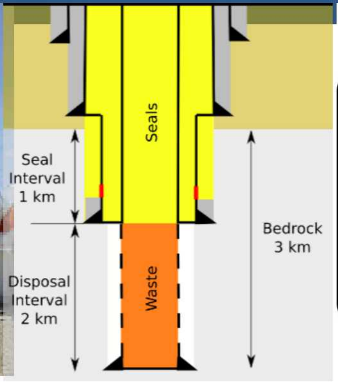
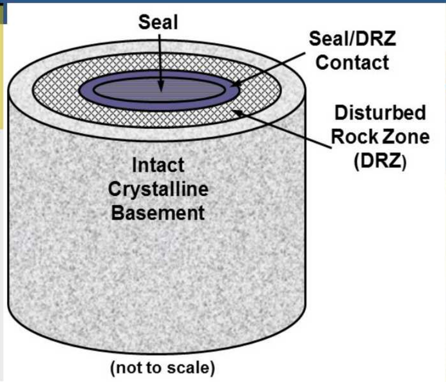
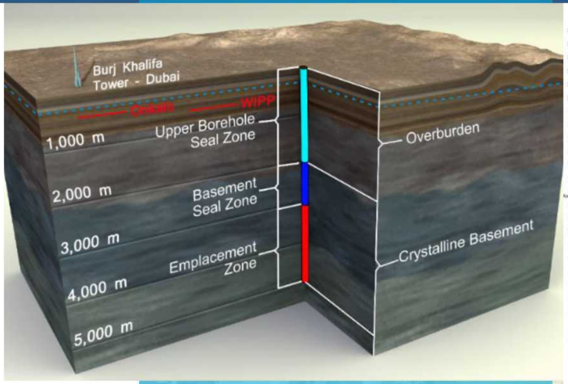
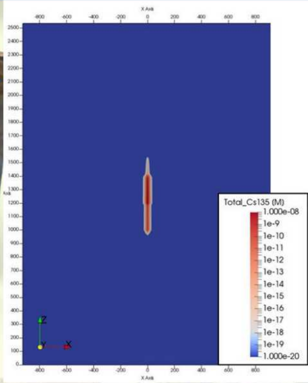
SAND2019-4624PE

Safety Case for IAEA Disposal Options - Very Deep Borehole Disposal









Presented by

David Sassani

Distinguished Member Technical Staff

IAEA Disposal Options for Small Inventories – Workshop

May 6 - 10, 2019, Vienna, Austria

Outline

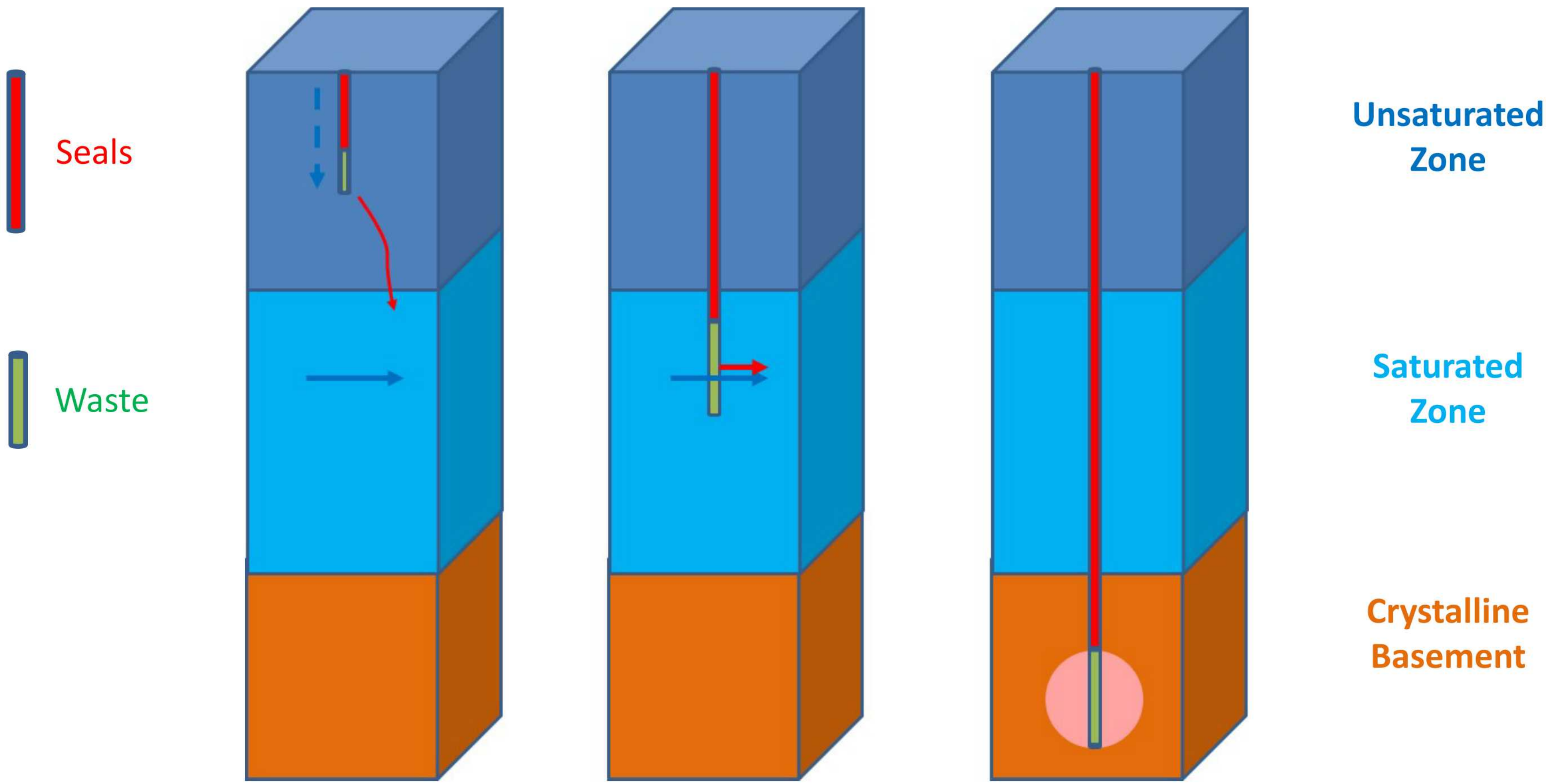
- Sandia Team Primaries:
  - Pat Brady; Geoff Freeze; Ernest Hardin; Kris Kuhlman; David Sassani; Robert MacKinnon
- Very Deep Borehole Disposal (DBD) Overview
  - Concept and Recent DBD Research in the U.S.
- Safety Case
  - Conceptual and Bases
    - Pre-Closure and Post-Closure Safety
  - Post-Closure Performance Assessment (PA)
    - Nominal Scenario
- Summary & Conclusions

Borehole Disposal Concepts

Shallow
[<100s of meters]
(e.g., LLW / sealed sources)

Deep
[<2000 m]
(e.g., ILW / HLW)

Very Deep
[2000 - 5000 m]
(e.g., SNF / HLW)

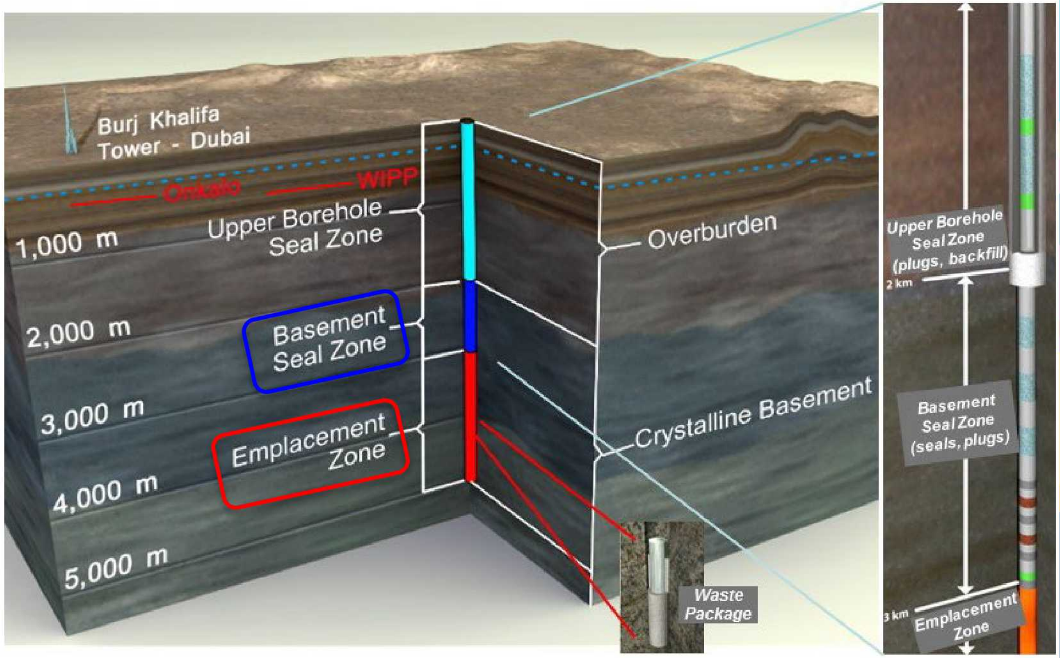


D. Sassani, SNL; IAEA Tech Workshop, May 6-10, 2019

Very Deep Borehole Disposal Concept

- Drill a borehole or array of boreholes into deep, competent rock (e.g., crystalline basement)
  - ~ 5,000 m* total depth (TD)
  - up to 17” (43 cm) diam. at TD
    - 17” for SNF (1 PWR assembly)
    - ≥ 8.5” for some HLW
- Emplacement Zone (EZ)
  - Waste in lower ~ 2,000 m*
- Seal Zone (SZ)
  - Engineered seals and plugs above EZ
    - ≥ 1,000 m* robust seal in competent basement rock

*** depths will be site and waste specific**



Robust Isolation from Biosphere

Natural Barriers – deep, low permeability host rock
Engineered Barriers – redundant seals, possibility of long-lived waste forms and waste packages

Research and Development (R&D) at Sandia National Laboratories (SNL)

- 2009 – 2012 (SNL internally funded)
  - DBD Consortium with Mass. Inst. of Tech. (MIT), U. of Sheffield, Industry
  - SNF disposal (Brady et al. 2009, Arnold et al. 2011)
- 2012 – 2014 (U.S. DOE funded R&D)
  - Preliminary siting, design, and post-closure PA focused on SNF disposal (Arnold et al. 2013; Freeze et al. 2013a)
  - DOE (2014a) recommended consideration of DBD of smaller DOE-managed waste forms, such as Cs and Sr capsules
- 2014-2017 (U.S. DOE funded R&D)
  - Lead Lab for a planned 5-year Deep Borehole Field Test (DBFT) to evaluate the feasibility of siting and operating a DBD facility
    - Collaboration with other National Labs: LANL, LBL, ORNL, PNNL, INL
    - DBFT to use “surrogate” waste packages (no radioactive waste)
    - Safety Case (Freeze et al., 2016)

DBD Safety Case

Very DBD Concept – Safety and Feasibility

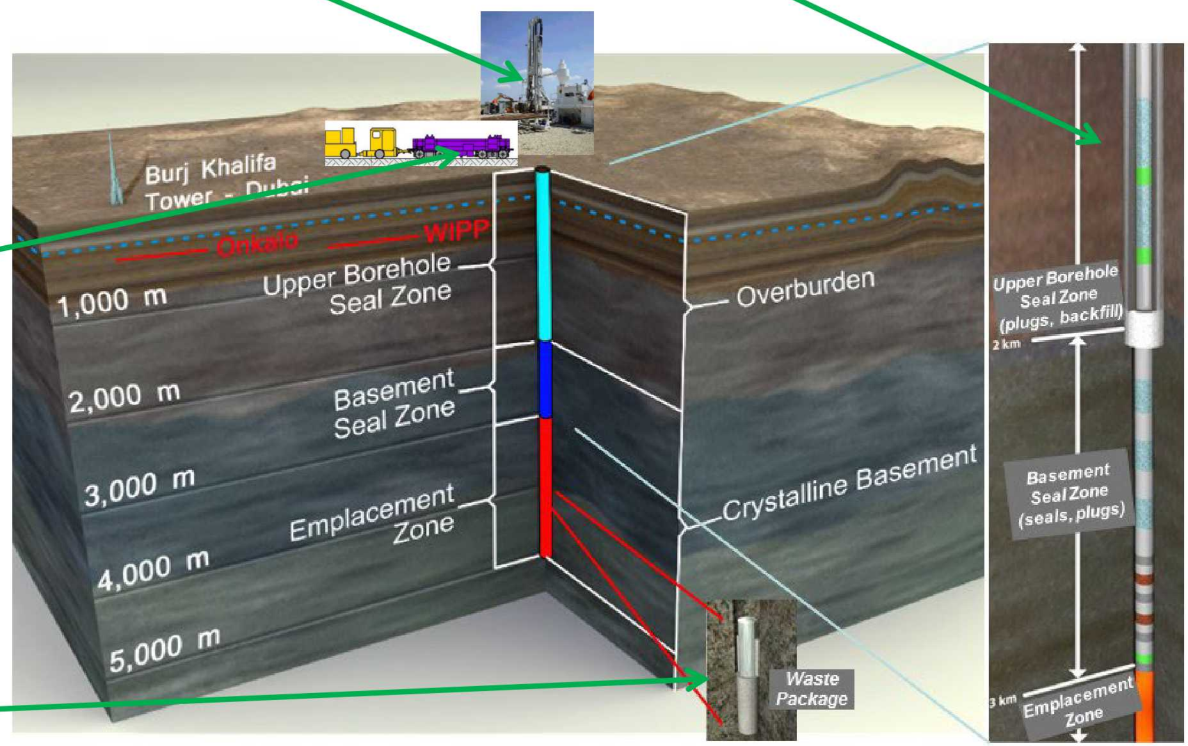
(Pre-Closure Engineering and Operations)

Drilling Technology exists to drill and case larger-diameter boreholes to 5,000 m depth in basement rock at acceptable cost

Borehole and Casing Design maintains borehole integrity (against borehole breakout) and minimizes probability of waste packages becoming stuck during emplacement

Emplacement System Design provides assurance the waste packages can be safely surface-handled and emplaced at depth

Waste Package Design maintains structural integrity and prevents leakage of radioactive materials during operations



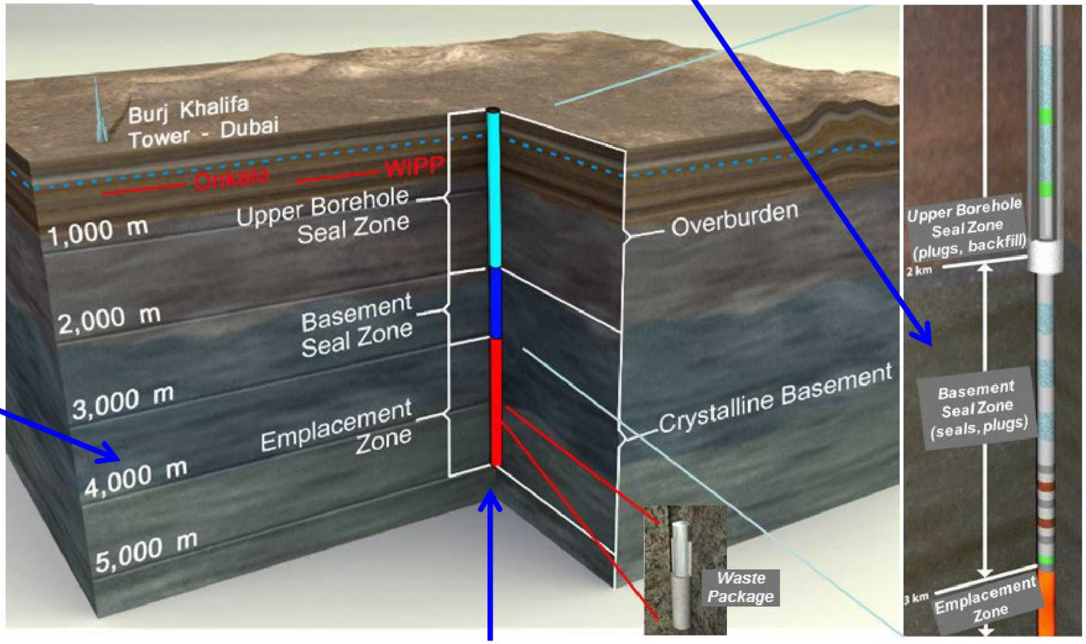
Very DBD Concept – Safety and Feasibility

(Post-Closure Hydrogeochemical Waste Isolation)

Identify adequate host rock with sufficient depth and thickness

Borehole Seals and Disturbed Rock Zone (DRZ) can be engineered/evolve to maintain a low-permeability barrier, at least over the time scale of thermally-induced upward flow

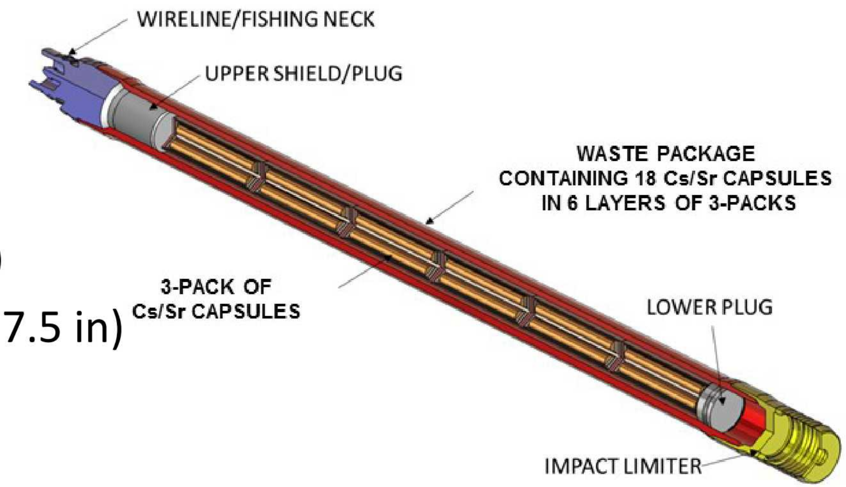
Deep basement rocks
- hydrologically isolated from shallow groundwater (low permeability and long groundwater residence time)
- deep groundwater typically exhibits density stratification (saline water underlying fresh water) that opposes upward flow
- geochemically reducing conditions at depth limit the solubility and enhance the sorption of many radionuclides



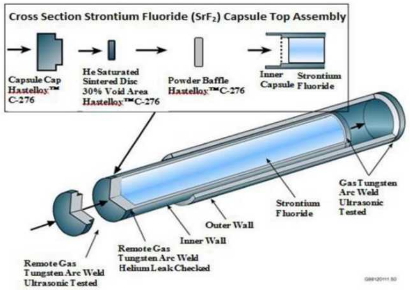
Waste is deep in basement rock
- well below typical depth of fresh groundwater ------
- with at least 1,000 m of basement rock (Seal Zone) overlying the Emplacement Zone

Safety Case Reference Design (HLW)

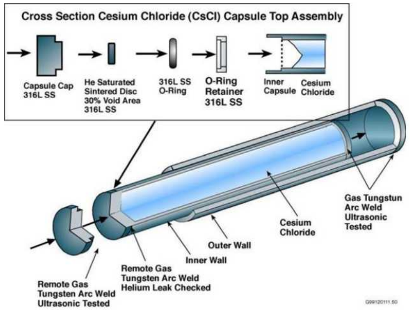
- Radionuclide Inventory (SNL 2014, Freeze et al. 2016)
  - 1936 Cs and Sr capsules aged to 2050
    - Decay heat for ~ 100 yrs
  - 108 waste packages (WPs)
    - 18 capsules per WP (6 layers of “3-packs”)
    - WP length = 4.76 m / WP diam. = 0.19 m (7.5 in)



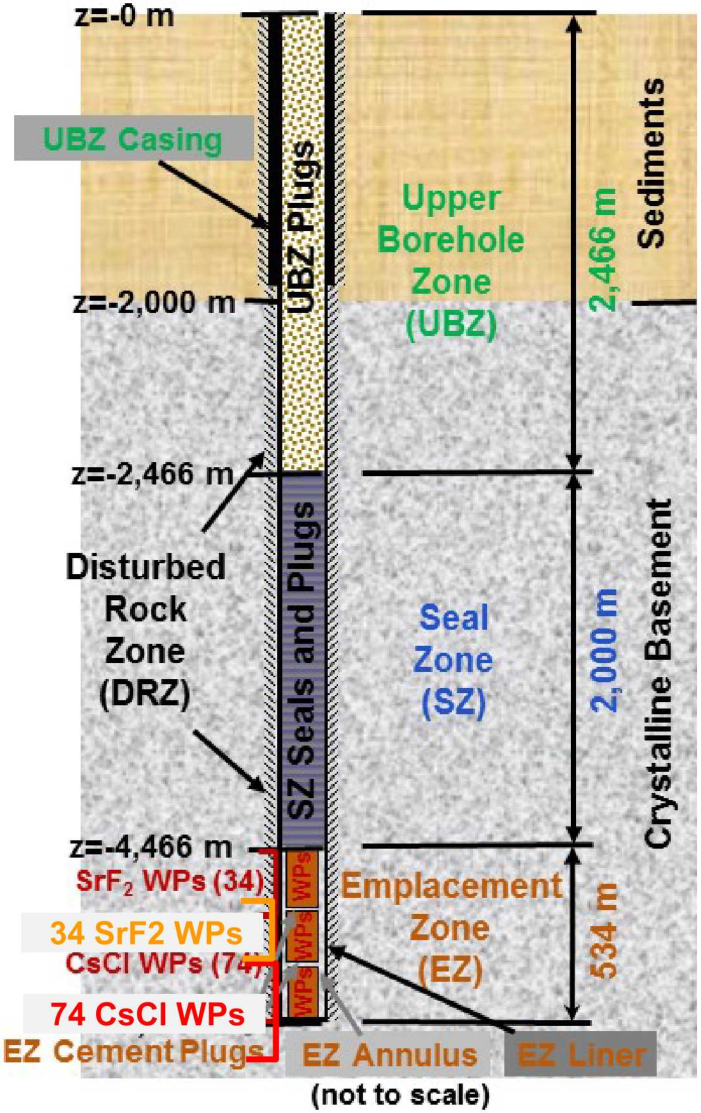
  - 601 SrF_2 capsules @ ~18 per WP = 34 Sr WPs
    - Inventory = ^{90}Sr ($t_{1/2}$ = 28.8 yr)



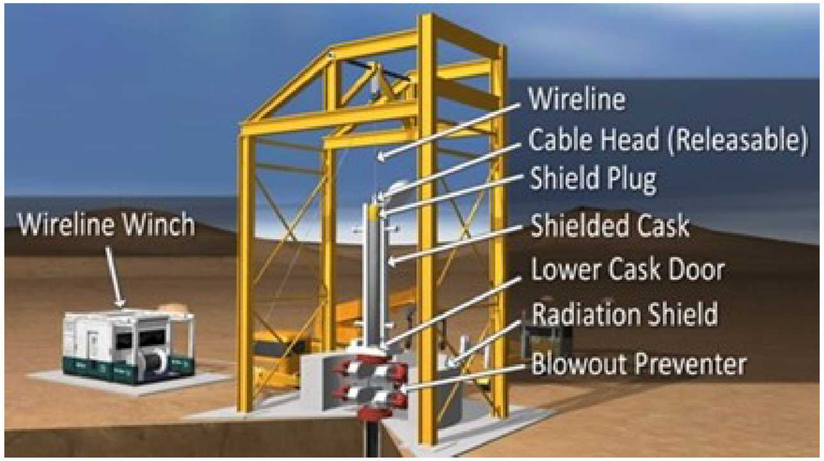
  - 1335 CsCl capsules @ ~18 per WP = 74 Cs WPs
    - Inventory = ^{137}Cs ($t_{1/2}$ = 30.1 yr), ^{135}Cs ($t_{1/2}$ = 2,300,000 yr)



Safety Case Reference Design (HLW)

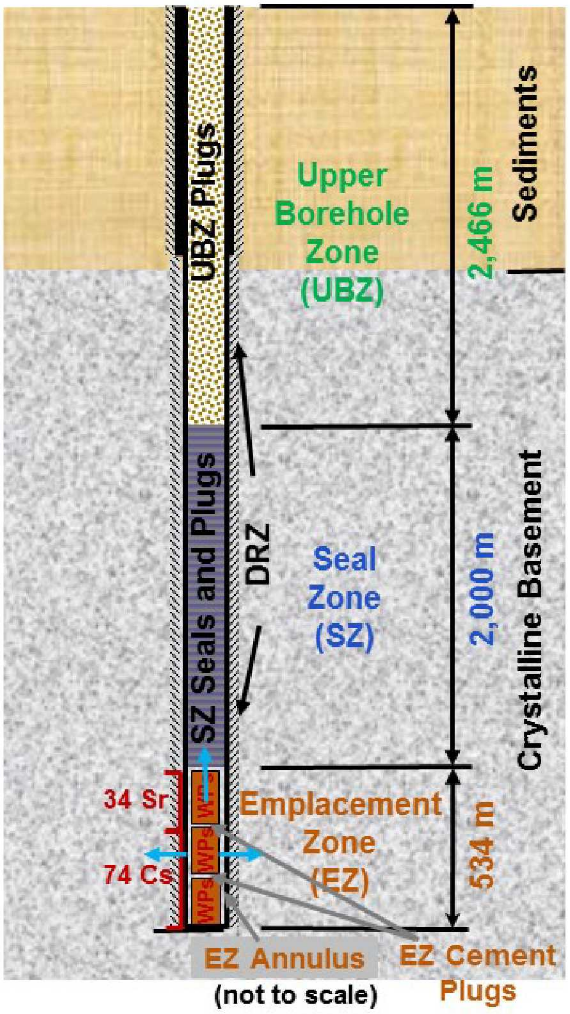


- All 108 WPs fit in a single borehole with a 534-m Emplacement Zone (EZ)
  - bottom-hole diameter of 12.25 in (31 cm)
- Seal Zone (SZ) consists of alternating bentonite and cement emplaced directly against borehole wall
- WPs are lowered, one at a time, on wireline inside a removable guidance casing



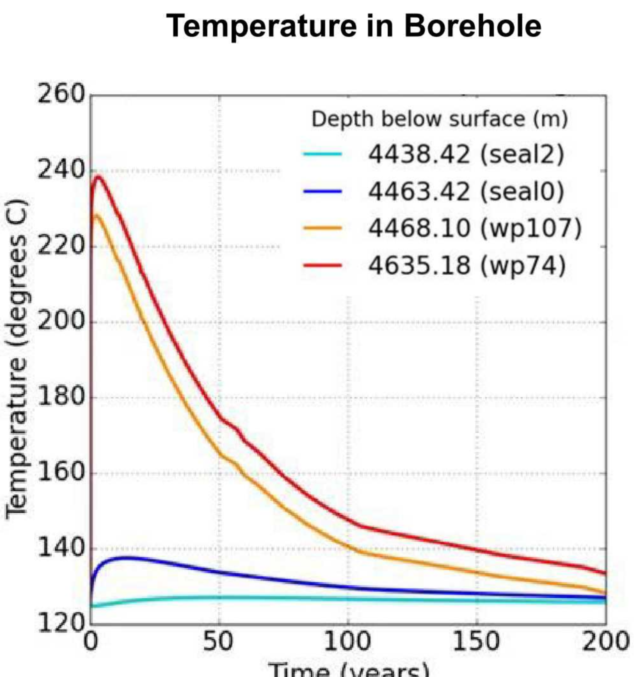
Post-Closure PA – Nominal Scenario

- Emplacement Zone
  - Decay heat produces thermally-driven upward groundwater flow in borehole and DRZ (for ~100 yrs)
  - Radionuclide dissolution and transport in groundwater
    - No credit for WF or WP integrity
    - Advection, diffusion, and decay (no sorption in EZ)
- Post-Closure Release Pathways
  - Radionuclide transport by advection (thermally-induced upward flux), diffusion (upward and lateral), sorption, and decay
    - Up borehole through seals (cement/bentonite) and DRZ
      - $k = 1 \times 10^{-18}$ m^2 / Cs k_d = 1525 mL/g (seals)
      - $k = 1 \times 10^{-16}$ m^2 / Cs k_d = 22.5 mL/g (DRZ)
    - To host rock surrounding EZ
      - $k = 1 \times 10^{-18}$ m^2 / Cs k_d = 22.5 mL/g (fractured granite)
      - No regional flow gradient in crystalline basement

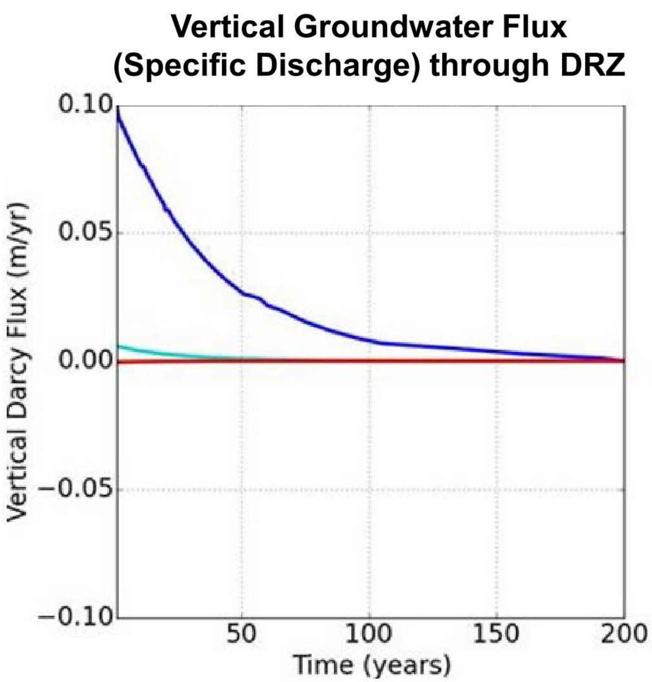


Nominal Scenario Deterministic Results – Thermally-Induced Upward Flow

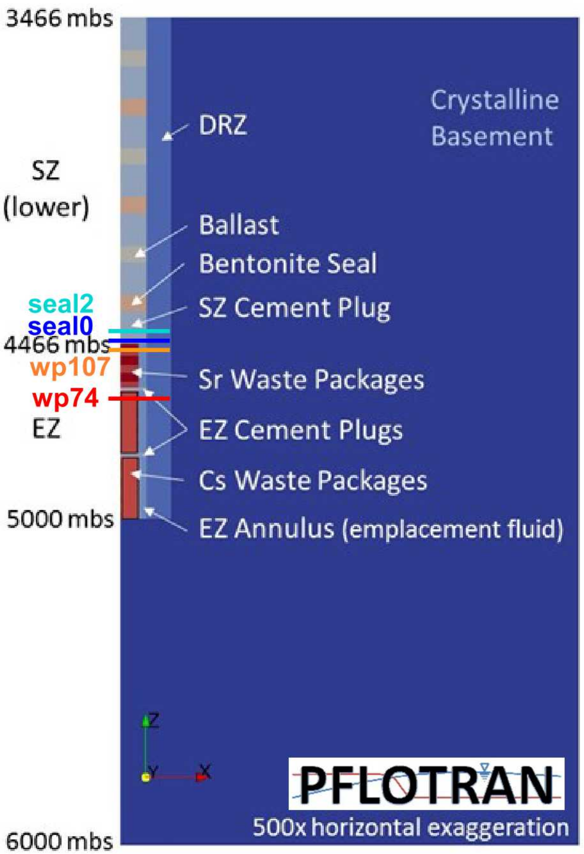
- Short-term temperature increase (from waste decay)
  - duration ~ 200 yrs, peak increase ~100°C in EZ
- Corresponding Darcy flux (specific discharge) up borehole and DRZ
  - highest in EZ annulus, overlying seal diverts flux to DRZ
    - (0.006 m/yr)(50 yrs)/(0.005 porosity) ~ 60 m
    - advection is even less with sorption



from Freeze et al. (2016), Figure 5-4

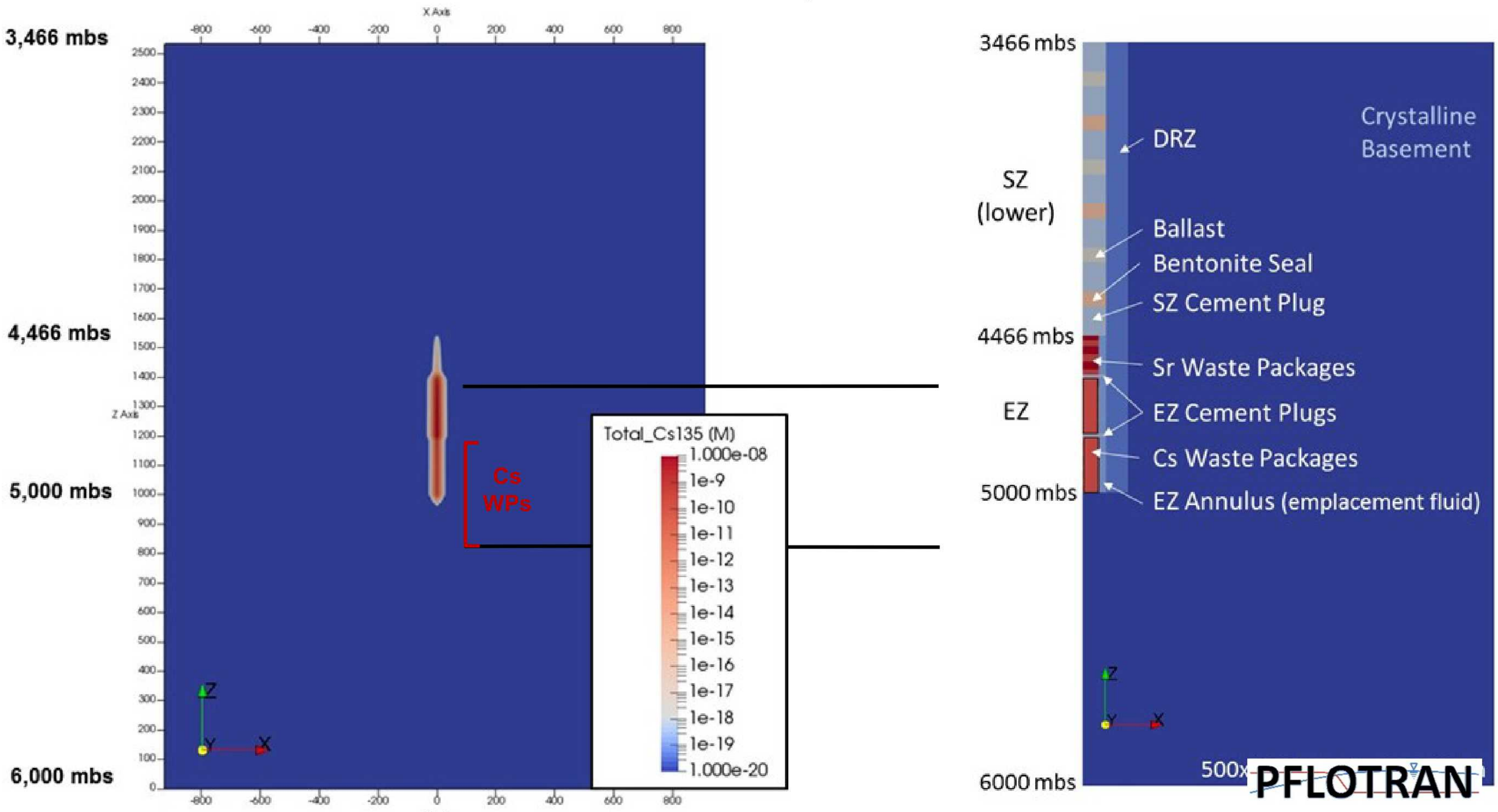


from Freeze et al. (2016), Figure 5-5



Nominal Scenario Deterministic Results – ^{135}Cs Dissolved Concentration (mol/L)

- Concentration of ^{135}Cs at 10,000,000 years
  - Minimal migration beyond Emplacement Zone



from Freeze et al. (2016), Figure 5-8

Very DBD Generic Safety Case - Summary

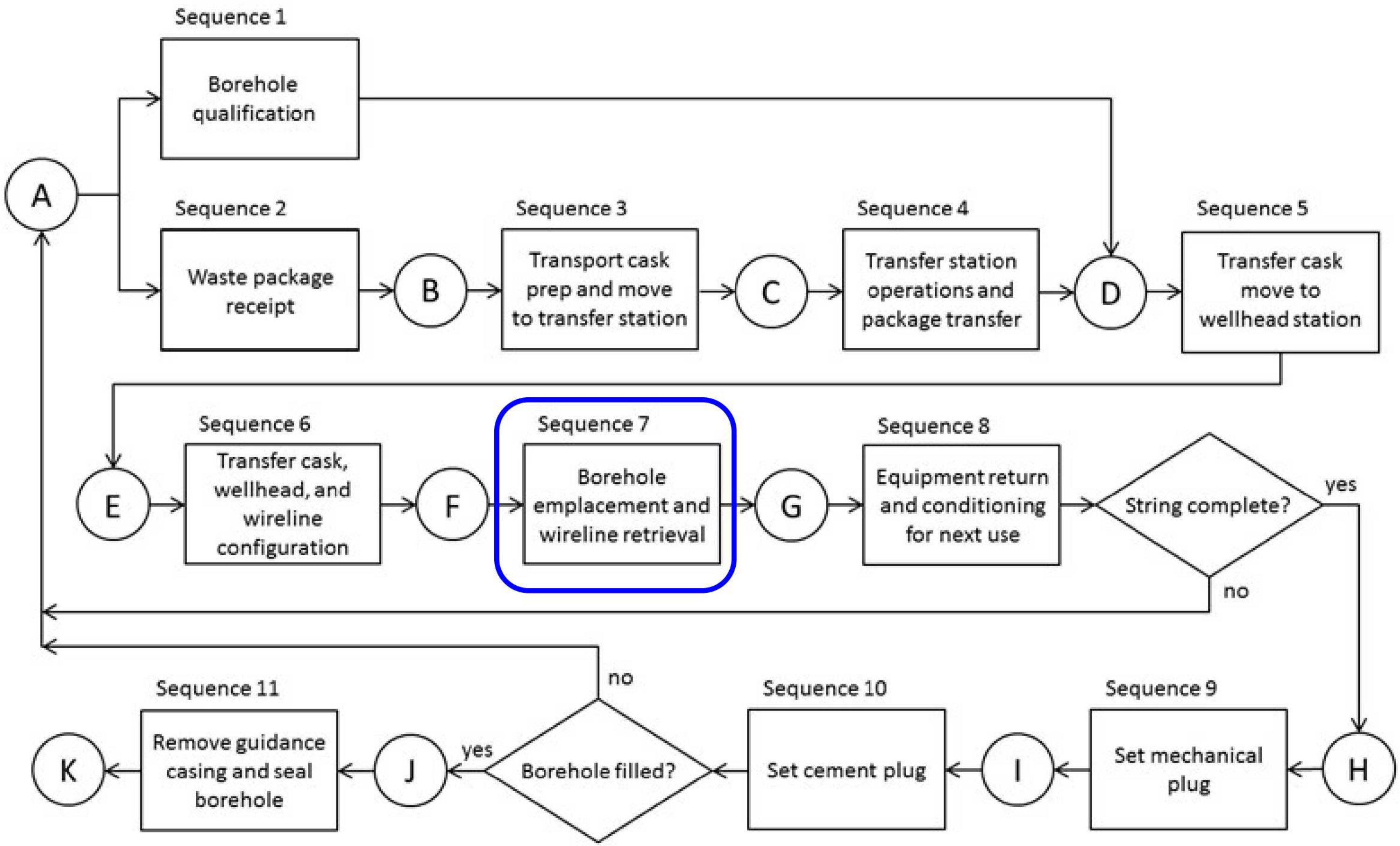
- Post-Closure Safety Case for VDBD:
  - Waste emplacement is deep; in low-permeability crystalline basement rock with limited interaction with shallower groundwater.
  - Borehole seals can be engineered to maintain their physical integrity, at least over the ~ 100-year time period of thermally-induced upward flow.
  - Preliminary results from post-closure PA calculations suggest minimal radionuclide releases beyond the disposal zone and zero dose at biosphere.
- Similar Results Obtained for DBD Safety Case for SNF
  - Arnold et al. (2013. App. A); Freeze et al. (2013)
- A Field Test Could Further Enhance Confidence
  - Pre-closure operations (e.g., waste handling and emplacement system)
  - Downhole characterization to support post-closure analyses

References and Backup Materials

DBD Pre-Closure Safety Analysis (PCSA)

Hardin et al. (2019)

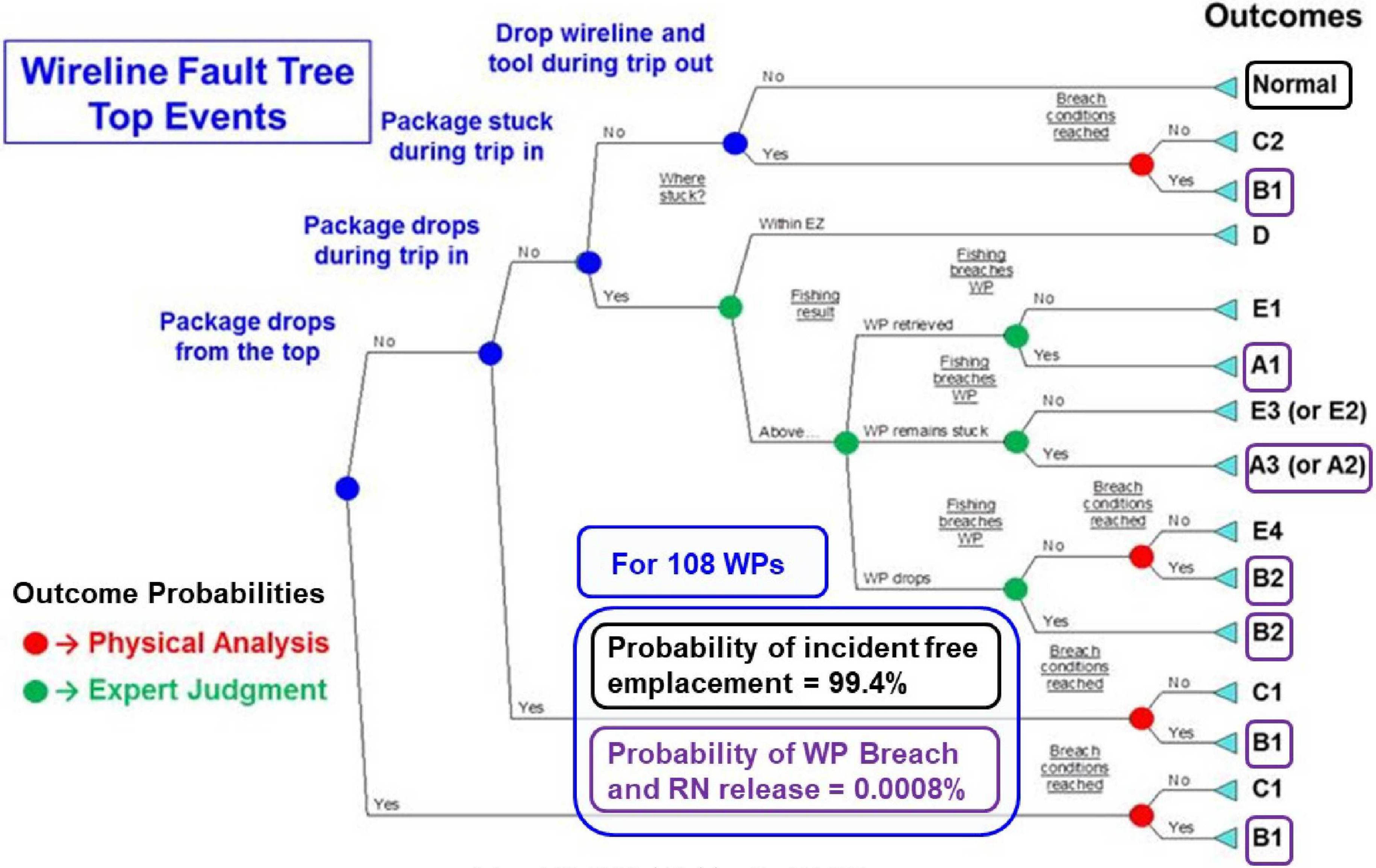
- Identification of activity sequences and risk factors for disposal operations
- PCSA modeling (fault trees, event trees, and probability estimates)



Source: Hardin et al. 2019, Figure 5-1

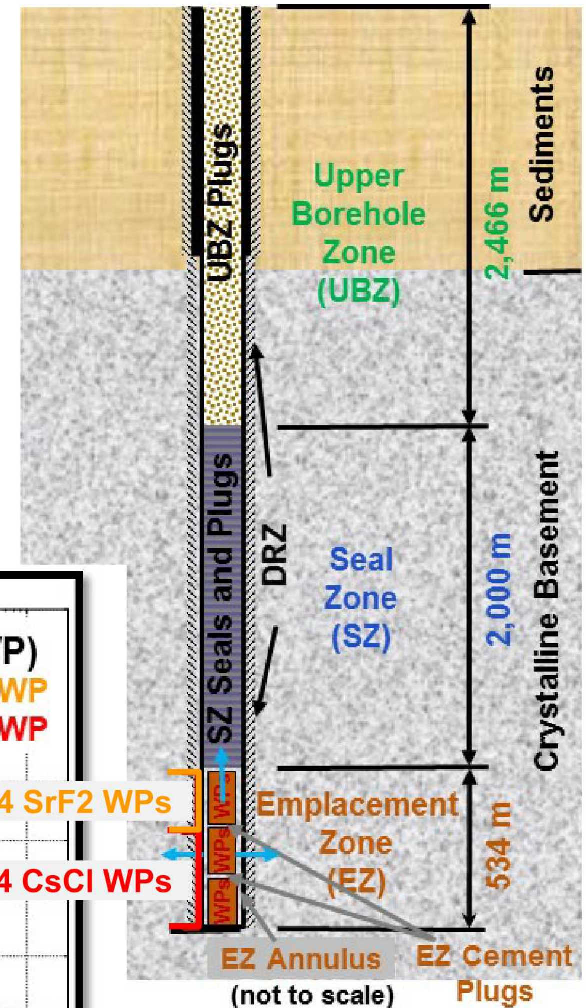
DBD PCSA – Wireline Emplacement Event Tree

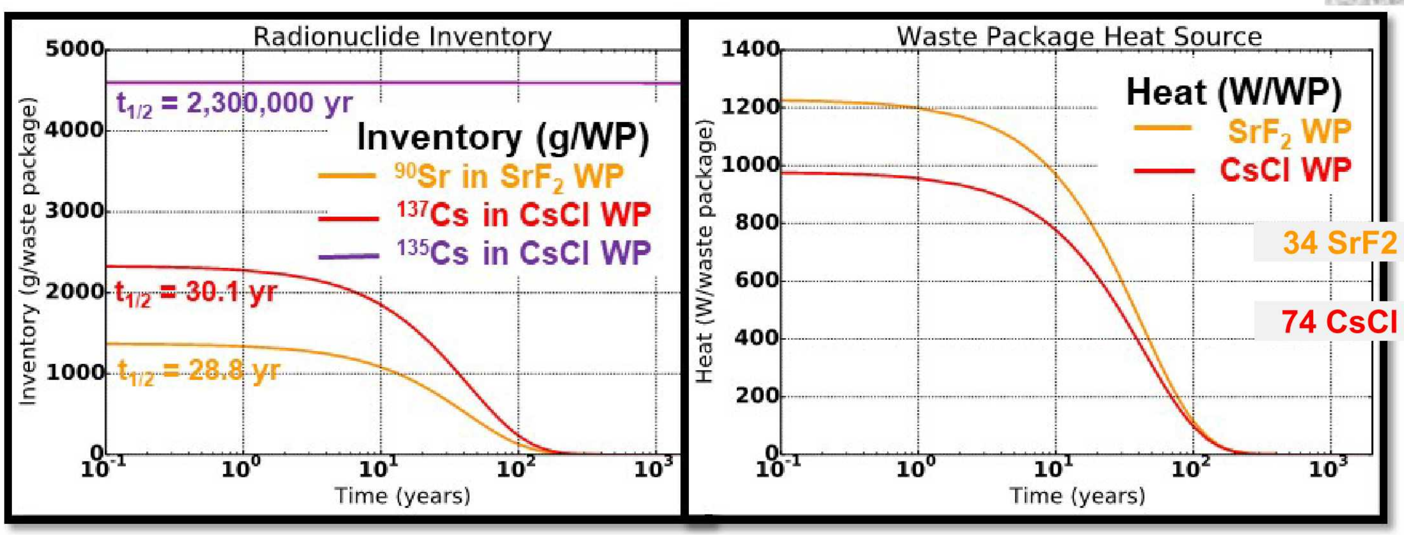
Freeze et al. (2016, Section 5.1), SNL (2016)



Post-Closure PA – Nominal Scenario

- Radionuclide Inventory (SNL 2014; Freeze et al. 2016)
  - Time 0 = Year 2050
  - 1335 CsCl capsules @ ~18 per WP = 74 Cs WPs
    - Inventory = ^{135}Cs, ^{137}Cs, ^{137m}Ba
    - Thermal output (avg.) ~ 972 W / WP (in 2050)
  - 601 SrF_2 capsules @ ~18 per WP = 34 Sr WPs
    - Inventory = ^{90}Sr, ^{90}Y
    - Thermal output (avg.) ~ 1242 W / WP (in 2050)
    - 2050 Inventory = ^{90}Sr, ^{90}Y

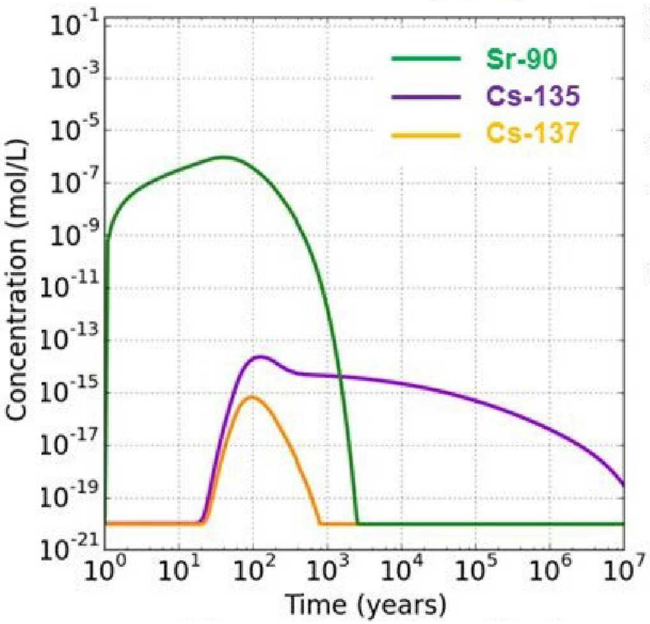




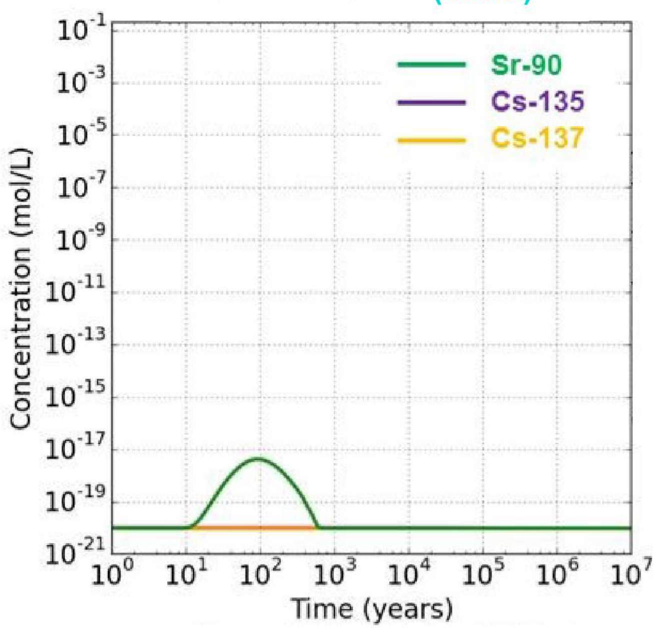
Nominal Scenario Deterministic Results – Dissolved Concentrations (mol/L)

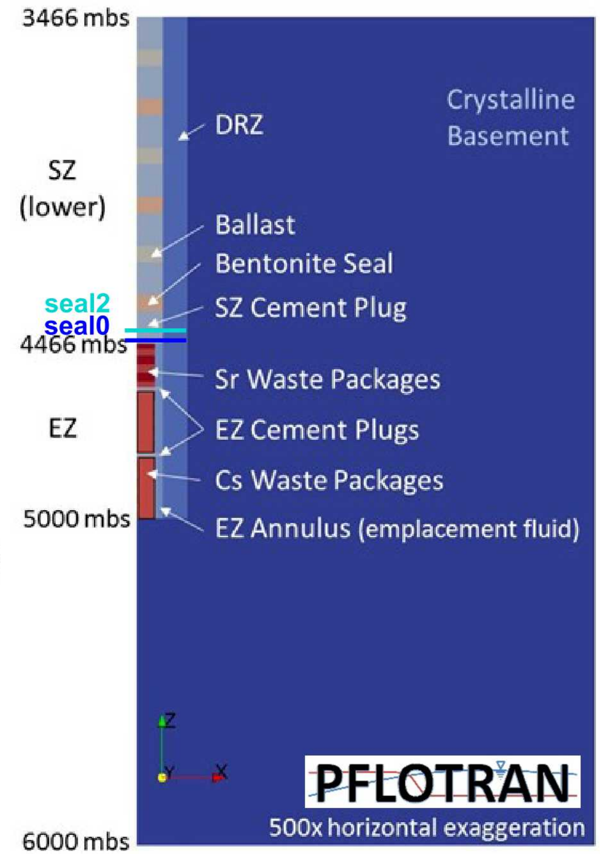
- Concentrations in SZ cement plug at 2 elevations
- Concentrations in DRZ at same elevations are similar

In SZ Cement Plug
at z=4463.4 m (seal0)



In SZ Cement Plug
at z=4438.4 m (seal2)

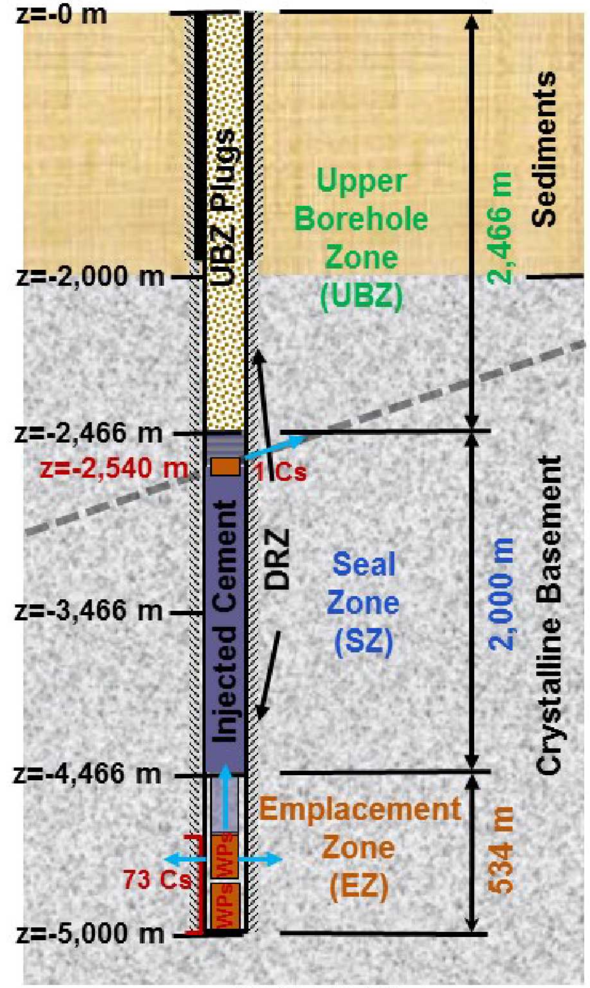




from Freeze et al. (2016), Figure 5-6

DBD Post-Closure PA – Disturbed Scenario

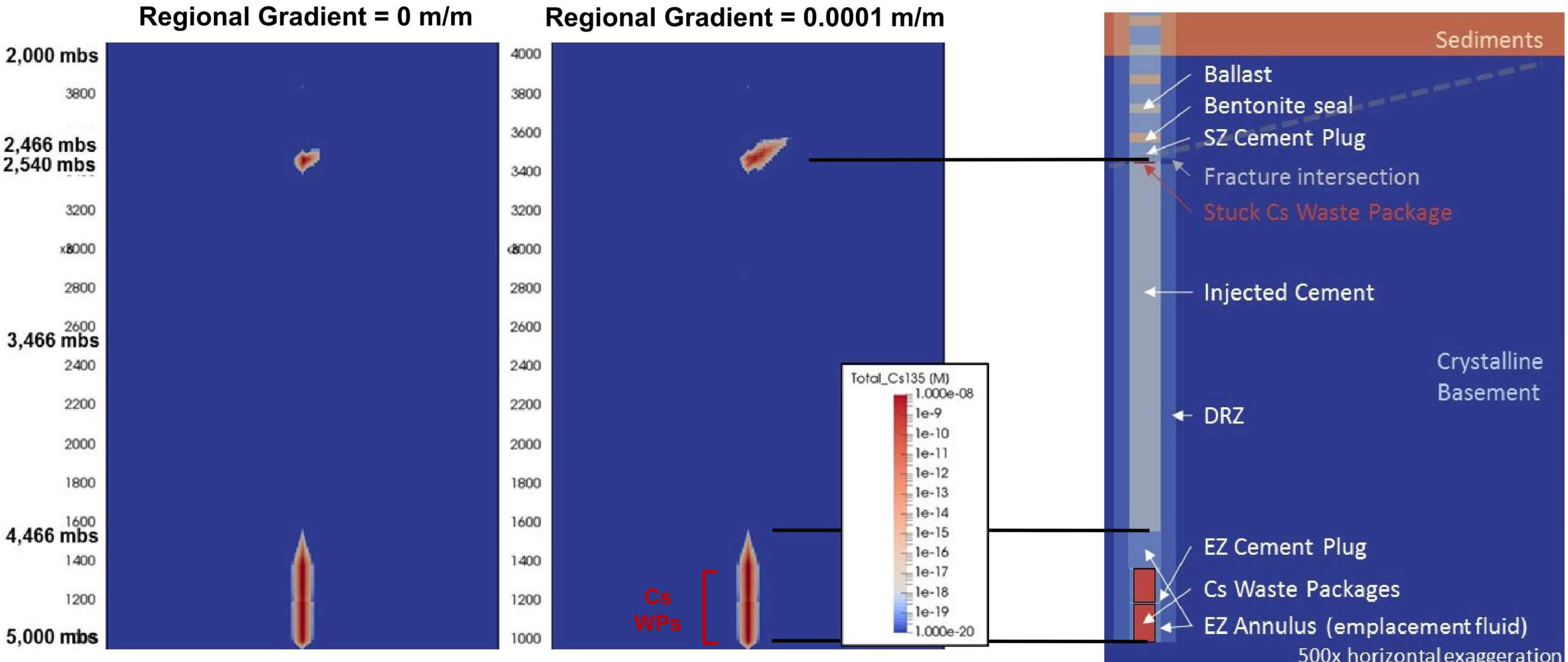
- Post-Closure Release Pathways
  - Undisturbed pathways from nominal scenario
  - WP (74^{th} Cs) stuck in borehole-intersecting fracture
    - fracture: $k = 10^{-14}$ m^2, $D_e = 1 \times 10^{-12}$ m^2/s
    - cement injected below stuck package
    - SZ and UBZ sealed above stuck package
  - Regional flow gradient in crystalline basement
    - case 1 = 0 m/m (same as nominal scenario)
    - case 2 = 0.0001 m/m
  - Other disturbed scenarios (not yet examined)
    - Seismic, igneous, human intrusion



(not to scale)

Disturbed Scenario Deterministic Results – ^{135}Cs Dissolved Concentration (mol/L)

- Concentration of ^{135}Cs at 10,000,000 years
  - Advection of ^{135}Cs up fracture (~200 m) due to regional gradient
  - ^{135}Cs still remains well below sedimentary overburden



from Freeze et al. (2017), Fig. 9

PFLOTRAN

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