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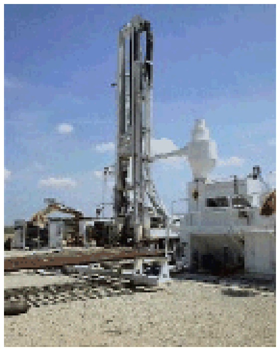

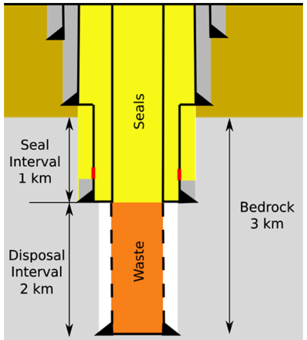

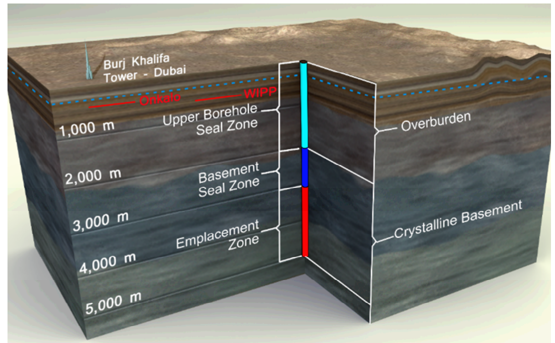

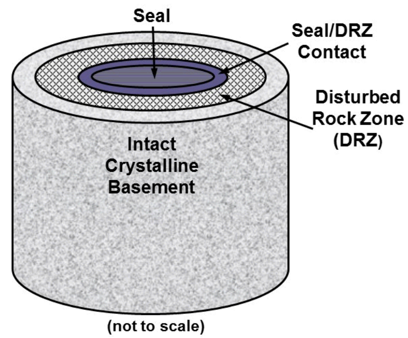

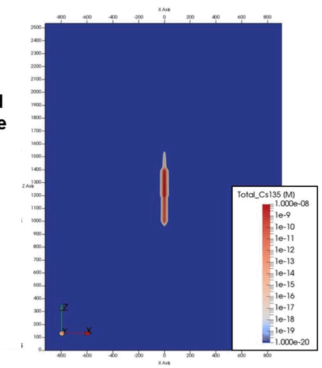

Deep Borehole Disposal in Israel

Team

Ran Calvo (GSI), Ofra Klein-Ben David (NRCN)

Robert MacKinnon (SNL), Geoff Freeze (SNL), Frank Perry (LANL), Antoun Tarabay (LLNL), Mike Homel (LLNL)

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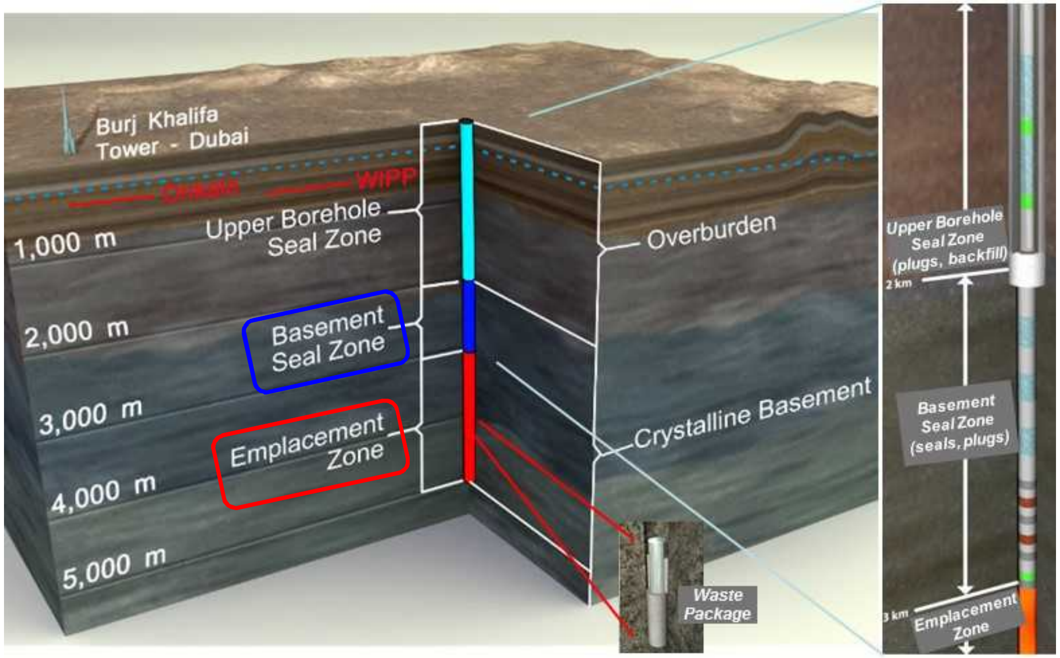
Outline

- Deep Borehole Disposal (DBD) Overview
- US DOE DBD R&D
- Potential deep borehole site
- IAEC/NNSA DBD Team Progress to Date
- DBD Concept for Israel
- Deep Geologic Repository (DGR) vs Deep Borehole Disposal (DBD)
- DGR and DBD Costs
- Deep Borehole Field Test and Estimated Costs
- Summary

US 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



Robust Isolation from Biosphere

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

* depths will be site and waste specific

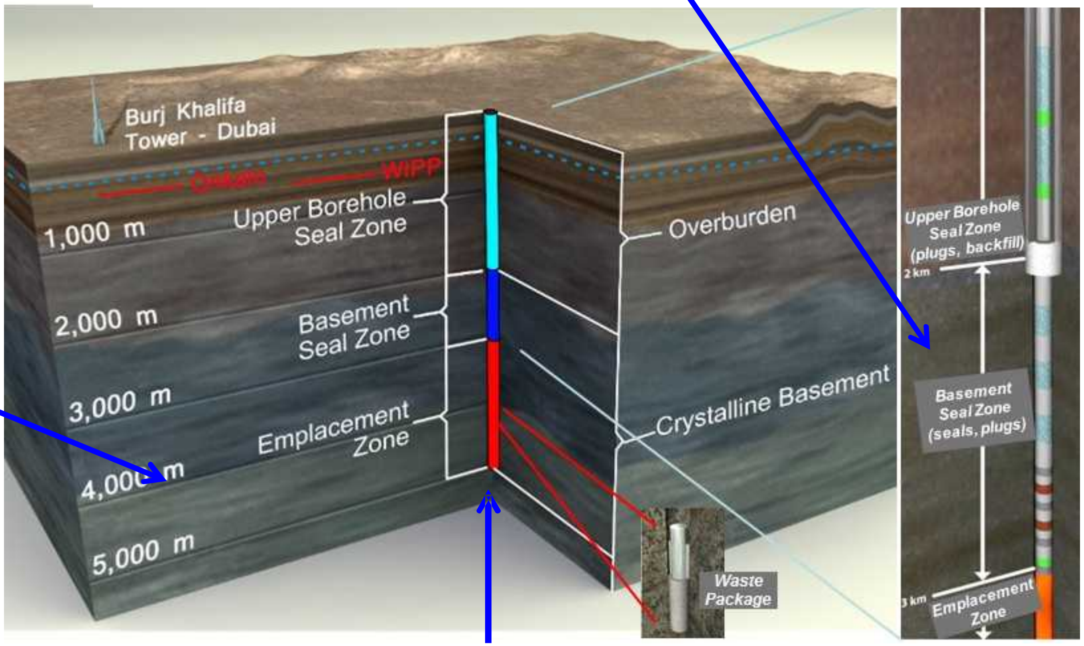
US DBD Concept – Safety and Feasibility

(Post-Closure Hydrogeochemical Waste Isolation)

Zenifim Formation may exhibit adequate host rock properties with sufficient depth and thickness

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

Deep Crystalline Basement
- hydrologically isolated from shallow groundwater (low permeability and potentially 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

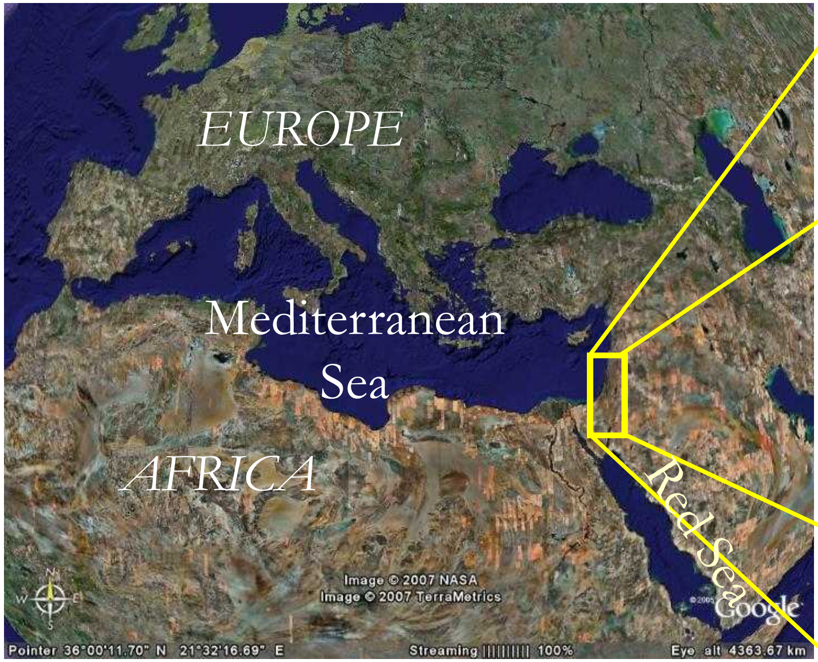


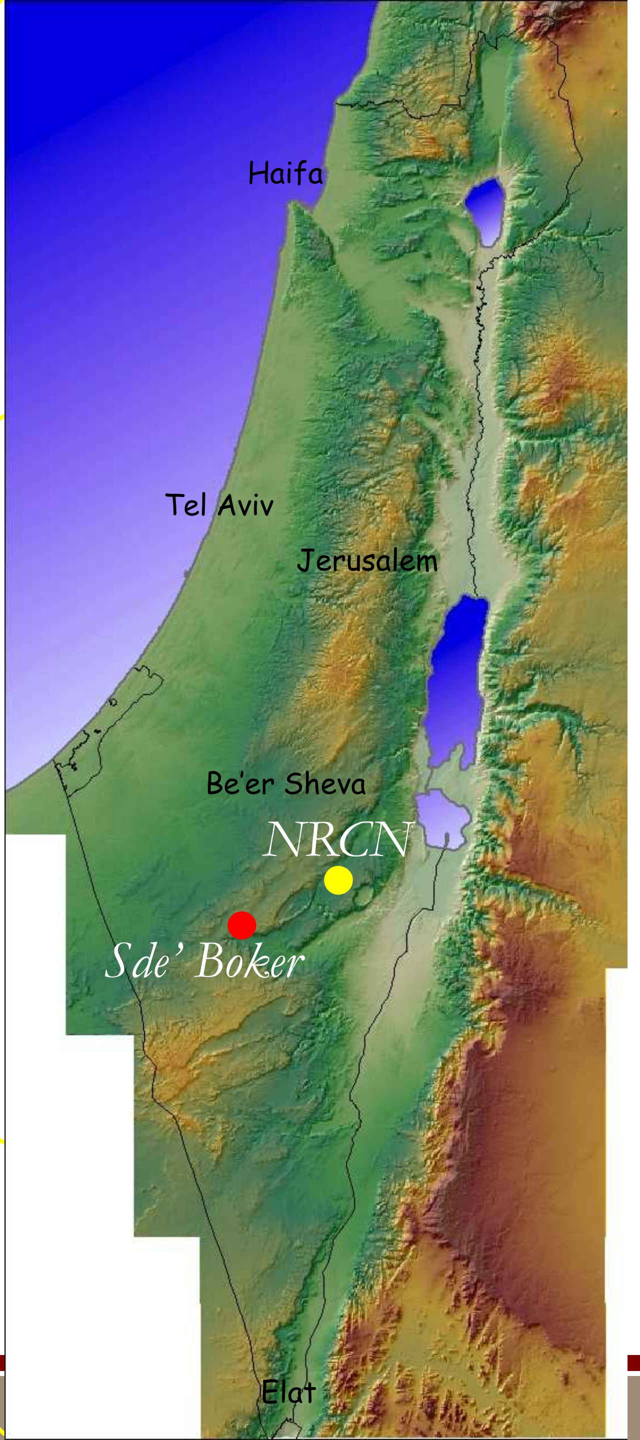
Waste is deep in basement rock
- well below typical depth of fresh groundwater ------
- with at least 1,000 m of basement rock (Seal Zone) overlying the Emplacement Zone

DOE DBD Research and Development (R&D)

- 2009 – 2012 (SNL internally funded) ~ $1 M
- 2012 – 2014 (U.S. DOE funded R&D) ~ $2 M
- 2014-2017 (U.S. DOE funded DBFT) ~ $ 12 M
  - SNL Lead Lab for a planned 5-year Deep Borehole Field Test (DBFT) Collaboration with LANL, LLNL, LBL, ORNL, PNNL, INL
    - Developed siting guidelines
    - Developed conceptual design for characterization borehole
    - Established data needs, requirements, sampling plan and management
    - Developed drilling and test plan
    - Developed conceptual design of field test borehole
    - Developed conceptual design of emplacement system and waste packages
    - Conducted a design review with AREVA
    - Developed preliminary pre-closure safety analysis
    - Developed preliminary post-closure safety analysis

Proposed Site Location

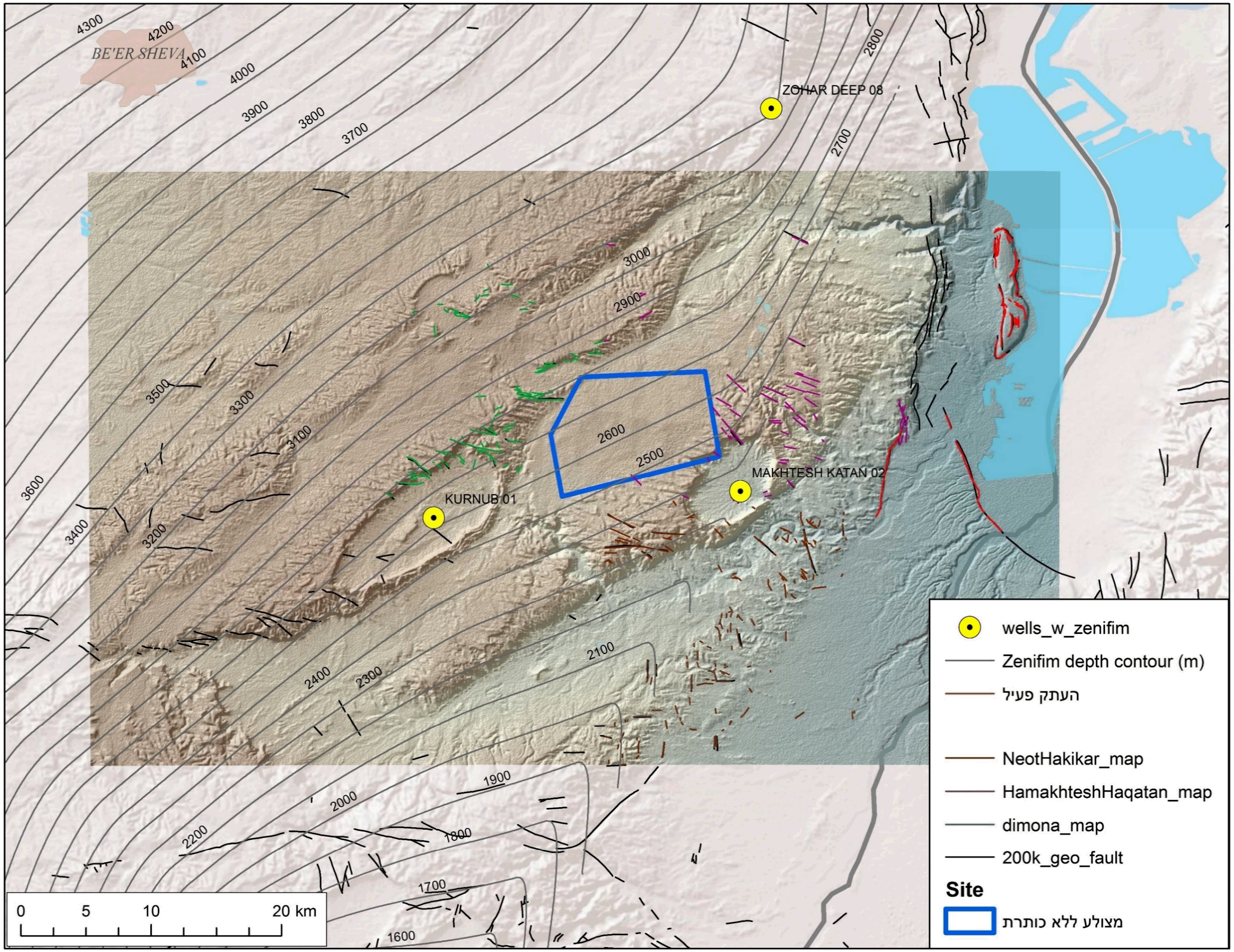




Southern Israel

- Tectonic features (faults and folds)
- Paleogeography through time (geological history)
- Geological columnar section (stratigraphy)
- Hydrogeology (aquifers and aquitard)
- Thermal gradient / heat flow
- Seismicity

NRCN Site


BE'ER SHEVA
ZOHAR DEEP 08
KURNUB 01
MAKHTESH KATAN 02
4300
4200
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1600
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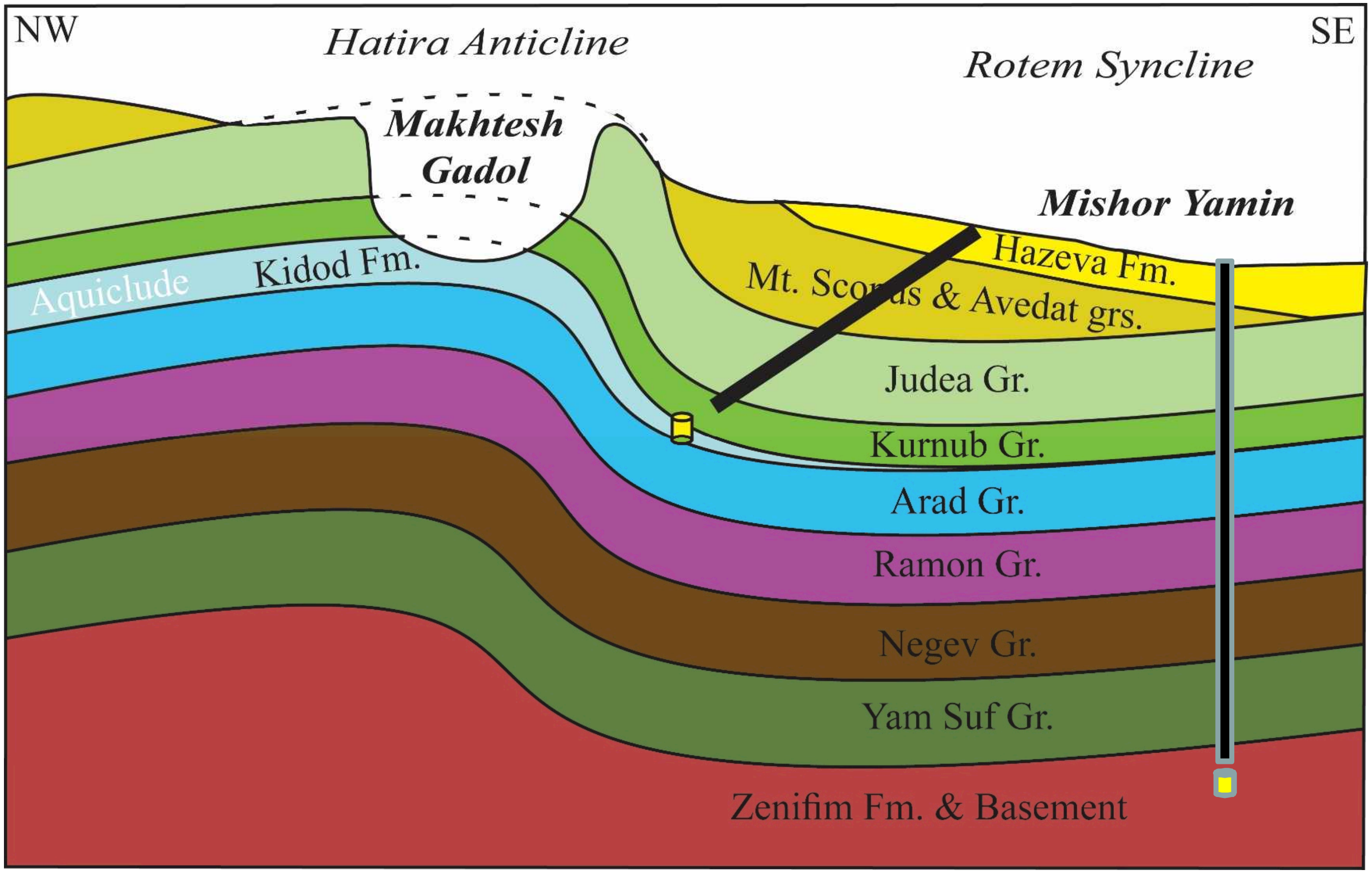
wells_w_zenifim
Zenifim depth contour (m)
העתק פעיל
NeotHakikar_map
HamakhteshHaqatan_map
dimona_map
200k_geo_fault
Site
מצולע ללא כותרת

Simplified Geologic Cross Section at Potential NRCN Site



Progress to Date

- Deep borehole working group (NRCN, GSI, SNL, LANL, LLNL) kick-off meeting in August 2017
- Six team telecom meetings to date
- Workshop in December
- Main research activities:
  - Identified regional and site hydrogeology, geology, and safety assessment data needs.
  - Developed a list of specific thermal-mechanical data needs related to borehole stability
  - Compiled a bibliography of DBD reports and shared with team
  - Compile existing geology of Israel
  - Preliminary assessment of geology in the context of deep borehole
  - Initial data digitation into available software

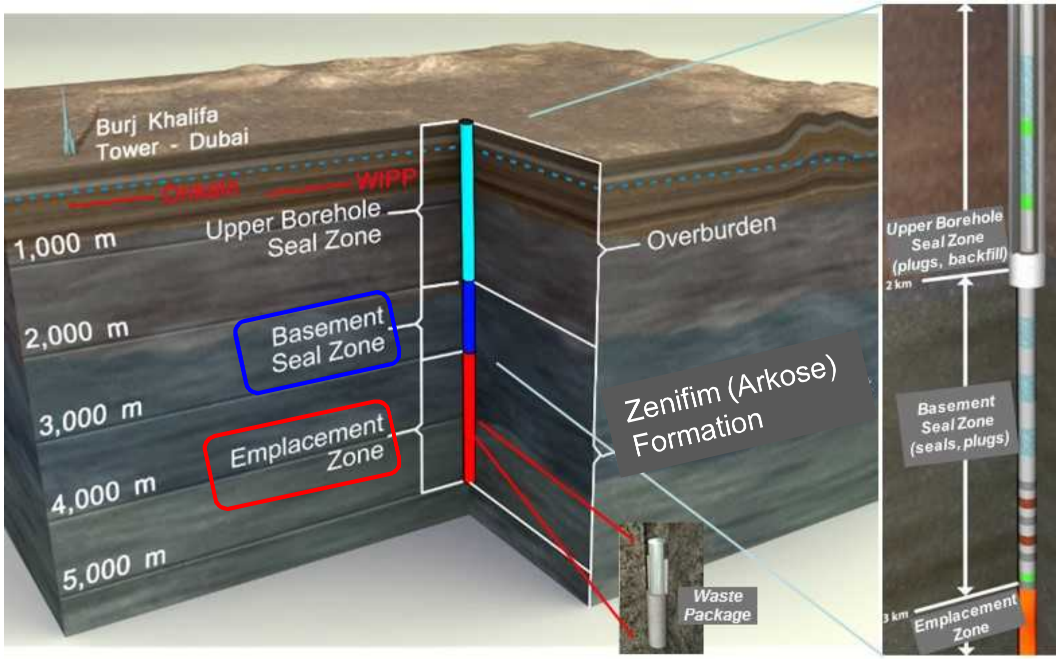
Evaluation Steps

1. Assess suitability of US siting guidelines for DBH for the Israeli case
2. Review Israel Geology and available data for recommended site
3. Evaluate site against siting guidelines using existing data
   - No apparent showstoppers with potential site
4. Characterize waste forms – primarily size, type, inventory, volumes – to be disposed
5. Develop conceptual borehole designs compatible with potential geologies, waste forms, and existing drilling and construction technology
6. Estimate characterization and disposal costs for actual disposal
7. Preliminary evaluation of pre-closure and post-closure safety
8. Outline field test demonstration
9. Activities and schedule
10. Detailed Cost plan
11. Summarize information for decision makers

Deep Borehole Disposal Concept for Israel

- Drill a borehole or array of boreholes into deep, competent rock (e.g., Zenifim)
  - ~ 5,000 m* total depth (TD)
  - up to 17” (43 cm) diam. at TD
    - Size to accommodate RR SNF
- 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

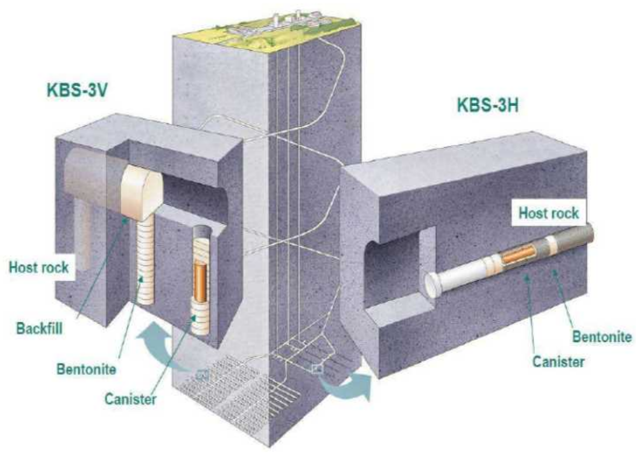
• **depths to be determined from characterization borehole**

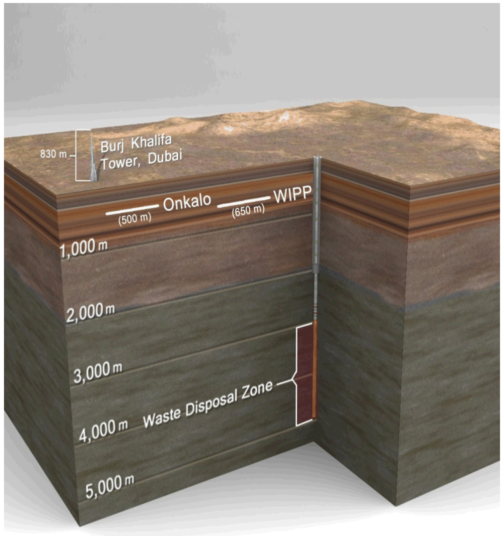


Robust Isolation from Biosphere

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

Repository vs Deep Borehole





Repository

Large upfront costs

- Shafts and Ramps
- Underground mined space and initial emplacement zone
- Ventilation and underground utilities

Underground operations and mine safety

Relies significantly on engineered barrier system for isolation from biosphere

Extensive site characterization because of lateral orientation in subsurface accessible to groundwater

SNF Retrievable

Deep Borehole

Scalable Costs

- Number of boreholes scale with the inventory

Simple surface operations only

Relies primarily on geologic system for isolation from biosphere

Vertical orientation in deep groundwater isolated from subsurface groundwater

SNF virtually irretrievable

Cost Estimate DBD vs DGR: Key Assumptions

- Project Management and regulatory costs not included
- Cost of surface facilities not included
- Dispose 2000 BWR assemblies

Deep Borehole Disposal

- 1 characterization borehole (0.21 m BHD), 5 disposal boreholes (0.43 m BHD)
- 400 carbon steel waste packages per borehole with 1 BWR assembly per package ~ 80 MTU/Borehole

Deep Geologic Repository (DGR)

- 9 BWR assemblies per emplaced waste package
- 222 waste packages
- A maximum of about 0.2 MTU (initial) for BWR assemblies gives a total emplaced inventory of 400 MTU (same as the 5-borehole model)
- Waste package material is either low-alloy steel or copper

Estimated Costs for DBD and DGR

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Comparison of Swedish (SKB) Cost Model (repository in hard rock) to DBD Costs

DBD Cost Item	Single Deep Borehole Item (10^6\$ per borehole)	Total DBD Cost (5 boreholes) (10^6\$)	Repository Cost Item	Repository Total Cost (222 WPs) (10^6\$)
Siting	45	45	Siting	333
Construction	20	100	Construction	363
Operation	20	100	Operation	179
Closure	5	20	Closure	20
Encapsulation	10	50	Encapsulation	190
TOTAL (2017 10^6\$)	**100**	**315**	**TOTAL (2017 10^6\$)**	**1085**

Comparison of Swiss (Nagra) Cost Model (repository in sedimentary rock) to DBD Costs

DBD Cost Item	Single Deep Borehole Item (10^6\$ per borehole)	Total DBD Cost (5 boreholes) (10^6\$)	Repository Cost Item	Repository Total Cost (222 WPs) (10^6\$)
Siting	45	45	Siting	732
Construction	20	100	Construction	543
Operation	20	100	Operation	245
Closure	5	20	Closure	29
Encapsulation	10	50	Encapsulation	326
TOTAL (2017 10^6\$)	**100**	**315**	**TOTAL (2017 10^6\$)**	**1875**

DBFT – Planned Activities

Regional geoscience evaluation

Characterize overburden, fluids, and hydrologic conditions

Characterize disturbed rock zone (DRZ)

Characterize crystalline basement, fluids, and hydrologic conditions

Develop site-specific geologic framework model

Design, drill, and construct CB

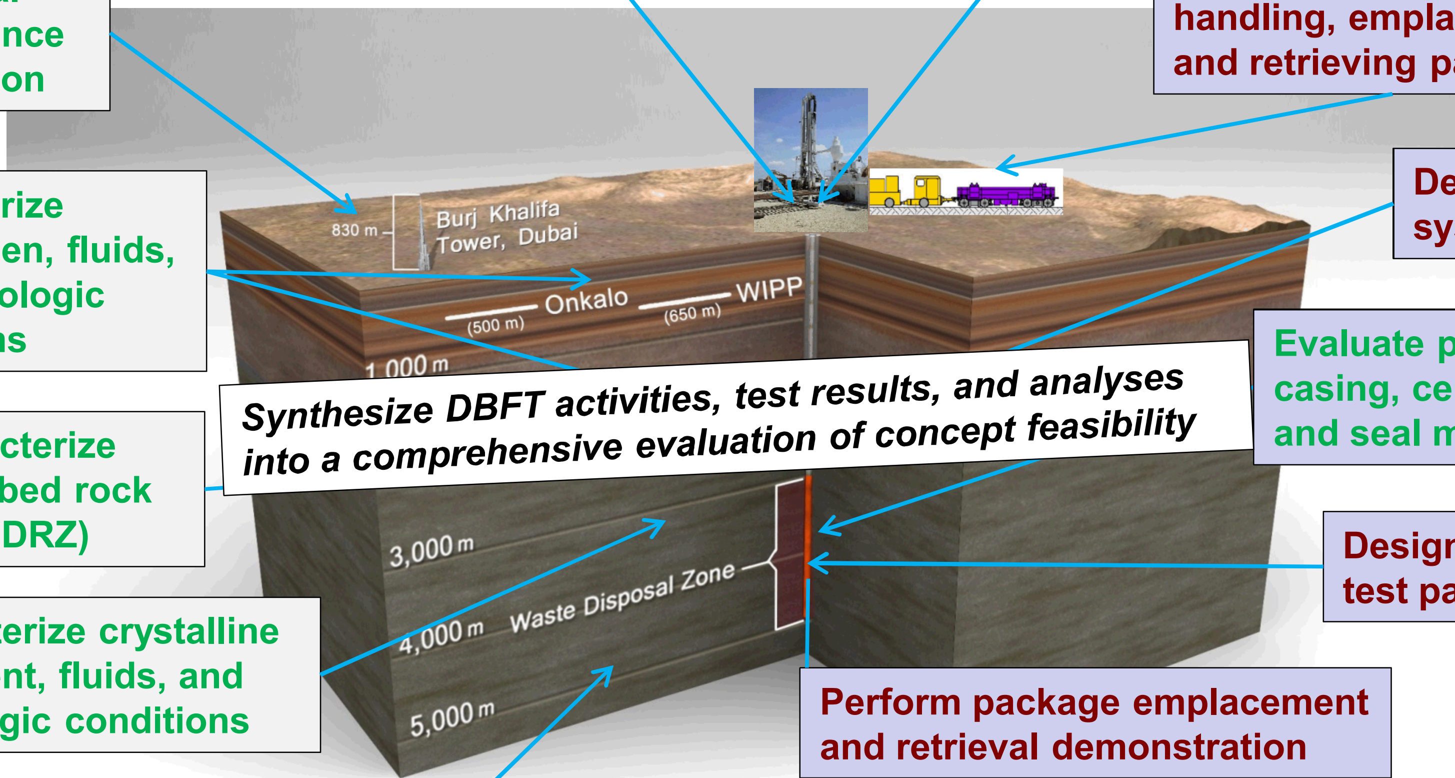
Design, drill, and construct FTB

Develop systems for handling, emplacing, and retrieving packages

Design seal system

Evaluate package, casing, cement, and seal materials

Design and test packages



Synthesize DBFT activities, test results, and analyses into a comprehensive evaluation of concept feasibility

Perform package emplacement and retrieval demonstration

Assess post-closure safety

Assess pre-closure safety

Estimated Costs for a DB Field Test

Work Scope Element	FY1	FY2	FY3	FY4	FY5	FY6	Total
Site Evaluation	1.9	2.4	1.2				**5.5**
Characterization Borehole (0.22 m BHD) (Site Management, Design, Drilling, and Testing)	1.2	16.0	13.8	2.8			**33.8**
Deep Borehole Disposal System Analysis (Post Closure)	0.3	0.4	0.4	0.5			**1.6**
Project Management	0.40	1.2	1.2	0.6			**3.4**
Field Test Borehole (0.43 m BHD) (Site Management, Design, and Drilling)	0.4	0.3	3.3	13.5	13.2	0.7	**31.4**
Emplacement System (Design, Packaging, Emplacement System Components, and Demonstration)	1.9	1.2	1.9	3.3	4.4	2.5	**15.2**
Deep Borehole Disposal System Analysis (Pre-Closure)					1.0	1.0	**2.0**
Project Management				0.6	1.2	1.2	**3.0**
Total	**6.1**	**21.5**	**21.8**	**21.3**	**19.3**	**4.9**	**95.9**

~ $44 M USD

~ $52 M USD

Summary

- No show stoppers have been identified, although assessment of existing geologic data is preliminary and based on existing data
- A characterization borehole will be required to evaluate feasibility of deep borehole disposal
- Estimated costs of DBD and DGR indicate that DBD is cheaper by a factor of ~ 3 to 6
- A deep borehole field test is estimated to cost
  - $45 M (USD) for a characterization borehole construction, and data collection and analysis
  - $52 M (USD) for demonstration borehole, emplacement system, operations, and analysis
- NNSA labs need funding to develop specific plan and costs for decision makers

Backup Slides

DBD Siting Guidelines – Technical Factors

Freeze et al. (2016, Section 3.2.1.2), DOE (2016)

- Depth
  - crystalline basement ≤ 2,000 m
- Nature of Crystalline Basement Fabric and Stress State
  - lack of steeply dipping foliation or layering
  - low horizontal differential stress
- Absence of Regional Structures, Basement Shear Zones, and Other Tectonic Features
  - within 50 km of site
- Lack of Groundwater Flow at Depth
  - conditions/features might include, for example:
    - lack of significant topographic relief that would drive deep recharge
    - evidence of ancient groundwater at depth
    - data suggesting high-salinity groundwater at depth

DBD Siting Guidelines – Technical Factors

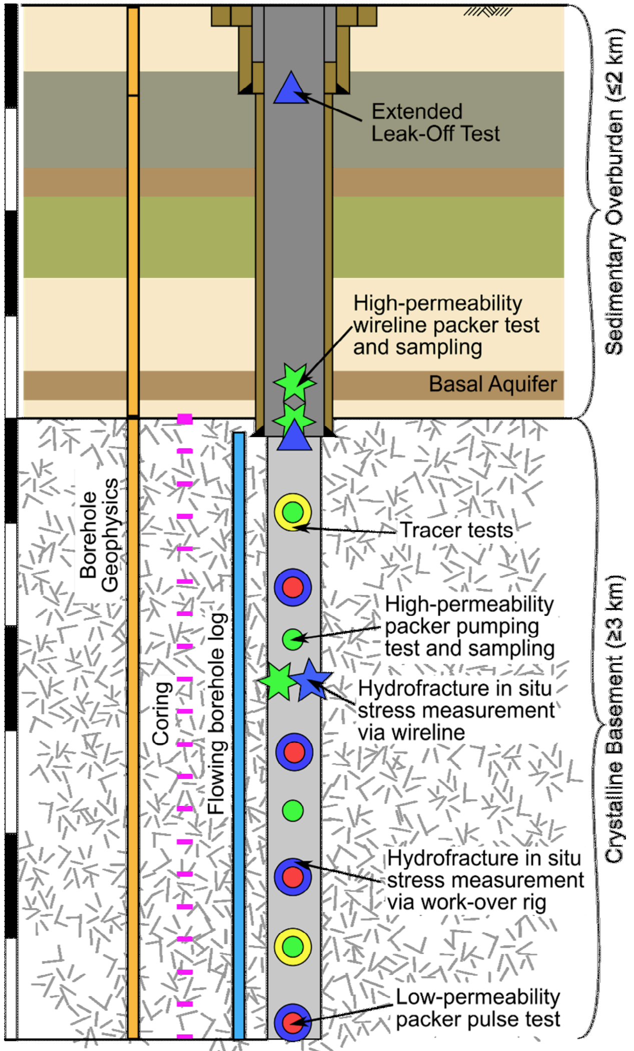
- Favorable Geochemical Environment at Depth
  - high-salinity, increasing with depth to produce stable density stratification
  - geochemically-reducing conditions
- Low Geothermal Heat Flux
  - ≤ 75 mW/m^2
- Low Probability of Seismic/Tectonic/Volcanic Activity
  - less than 2% probability within 50 years of peak ground acceleration > 0.16 g
  - distance to Quaternary age volcanism or faulting > 10 km
- Absence of Natural Resources Potential or Interfering Conditions
  - resource exploration and/or production might include, for example, drilling or mining for petroleum, minerals, or water
  - interfering conditions might include, for example, wastewater disposal by deep well injection, CO_2 injection, strategic petroleum reserve sites

DBFT Objective – Testing and Sampling Plan

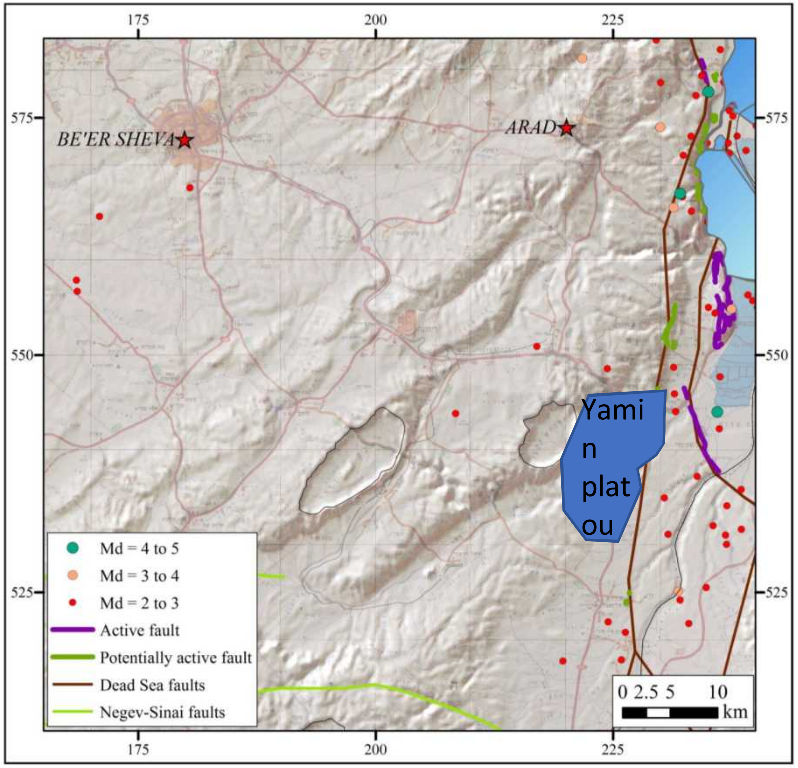
SNL (2016b)

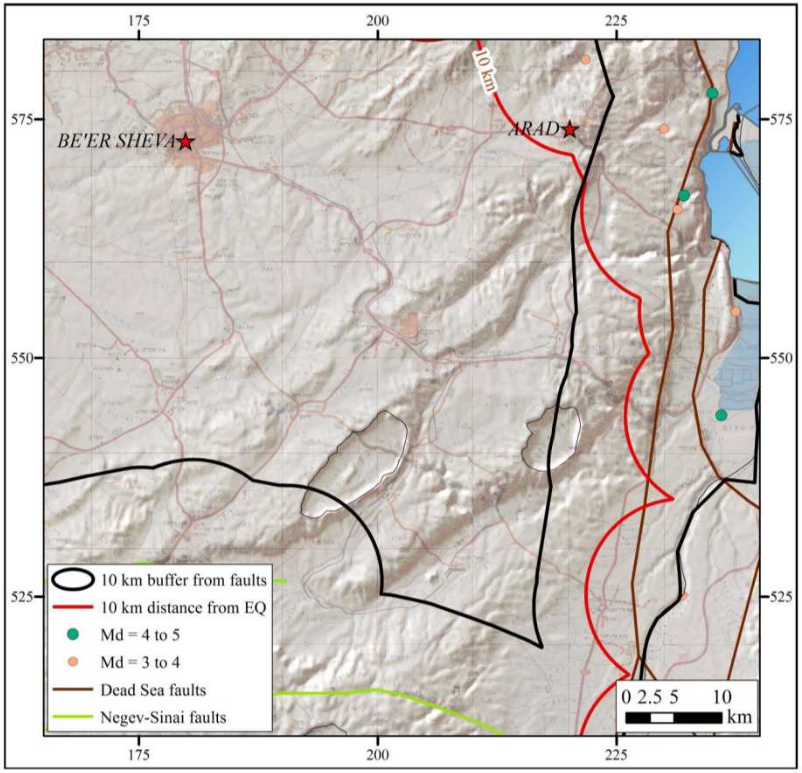
- During Drilling (in CB)
  - Coring
  - Borehole Geophysics
  - Sampling
    - Fluid density/temperature/major ions
      - Samples pumped from high-permeability regions
      - Samples from cores in low-permeability regions
- After Drilling (in CB)
  - Flowing Fluid Electrical Conductivity (FFEC) Log
  - In Situ Packer Testing
    - Hydrologic and tracer tests
      - Formation hydraulic/transport properties
    - Hydraulic fracturing tests
      - In situ stress (breakouts)
  - Workable at 50 MPa / 150°C / 4 km tubing?

Characterization Borehole (CB)



Source: SNL 2016b, Figure 3





Active faults (purple) and earth-quake locations (Calvo 2015)

10 km buffer from earthquake with a magnitudes over 3 in the Yamin plateau area(Calvo 2015)

US DBD Concept – Safety and Feasibility

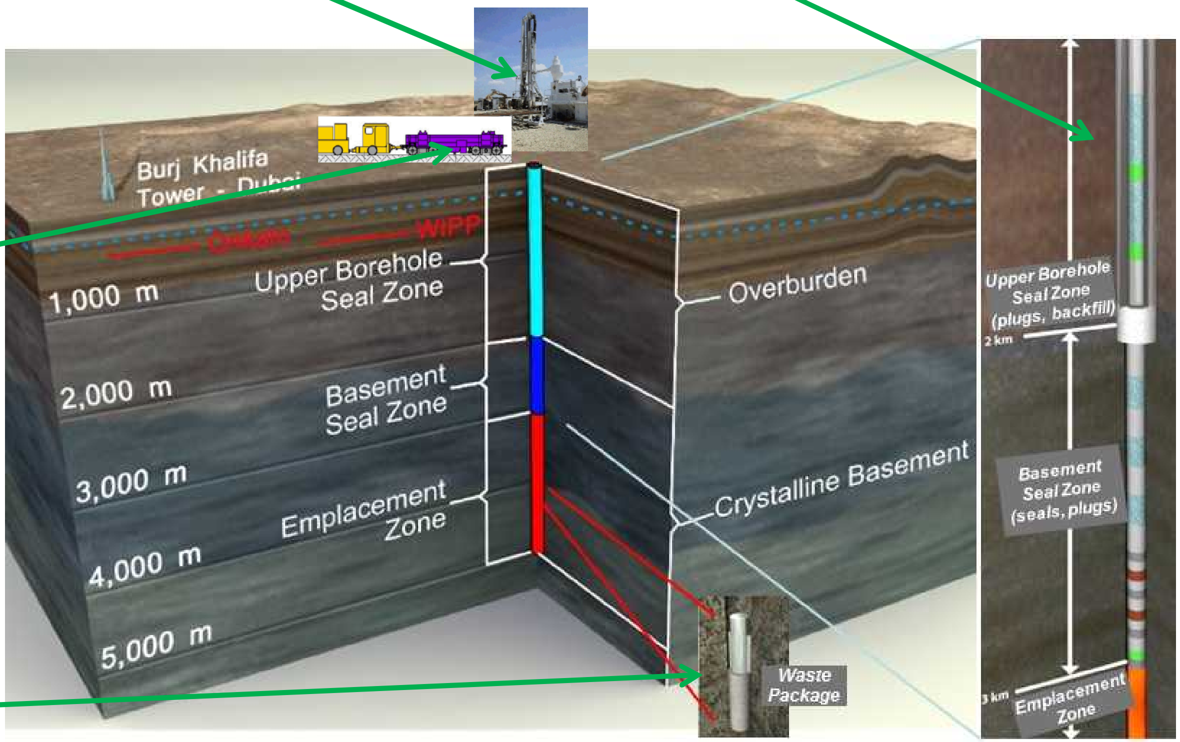
(Pre-Closure Engineering and Operations)

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

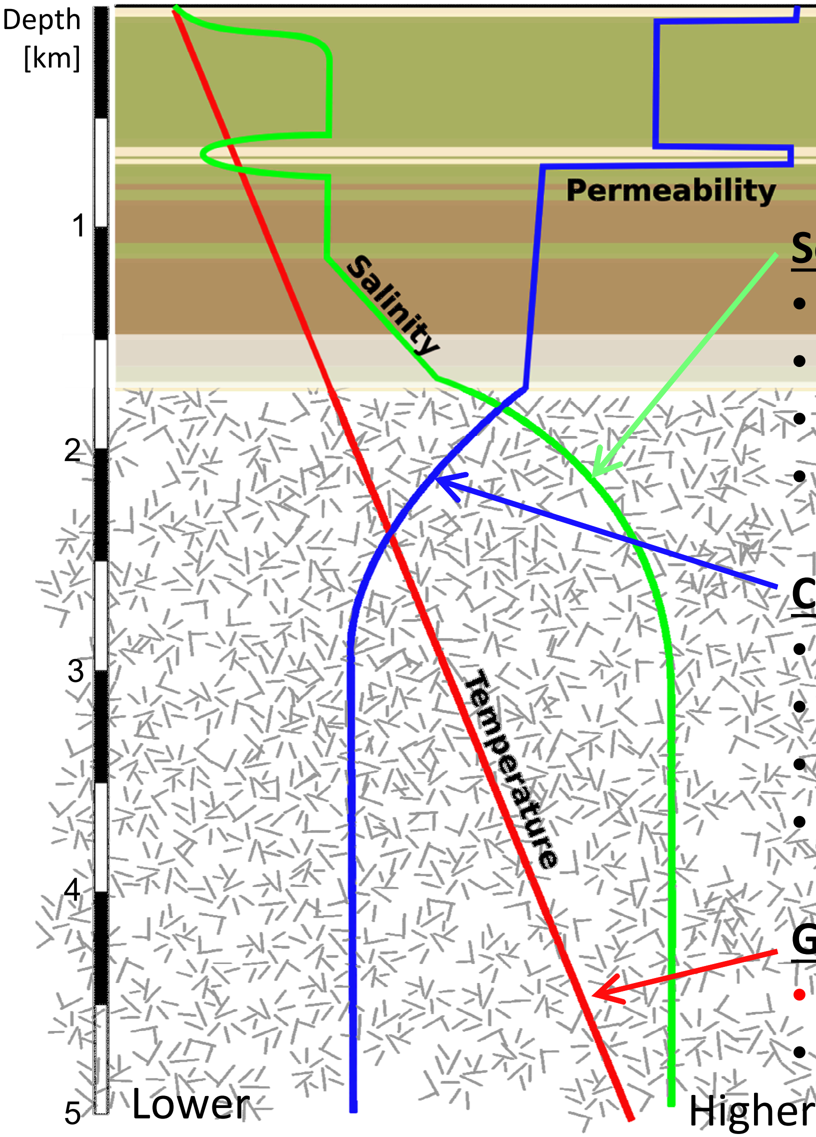
Borehole and Casing Design maintains borehole integrity (against borehole breakout) and minimizes probability of waste packages becoming stuck during emplacement

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 – Geologic THC Profiles



Sources of Salinity
- Evaporite dissolution
- H_2O-rock interactions
- Ancient seawater
- Fluid inclusions

Controls on Permeability
- Increasing confining stress
- Fracture zones
- Mineral precipitation
- Overpressure → hydrofracture

Geothermal Gradient
- Radioactive decay
- Regional heat flux

Sedimentary Overburden ≤ 2 km

Crystalline Basement ≥ 3 km

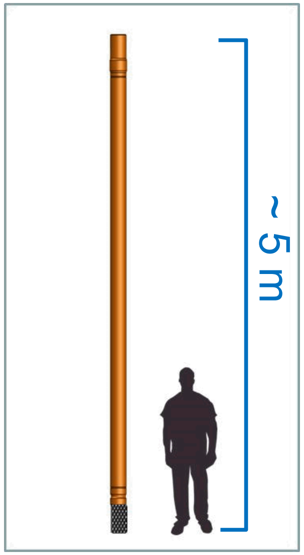
Deep Borehole Field Test (DBFT)

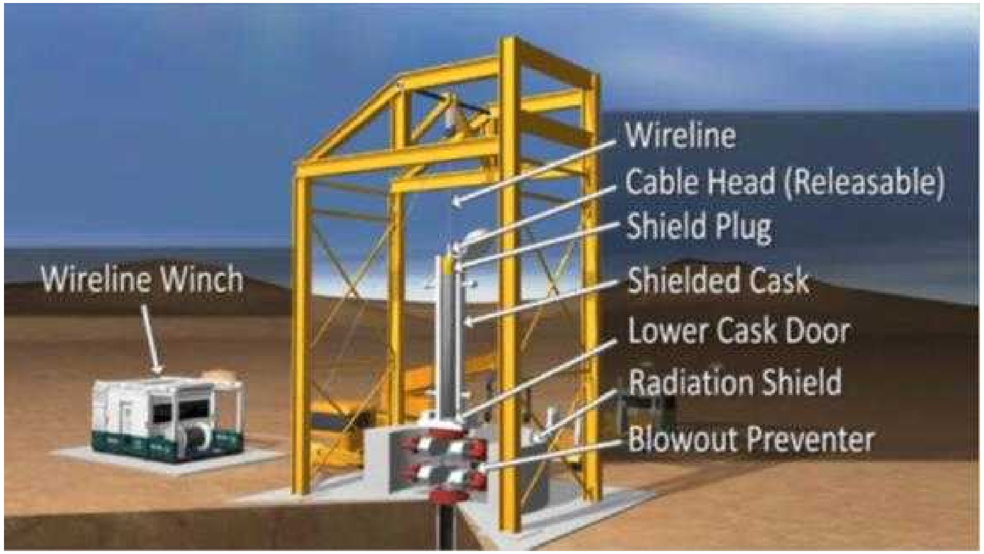
- Planned to improve scientific understanding of the DBD concept
  - Drill two boreholes to a depth of 5,000 m in a suitable location
    - Characterization Borehole (CB): 8.5 in. (22 cm) @ TD
    - Field Test Borehole (FTB): 17 in. (43 cm) @ TD
- DBFT Objectives (further details in later slides):
  - Demonstrate technology to drill deep, wide, straight boreholes (CB + FTB)
  - Evaluate the feasibility of characterizing deep boreholes (CB)
    - Testing deep formations in situ
    - Sampling for deep geochemical profiles
  - Demonstrate safe operations for downhole package emplacement and retrieval (FTB)
    - Without emplacement of radioactive wastes
  - Investigate seal design and performance
    - Laboratory studies of methodologies, designs, and material behaviors
  - Perform modeling and analyses to support a preliminary DBD safety case

DBFT Objective – Safe Package Emplacement

SNL (2015); SNL (2016a)

- Demonstrate downhole package emplacement and retrieval (in FTB)
  - Wireline Emplacement
    - Design and fabricate test packages
    - Design surface package handling components and facilities
  - Emplacement Demonstration
    - Demonstrate shielded surface operations where practical
    - Lower and retrieve one test package at a time

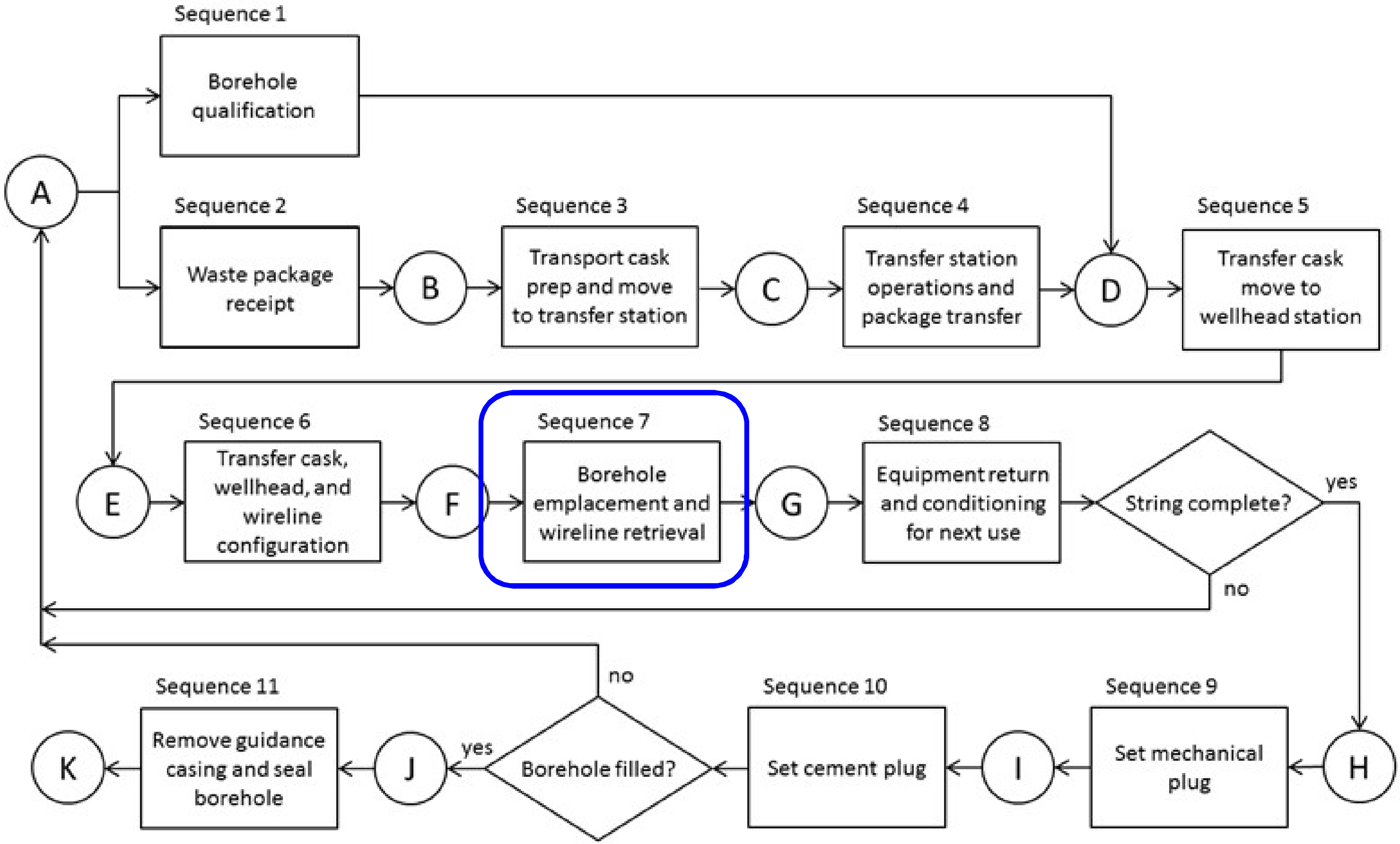




DBD Pre-Closure Safety Analysis (PCSA)

Hardin et al. (2017a)

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



Source: Hardin et al. 2017a, Figure 1

DBD PCSA – Wireline Emplacement Event Tree

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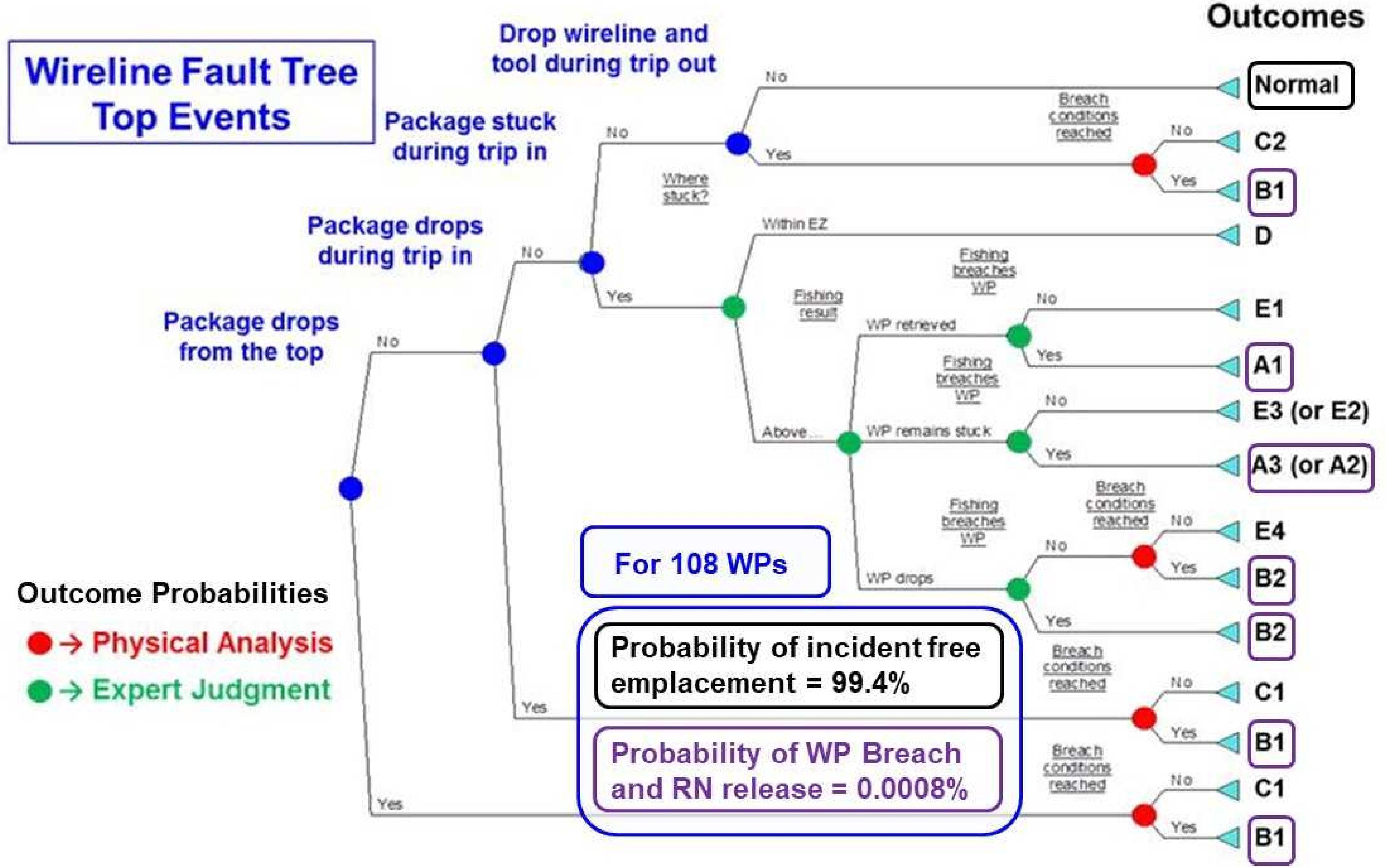
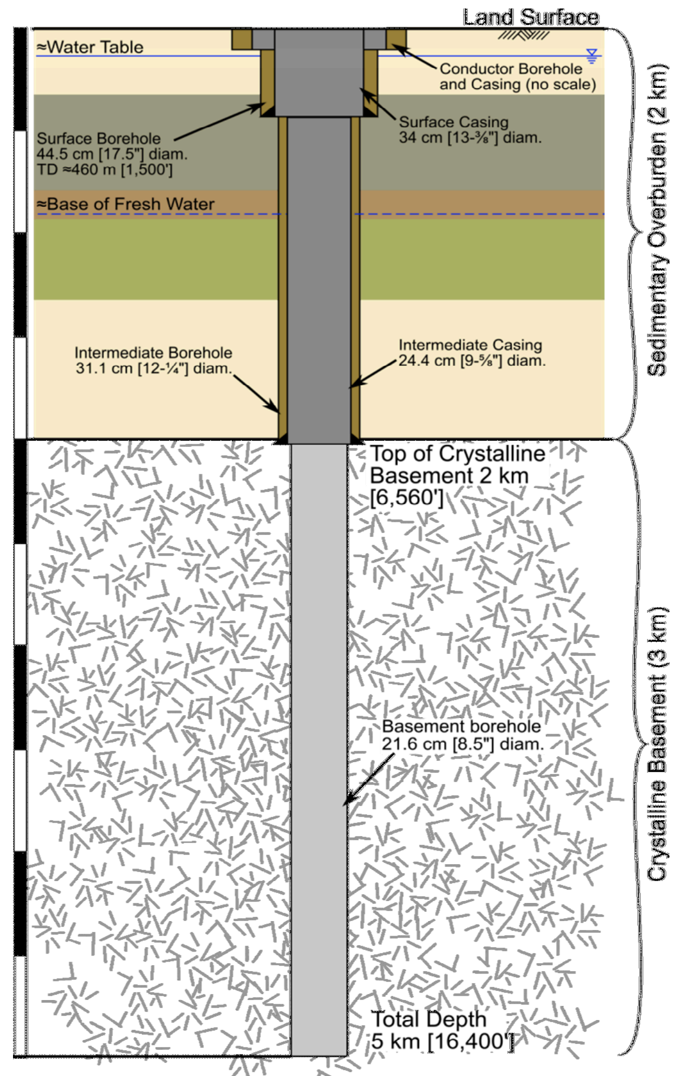
Freeze et al. (2016, Section 5.1), SNL (2016b)



DBFT – Characterization Borehole (CB)

- Drill and case sedimentary section
  - minimal testing (not DBFT focus)
- Drill crystalline basement section
  - logging while drilling
  - borehole geophysics
  - rock samples (coring, cuttings/rock flour)
  - pore fluid samples (high-k and low-k zones)
  - testing while drilling (hydrofracture tests)
  - flowing borehole log
- Test crystalline basement section
  - packer shut-in tests (low-k zones)
  - packer pumping tests (high-k zones)
  - tracer tests

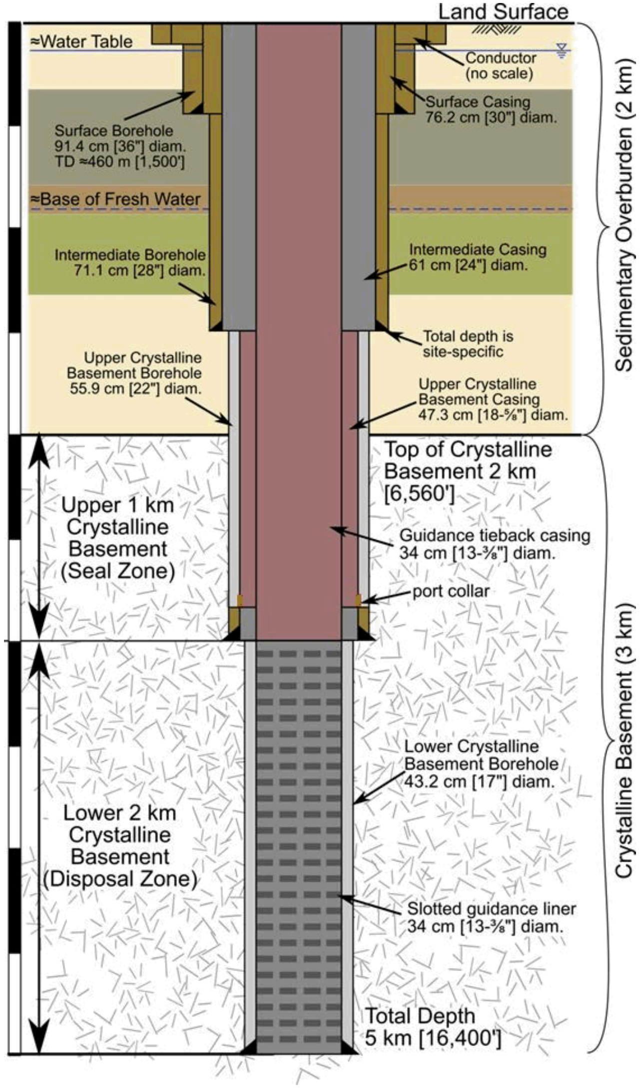


Kuhlman et al. (2015)

Dark gray represents permanent casing or liner, olive represents cemented annulus, light gray represents uncemented borehole.

DBFT – Field Test Borehole (FTB)

- Drill and case sedimentary section
- Drill upper crystalline basement (Seal Zone)
  - minimal, confirmatory testing
  - install temporary liner
    - liner to be removed after package emplacement for effective seal
- Drill lower crystalline basement (Emplacement Zone)
  - install slotted/perforated guidance liner
- Install temporary guidance tieback casing
  - constant diameter emplacement pathway



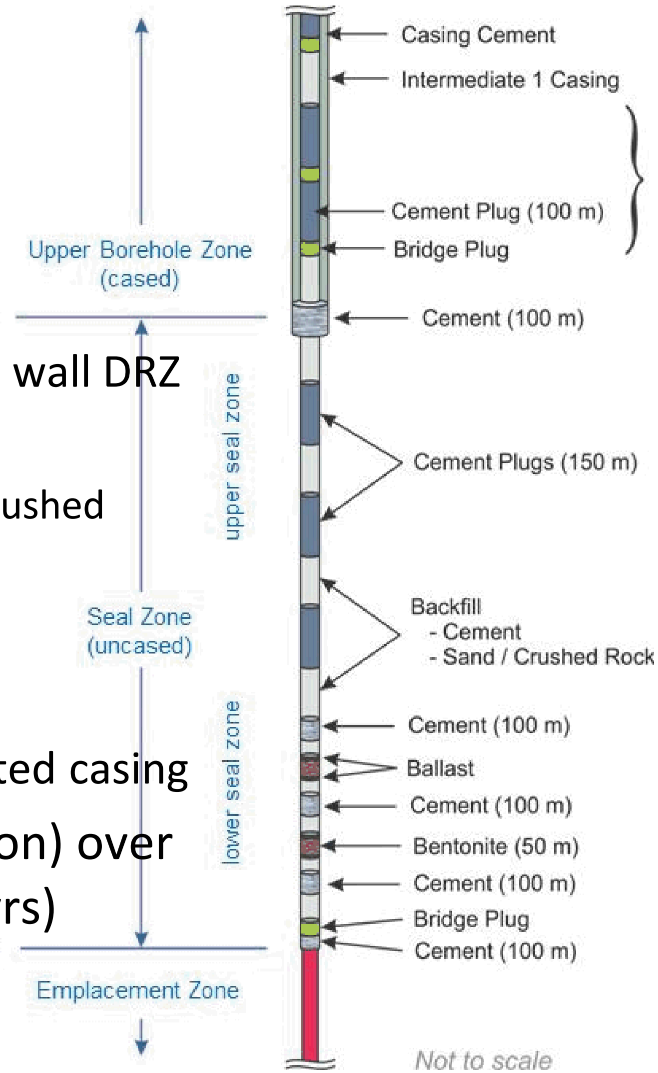
Kuhlman et al. (2015)

Dark gray represents permanent casing or liner, olive represents cemented annulus, light gray represents uncemented borehole, pink represents casing/liner to be removed.

DBFT Objective – Seal Design

Freeze et al. (2016)

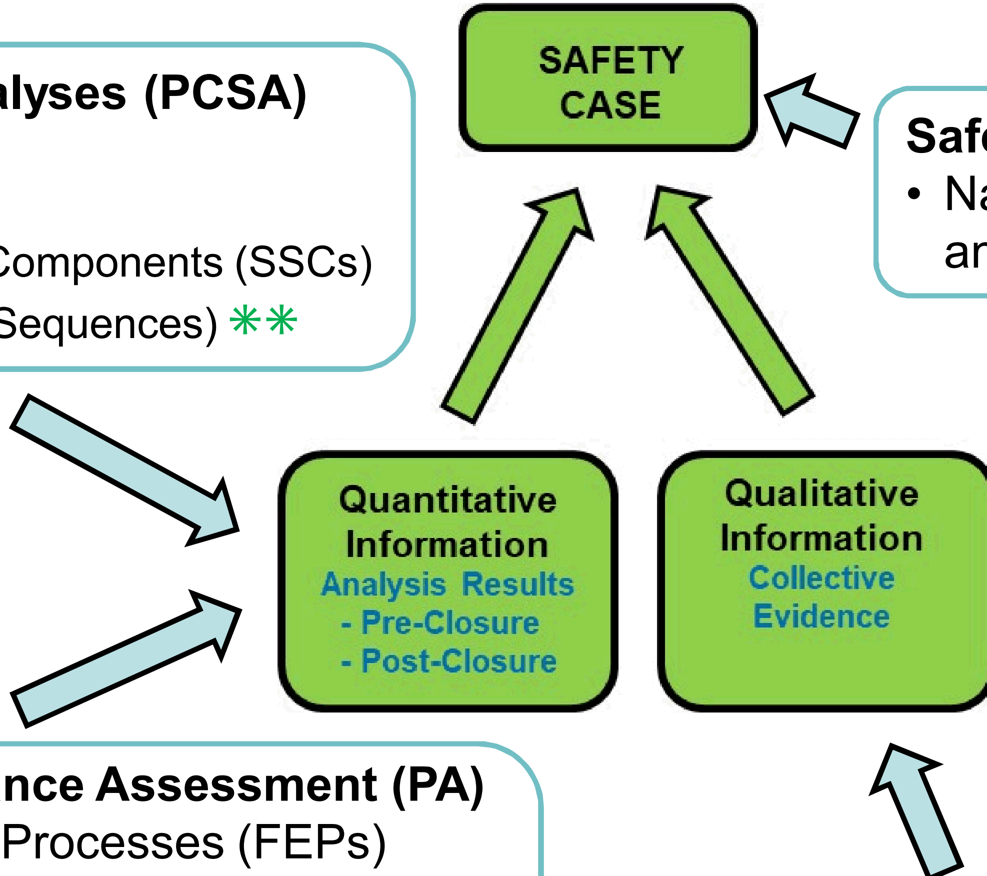
- Preliminary reference design
  - Seal Zone (SZ)
    - Entirely within competent basement rock
    - Seals and plugs emplaced directly against borehole wall DRZ
    - Alternating sequence of materials
      - bentonite seals, cement plugs, ballast (silica sand/crushed rock)
  - Upper Borehole Zone (UBZ)
    - Primarily within sediments
    - Cement plugs and ballast emplaced against cemented casing
  - Seal materials maintain integrity (some degradation) over period of thermally-induced upward flow ($\leq$ 500 yrs)
- Other potential sealing methods
  - Ceramic plugs
  - Rock welding



DBFT Objective – 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