-term performance.
  - Detailed assessment of the sealing environment is required.

Panel 4 (Hydrogeology): Key Observations

- Available evidence indicates that drilling, emplacement and monitoring strategies must recognize that high stress levels, potentially active faults, and highly permeable fractures and faults persist to 5 km depth. These features represent potential pathways for migration of gases and brines.
- Transient hydrologic phenomena such as gas generation and seismicity can significantly increase permeability. This has been documented in crystalline rocks in the upper few km and may also occur at greater depths.

Panel 4 (Hydrogeology): Key Observations

- Measurement of permeability and formation pressures may prove to be very difficult within the disposal zone due to borehole quality, heterogeneity and very low permeability. We anticipate a long time will be required for hydrologic tests of characterization boreholes at any proposed disposal site.
- Adequate assessment of heterogeneity at a proposed disposal site should include multiple characterization boreholes and contiguous measurements within the disposal zone..
- Emplacement strategies, monitoring and safety assessment will need to be adaptive to deal with hydrogeologic heterogeneity.

Panel 4 (Hydrogeology): Key Observations

- Long groundwater residence times (millions of years) inferred from environmental tracers in pore fluids (noble gases, isotopes, etc.) do not preclude the potential for active flow through interconnected permeable pathways from disposal depths.to the near surface.

Panel 5 (Geochemistry): Key Observations

- Careful, coordinated planning (e.g. geophysics, hydrogeology, geochemistry, microbiology) needed for sampling, analyses & modeling
- Introduce mulitple tracers during drilling & emplacement of waste
- Measure “everything” (don’t necessarily know beforehand what will be useful in long-term for tracing contamination transport pathways)
- Importance of slanted boreholes for characterization
- Need multiple boreholes for characterization & monitoring
- Need large-scale hydrogeological characterization & modeling for long range transport
- Need baseline data (e.g. gases, solutes) for shallow aquifers
- Need borehole tests that are more realistic for storage of radioactive waste (e.g. heater + tracer); what do you need to make it a successful & translatable “proof of concept” project?
- How will drilling & emplacement of waste alter subsurface conditions?
- Gases will be present & could be a safety/storage concern in repository or near-surface environment (e.g. metal embrittlement, explosions)

Panel 5 (Geochemistry): Key Observations

- Deep borehole disposal of Cs/Sr solves a short-term problem, but not longer-term issue of other radioactive waste disposal
- Show stoppers: Low salinity (<seawater TDS), detectable O2, evidence of young, meteoric water, upward hydraulic gradient, soluble pathways (e.g. gypsum fracture fills), large faults/fractures, high heat flow
- Reverse geology may be present
- In some locations, saline fluids closer to surface (<1km depth), may also have dilute waters at depth (salinity overturns)
- It will likely take several years to adequately plan for coordination of sampling activities with drilling
- Predicting solubilities and mobilities; continue to improve thermodynamic properties for elements and phases likely to react with brines.

Panel 6 (Barriers): Key Observations

- The DBD concept is intended to be multi-barrier but with primary reliance on the geological barrier
- More systematic consideration of multi-barriers should be carried out at an early stage
- Ideally, we need a good understanding of the geochemical environment to achieve this – but we recognize considerable uncertainties
- This could be mitigated by more robust waste packages and assigning appropriate credit to performance
- Surface monitoring of gas production would be valuable to assess evolution of borehole seals and engineered barriers; also monitoring of Eh pH during operational phase

Panel 6 (Barriers): Key Observations

- Key advantage for disposal of Cs / Sr capsules by DBD is potentially earlier disposition – but this is subject to uncertainty
- Disposal of Cs / Sr capsules is conceivable in a mined facility – after extended storage, otherwise could require treatment
- Conceptual safety challenge in assuming initial repository state involves dissolution of radio Cs / Sr in solution rather than being retained as a solid
- Materials and processes are available to adequately condition proposed wastes for DBD to improve passive safety (e.g. solubility, dispersibility).

Panel 6 (Barriers): Key Observations

- Understanding wasteform evolution under DBD conditions is a knowledge gap, including absence of associated thermodynamic solubility data.
- The seal / liner / RDZ is a likely pathway for radionuclide migration – conceptually this is thought to be within engineering capability, but remains to be demonstrated.
- Microbial degradation of engineered barriers in the seal zone could be important and is not well understood.
- Ultimately, reliance on engineered barriers should be proportionate to the performance capability.

Panel 7 (Efficacy): Key Observations

- Advantages – disadvantages?
  - Claimed passive safety
  - No full site characterisation or safety assessment yet performed
- Calculated doses mean little without developed concept and site
- Expected uncertainties:
  - Operational risks likely to dominate
  - Post-closure risks may pop up when you have a better understanding of scenarios
- Effect of high temperatures: Depends on waste form and needs consideration
- Lack of international experience: No benchmark available