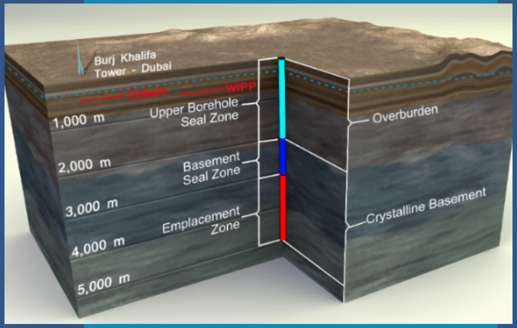
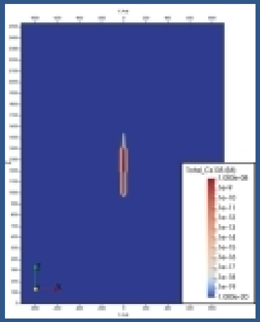
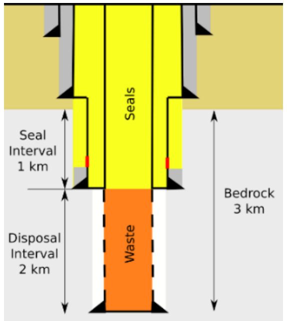
SAND2021-14056PE

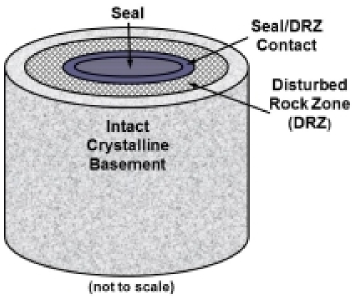
Sandia National Laboratories

Nuclear Waste Management and Deep Borehole Disposal R&D at Sandia National Laboratories







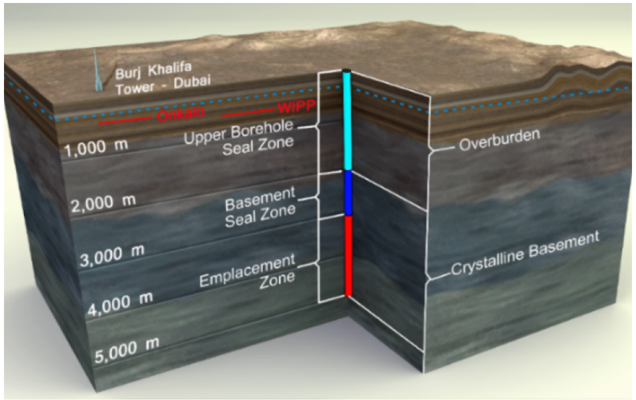


Geoff Freeze, Manager
Advanced Nuclear Fuel Cycle Technologies

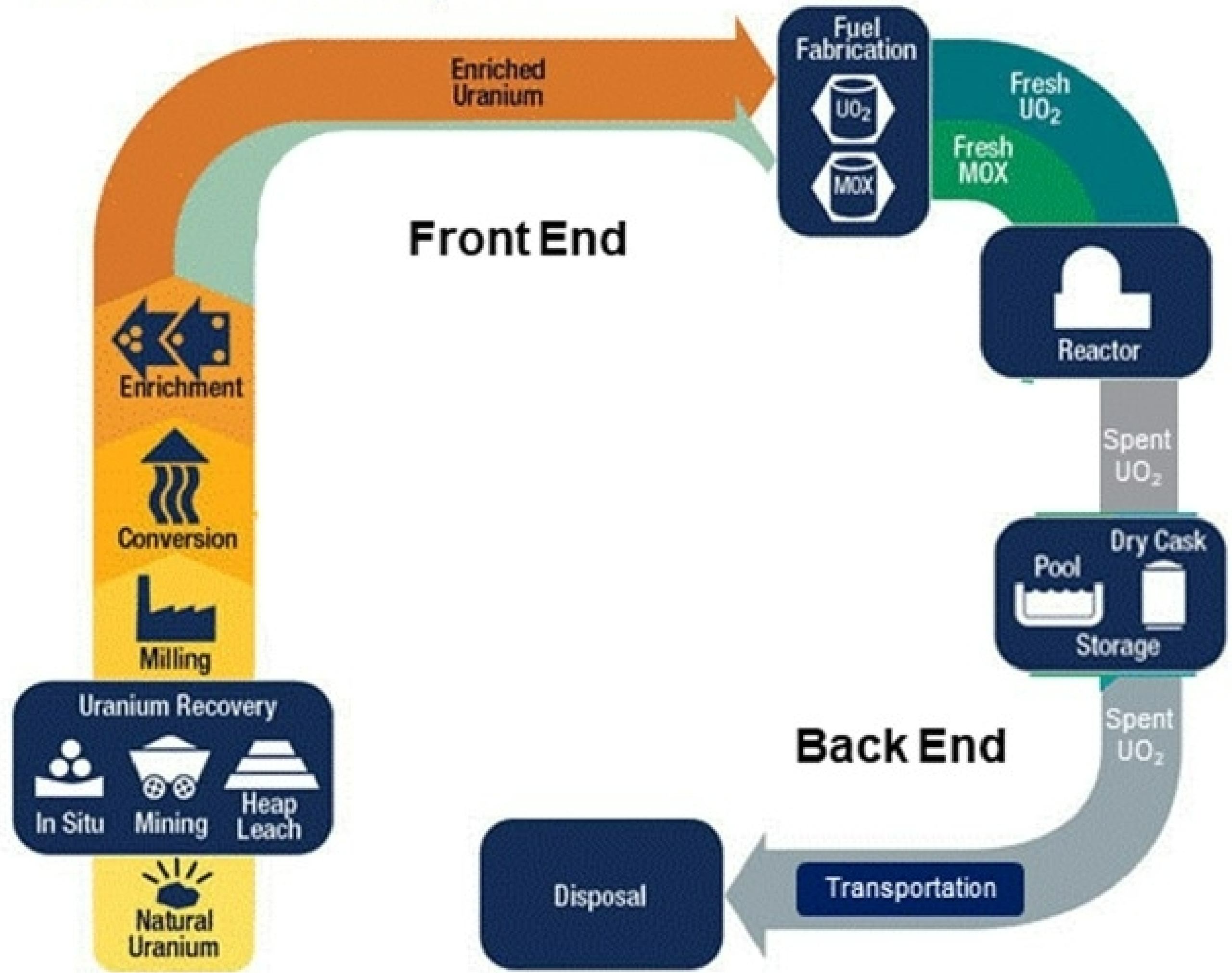
UNM INMM Chapter
University of New Mexico, Albuquerque, NM, November 5, 2021

Outline

- U.S. Nuclear Waste Management Overview
  - Nuclear Fuel Cycle
  - Chronology of Waste Management and Repository Program
    - Spent Nuclear Fuel (SNF)
    - High-Level Radioactive Waste (HLW)
  - Current State
- Geologic Disposal Options
  - Deep Mined Repository
  - Deep Borehole Disposal (DBD)
    - Concepts
    - Safety and Feasibility
- Summary

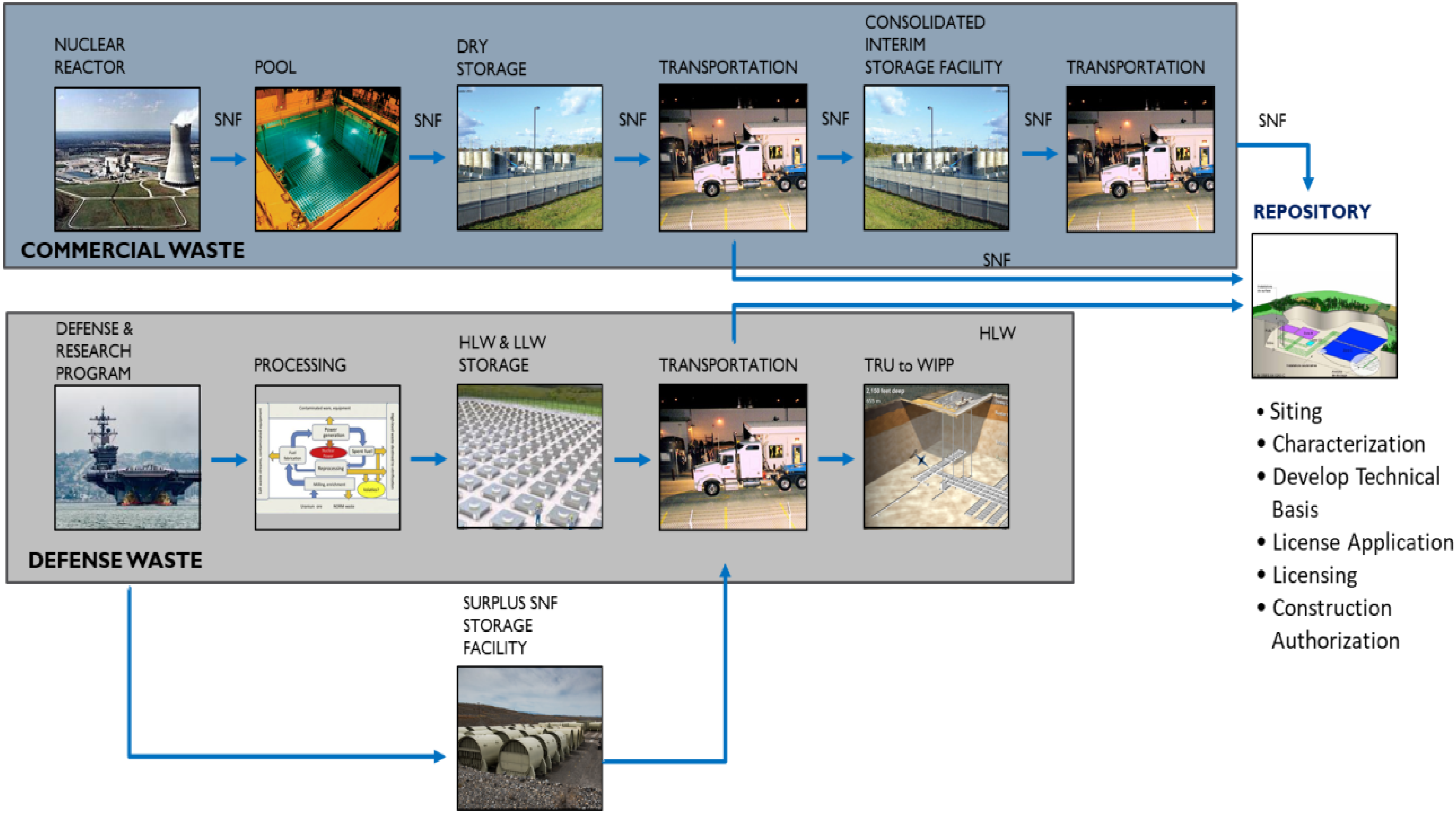


The Nuclear Fuel Cycle



Source: adapted from NRC (2020i)

Back End of the Nuclear Fuel Cycle



Source: Bonano (2019)

U.S. Nuclear Waste Management (1957-1982)

- **1957**: "**The Disposal of Radioactive Waste in Land**", U.S. National Academy of Sciences.
  - This study focused on disposal of liquid HLW from commercial reprocessing and concluded that disposal in bedded or domed salts was "possibly promising the most practical immediate solution to the problem"
- **1976**: The United States begins the first federal program for potential repository, focusing on salt deposits and federal nuclear facilities
- **1980**: The DOE confirms **geologic disposal as the preferred alternative** in an Environmental Impact Statement that considered various modes of disposal
  - Sub-seabed, island, ice sheets, deep hole, rock melt, deep well injection, outer space, and long-term storage on site
- **1982:** Congress passes the **Nuclear Waste Policy Act (NWPA)**
  - Establishes a repository siting process requiring 2 geologic repositories in different geologic media
    - The first repository would be limited to a disposal inventory of **70,000 metric tons of heavy metal (MTHM)**
  - U.S. Environmental Protection Agency (EPA) to develop health standards for a geologic repository
  - U.S. Nuclear Regulatory Commission (NRC) to license the geologic repository, based on the EPA Standards
  - DOE Office of Civilian Radioactive Waste Management (OCRWM) to develop and manage the repository program

Source: Bonano (2019)

U.S. Repository Program (1982 – 2010)

1982
Nuclear Waste Policy Act of 1982

January 31, 1998
DOE fails to open a repository by the statutory deadline

June 3, 2008
Yucca Mountain Repository License Application submitted to the NRC

1987
Nuclear Waste Policy Amendments Act selects Yucca Mountain as sole site for further characterization

February 2002
Yucca Mountain Site Recommendation. Site is designated by DOE and President G.W. Bush as suitable for repository development and licensing

2010
Obama Administration decides Yucca Mountain "is not a workable option"; project suspended

Source: Bonano (2019)

U.S. Repository Program (2010 – Present)

2010

- Last year of Congressional appropriations for Yucca Mountain project and DOE OCRWM
- DOE activities related to disposal of SNF and HLW moved to the DOE Office of Nuclear Energy (NE)

2012

- Blue Ribbon Commission on America's Nuclear Future (BRC) completes its recommendations, including a call for a consent-based process to identify alternative storage and disposal sites

2015

- NRC staff completes Yucca Mountain review, its Safety Evaluation Report finds that "DOE has demonstrated compliance with the NRC regulatory requirements" for both pre-closure and post-closure safety (NRC 2014, NRC 2015)

2015

- DOE initiates first phase of public interactions planning for a consent-based siting process for both storage and disposal facilities
- Activity terminated 2017

2021

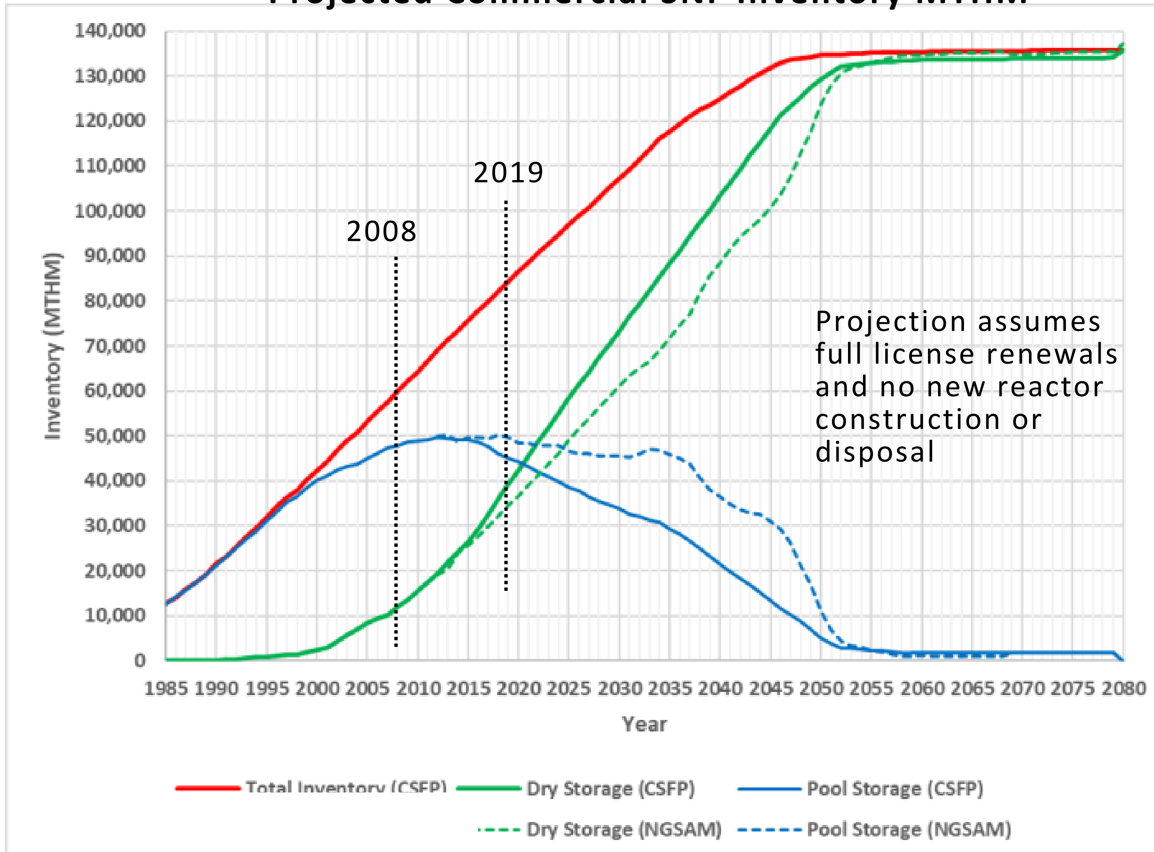
- Repository program remains suspended and future plans are uncertain.
- NWPA remains in effect and precludes site-specific work at sites other than Yucca Mountain without Congressional authorization and appropriation (NWPA Sec. 161)
- DOE-NE continues R&D on "generic" sites.

Source: Bonano (2019) and Sassani (2019)

U.S. Nuclear Waste Management – Current State

- 94 commercial reactors at 56 sites in 28 states (as of Dec. 2020)
  - Collectively generate ~2,200 MTHM of SNF each year
  - SNF continues to accumulate in dry storage at commercial reactor sites
  - HLW remains in storage at DOE sites.

Projected Commercial SNF Inventory MTHM

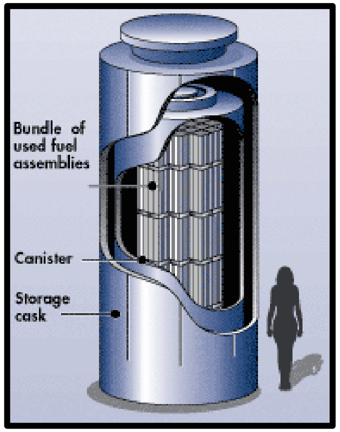


- **Commercial SNF as of Dec. 2019**
  - **~ 84,000 MTHM in storage**
  - **~ 39,000 MTHM in dry storage at reactor sites**
    - **in approximately 3,200 dry cask storage systems (DCSSs)**

- **Commercial SNF as of 2080**
  - **~ 136,000 MTHM in dry storage**
    - **in approximately 10,000 DCSSs**

Source: Freeze et al. (2021)

U.S. Nuclear Waste Management – Current State



- Dry storage of SNF and HLW is at NRC-licensed Independent Spent Fuel Storage Installations (ISFSIs) - 76 sites in 34 states
  - 54 at sites with an operating reactor
  - 18 at sites with no operating reactor ("shutdown" sites with "stranded" fuel)
  - 4 away-from-reactor sites (GE Morris, Fort St. Vrain, 2 at INL)
- Dry cask storage systems (DCSSs) and dual purpose canisters (DPCs)
  - SNF is most commonly loaded and stored in large welded stainless steel DPCs
    - DPCs are large (up to 37 PWR/89 BWR assemblies), heavy, and thermally hot
    - DPCs are NRC-certified for both storage and transportation, **but are not designed for disposal**
  - DCSSs incorporate a DPC inside concrete and steel storage cask/overpack for shielding and protection during storage
    - DCSSs may be vertical (above or below ground) or horizontal
- ISFSI licenses for proposed consolidated interim storage (CIS) facilities (no CIS are currently operational)
  - 1 license at Private Fuel Storage (PFS) in Utah
  - 2 in-process private sector license applications
    - Interim Storage Partners (was Waste Control Specialists) in Andrews TX
    - Holtec in Eddy/Lea Counties, NM

Source: Freeze et al. (2021)

U.S. Nuclear Waste Management – Current State

- **Repository program remains suspended. NWPA remains in effect and precludes site-specific work at sites other than Yucca Mountain without Congressional authorization and appropriation.**
- **Commercial SNF continues to accumulate in DPCs in extended dry storage at 76 sites in 34 sites.**

Current practice is safe and secure	Current practice is optimized for reactor site operations	Current practice is not optimized for transportation or disposal
• Extending current practice raises data needs: e.g., longer-term fuel/cladding and canister integrity, aging management practices	• Occupational dose • Operational efficiency of the reactor • Cost-effective on-site safety	• Thermal load • Package size and design • Potential for criticality in DPCs in disposal environment

Placing SNF in dry storage in DPCs commits the US to some combination of three options:

- **Constructing one or more repositories that can accommodate DPCs**
- **Repackaging SNF into disposal-ready canisters the future**
- **Storing SNF at surface facilities indefinitely, repackaging as needed**

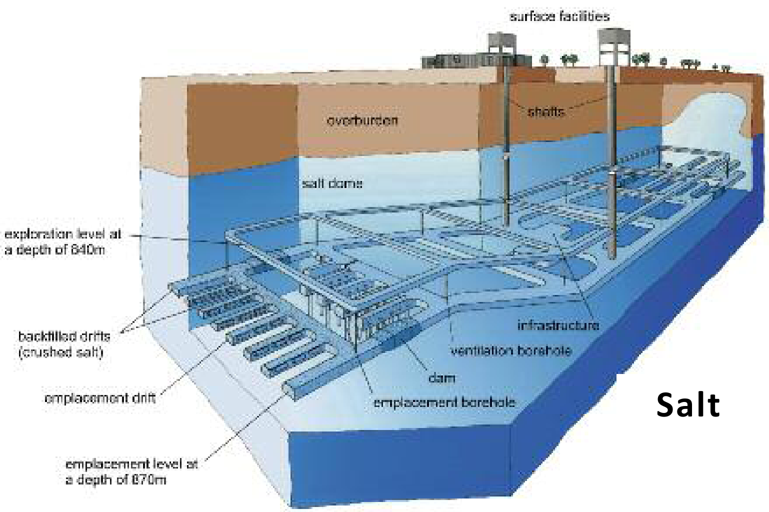
Each option is technically feasible, but none is what was originally planned

Source: Bonano (2019) and Freeze et al. (2021)

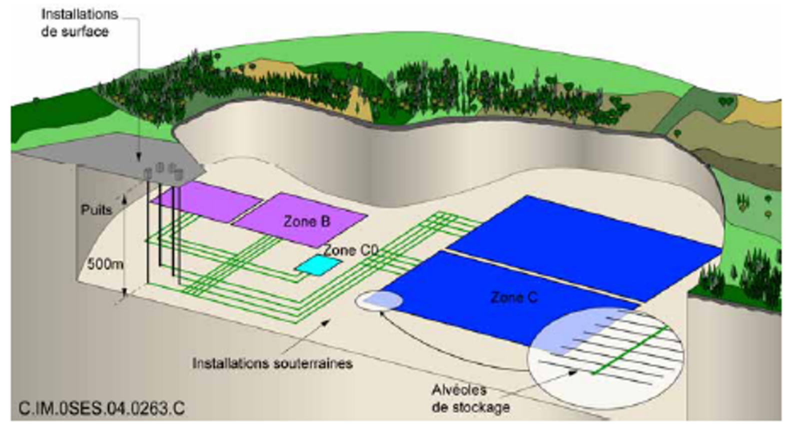
Deep Geologic Disposal of SNF and HLW

"There has been, for decades, a worldwide consensus in the nuclear technical community for disposal through geological isolation of high-level waste (HLW), including spent nuclear fuel (SNF)."

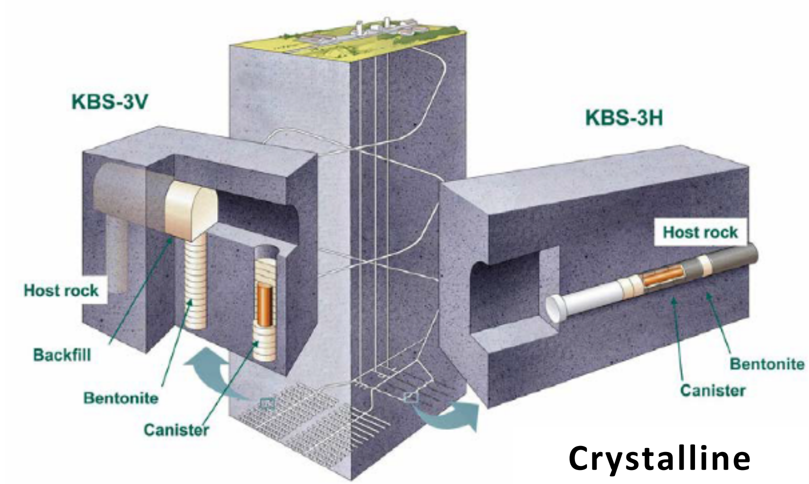
"Geological disposal remains the only long-term solution available." National Research Council, 2001



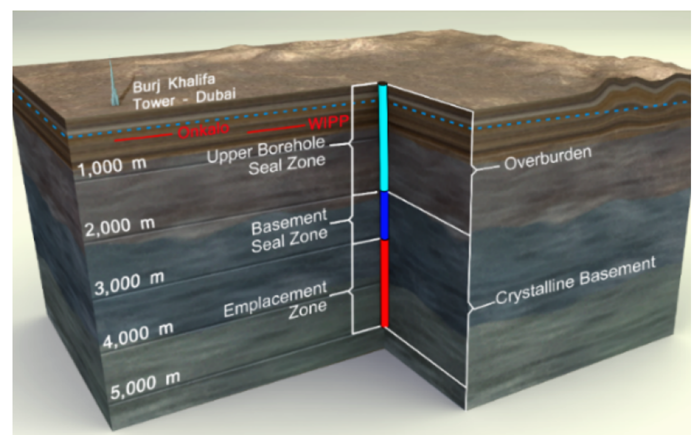
Salt



Argillite/Clay/Shale

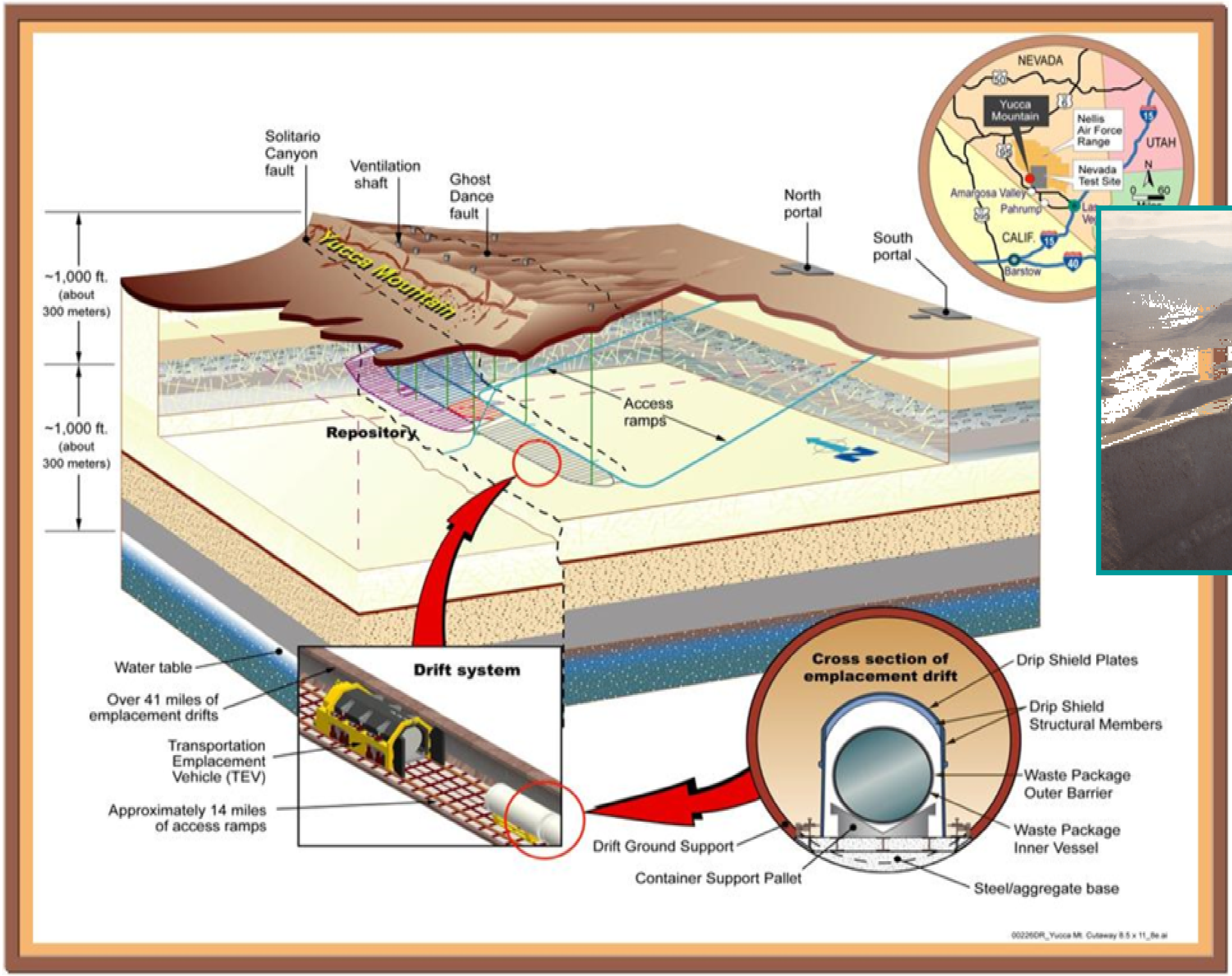


Crystalline



Deep Borehole

Deep Geologic Disposal of SNF and HLW – Yucca Mountain Project (1987 – 2010)

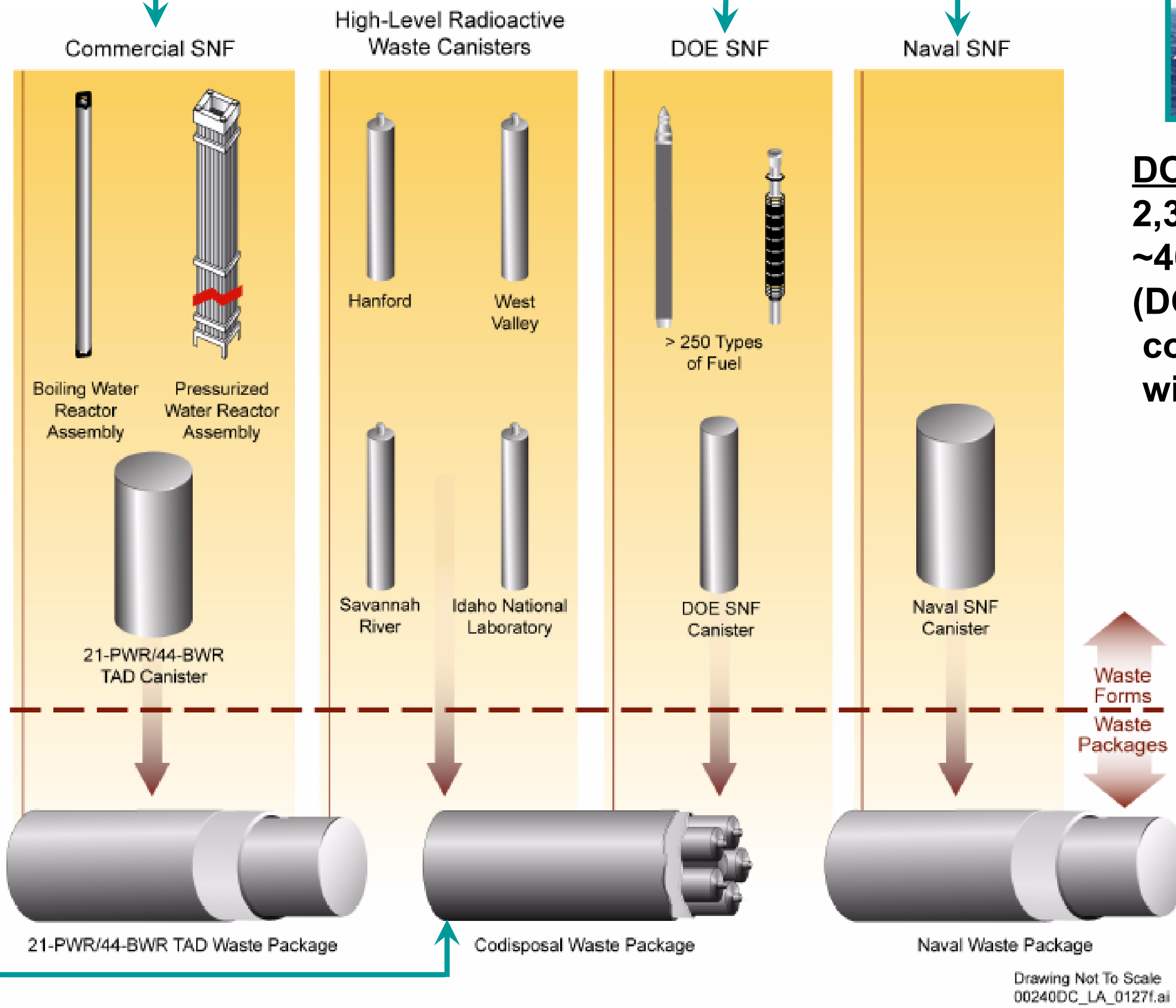


Bedded Volcanic Tuff (unsaturated)

Yucca Mountain Project Waste Inventory

Yucca Mountain Total = 70,000 MTHM
~11,000 WPs (each WP L~ 5m, D ~2m)

Commercial SNF:
63,000 MTHM
~7500 WPs



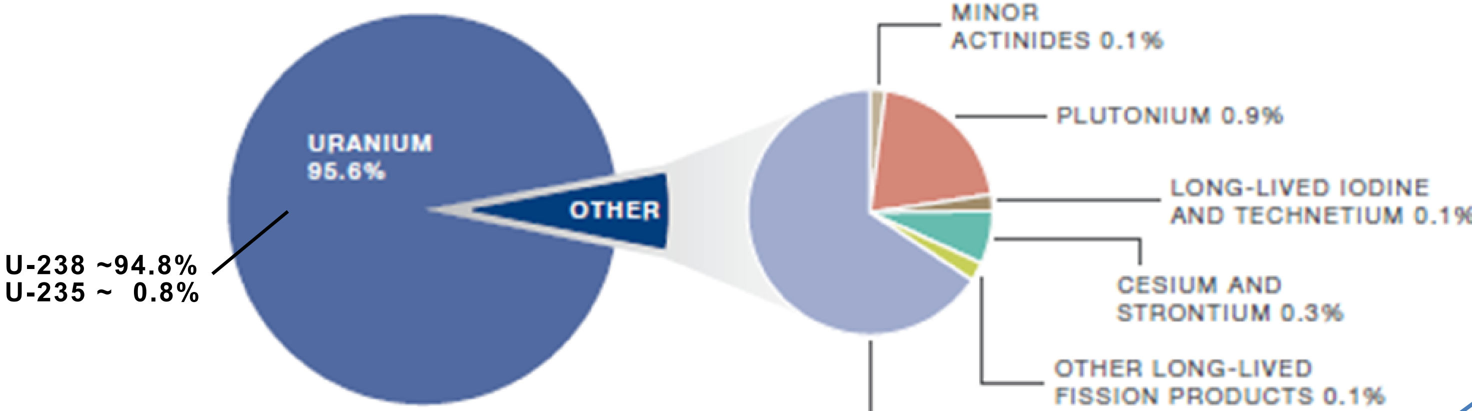
DOE & Naval SNF:
2,333 MTHM
~400 naval WPs
(DOE SNF co-disposed with HLW)

DOE & Commercial HLW:
4,667 MTHM
~3000 WPs (HLW co-disposed with DOE SNF)

TAD = Transportation, Aging, and Disposal canister
WP = Waste Packages

Source: Sassani (2019) and Freeze et al. (2021)

SNF Radionuclide Inventory



Energy yield of fission is always 1000 GWd/MTHM-fissioned

Source: BRC 2012, Figure 6

Np-237

Pu-242

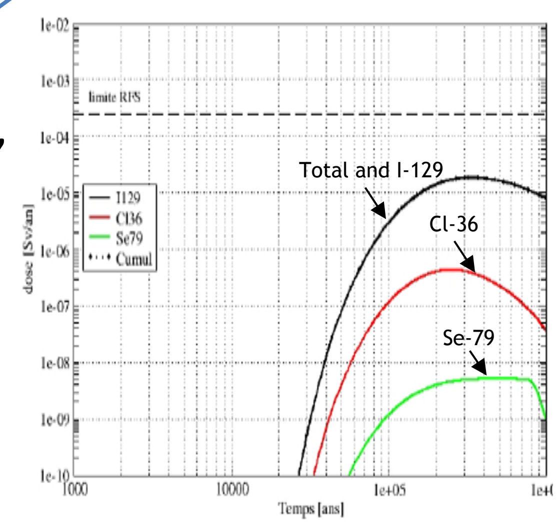
I-129
Tc-99

Cs-135

Se-79

Ra-226
Cl-36

- Radionuclides contributing to total post-closure dose (e.g., after 1,000,000 yrs) are long-lived and have low sorption:
  - For a repository in unsaturated, chemically oxidizing environment (e.g., Yucca Mountain)
    - actinides (Pu-242, Np-237, U-233) and fission products (Tc-99)
  - For a repository in saturated chemically-reducing environment (e.g., granite, clay/shale)
    - fission and activation products (I-129, Se-79, Cl-36, Ra-226)



Estimated doses for the French argillite repository concept, assuming direct disposal of spent fuel (Andra 2005, Figure 5.5-18)

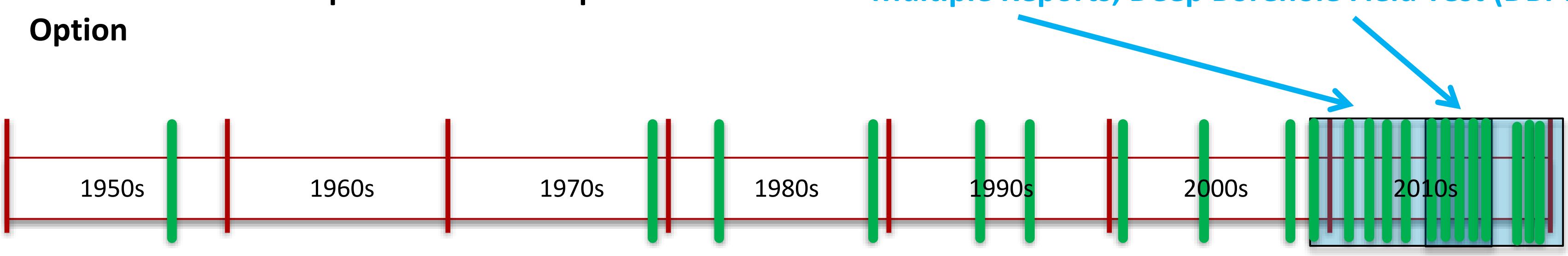
Deep Borehole Disposal (DBD) – Why?

- Potential for deep, robust isolation
  - Several km deeper than mined repository concepts
- In the U.S:
  - DBD is a not a replacement for a large mined repository for SNF
    - ~600 boreholes would be required for 70,000 MTHM of SNF
  - DBD does provide DOE the flexibility to consider options for disposal of smaller-diameter waste forms (DOE 2014a)
    - Potentially earlier disposal of some wastes than might be possible in a mined repository
    - Reduce costs associated with projected treatments of some wastes
- In other countries (IFNEC 2020):
  - DBD could be a cost effective solution for disposal of all SNF in countries with smaller SNF/HLW inventories
  - DBD could provide enhanced safeguards and security of nuclear material

Deep Borehole Disposal (DBD) Overview

DBD of spent nuclear fuel (SNF) and high-level radioactive waste (HLW) has been considered in the U.S. and elsewhere since the 1950s and has been periodically studied since the 1970s

- **National Academy of Sciences (1957)**
  Publication 519: The Disposal of Radioactive Waste on Land
- **O'Brien et al. (1979) LBL-7089**
  The Very Deep Hole Concept: Evaluation of an Alternative for Nuclear Waste disposal
- **Woodward-Clyde (1983) ONWI-226**
  Very Deep Hole Systems Engineering Studies
- **Juhlin and Sandstedt (1989) SKB 89-39**
  Storage of Nuclear Waste in Very Deep Boreholes
- **Ferguson (1994) WSRC-TR-94-0266**
  Excess Plutonium Disposition: The Deep Borehole Option
- **Heiken et al. (1996) LA-13168-MS**
  Disposition of Excess Weapon Plutonium in Deep Borehole: Site Selection Handbook
- **Harrison (2000) SKB-R-00-35**
  Very Deep Borehole – Deutag's Opinion on Boring, Canister Emplacement and Retreivability
- **Nirex (2004) N/108**
  A Review of the Deep Borehole Disposal Concept
- **Beswick (2008)**
  Status of Technology for Deep Borehole Disposal
- **Sandia National Laboratories (2009-21)**
  Multiple Reports; Deep Borehole Field Test (DBFT)



Deep Borehole Disposal (DBD) Overview

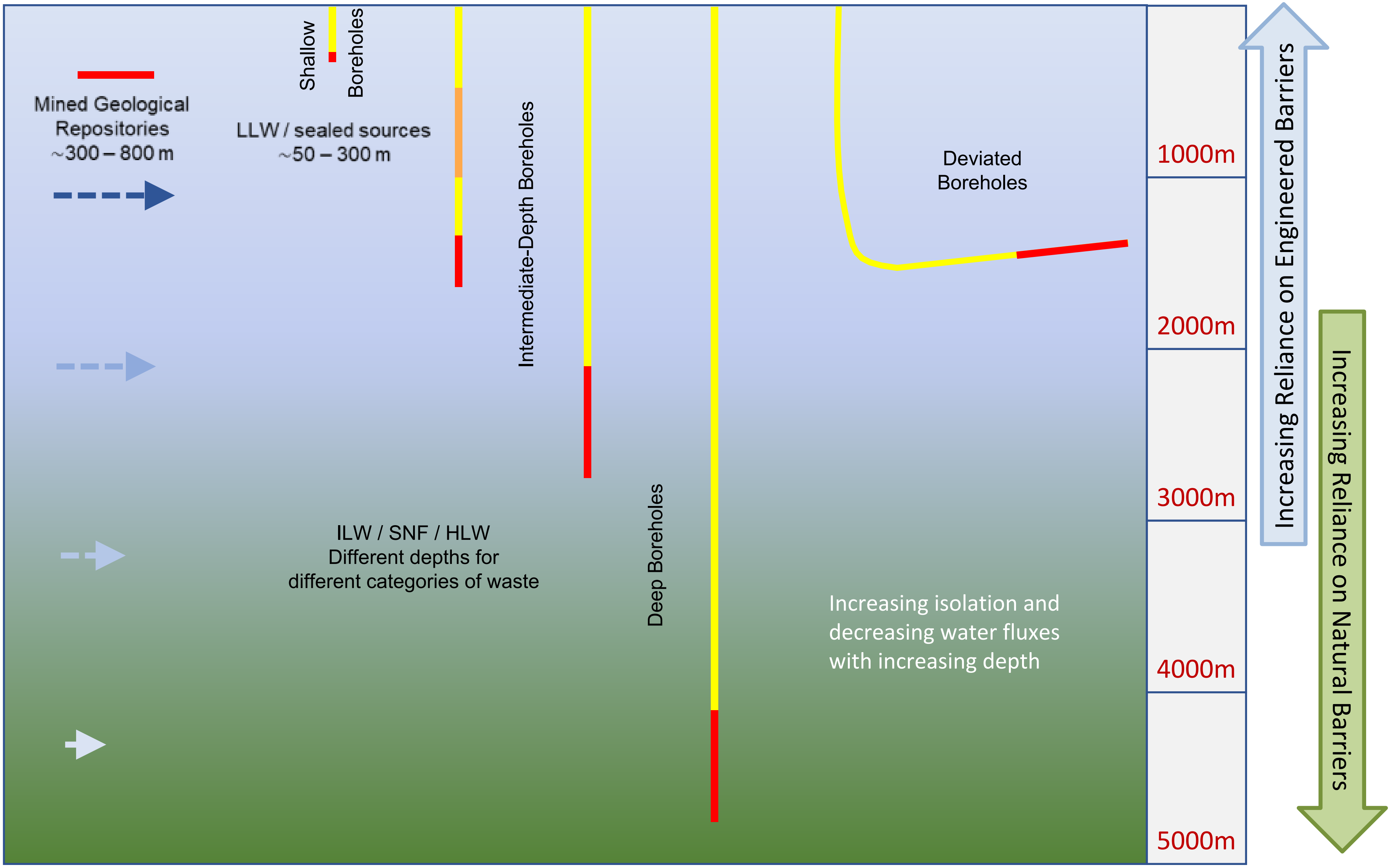
DBD research by country

(SNL Reports in light blue)

Country / Region	References
Canada	Brunskill 2006; Jackson and Dormuth 2008; Brunskill and Wilson 2011
China	Brady 2016
East Asia	von Hippel and Hayes 2010; Chapman 2013
Japan	Tokunaga 2013
Germany	Bracke 2015; Schilling and Müller 2015
Netherlands	Hart et al. 2015, Section 4.2.2
South Korea	Lee 2015
Sweden	Juhlin and Sandstedt 1989; Harrison 2000; Grundfelt 2013
Ukraine	Shestopalov et al. 2004
U.K.	Gibb 1999; Nirex 2004; Baldwin et al. 2008; Beswick 2008; Beswick et al. 2014
U.S. (SNF/HLW)	O'Brien et al. 1979; Woodward-Clyde Consultants 1983; Sapiie and Driscoll 2009; Brady et al. 2009; Arnold et al. 2011; Arnold et al. 2012; Arnold et al. 2013; Arnold et al. 2014; Bates 2015
U.S. (Excess Pu)	Ferguson 1994; Heiken et al. 1996; DOE 2014b, Section 5.2.5
U.S. (DBFT)	SNL 2014a; Sassani et al. 2016; SNL 2016a; SNL 2016b; Freeze et al. 2016; Hardin et al. 2019; Kuhlman et al. 2019; Freeze et al. 2019

Borehole Disposal Concepts

- a spectrum of potential depths and designs -

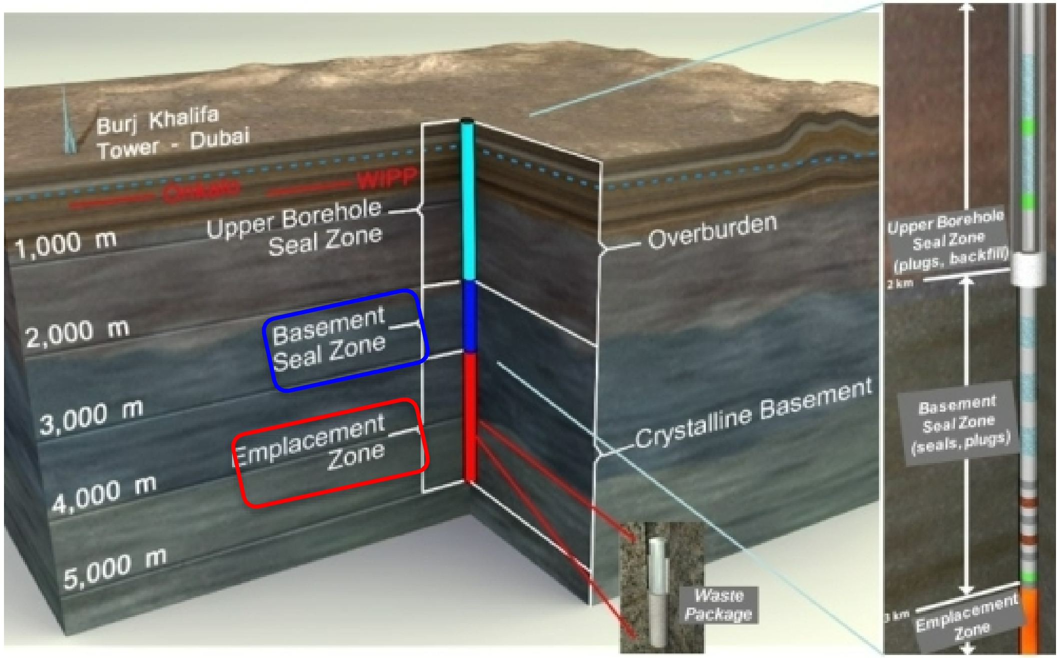


Adapted from IFNEC 2020

Deep Borehole Disposal (DBD) 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

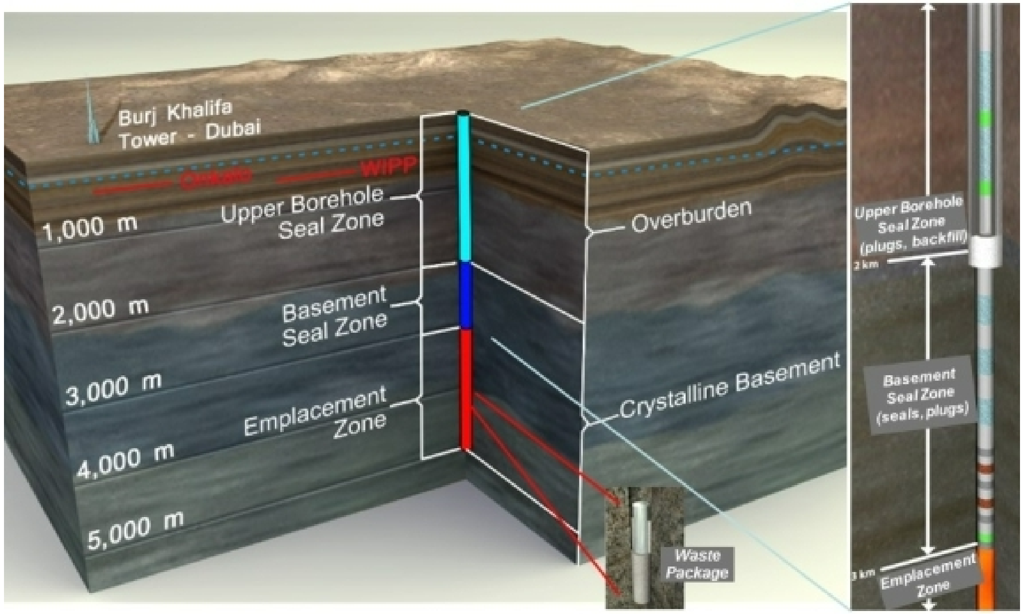


Robust Isolation from Biosphere

Natural Barriers – deep, low permeability host rock

Engineered Barriers – redundant seals, possibility of long-lived waste forms and waste packages

Borehole Disposal Safety and Feasibility



Deep Borehole Disposal (DBD)

- Waste is deep in competent rock
- Groundwater is hydrologically isolated, with density stratification, and geochemically reducing conditions
- Minimal reliance on engineered barriers (waste package, seals)
  - Seal thickness is > 1,000 m
- Drilling technology exists
- Deep waste emplacement needs to be demonstrated
- Seal placement needs to be demonstrated

Intermediate-depth Borehole Disposal (IBD)

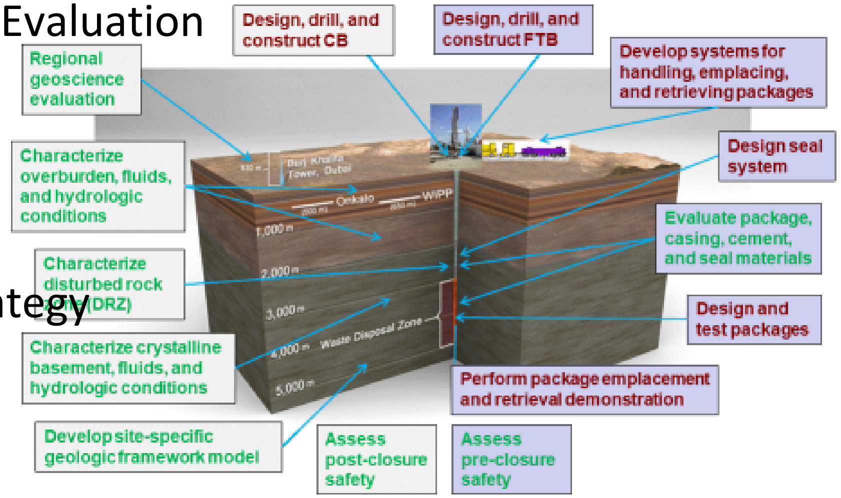
- Waste depth is similar to mined repositories
- Groundwater discharges to accessible environment, may be geochemically oxidizing if unsaturated
- Greater reliance on engineered barriers (waste package, seals)
  - Seal thickness and disturbed rock zone (DRZ) is 100s of m
- Shallower drilling permits larger diameter
- Shallower waste emplacement and sealing may be simpler

DBD 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)
  - DOE (2014a) recommended consideration of DBD of smaller DOE-managed waste forms, such as Cs and Sr capsules
- 2014-2017 (U.S. DOE funded DBFT)
  - 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)
- 2017-Present (SNL internally funded)
  - International collaboration for a deep borehole disposal field demonstration (CSIRO, ANSTO, IAEA)

Deep Borehole Field Test (DBFT) (2014-17)

- Objectives
  - Evaluate the feasibility of **drilling** and characterizing deep boreholes
  - Demonstrate safe operations for downhole **package emplacement** and retrieval
    - Without emplacement of radioactive wastes
  - Investigate **seal design** and performance
  - Perform modeling/analyses to support a **preliminary DBD safety assessment**
  - Potential sites were identified, but project terminated prior to drilling
- Accomplishments
  - DBFT Site Geoscience Guidelines and Data Evaluation
    - Perry and Kelley 2017
  - DBFT Conceptual Design
    - SNL 2016a; **Hardin et al. 2019**
  - DBFT Laboratory and Borehole Testing Strategy
    - SNL 2016b; **Kuhlman et al. 2019**
  - DBD Generic Safety Assessment
    - **Freeze et al. 2016; Freeze et al. 2019**

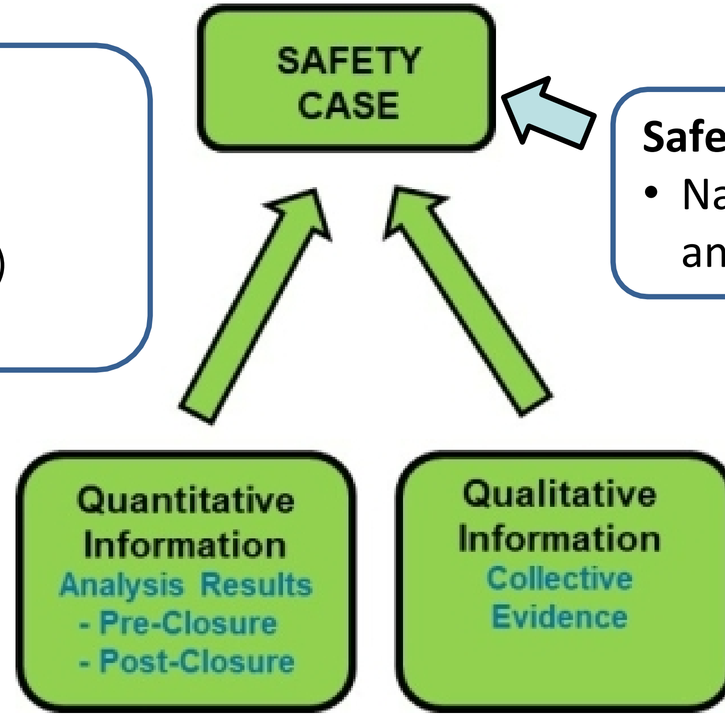


Deep Borehole Field Test (DBFT) (2014-17)

- DBFT site acquisition was attempted through two RFPs but was suspended by non-technical considerations
  - Lack of advance notice to local communities
  - Lack of trust of Federal government
  - Concern that a successful DBFT would lead to subsequent nuclear waste disposal at the same site
  - State-level support did not equal local support
  - Differing priorities of new Administration
- DBFT siting was "successful" in the sense that:
  - Lack of local "consent" resulted in evaluation of other options
    - No enactment of "eminent domain"
  - Greater local community outreach was incorporated into RFP#2

Borehole Disposal Safety Case

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



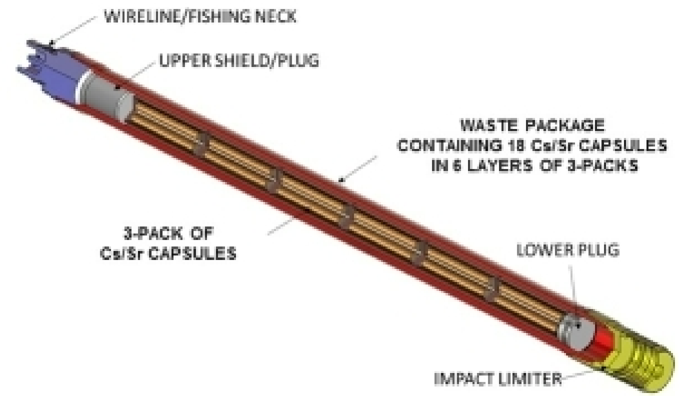
Safety Strategy
- National Policy and Regulations

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

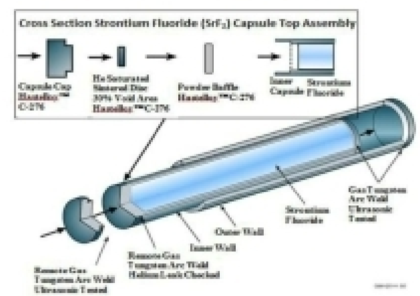
Confidence Enhancement
- Natural Analogs
- Independent Evidence

Deep Borehole Disposal Reference Design

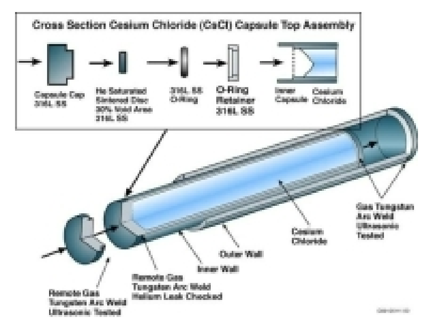
- Radionuclide Inventory (SNL 2014, Freeze et al. 2016)
  - 1936 Cs and Sr capsules aged to 2050
    - Decay heat for ~ 100 yrs
  - 108 waste packages (WPs)
    - 18 capsules per WP (6 layers of "3-packs")
  - WP length = 4.76 m / WP diam. = 0.19m (7.5 in)



  - 601 SrF_2 capsules @ ~18 per WP = 34 Sr WPs
    - Inventory = ^{90}Sr (t1/2 = 28.8 yr)

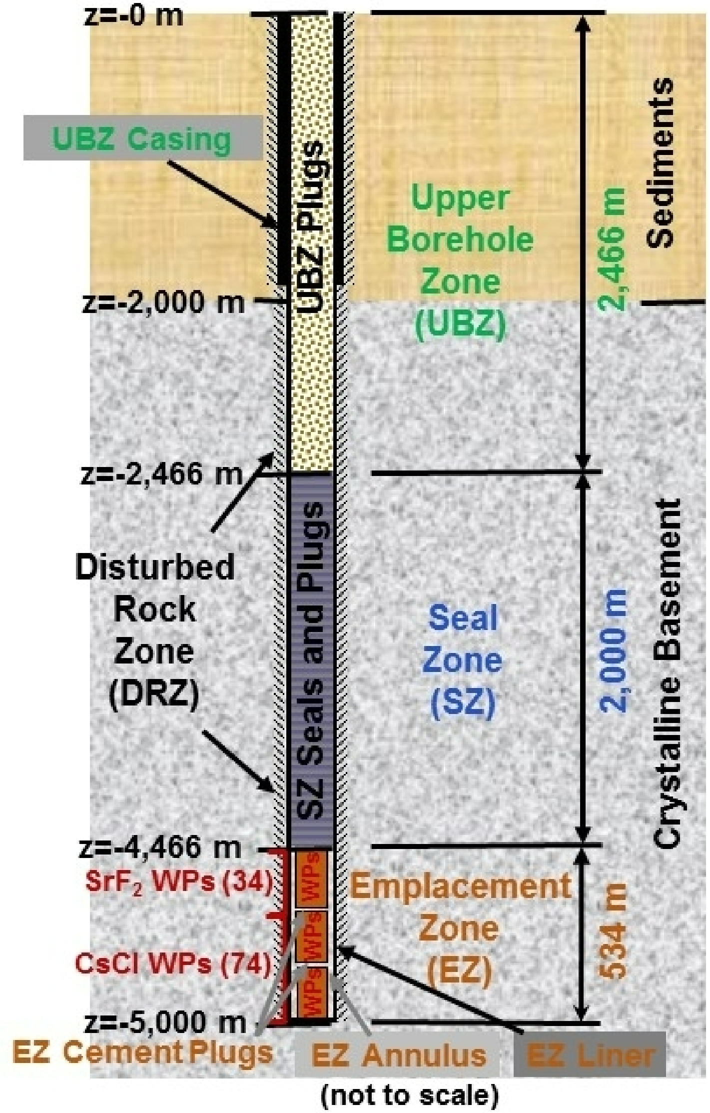


  - 1335 CsCl capsules @ ~18 per WP = 74 Cs WPs
    - Inventory = ^{137}Cs (t1/2 = 30.1 yr), ^{135}Cs (t1/2 = 2,300,000 yr)



Deep Borehole Disposal Reference Design

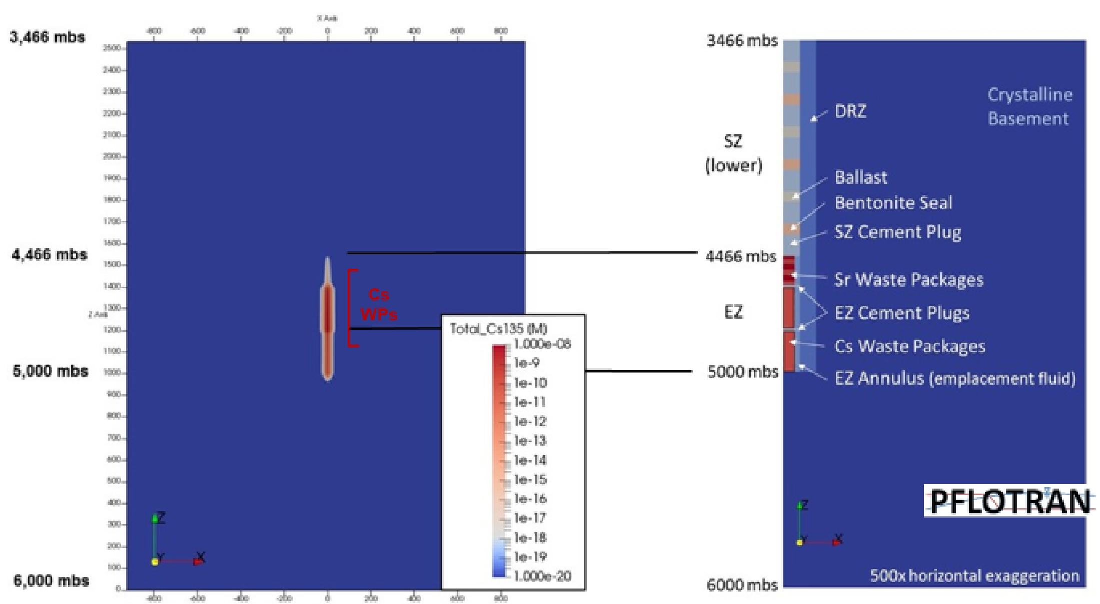
- All 108 WPs fit in a single borehole with a 534-m Emplacement Zone (EZ)
  - bottom-hole diameter of 12.25 in (31 cm)
- Seal Zone (SZ) consists of alternating bentonite and cement emplaced directly against borehole wall
- WPs are lowered, one at a time, on wireline inside a removable guidance casing
- Reference design and safety case for SNF
  - Arnold et al. (2013. App. A); Freeze et al. (2013)



DBD Post-Closure Safety – Status of R&D

- Safety assessments for borehole disposal of SNF, HLW, and/or ILW to date have been generic and have primarily focused on post-closure safety
  - Preliminary generic post-closure performance assessments (PAs) have affirmed that robust post-closure waste isolation can be attained in deep borehole disposal in basement rock that is hydrologically isolated from overlying circulating groundwater systems

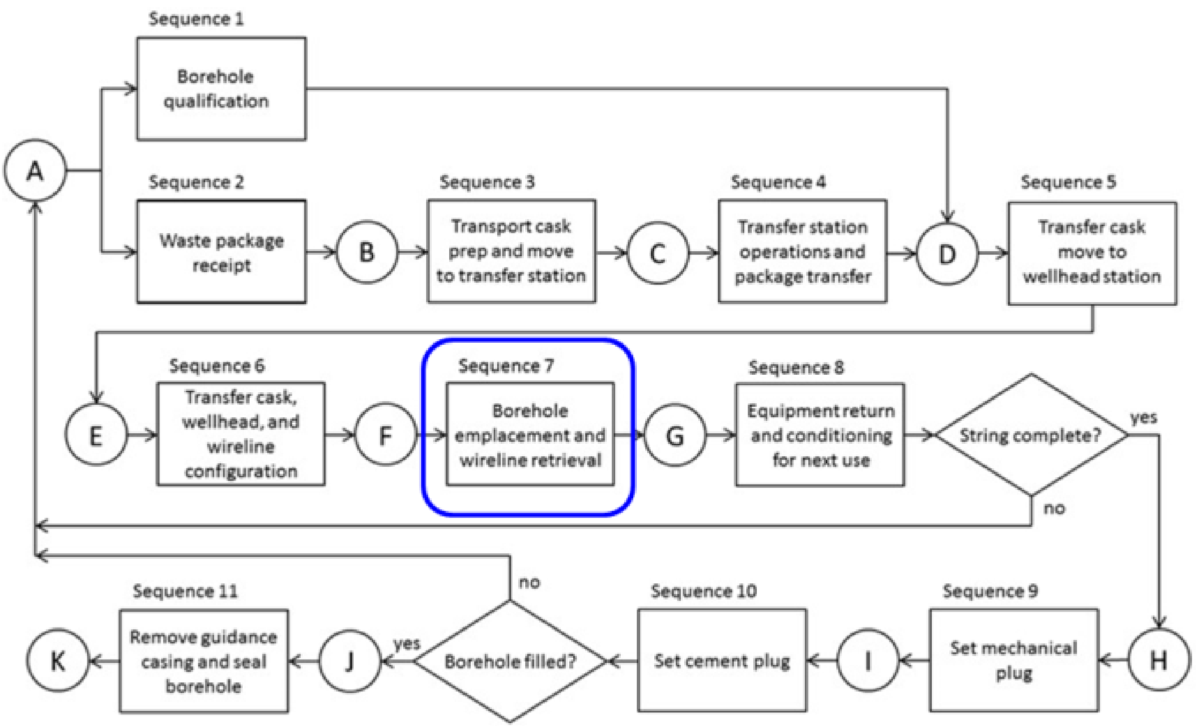
Minimal migration of dissolved ^{135}Cs beyond deep Emplacement Zone in 10,000,000 years



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

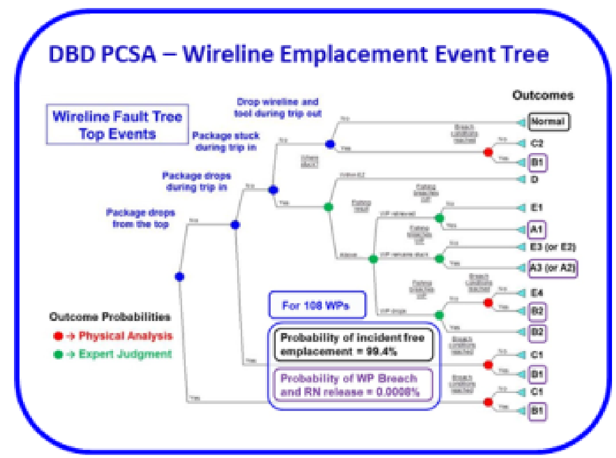
DBD Pre-Closure Safety – Status of R&D

- Pre-closure operational aspects (e.g., surface handling and downhole emplacement of waste containers) and safety have not been studied in as much detail as post-closure safety



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

Event trees and probability estimates for activity sequences



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

- Confidence in the viability of the borehole disposal concept would benefit from additional R&D focused on pre-closure operations and safety

Summary

- Recent studies have identified no fundamental flaws regarding safety or implementation of the DBD concept
  - Preliminary DBD safety case analyses suggest:
    - Pre-closure – low probability of operational failures
    - Post-closure – robust waste isolation for >1,000,000 years (^{129}I, ^{135}Cs)
- A field-scale demonstration would enhance confidence in the surface handling and downhole emplacement operations and contribute to the overall safety and viability of the borehole disposal concept
  - An integrated full-scale drilling and waste emplacement test has not yet been undertaken, but is achievable in a 5-10 year timeframe
  - A demonstration could also provide insights into borehole sealing methods, downhole characterization techniques to support post-closure safety, and other enabling technologies

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Backup Slides

DBD Concept – Safety and Feasibility

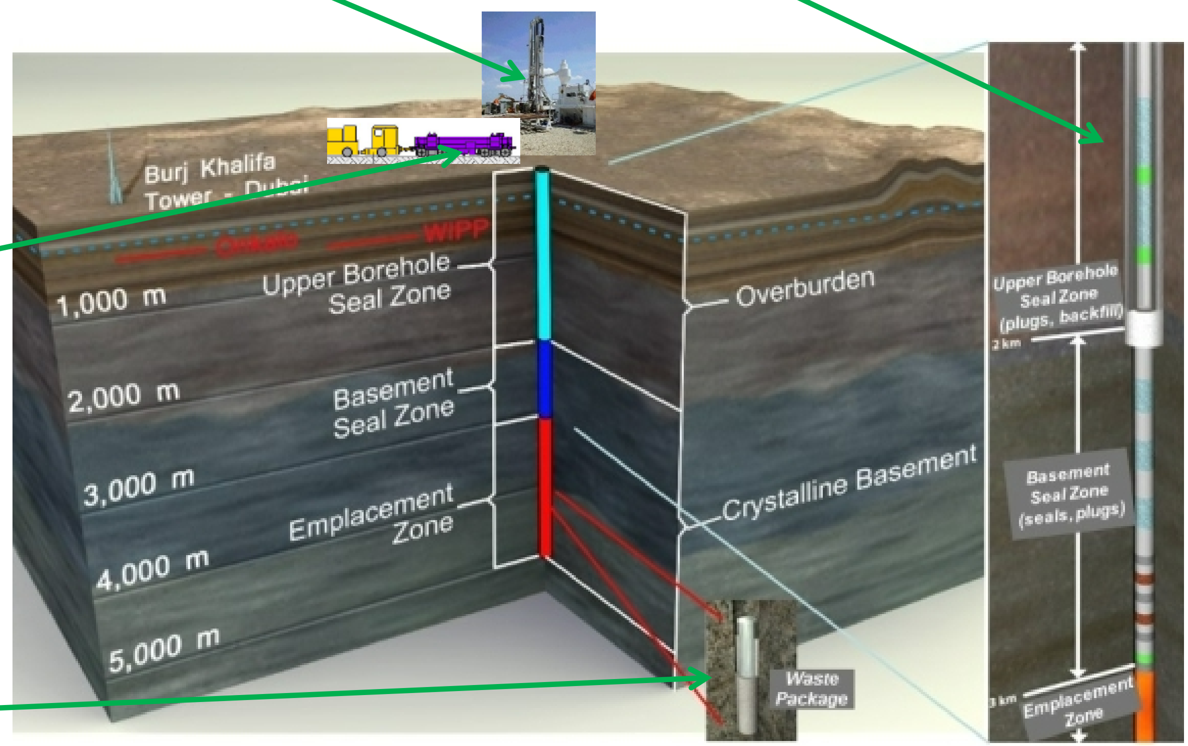
(Pre-Closure Engineering and Operations)

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



DBD Concept – Safety and Feasibility

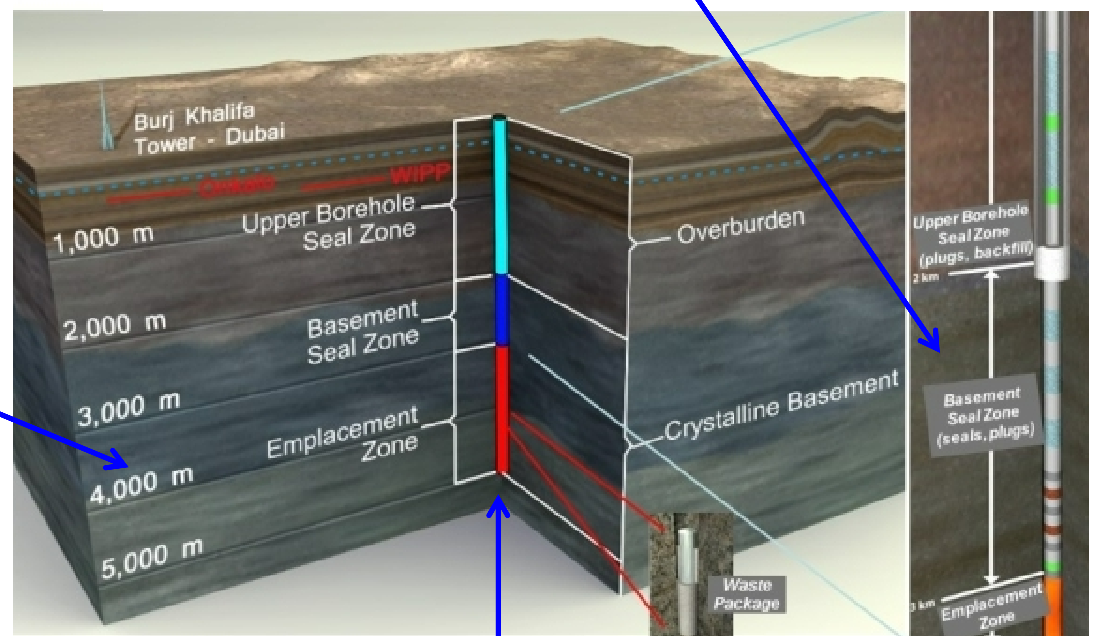
(Post-Closure Hydrogeochemical Waste Isolation)

Select host rock properties 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

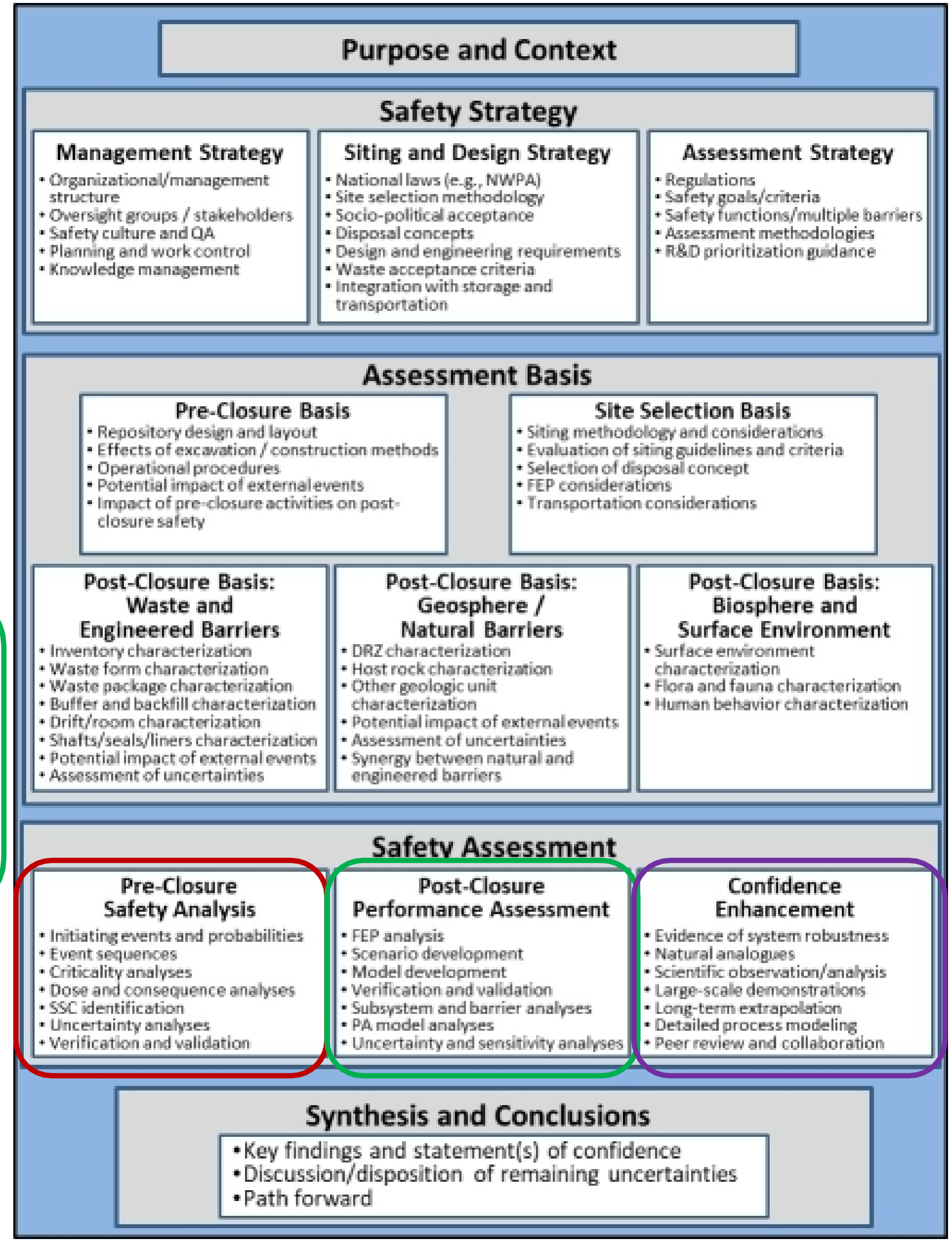
Borehole Disposal Safety Case Elements

- **Adapted from NEA (2013) as documented in Freeze et al. (2016) and Freeze et al. (2019)**

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

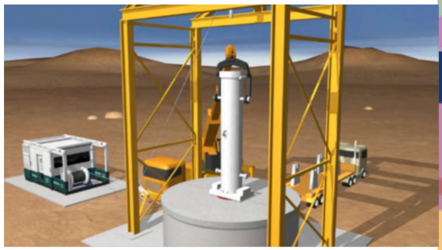
Post-Closure Performance Assessment (PA)
- Features, Events, and Processes (FEPs)
- Scenario Development
- PA Model [PFLOTRAN]
  - Undisturbed (Nominal) Scenario
  - Disturbed Scenario(s) (e.g., stuck package)

Confidence Enhancement
- Natural Analogs
- Independent Evidence



Field-Scale Demonstration – Primary Objectives

- A field-scale demonstration should include, at a minimum:
  - Radiation-shielded surface handling of full-scale surrogate waste containers
    - Surrogate containers do not contain any radioactive waste or materials
    - Surface operations would use radiation-shielded equipment and remote handling methods to maneuver the surrogate containers as if they had the radiation and thermal signatures of actual radioactive waste



  - Repeated emplacement of surrogate containers into a full-diameter borehole
  - Repeated removal of surrogate containers from the borehole
    - to partially address concerns about retrieval of a “stuck” waste container
  - Integrated technology and protocols
- Details of the demonstration would be waste and concept specific
  - Waste container geometry and materials, shielded surface handing equipment and configuration, and emplacement methods (e.g., drill string, wireline, or coiled tubing) would all need to be specified
    - Can be informed by prior DBFT research and the Climax Mine and German BSK3

Field-Scale Demonstration - Considerations

- Demonstration Borehole Diameter
  - Must be large enough to test emplacement of a full-scale surrogate container
    - With appropriate tolerance between canister and borehole casing
- Demonstration Borehole Depth
  - A full-diameter borehole extending to less than full depth would be sufficient to assess surface handling and emplacement protocols at the field scale
    - A test depth of tens to hundreds of meters would likely be sufficient
- Location
  - The demonstration test could be performed at any number of sites
    - Demo site need not have favorable long-term isolation characteristics
    - Could be in laboratory-type conditions in an artificial “borehole” (e.g., representative-sized casing)
- Secondary Objectives
  - Borehole sealing methods and materials
  - Downhole characterization techniques to inform post-closure safety