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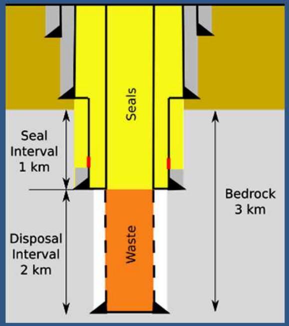

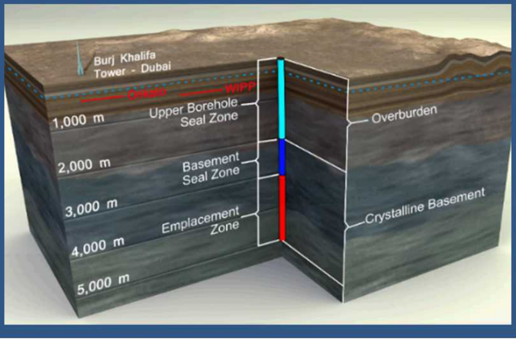

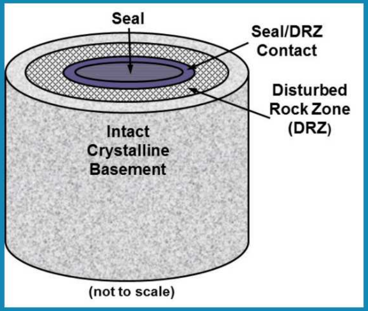

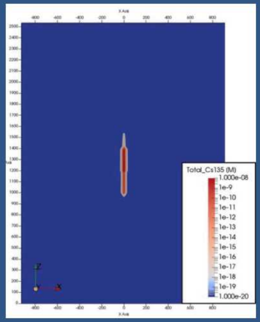

Borehole Disposal of Radioactive Waste in Israel

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Outline

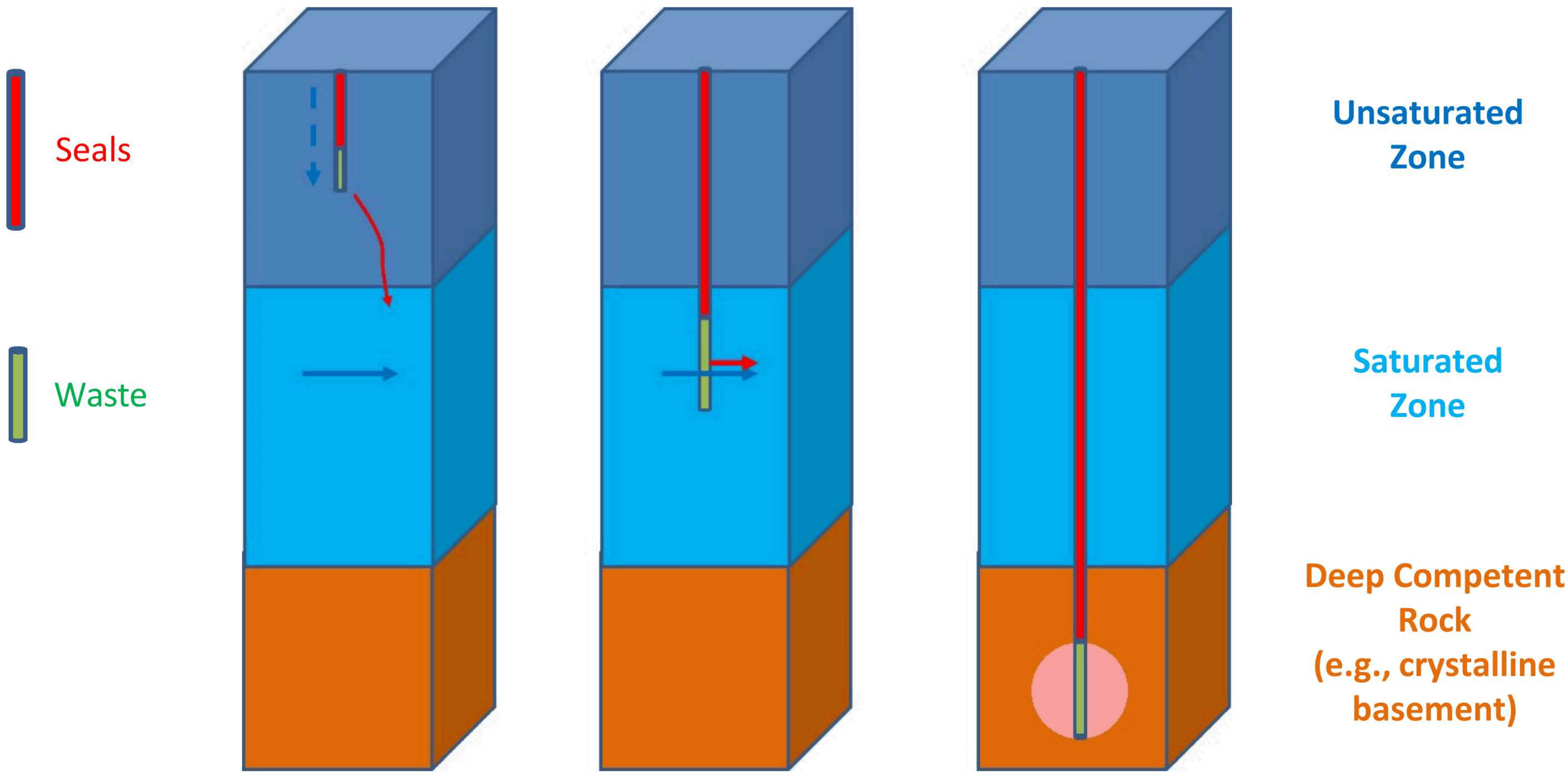
- Borehole Disposal Overview
  - Concepts
  - Safety and Feasibility
- Intermediate Depth Borehole Disposal in Israel
  - Disposal Concept
  - Lessons Learned from Relevant Projects
  - Path Forward
- Summary and Conclusions

Borehole Disposal Concepts

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

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

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



Borehole Disposal Concepts

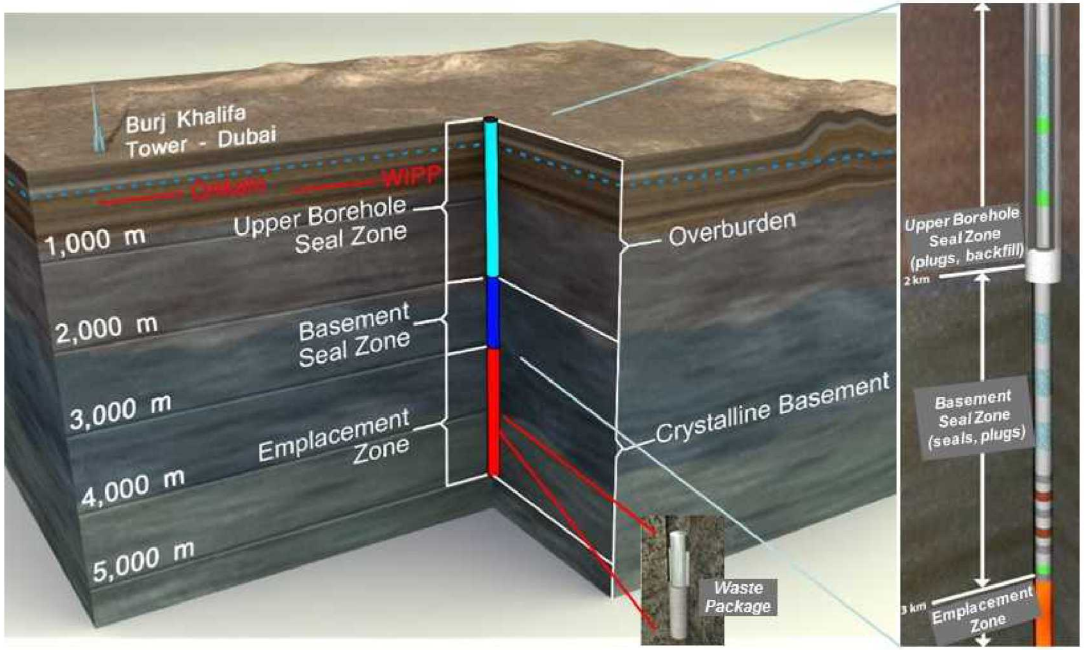
- Designs have been proposed by Beswick et al. (2014) and Rigali et al. (2016)

Depth (m)	Hole Diameter (in. / m)	Casing Diameter (in. / m)
0-50	60 / 1.52	54 / 1.37
50-1500	48 / 1.22	40 / 1.02
1500-2500	36 / 0.91	30 / 0.76
2500-5000	24-26 / 0.61-0.66	20 / 0.51

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 and sealing needs to be demonstrated demonstrated and seal placement

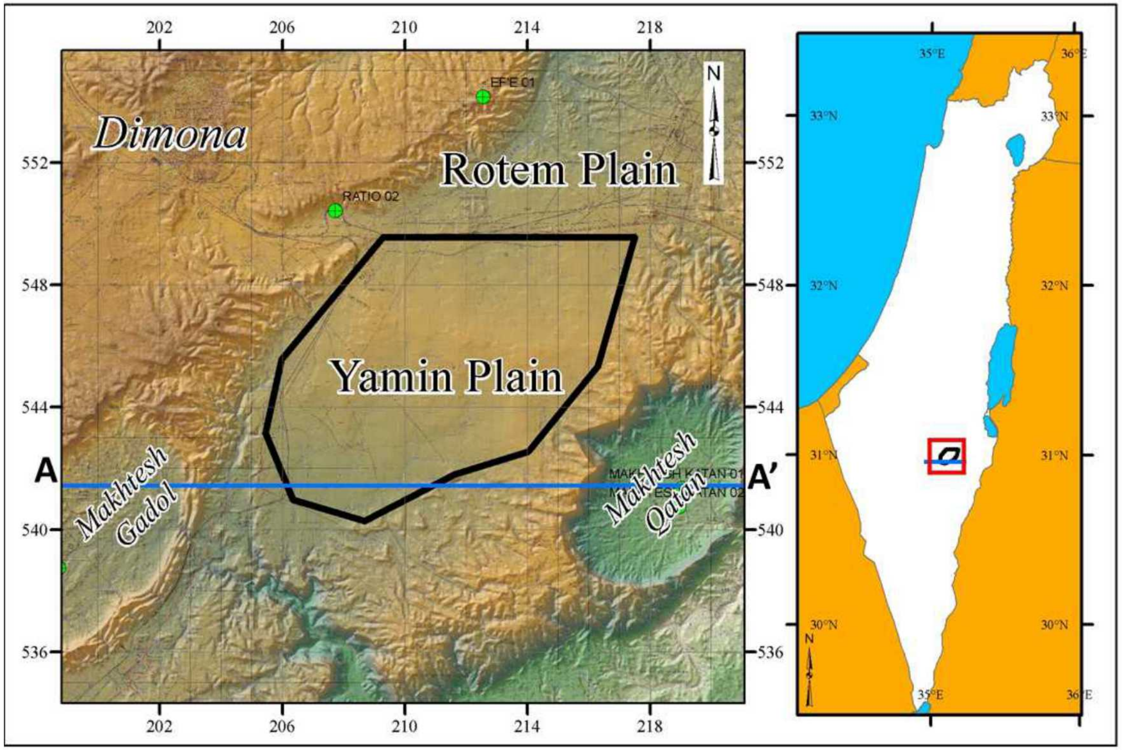


Intermediate-depth borehole disposal (IBD)

- 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, waste emplacement, and sealing may be simpler

Intermediate Depth Borehole Disposal (IDB) Concept in Israel

- Borehole (or array of boreholes) in the alluvial Yamin Plain region in the Negev Desert in south-central Israel (Dody et al. 2017)
  - Yamin Plain is located between two erosional craters (makhteshs)
  - Yamin Plain is located > 10 km from Dead Sea Fault Zone
  - Annual precipitation [72 mm (2.8 in)] << annual evapotranspiration [~2,600 mm (~100 in)]

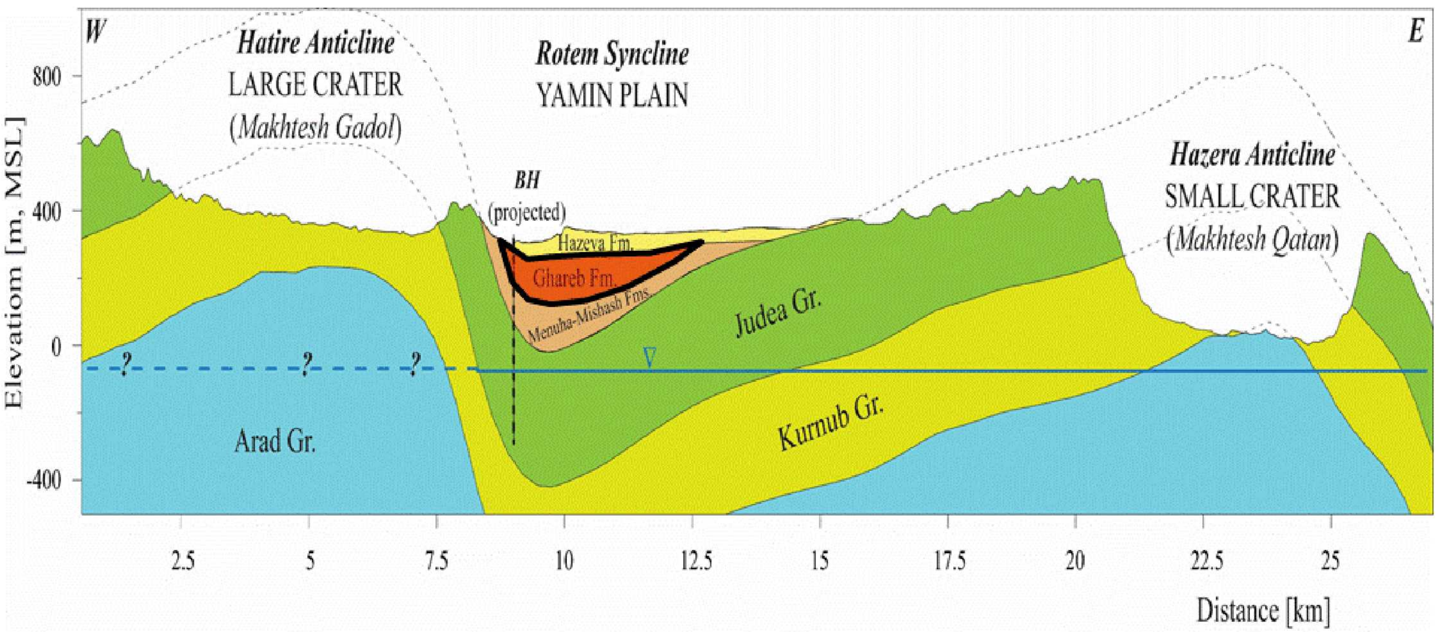


IDB Concept in Israel

- Stratigraphy is influenced by Syrian Arch fold system

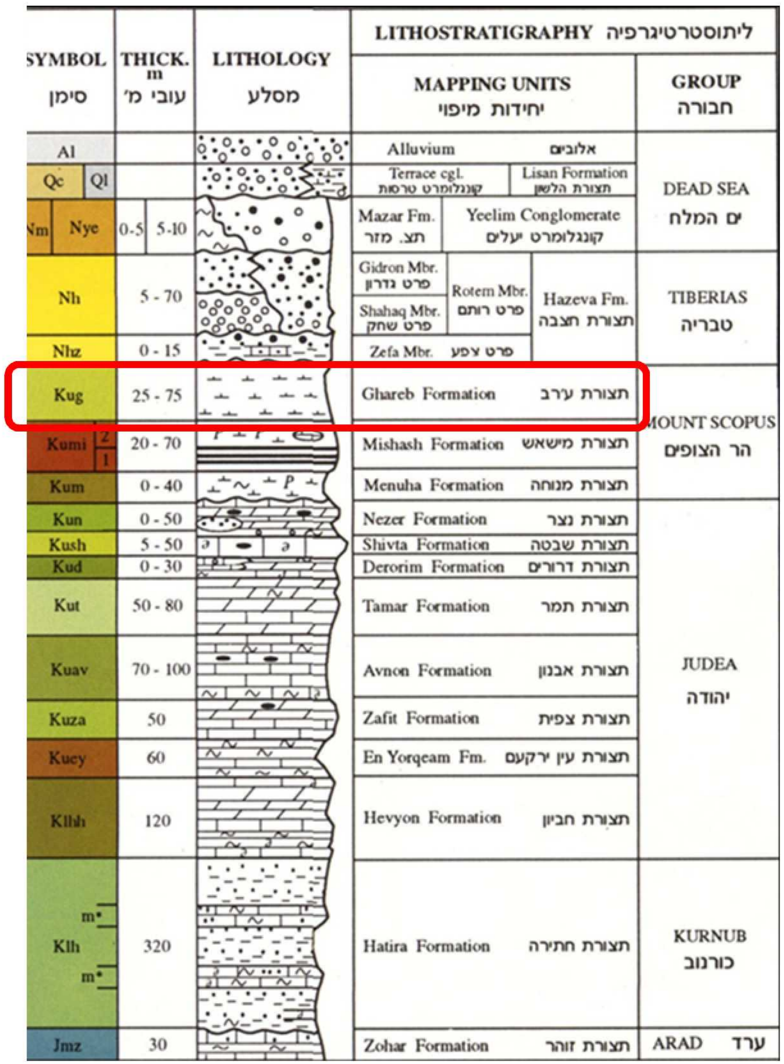
  Hirsch (1995), Minster (1996), Calvo et al. (2019)

- Water table depth is ~550 m
- Disposal borehole to the base of the Ghareb Formation (~200-300 m)
  - Disposal Zone ~100 m thick within the unsaturated Ghareb Fm.
    - low permeability chalk, bituminous marl (k = 10^{-17} – 10^{-15} m^2, Φ =0.30-0.40)
  - Seal Zone ~ 100-200 m thick in the Hazeva Fm.
    - sandstone, conglomerate, shale (k = 10^{-17} – 10^{-12} m^2 , Φ =0.10-0.20)



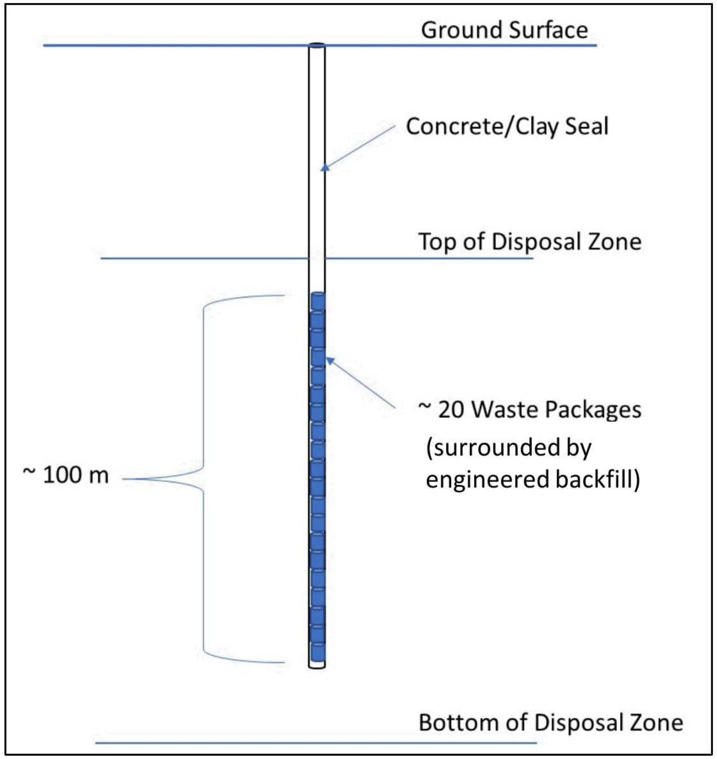
IDB Concept in Israel

- Subsurface characterization is ongoing
  - Lithology
  - Hydrologic properties (e.g., permeability, porosity, underlying aquifers)
  - Geochemistry (e.g., major elements)
  - Mechanical properties (e.g., stress regime)
  - Heat and geothermal gradients
  - Gravity and magnetic signals
  - Seismic hazards
  - Natural resource potential
    - Oil shale, phosphates
- Characterization borehole is planned



IDB Concept in Israel

- Emplacement within the unsaturated Ghareb Formation
  - Large diameter planned, depending on depth
  - Each WP surrounded by backfill or cement
    - structural support and waste isolation
- Seals will be alternating layers of bentonite, cement, geomaterials
- Viability of the IDB concept is informed by lessons learned from:
  - Spent Fuel Test - Climax Mine
  - Greater Confinement Disposal (GCD) Facility
  - US DOE Deep Borehole Field Test (DBFT)
  - Shallow disposal of disused sealed radioactive sources (SRS)



(not to scale)

IDB Lessons Learned - Operational

- Spent Fuel Test - Climax Mine (1978-1985)

  DOE (1980), Patrick (1986), SNL (2016)

  - Demonstration of commercial spent nuclear fuel (SNF) surface handling and wireline emplacement
    - 11 canisters (diameter = 0.36 m (14 in), length = 4.6 m (15 ft))
  - Lowered 427 m through a 0.51 m (20 in) cased borehole and retrieved 3.5 years later

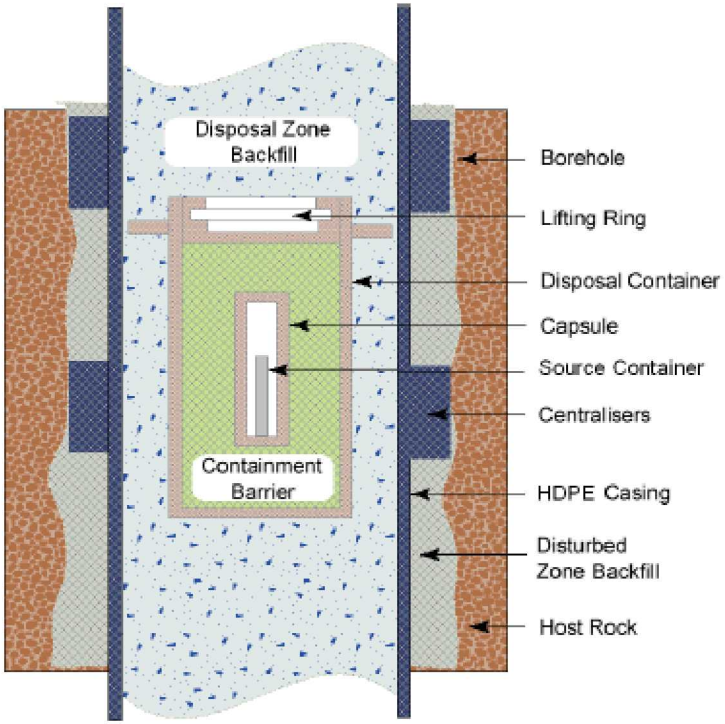
- US DOE Deep Borehole Field Test (DBFT) R&D (2014-2017)

  SNL (2016), Freeze et al. (2016), Hardin et al. (2019)

  - Waste package design
  - Surface waste handling with shielding
  - Downhole emplacement methods
  - Borehole sealing concepts

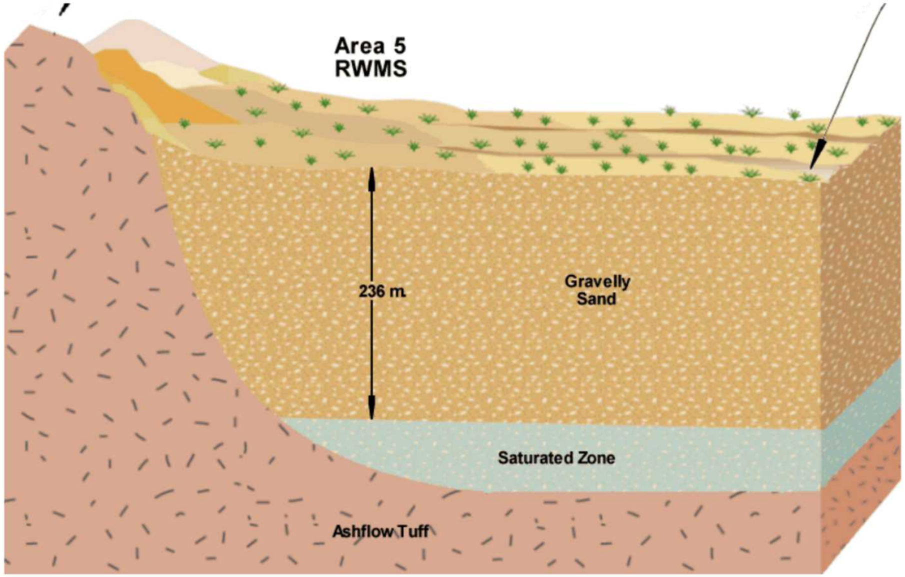
IDB Lessons Learned –
Disused Sealed Radioactive Sources (SRS)

- Endorsed by IAEA (IAEA 2017), summarized by Cochran et al. (2018)
  - Shallow depth (~100-200 m)
  - Small diameter (0.26 m / ~10 in)
  - Safe and secure isolation for 1000s of years using engineered multi-barrier SRS containers
  - Includes consideration of transportation and operations



IDB Lessons Learned – Greater Confinement Disposal (GCD) Facility

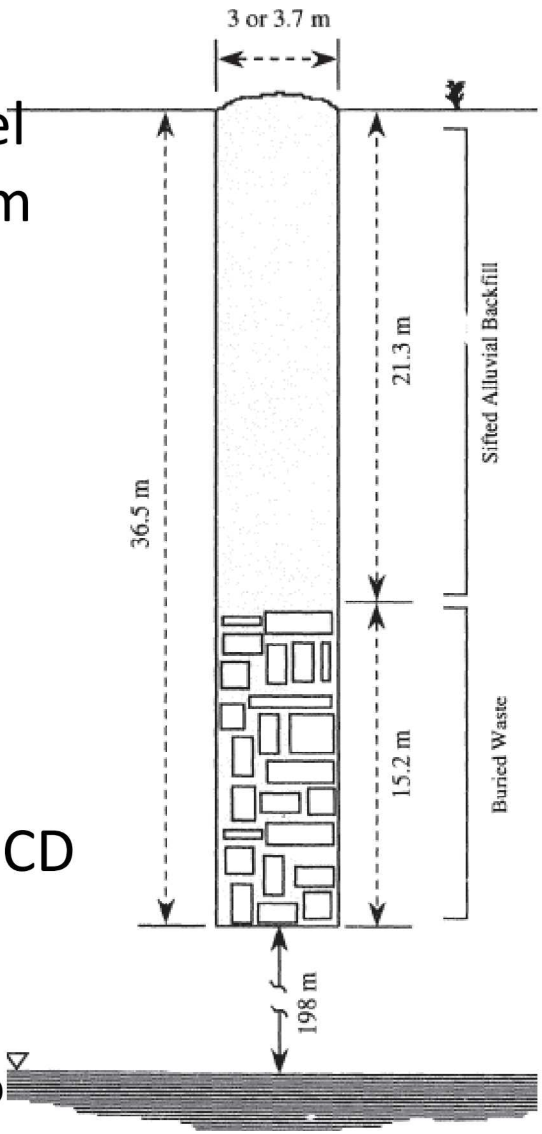
- GCD facility developed in the 1980s by the U.S. Department of Energy (DOE) at the Nevada National Security Site (NNSS)
  - Arid climate (112 mm/yr)
  - Deep groundwater (~235 m to groundwater)
  - Deep structural basin filled with alluvium (sand and gravel)
  - Remote location / low population densities
  - Government owned land



IDB Post-Closure Lesson Learned – Greater Confinement Disposal (GCD) Facility

DOE (1989), Price (1994), Cochran et al. (2001)

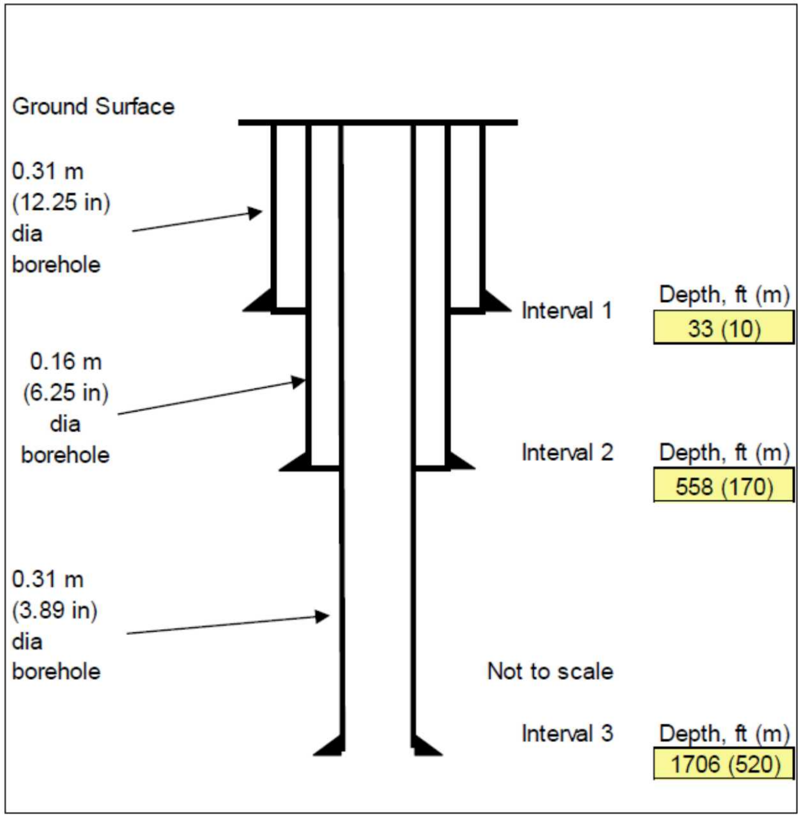
- Used to dispose of high specific-activity low-level wastes, intermediate-level wastes, and SRSs from 1984-1989
- Large number of studies to test concept
  - waste handling and placement, operational safety, rad protection, monitoring, test borehole
- 13 large-diameter boreholes
  - diameter = 3 m, depth = 36 m
  - backfilled with alluvial materials using a tremie pipe
- The arid climate and deep groundwater at the GCD site provided a high degree of containment potential
  - Negligible liquid water movement, slow upward flux to root zone



(not to scale) (Price, 1994)

IDB Concept in Israel – Path Forward

- Assess the suitability of the vadose zone in the Yamin Plain for IBD
  - Continued surface-based characterization
- Develop a preliminary plan, including resources and costs, for a small-diameter characterization borehole
  - drilled to the depth of the regional water table
  - better understanding of the geomechanical and hydrogeochemical properties and percolation flux of the vadose zone
- Refine concepts for a disposal borehole
  - preliminary schedule, resources and costs



Summary and Conclusions

- Preliminary studies of the feasibility of IBD of radioactive waste in the vadose zone of the Yamin Plain in Israel have been conducted
  - A conceptual IBD design has been developed based on existing available surface and subsurface information on geology, stratigraphy, rock petrophysics and mechanics, hydrology, seismicity, igneous activity, and natural resources
- Additional information is needed
  - A characterization borehole can provide additional relevant information to better understand geomechanical and hydrogeochemical properties and percolation flux of the vadose zone
  - Research on surface handling and emplacement and sealing methods is needed
  - The information can then be synthesized to integrate the natural and engineered barriers and develop a post-closure safety assessment for the IBD concept

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