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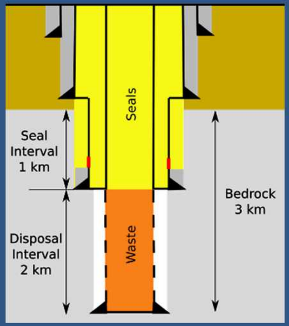

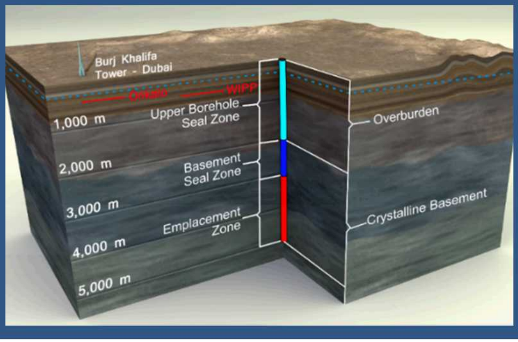

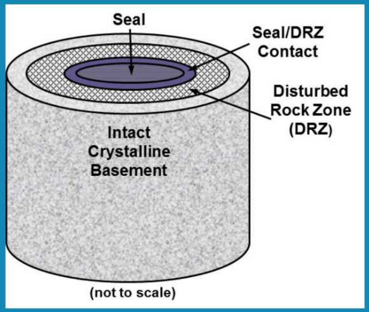

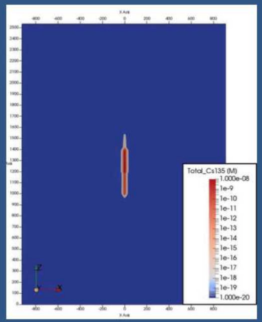

Performance Assessment (PA) and Safety Case Overview for Borehole Disposal of Radioactive Waste

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Outline

- Safety Case Overview
  - Post-Closure Performance Assessment (PA)
- Sandia History of PA Methodology Development and Application
- Borehole Disposal
  - Concepts / Options
  - Safety Case and PA

Safety Case Overview

- Safety Case
  - An **integration of arguments and evidence** that describe, quantify and substantiate the **safety of the geological disposal facility** and the **associated level of confidence** (NEA 2012, Section 3.1)
    - See also IAEA (2012), NEA (2013), Freeze et al. (2016)
- License Application (LA)
  - Formal documentation of a safety case for a specific facility relative to specific regulations
    - submitted to a regulatory agency to initiate a phase of repository development (e.g., construction, waste receipt, closure)
    - LAs have been submitted in Finland, Sweden, and U.S. (WIPP and Yucca Mountain)

Safety Assessment Overview

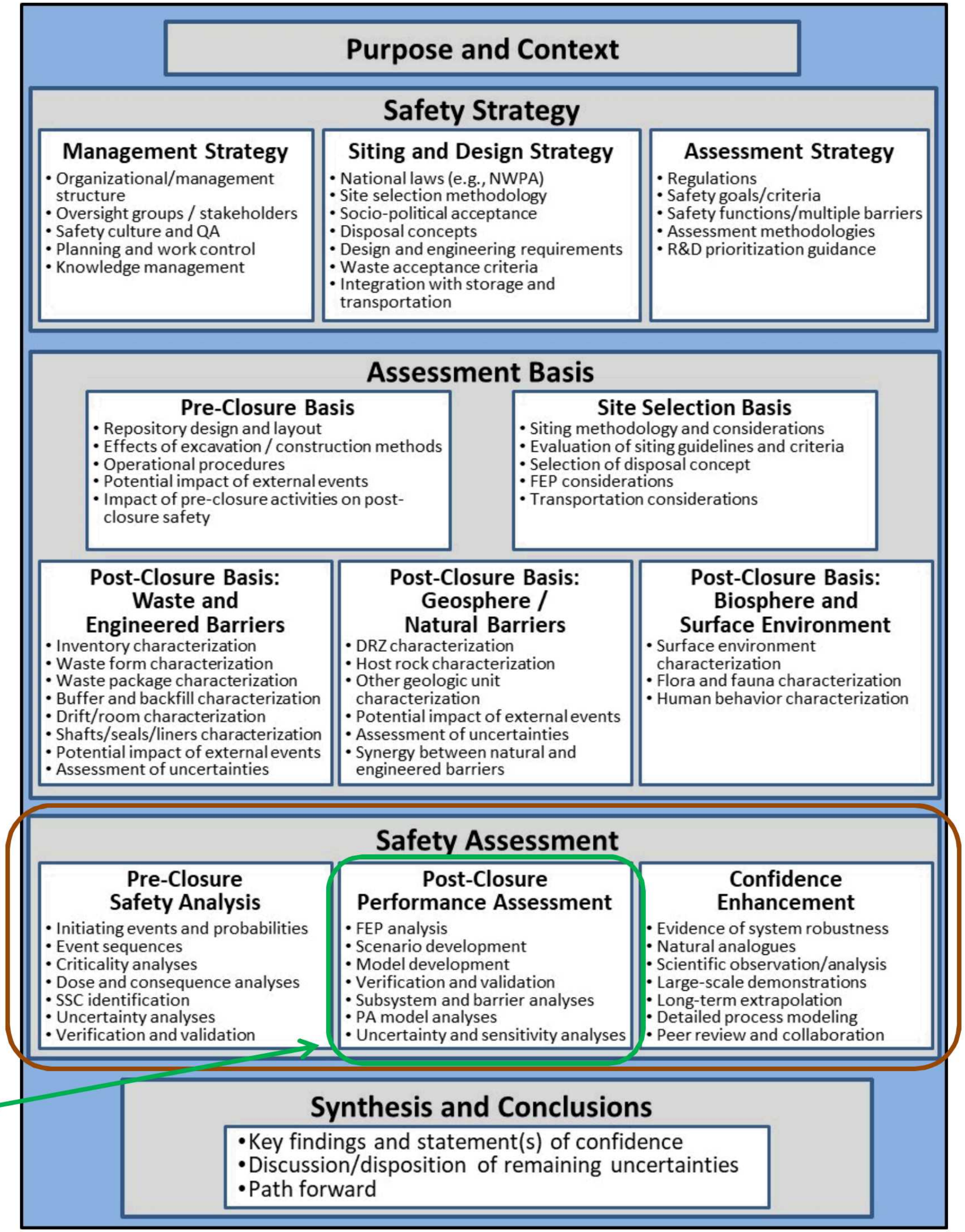
- Safety Assessment
  - An **iterative** set of assessments for evaluating the performance of a repository system and its potential impact that aims to **provide reasonable assurance** that the repository system will achieve sufficient safety and meet the relevant requirements for the protection of humans and the environment over a prolonged period (NEA 2013, Section 5.1)
  - Within a safety case, safety assessment includes:
    - Pre-Closure Safety Analysis
    - Post-Closure Performance Assessment
    - Confidence Enhancement

Safety Assessment Overview

- Pre-Closure Safety Analysis (PCSA)
  - **Quantitative evaluation** of the potential natural and operational hazards for the pre-closure period, which includes initiating events and resulting event sequences and potential radiological exposures to workers and the public (10 CFR 63.102(f), MacKinnon et al. 2012, Freeze et al. 2016)
- Post-Closure Performance Assessment (PA)
  - **Quantitative evaluation** of long-term repository performance for all potential system evolutions (i.e., scenarios), analysis of the **associated uncertainties**, and comparison with the relevant safety standards (MacKinnon et al. 2012; NEA 2013, Section 5)
- Confidence Enhancement
  - **Qualitative evidence and arguments** (e.g., natural analogues) related to the intrinsic robustness of the system that provides additional support for evaluations of pre-closure and post-closure safety of the repository system (Mackinnon et al. 2012, Section 3.1; NEA 2013, Section 2)

Safety Case

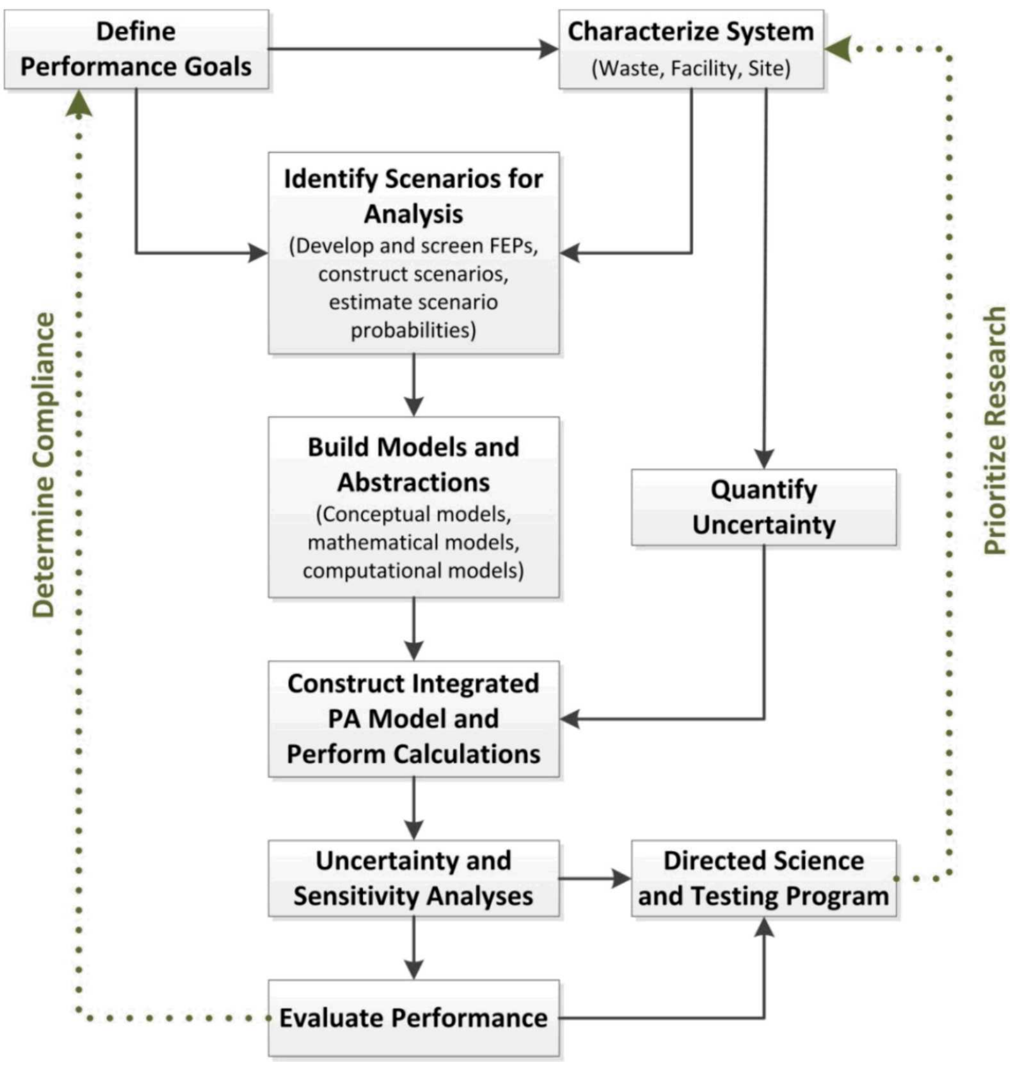
Freeze et al. (2019, Figure 1-2) modified from NEA (2013, Figure 2.1)



Safety Assessment

Post-Closure PA

Sandia PA Methodology



Source: Meacham et al. (2011, Figure 2)

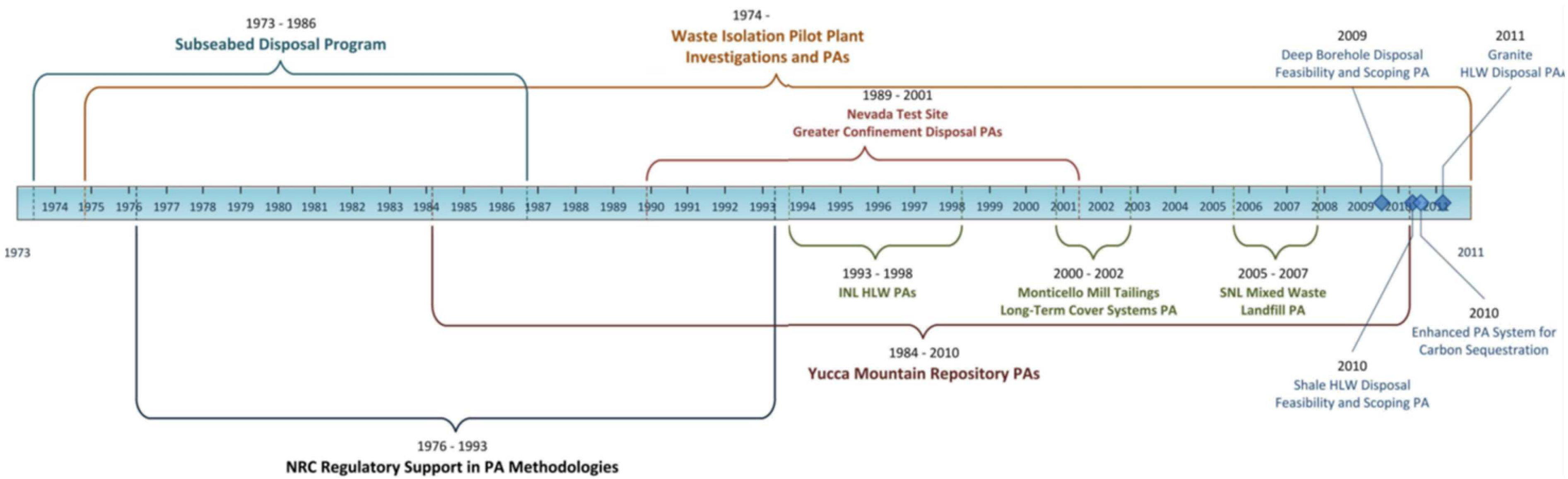
History of Sandia PA Methodology

Meacham et al. (2011)

- Since the early 1970s, Sandia National Laboratories (Sandia) has developed and applied a PA methodology, based on probabilistic risk assessment, that has informed key decisions concerning radioactive waste management
- SNL PA methodology development has:
  - helped to advance the science of probabilistic analysis
  - gained wide acceptance in the international community
  - continues to extend PA capabilities through utilization of high-performance computing (HPC)
- SNL PA methodology application has been used to:
  - evaluate disposal designs and sites in a variety of geologic media
  - inform development of regulatory requirements
  - identify, prioritize, and guide research aimed at reducing uncertainties for objective estimations of risk
  - support safety assessments

History of Sandia PA Methodology

- 1973 – 2011



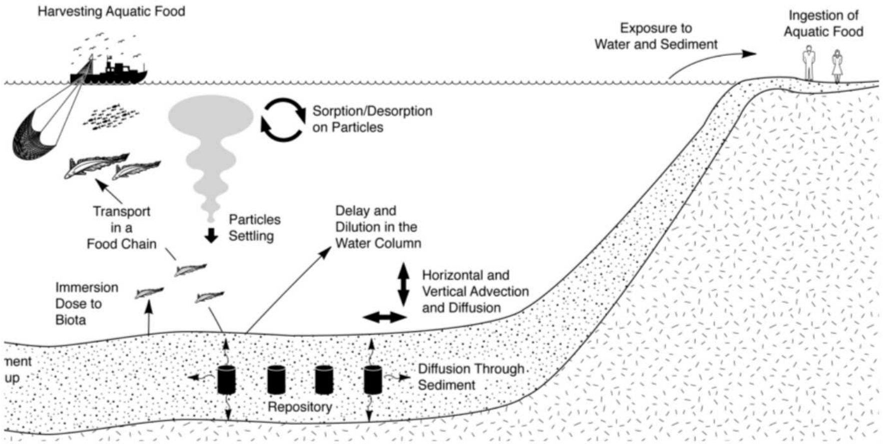
Source: Meacham et al. (2011, Figure 1)

- 2012 – Present
  - Development of HPC applications
    - Nuclear Energy Advanced Modeling and Simulation (NEAMS)
    - Geologic Disposal Safety Assessment (GDSA) Framework – PFLOTRAN / DAKOTA
  - PAs for generic mined repositories in various geologic media (salt, crystalline, argillite)
  - PAs for deep borehole disposal

History of Sandia PA Methodology: Early Development (1970s and 1980s)

Meacham et al. (2011)

- Subseabed Disposal Project (SDP) (1973-1986)
  - PAs for feasibility of HLW disposal

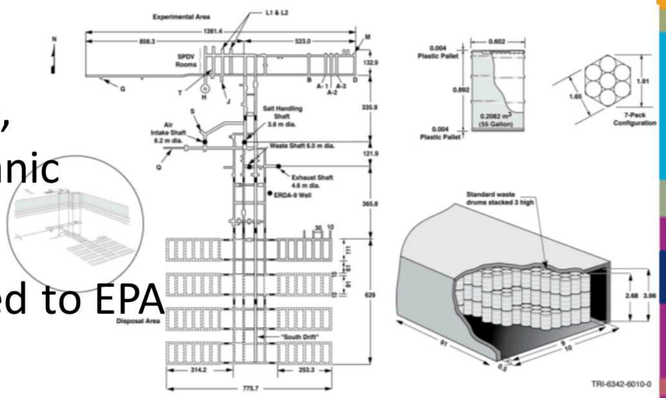


- Reactor Safety Studies (1970s, 1980s)
- NRC PA methodology development and demonstration (1976-1991)
  - deep geologic disposal of SNF and HLW (salt, basalt, tuff)
  - near-surface LLW disposal
- Technical support to NRC and EPA in the development of radioactive waste disposal health standards and regulations (1976-1987)
  - NRC: 10 CFR 60 and 10 CFR 63
  - EPA: 40 CFR 191 and 40 CFR 197

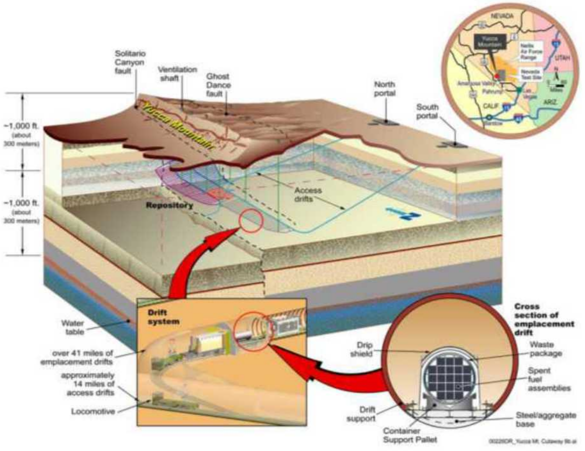
History of Sandia PA Methodology: Major Program PAs Supporting License Application

Meacham et al. (2011)

- Waste Isolation Pilot Plant (WIPP) (1974 – present)
  - 1975: Sandia selected as Lead Lab for site characterization, conceptual design, and PA for disposal of defense transuranic (TRU) waste
  - 1996: Compliance Certification Application (CCA) submitted to EPA
    - CAMCON (BRAGFLO, SECO2D, other codes) for PA
  - 2004, 2009, 2014, 2019 (in process): Recertification Applications



- Yucca Mountain Project (YMP) (1984 – 2010)
  - 1984: Iterative FEP and scenario analysis and total system PA (TSPA) for disposal of SNF and HLW
  - 2006: Sandia selected as Lead Lab for scientific programs
  - 2008: License Application (LA) submitted to NRC
    - GoldSim code for PA



- Key Methodology Developments/Refinements
  - Multiple, iterative PAs
  - Feature, event, and process (FEP) and scenario analysis
  - Probabilistic approach with uncertainty quantification (e.g., LHS)

History of Sandia PA Methodology: Other PA Applications (1990s and 2000s)

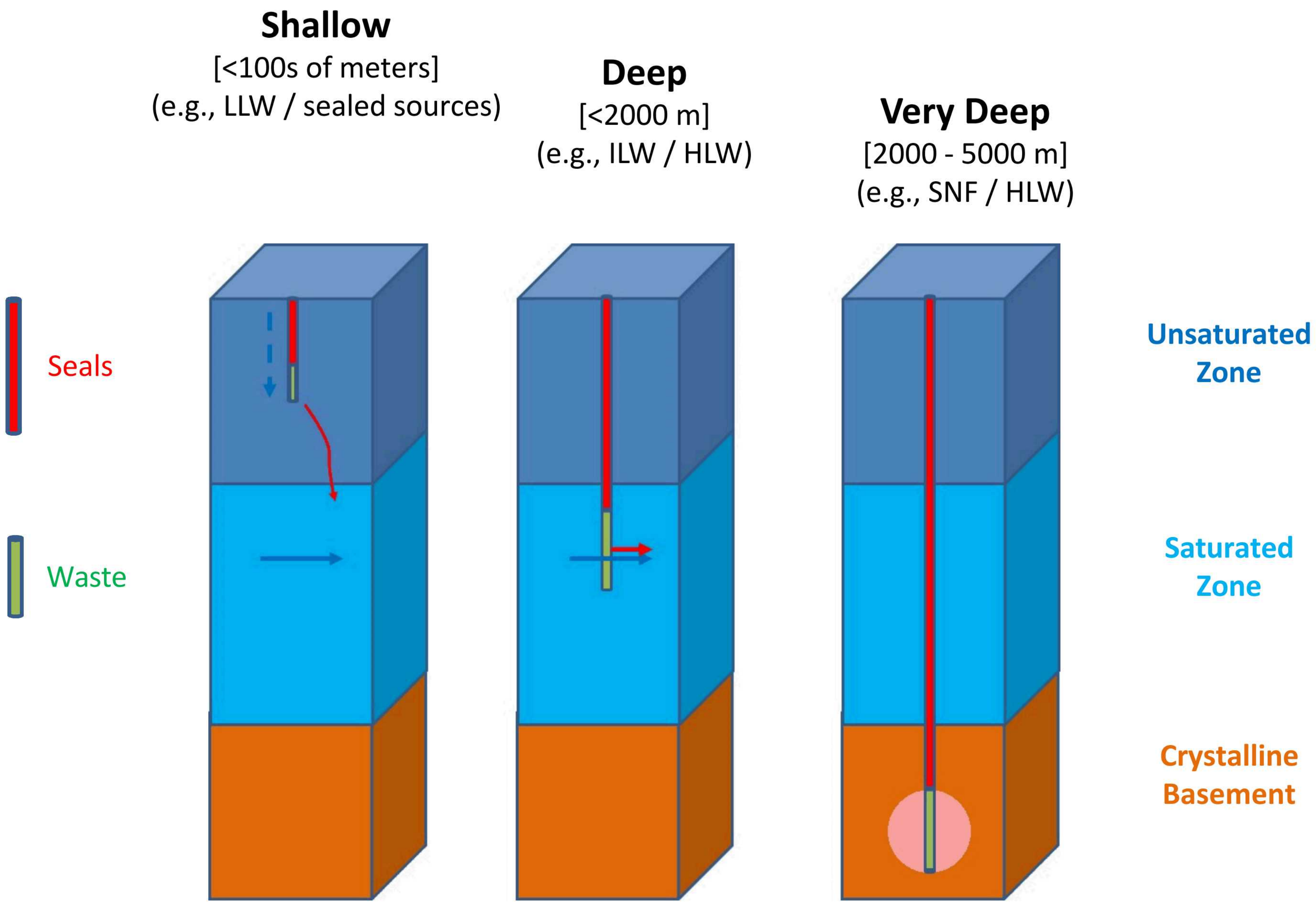
Meacham et al. (2011)

- Greater Confinement Disposal (GCD) at Nevada National Security Site (1989-2001)
  - Borehole (40-m deep, 3-m diameter) PAs for TRU waste, LLW, and hazardous waste
- Disposal Demonstrations for DOE-Owned HLW and SNF stored at Idaho National Laboratory (INL) (1993-1998)
  - Generic repository PAs (bedded salt, fractured granite, unsaturated tuff)
- PA for Near-Surface Disposal of Mill Tailings at Monticello, Utah (2000-2002)
- PA for the Sandia Mixed Waste Landfill (2005-2007)
- Support for international radioactive waste management efforts (1998-present)
  - Taiwan: PA for LLW disposal (near surface and deep geologic options)
  - Egypt: PA for siting boreholes for disposal of sealed sources
  - Malaysia: PA review for borehole disposal of sealed sources
- Development of an enhanced PA system for carbon sequestration and storage systems

History of Sandia PA Methodology: Recent PA Developments and Applications (2010s)

- Development of HPC Applications
  - Nuclear Energy Advanced Modeling and Simulation (NEAMS) (Freeze et al. 2011)
  - GDSA Framework – PFLOTRAN / DAKOTA (Mariner et al. 2018)
- PAs for Generic Mined Geologic Repositories for SNF and HLW
  - Salt (Freeze et al. 2013b; Sevougian et al. 2014; Mariner et al. 2015)
  - Crystalline (Mariner et al. 2016)
  - Argillite (Mariner et al. 2017)
- PAs and Safety Case for Feasibility and Safety of Deep Borehole Disposal
  - SNF (Brady et al. 2009; Arnold et al. 2013; Freeze et al. 2013a)
  - HLW (Freeze et al 2016, Freeze et al. 2019)

Borehole Disposal Concepts



Borehole Disposal Designs

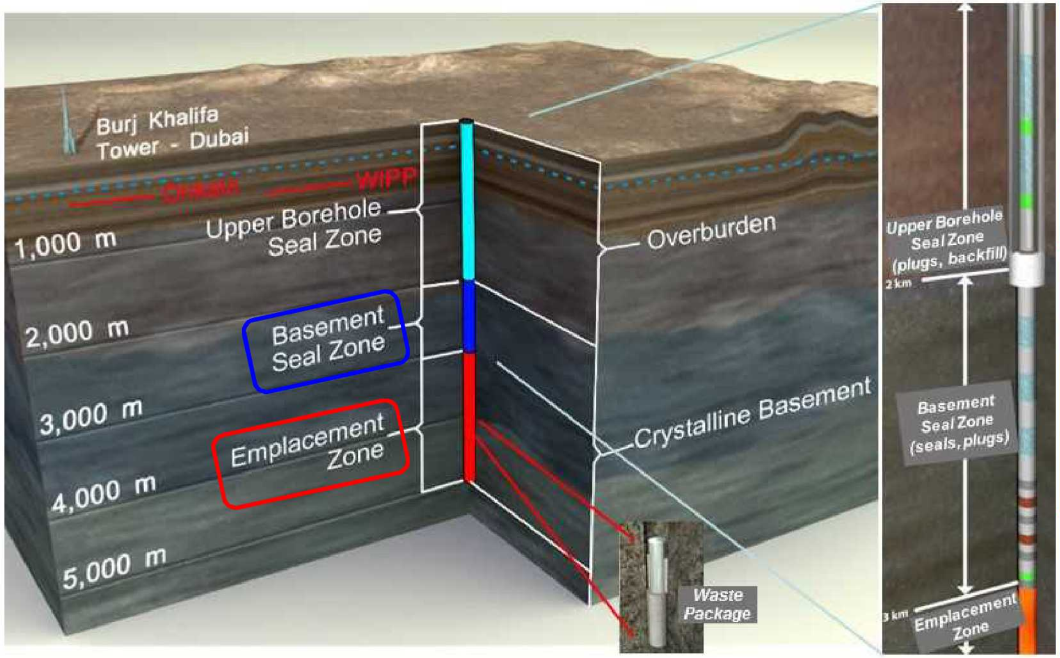
- Beswick et al. (2014) propose the following design:

Depth (m)	Hole Diameter (in.)	Casing Diameter (in.)
0-500	60	54
500-1000	48	40
1500-2500	36	30 (28.5 i.d.)
2500-5000	24 to 26	20

"Very Deep" Borehole Disposal of SNF/HLW

- 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

Very Deep Concept – Safety and Feasibility

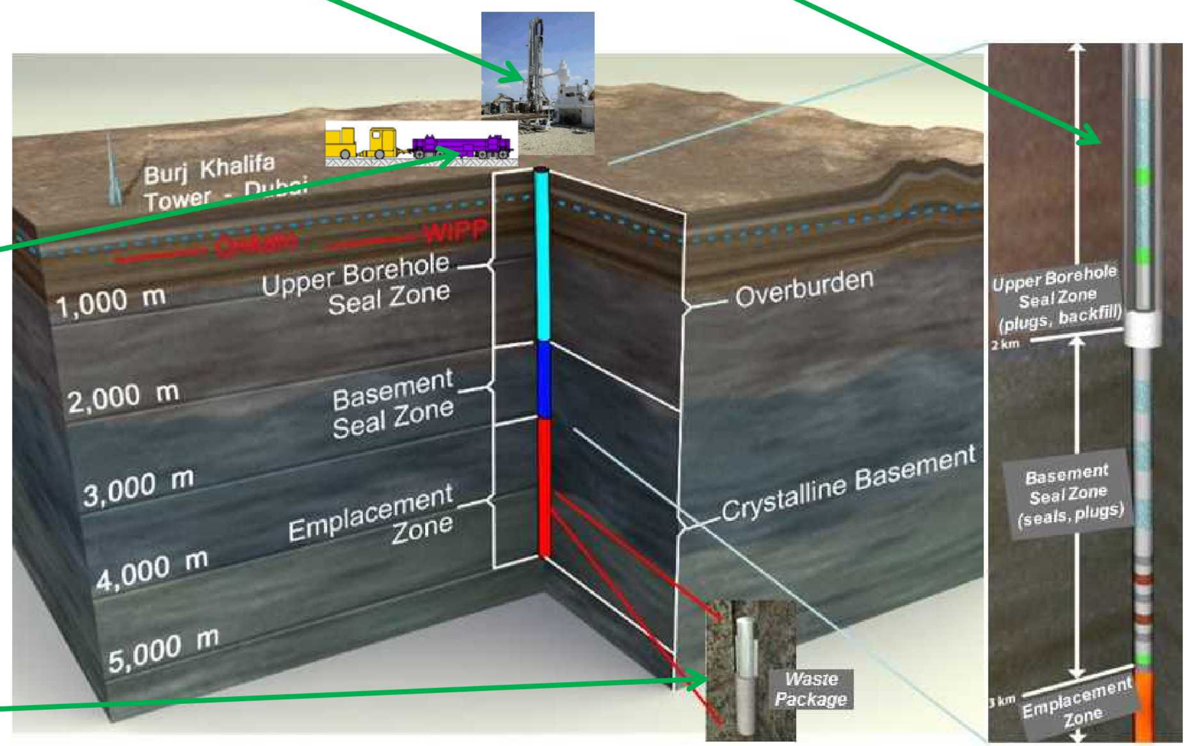
(Pre-Closure Engineering and Operations)

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 Deep Concept – Safety and Feasibility

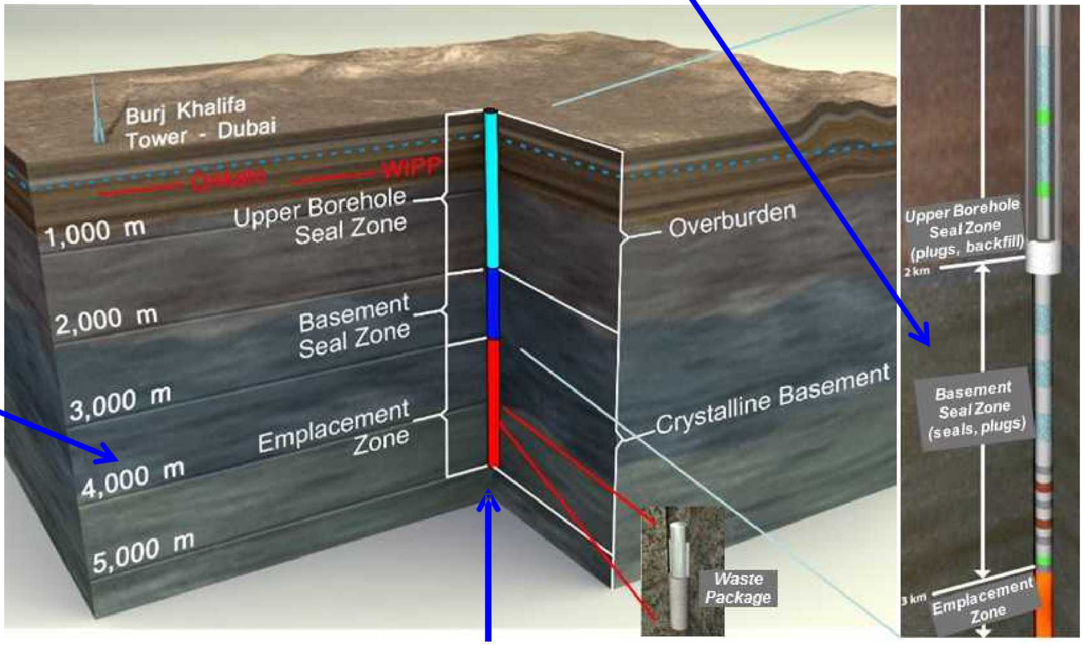
(Post-Closure Hydrogeochemical Waste Isolation)

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

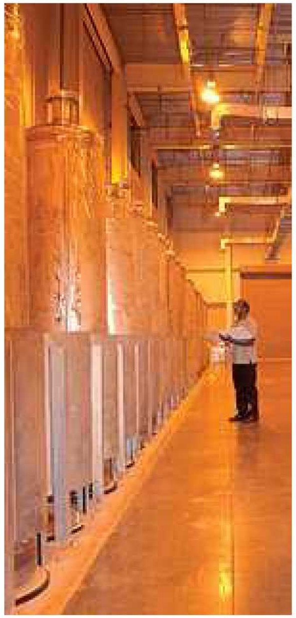


Waste is deep in basement rock

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

Disposal of Vitrified HLW

- Existing vitrified HLW in Australia may be larger diameter than the reference “very deep” design, however:
  - The very deep design could be modified (slightly larger diameter, somewhat shallower depth)
    - Rigali et al. (2016) examines boreholes that can accommodate waste packages with 22-28 in diameters
  - “Deep” and “Shallow” concepts may also be feasible depending on geology and engineered barriers



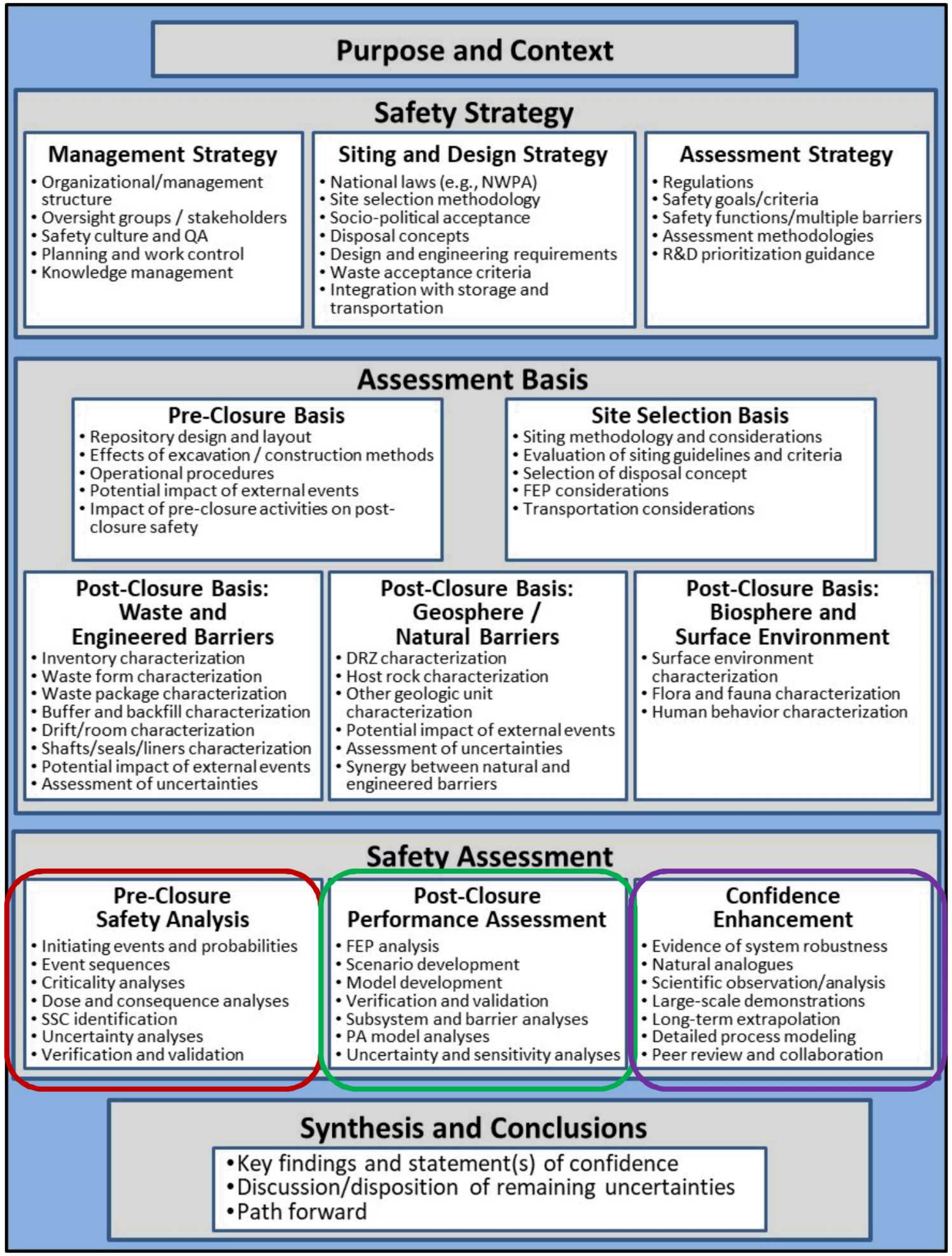
Very Deep Borehole Disposal (VDBD) Safety Case

- **Adapted from NEA (2013) as documented in Freeze et al. (2016) and Freeze et al. (2019)**
- **Reference case for very deep disposal of HLW (Cs/Sr capsules)**

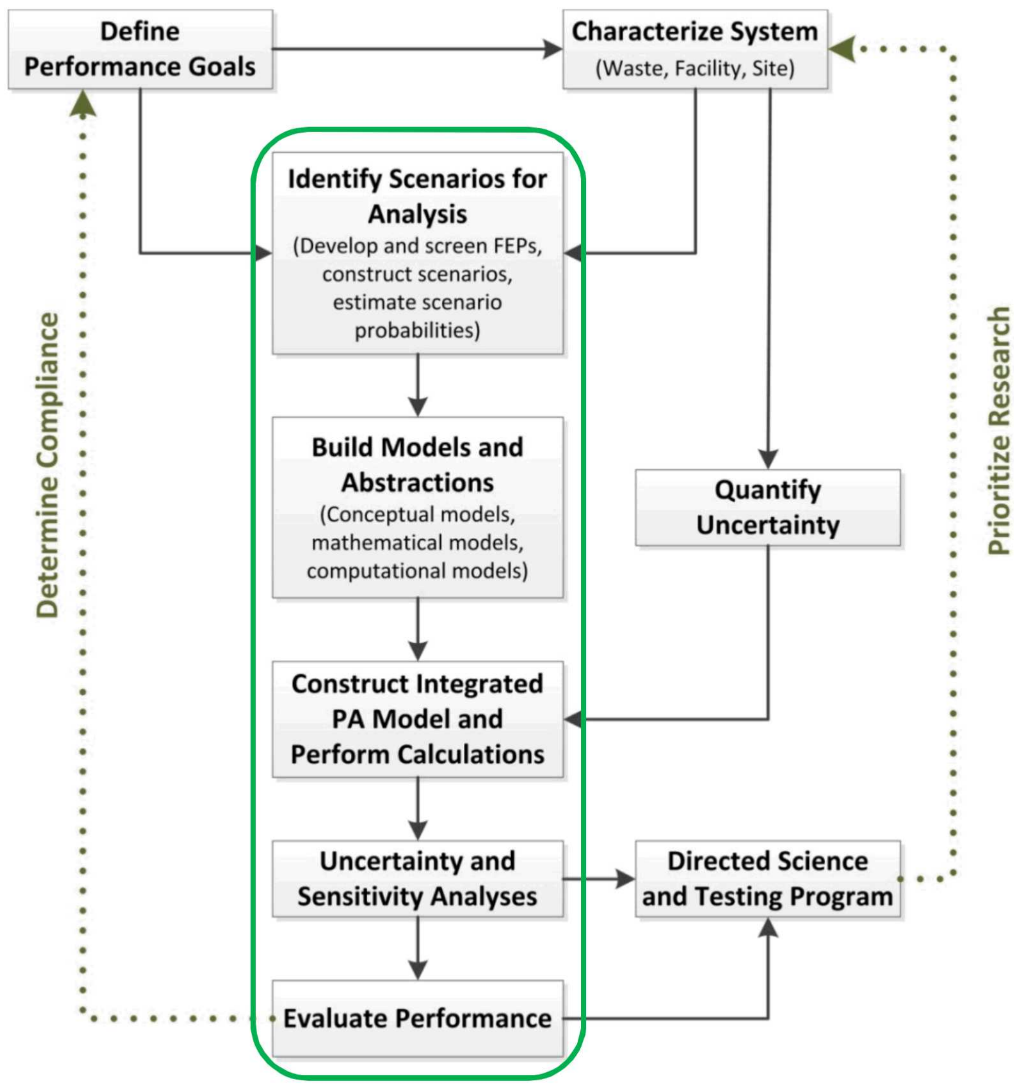
Pre-Closure Safety Analyses (PCSA)
- Structures, Systems, Components (SSCs)
- PCSA Model
    - Activity Sequences

Post-Closure Performance Assessment (PA)
- Features, Events, and Processes (FEPs)
- Scenario Development
- PA Model [PFLOTRAN]
    - Undisturbed (Nominal) Scenario
    - Disturbed (Stuck Package) Scenario

Confidence Enhancement
- Natural Analogs
- Independent Evidence



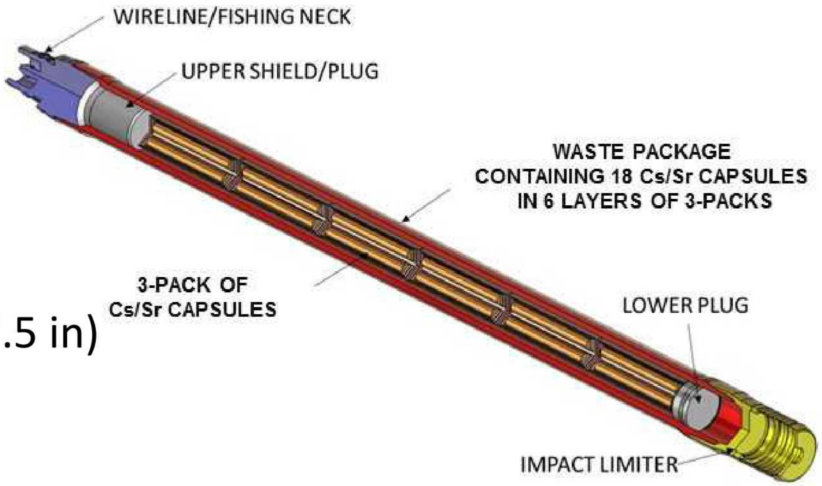
Sandia PA Methodology



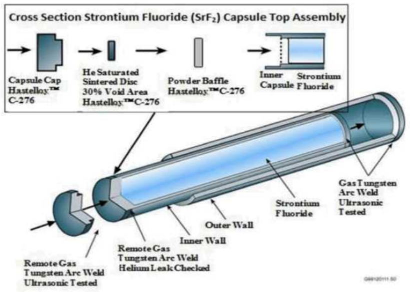
Source: Meacham et al. (2011, Figure 2)

VDBD Safety Case Reference Design (HLW)

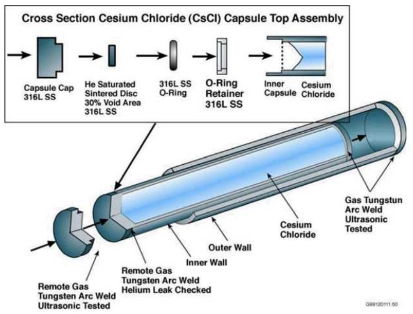
- Radionuclide Inventory (SNL 2014, Freeze et al. 2016)
  - 1936 Cs and Sr capsules aged to 2050
    - Decay heat for ~ 100 yrs
  - 108 waste packages (WPs)
    - 18 capsules per WP (6 layers of "3-packs")
    - WP length = 4.76 m / WP diam. = 0.19 m (7.5 in)



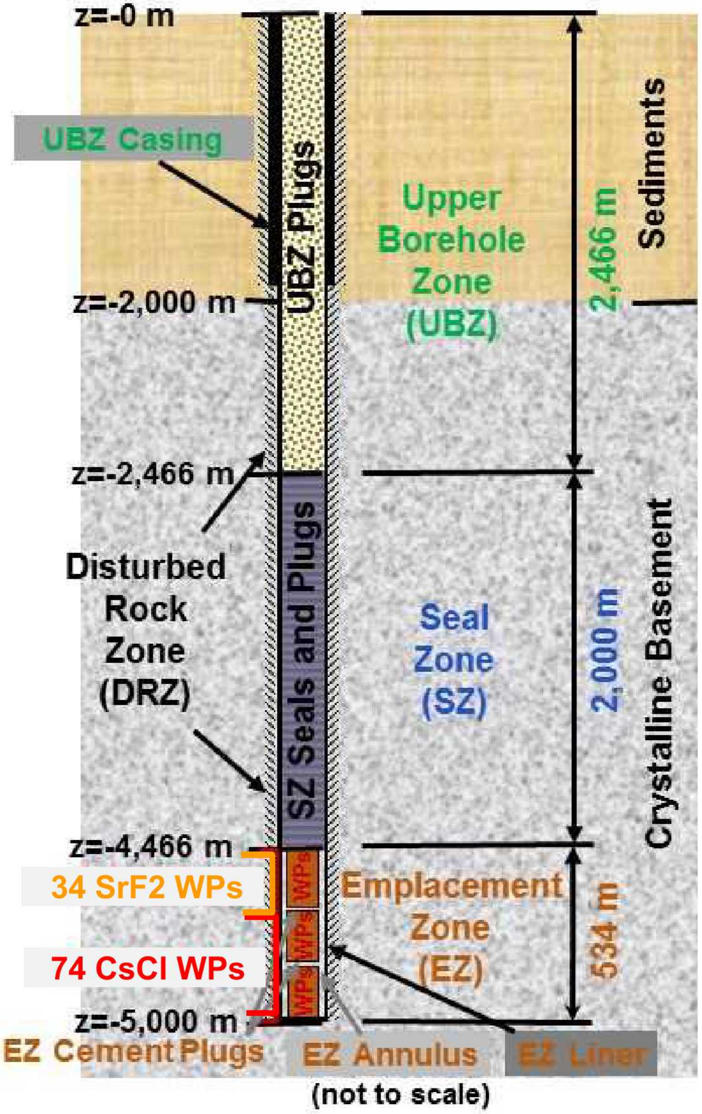
  - 601 SrF_2 capsules @ ~18 per WP = 34 Sr WPs
    - Inventory = ^{90}Sr ($t_{1/2}$ = 28.8 yr)



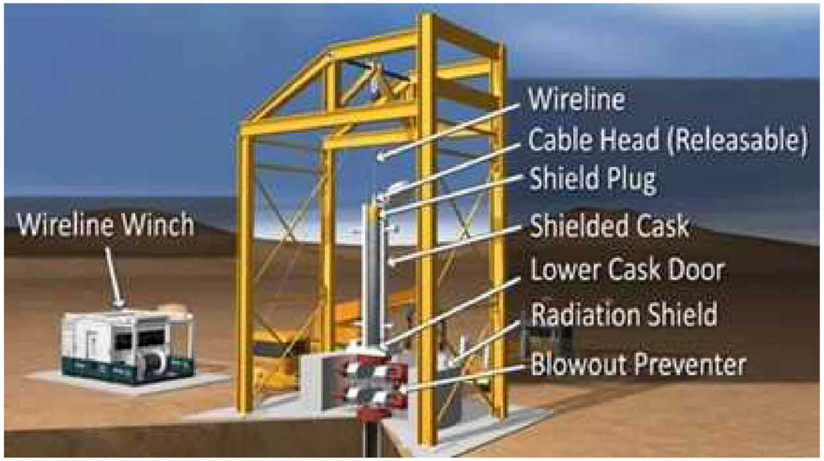
  - 1335 CsCl capsules @ ~18 per WP = 74 Cs WPs
    - Inventory = ^{137}Cs ($t_{1/2}$ = 30.1 yr), ^{135}Cs ($t_{1/2}$ = 2,300,000 yr)



VDBD Safety Case Reference Design (HLW)

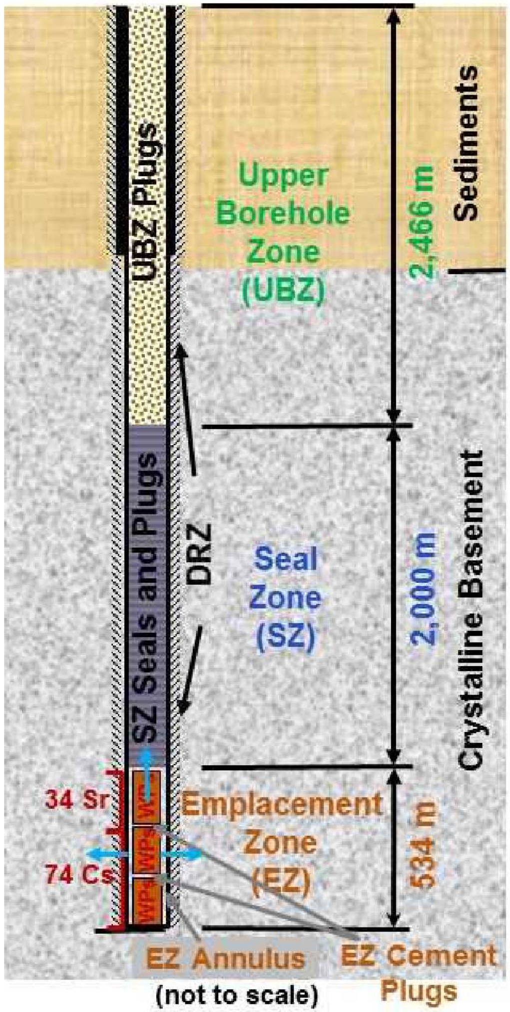


- All 108 WPs fit in a single borehole with a 534-m Emplacement Zone (EZ)
  - bottom-hole diameter of 12.25 in (31 cm)
- Seal Zone (SZ) consists of alternating bentonite and cement emplaced directly against borehole wall
- WPs are lowered, one at a time, on wireline inside a removable guidance casing



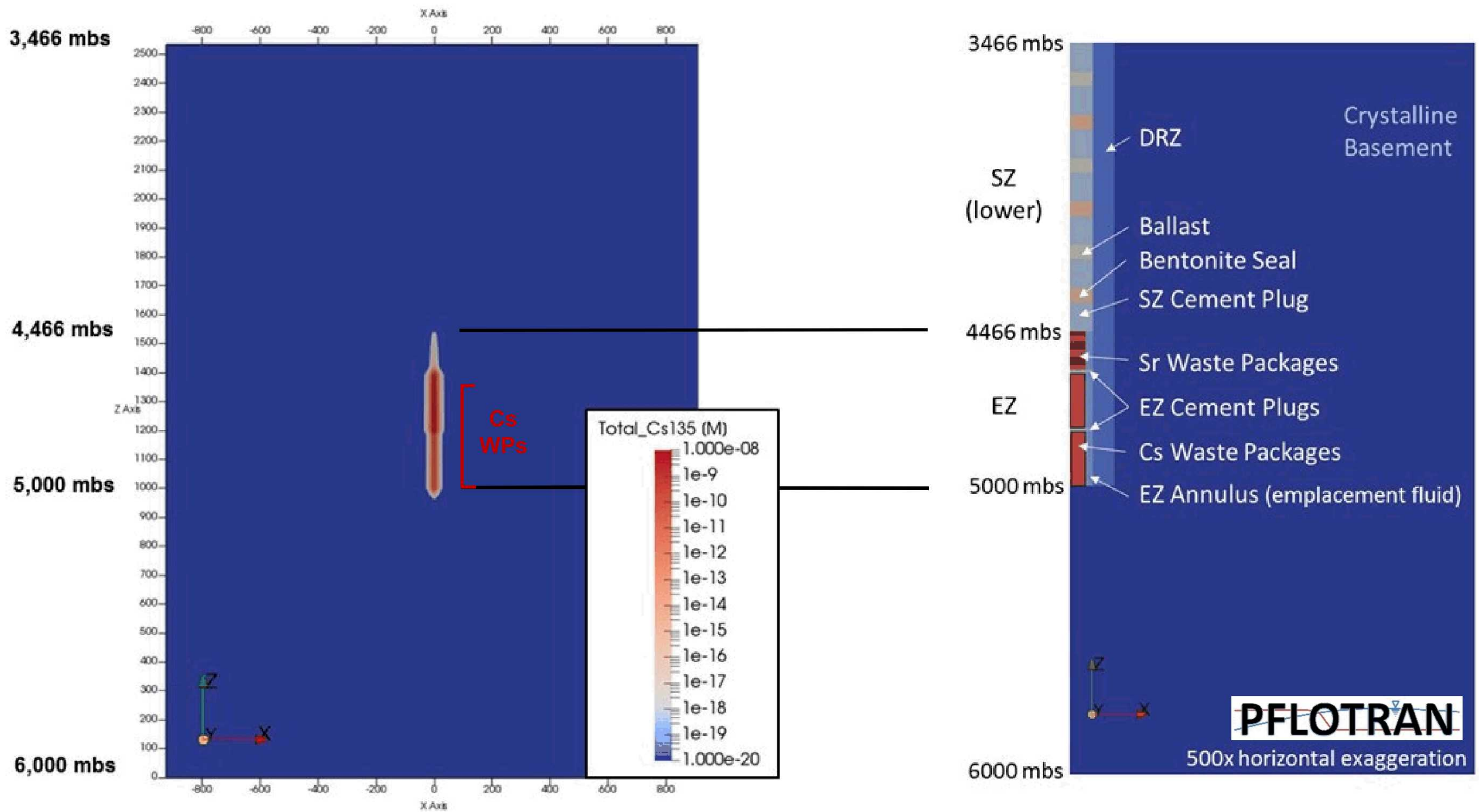
VDBD Post-Closure PA – Nominal Scenario

- 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 – ^{135}Cs Dissolved Concentration (mol/L)

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

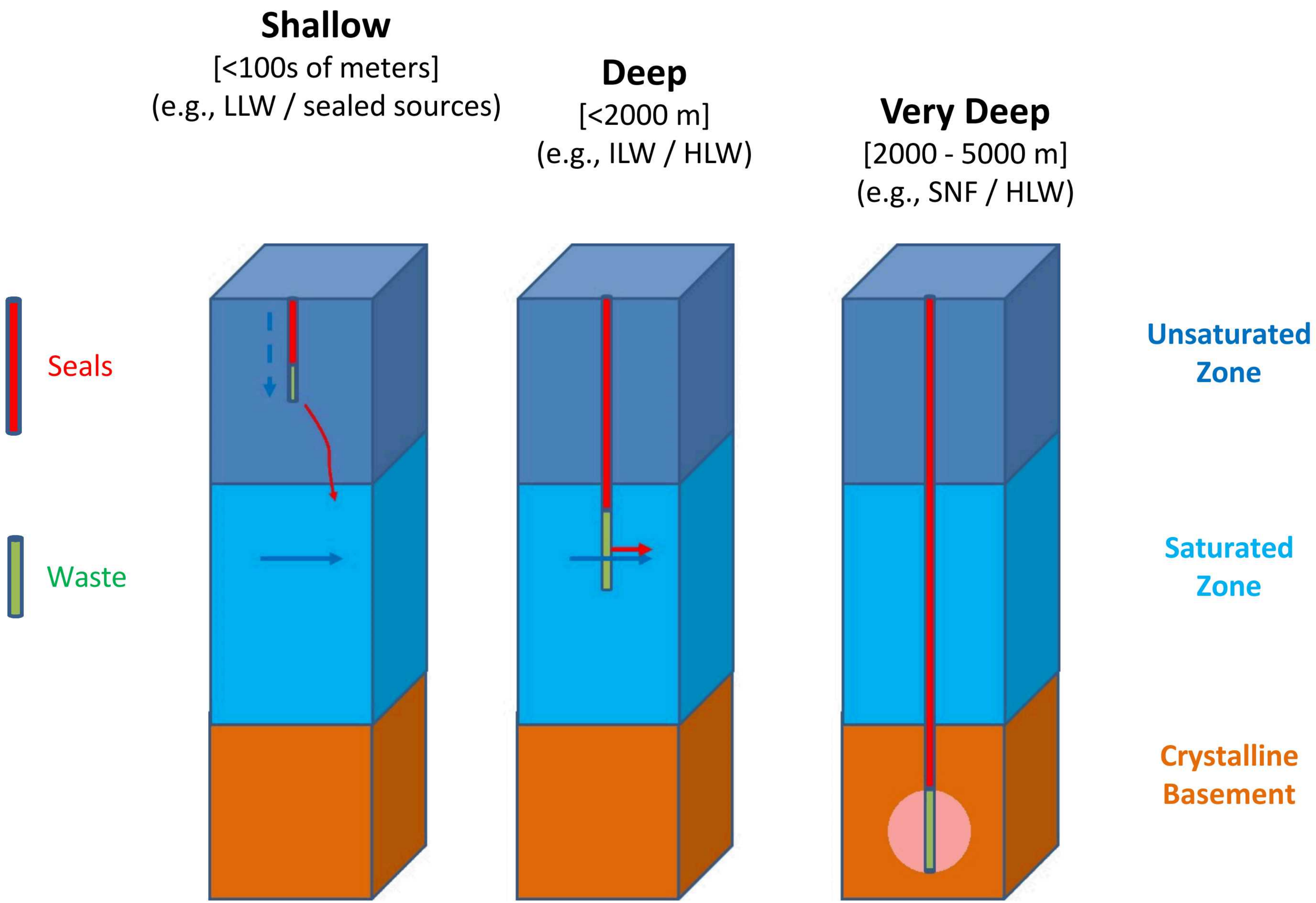


from Freeze et al. (2016), Figure 5-8

VDBD 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 of SNF
  - Arnold et al. (2013. App. A); Freeze et al. (2013)
- A field test could further enhance confidence in the DBD concept
  - Pre-closure operations (e.g., waste handling and emplacement system)
  - Downhole characterization to support post-closure analyses

Borehole Disposal Concepts



Borehole Disposal Safety Case Summary

- Very Deep Borehole Disposal (VDBD)
  - Relies predominately on the natural system for post-closure safety
    - **Waste Packages**: provides structural integrity for handling and emplacement, but no reliance on waste form or waste package to delay or limit radionuclide releases
    - **Radionuclide Releases**: slow diffusion from the emplacement zone into low permeability basement rock and up the borehole and annular DRZ
- Shallow and Deep Borehole Disposal (SBD and DBD)
  - Rely on both engineered and natural systems for post-closure safety
    - **Waste Packages**: provides structural integrity for handling and emplacement; reliance on waste form and waste package longevity to delay or limit releases
    - **Radionuclide Releases**: advection and diffusion from the emplacement zone to the subsurface hydrogeology
      - For waste emplaced below the water table (i.e., DBD), radionuclide releases will be directly to the subsurface hydrogeology, with transport in the direction of groundwater flow
      - For waste emplaced in the unsaturated zone (i.e., SBD), radionuclide releases will be downward to the underlying aquifer, and may be influenced by both infiltration at the surface and the distribution of water saturation above the water table

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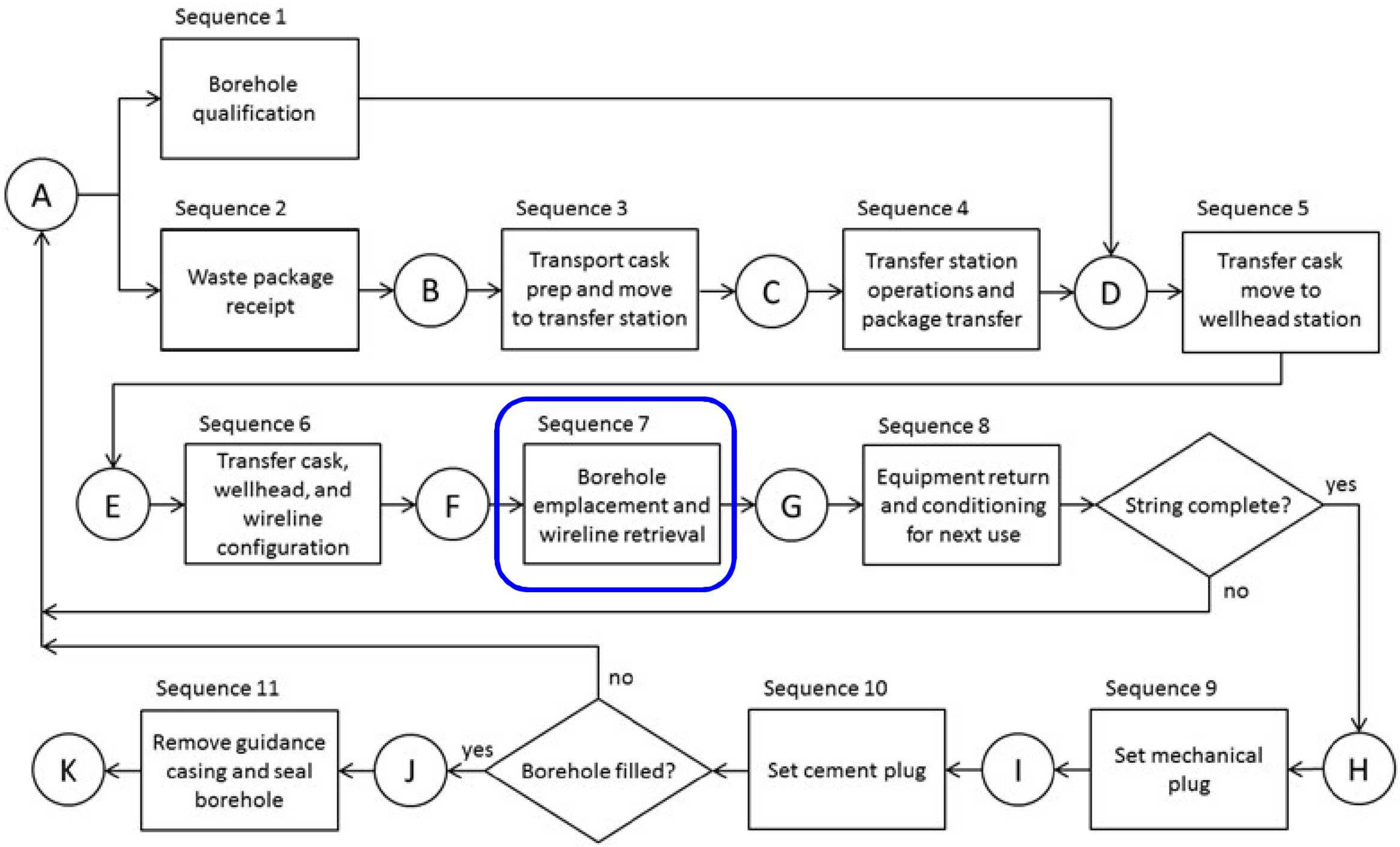
Backup Slides

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)