Deep Borehole Disposal (DBD): Licensing and Post-Closure Safety Assessment

Geoff Freeze
Sandia National Laboratories

U.S. Nuclear Waste Technical Review Board Briefing
Albuquerque, NM
July 16, 2015
Licensing and Post-Closure Safety Assessment: Outline

- Basis for Long-Term Isolation
  - Post-Closure Safety Case

- Regulatory and Licensing Considerations
  - Potential Regulatory Topics

- DBD Post-Closure System Assessment
  - Conceptual Model
  - Coupled Process Models
  - Performance Assessment (PA) Model
    - PA Model Results
    - Sensitivity Analyses

- Summary
Basis for Long-Term Isolation – DBD Safety Case

- Pre-Closure
  - Safety Analysis
- Post-Closure
  - Performance Assessment (PA)
    - Repository System Design
    - Regulations and Licensing
    - Features, Events, and Processes (FEPs) Analysis
    - Scenario Development
    - PA Model

SAFETY CASE

Quantitative Information
- Analysis Results
  - Pre-Closure
  - Post-Closure

Qualitative Information
- Collective Evidence

Deep Borehole Field Test

• Arnold et al. (2013, Appendix A)
• Freeze et al. (2013)
Regulatory and Licensing Considerations

- **Pre-Closure / Operational**
  - Transportation
  - Construction (borehole and surface facilities)
  - Operations (waste storage, handling, and downhole emplacement)
  - Decommissioning

- **Post-Closure**
  - Siting and Site Suitability
      - Separate repository for HLW resulting from atomic energy defense activities is possible (NWPA 1983, Section 8(b); DOE 2015)
    - 10 CFR 960 and 963
  - Licensing (NRC) and Environmental Protection (EPA)
    - 10 CFR 60 and 40 CFR 191 - (Generic – 1981 and later amendments)
    - 10 CFR 63 and 40 CFR 197 (Yucca Mountain specific – 2001 and later amendments)
    - *International (e.g., IAEA Guidelines (IAEA 2011))*
Licensing and Environmental Protection:

- Existing regulations for disposal of SNF/HLW (10 CFR 60 and 40 CFR 191) could, in principle, be applied to other disposal concepts and/or sites, without revision
  - 10 CFR 60 and 40 CFR 191 predate the 1987 NWPA amendment, may be revised or replaced in the future
  - 10 CFR 63 and 40 CFR 197 could provide inferences to other concepts and/or sites
- Specific regulatory topics that may benefit from clarification for deep borehole disposal include (Arnold et al. 2013, Appendix A; NWTRB 2015; Winterle et al. 2011):
  - Performance Standards
    - Containment/Cumulative Release vs. Dose/Risk
    - DBD Reference Biosphere and Receptor for Dose/Risk
  - Multiple Barriers / Subsystem Performance
  - Retrievability
  - Human Intrusion
  - Licensing (Non-Phased Approach / Multiple Deep Boreholes)
  - Underground Injection (40 CFR 144 to 148)
DBD Post-Closure PA Model Development – Chronology

Past PA Work (2009 – 2014)

- **Excel Spreadsheet Model**
  - Brady et al. 2009, Sections 4 and 5

- **GoldSim-based 1-D Model**
  - Wang and Lee 2010, Section 5
  - Clayton et al. 2011, Section 3.4
  - Freeze et al. 2013, Sections 4.3 and 4.4
  - Arnold et al. 2013, Section 4.4

Current/Future PA Work (2015 – future)

- **PFLOTRAN-based 3-D Model**
  - Current iteration of development
DBD Post-Closure Conceptual Model – Components

**Natural System**
- Overlying Sediments
- Crystalline Basement
  - Low permeability and long residence time
  - Density stratification of saline groundwater opposes upward convection
  - Geochemically reducing conditions limit the solubility and enhance the sorption of many radionuclides

**Engineered Barriers**
- Waste forms
- Waste packages
- Borehole seals (and DRZ)
Inventory / Waste Form
- DOE-managed HLW (Cs/Sr Capsules)
- Commercial SNF (PWR assemblies)

Waste Package
- Provides operational protection, assumed to rapidly degrade after emplacement

Post-Closure Release Pathways
- Undisturbed
  - Up borehole through seals / DRZ
  - To host rock surrounding disposal zone
    - High-permeability pathway to shallow groundwater
- Disturbed
  - Volcanic/igneous
  - Human Intrusion

Biosphere (Dose)
- Subsurface release to aquifer
- Pumping from aquifer to surface receptor
Crystalline Basement Host Rock (assumed to be granite):

- Low permeability ($k$) and porosity ($\Phi$)
  - $k = 1 \times 10^{-19} \text{ m}^2$ (base case), $1 \times 10^{-16} \text{ m}^2$ (high)
  - $\Phi = 0.01$
  - Parameterization ongoing (e.g., permeability variation with depth)

- Ambient reducing geochemical conditions at depth

- Ambient temperature = 10°C at surface
  - Thermal gradient = 25°C/km (110°C at center of disposal zone)
  - Thermal conductivity = 3.0 W/m°C
  - Specific heat = 790 J/kg°C

- Salinity and density gradients

Arnold et al. 2013, Figure 4-3
Inventory and Waste Form

Past PA Work
- 400 PWR assemblies stacked in a 2,000 m zone
  - Radionuclide inventory and thermal output from Carter et al. (2012, Table C-1)
  - Waste form degradation = fractional rate
    - slower = $1 \times 10^{-7}$ yr$^{-1}$
      - (mass release: 50% by 4,800,000 yrs; 76% by 10,000,000 yrs)
    - faster = $2 \times 10^{-5}$ yr$^{-1}$
      - (mass release: 50% by 35,000 yrs; 99.9% by 350,000 yrs)

Current/Future PA Work
- 1936 Cs/Sr capsules stacked in 1,300 m zone
  - Radionuclide inventory and thermal output from 1335 Cs capsules and 601 Sr capsules (SNL 2014)
  - Waste form degradation assumed to be rapid
**Waste Packages**
- Assumed to degrade at time zero (after emplacement)
- Mobilization of radionuclides from degraded waste form

**Waste Disposal Zone**
- Decay heat effects calculated with the Regional TH Model:
  - *Heat conduction in surrounding crystalline basement rock (assumed to be granite)*
  - *Thermal perturbation in borehole produces thermally-driven upward groundwater flow*
- Radionuclide dissolution and transport (advection/dispersion, diffusion, sorption, and decay in the groundwater)
  - *Based on ambient reducing geochemical conditions*
Regional TH Model – Past Work

SNF (Arnold et al. 2013, Section 4.2.1) - FEHM

- 3-D multi-borehole configuration
- 400 PWR WPs per borehole (2000 m disposal zone)
  - ~ 240 W/m borehole length

Temperature in Disposal Zone (4,000 m depth, r=0.8 m)
of Central Borehole in 81-Borehole Array

![25-Borehole Array Schematic](image)

Vertical Groundwater Flux (at various depths)
in Central Borehole in 81-Borehole Array

![Vertical Groundwater Flux Graph](image)

Arnold et al. 2013, Figure 4-4

Arnold et al. 2013, Figure 4-5
HLW (Arnold et al. 2014, Section 3.2.5) – FEHM / PFLOTRAN

- 3-D single-borehole configuration
- 1936 Cs/Sr capsules in 1 borehole (1,300 m disposal zone)
  - 200–300 W/m borehole length (avg.) (Arnold et al. 2014, Fig 3-2)

**Temperature in Disposal Zone**
(4,000 m depth, r=0.0 and 1.0 m) of Single Borehole

**Vertical Groundwater Flux**
At Top of Disposal Zone (3,700 m depth) in Single Borehole

Arnold et al. 2014, Figure 3-23
Arnold et al. 2014, Figure 3-24
Section 4: Seal Zone

- Enhanced permeability ($k$) in the DRZ/sealed borehole
  - composite $k = 1 \times 10^{-16} \text{ m}^2$ (base case), $1 \times 10^{-12} \text{ m}^2$ (high)
  - composite porosity ($\Phi$) = 0.034 (bentonite/seal = 0.35, DRZ = 0.01)
  - composite tortuosity ($\tau$) = 0.324
  - parameterization ongoing (e.g., explicit representation of DRZ and seals)

- Thermally-induced upward groundwater flux

- Transport by advection and diffusion (upward and lateral) with sorption and decay
  - Advective center of mass moves upward $\sim 30 \text{ m}$
    - $(0.01 \text{ m/yr})(100 \text{ yrs})/(0.034 \text{ porosity})$
DBD Conceptual Model – Undisturbed Scenario

- **Upper Borehole Zone**
  - Release of radionuclides upward in the borehole from the Seal Zone to Upper Borehole Zone
  - Transport by diffusion (upward and lateral) with sorption and decay to aquifer and/or surface

- **Biosphere**
  
  **Past PA Work**
  - IAEA BIOMASS ERB 1B Biosphere (IAEA 2003)
    - Pumping of groundwater from Upper Borehole Zone for water supply with specified dilution rate and individual consumption rate
    - IAEA Dose Conversion Factors (DCFs)

  **Current/Future PA Work**
  - Explicit flow and transport modeling in Upper Borehole Zone and sedimentary units, including aquifer
    - Pumping of the groundwater from the aquifer for water supply
    - IAEA Dose Conversion Factors (DCFs)
DBD PA Model Results – Base Case

(Clayton et al. 2011)
- Probabilistic ($^{129}$I $k_d = 0-13$ ml/g)
- Slower WF degradation ($1 \times 10^{-7}$ yr$^{-1}$)
- Granite $k=10^{-19}$ m$^2$, Seal/DRZ $k=10^{-16}$ m$^2$
- SNF (400 PWRs)

(Freeze et al. 2013)
- Deterministic ($^{129}$I $k_d = 0$ ml/g)
- Faster WF degradation ($2 \times 10^{-5}$ yr$^{-1}$)
- Granite $k=10^{-19}$ m$^2$, Seal/DRZ $k=10^{-16}$ m$^2$
- SNF (400 PWRs)
Sensitivity of $^{129}$I Annual Dose

- Faster transport than $^{135}$Cs, $^{137}$Cs, or $^{90}$Sr

(Freeze et al. 2013)
**Base-Case (Clayton et al. 2011)**
No lateral diffusion into granite

**Base-Case (Arnold et al. 2013)**
Lateral diffusion into granite

---

Clayton et al. 2011, Figure 3.4-9

Arnold et al. 2013, Figure 4-19
Past PA Model results suggest minimal radionuclide releases/dose

- Results are sensitive to:
  - waste form degradation rate
  - radionuclide sorption ($k_d$)
  - granite and seal permeability
  - thermally-induced upward flow (waste thermal characteristics)
  - waste package degradation

Future PA Model enhancements

- Full consideration of features, events, and processes relevant to potential release pathways and scenarios (e.g., PFLOTRAN implementation)
- Incorporation of more detailed modeling, including coupled processes
  - Seal and DRZ conceptualization
  - Coupled thermal-hydrologic-mechanical-chemical behavior near the borehole
- Refinement of parameter values
  - Cs/Sr capsule waste form
  - Data from DBFT
References


Backup Slides
Siting

- No disposal options for commercial SNF/HLW other than Yucca Mountain are possible without amending the Nuclear Waste Policy Act (NWPA 1983)
- Separate repository for HLW resulting from atomic energy defense activities is possible (NWPA 1983, Section 8(b); DOE 2015)
- NWPA (1983, Sec. 112-120) and 10 CFR 963 provide technical and administrative guidance on site suitability and site characterization activities specific to Yucca Mountain
  - *Could, in principle, provide insights to siting for other SNF/HLW disposal concepts and/or sites*
Potential Regulatory Topics

**10,000-Yr Performance Standards (10 CFR 60 and 40 CFR 191)**
- 40 CFR 191.13 Containment Standard
  - *cumulative releases of radionuclides to the accessible environment*
  - Release limits normalized to initial inventory (no benefit for smaller repositories)
  - Cumulative limits remove uncertainty associated with exposure pathways and future human lifestyles
  - *includes consideration of human intrusion*
- 40 CFR 191.15 Individual Protection Standard (undisturbed only)
- 40 CFR 191.24 Groundwater Protection Standard (undisturbed only)

**1,000,000-yr Performance Standards (10 CFR 63 and 40 CFR 197)**
- 40 CFR 197.20 Annual Dose Standard for Individual Protection
  - 10,000-yr (15 mrem/yr) and 1,000,000-yr (100 mrem/yr) limits
- 40 CFR 197.25 Human Intrusion Standard (separate standard)
- 40 CFR 197.30 Groundwater Protection Standard (10,000-yr only)

**New standards are likely to be Dose/Risk-based to 1,000,000 yrs**
- Consistent with IAEA guidelines (IAEA 2011) and the National Academy of Sciences (1995) recommendations on Yucca Mountain standards
Dose vs. Cumulative Release Standards

**Dose**
- Emphasis on low annual dose/risk
- Can be open-ended in time (or to peak dose)
- Uncertainty in human behavior (e.g., water use and diet) is large
- Encourages dilution and gradual release as well as isolation
- Encourages smaller initial inventories

**Cumulative Release**
- Emphasis on isolation
- Meaningful only for specified time period
- Allowable limit is a function of time
- Focuses on uncertainty in barrier system performance
- No benefit for dilution
- Normalization to initial inventory (as in 40 CFR 191) removes incentive for smaller repositories
Potential Regulatory Topics

Multiple Barriers / Subsystem Performance

- 10 CFR 60.113(a)
  - Substantially complete containment in waste packages for not less than 300 years
  - Release rate of any radionuclide from the engineered barrier system shall not exceed one part in 100,000 per year of the inventory of that radionuclide at 1000 years
  - Groundwater travel time to the accessible environment along the fastest path shall be at least 1,000 years

- 10 CFR 63.113(a)
  - “The geologic repository must include multiple barriers, consisting of both natural barriers and an engineered barrier system.”

- A deep borehole disposal system includes engineered barriers (waste form, waste package, seals, liner/casing)
  - Current design (waste package does not provide any post-closure isolation) may be satisfy engineered subsystem requirements in 10 CFR 60.113(a)
  - 10 CFR 60.113(b) states “On a case-by-case basis, the Commission may approve or specify some other radionuclide release rate, designed containment period or pre-waste-emplacement groundwater travel time, provided that the overall system performance objective, as it relates to anticipated processes and events, is satisfied.”
## Retrievability

- 40 CFR 191.14(f)
  
  • “Disposal systems shall be selected so that removal of most of the wastes is not precluded for a reasonable period of time after disposal.”

- 10 CFR 60.111 (and 10 CFR 63.111)
  
  • “(1) The geologic repository operations area shall be designed to preserve the option of waste retrieval throughout the period during which wastes are being emplaced and, thereafter, until the completion of a performance confirmation program ... To satisfy this objective, the geologic repository operations area shall be designed so that any or all of the emplaced waste could be retrieved on a reasonable schedule starting at any time up to 50 years after the waste emplacement operations are initiated, unless a different time period is approved or specified by the Commission.”

- 10 CFR 60.46(a) “… an amendment shall be required …”
  
  • “[for any] action which would make emplaced high-level radioactive waste irretrievable or which would substantially increase the difficulty of retrieving such emplaced waste”
Retrievability (cont.)

- EPA noted when promulgating 10 CFR 191 in 1985:
  - “The intent of this provision was not to make recovery of waste easy or cheap, but merely possible…”

- NEA (2001) noted:
  - “The introduction of provisions for retrievability must not be detrimental to long-term safety. Thus, for example, locating a repository at a depth that is less than optimum from a long-term safety perspective in order to facilitate retrieval is unlikely to be acceptable…”

- Prior to sealing, intact waste packages could potentially be retrieved from a cased borehole

- After sealing, large-diameter core drilling has the potential for “waste recovery”, at least for relatively narrower-diameter boreholes.

- “… deep borehole systems may not be the best choice if permanent and irreversible disposal is not intended.” (Brady et al. 2009)
Potential Regulatory Topics

- **Human Intrusion**
  - 40 CFR 191 and 197 are specific to mined repositories
    - *Single borehole – may be reasonable to assume low probability of intrusion*
    - *Multiple boreholes – may require further analysis*

- **Licensing**
  - Existing regulations contain an implicit assumption that a repository system will be licensed and constructed as a single unit
  - Need to consider approaches to licensing multiple boreholes
    - *License full multi-borehole system prior to waste emplacement?*
    - *Follow licensing approach for reactors?*
  - Phased licensing may not be applicable because emplacement may take place in months/years rather than decades (Winterle et al. 2011)
    - *Single license application (e.g., construct and operate)?*
Potential Regulatory Topics

- **Underground Injection (40 CFR 144 to 148)**

  - EPA requirements for the Underground Injection Control (UIC) program promulgated under the Safe Drinking Water Act
  - Focus is on subsurface injection of fluids, but may apply to deep borehole disposal
  - 40 CFR 144.6(a) includes as a Class I injection well:
    - “(3) Radioactive waste disposal wells which inject fluids below the lowermost formation containing an underground source of drinking water within one quarter mile of the well bore”
  - Permitting authority varies from state to state
  - In its 1993 repromulgation of 40 CFR 191, EPA determined
    - “that nuclear waste disposal systems should not be considered underground injection” (58 FR 66407).
  - Compliance with 40 CFR part 144 was considered for WIPP
    - *DOE concluded that emplacement in WIPP did not constitute “injection” (DOE 1996, BECR Section 8.1)*
  - Need further guidance from EPA to determine whether canistered solid or granular HLW can be excluded from UIC
DBD PA Computational Model – Past Work (GoldSim)

- Thermal energy from decay heat
- Heat conduction
- Multiphase flow

[FEHM]

Input Parameter Distributions

- Radionuclide Source Term
  - Waste Form Degradation
  - Radionuclide Solubility
- 1-D Flow and Transport
  - Advection and Diffusion
  - Sorption and Decay
- Biosphere
  - Aquifer dilution
  - Pumping and Individual Uptake
- LHS Sampling, Sensitivity Analysis

Results
DBD PA Computational Model – Current/Future Work (PFLOTRAN)

Input Parameter Distributions

Sensitivity Analysis and Uncertainty Quantification

Computational Support
- Mesh Generation - Cubit
- Visualization – ParaView, VisIt
- Parameter Database

Radionuclide Source Term
- Waste Form Degradation
- Radionuclide Solubility

3-D Thermal-Hydro-Chemistry
- Thermal Effects
- Advection and Diffusion
- Sorption and Decay

Biosphere
- Aquifer flow and transport
- Pumping and Individual Uptake

Results
DBD Conceptual Model – Undisturbed Scenario

■ Biosphere (Past Work)
  – Assume IAEA BIOMASS ERB 1B Biosphere
    • Potentially contaminated water from Seal Zone mixes in Upper Zone and surrounding permeable sediments
    • Pumping of the groundwater from Upper Zone for water supply
      – Dilution rate = 10,000 m³/yr
      – Individual consumption rate = 1.2 m³/yr
    • IAEA Dose Conversion Factors (DCFs)

■ Biosphere (Current/Future Work)
  – Explicit flow and transport modeling in Upper Zone and sedimentary unit, including aquifer
    • Pumping of the groundwater from the aquifer for water supply
    • IAEA Dose Conversion Factors (DCFs)
Additional References for Backup Slides


