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Deep Borehole Disposal for Small Programs: Enabling Technologies

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Panel: Waste Disposal Options for Small Volumes of Waste Requiring Disposal at Depth

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National Nuclear Security Administration

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Enabling Technology Developments

- Drilling capabilities
- Groundwater characterization technology
  - Isotopic sampling and analysis
  - Modeling and simulation
- Waste package emplacement methods

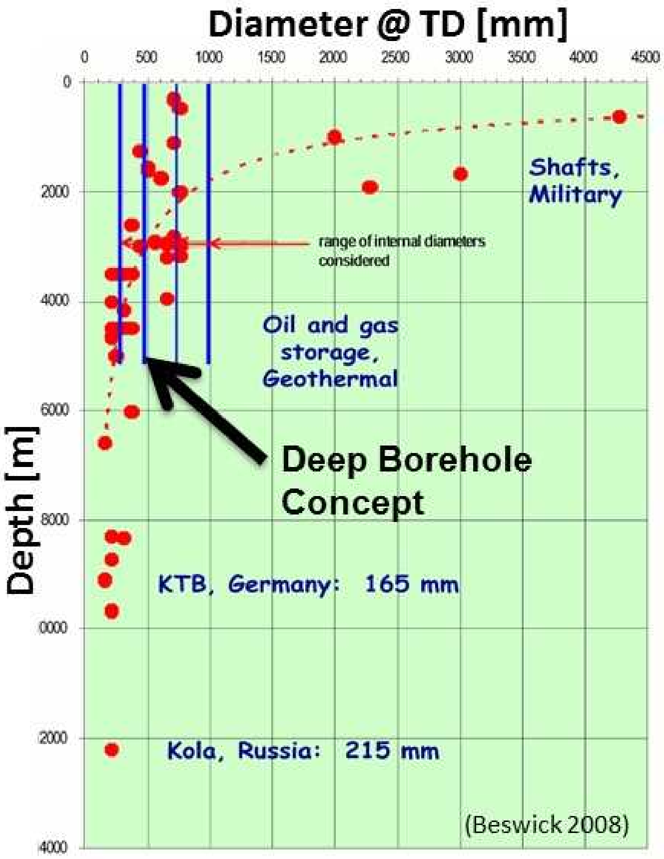
Deep Drilling Experience

"Scientific Boreholes" in Hard Rock

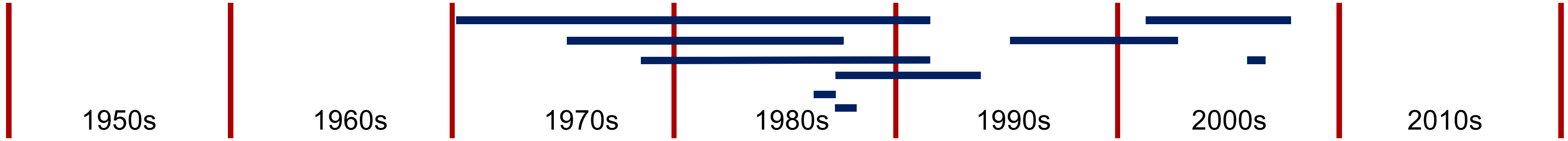
Site	Location	Years	Depth [km]	Diam. * [in]	Purpose
Kola SG-3	NW USSR	1970-1992	12.2	8½	Geologic Exploration + Tech. Development
Fenton Hill	New Mexico	1975-1987	4.6	9⅞	Enhanced Geothermal
Urach-3	SW Germany	1978-1992	4.4	5½	Enhanced Geothermal
Gravberg	Sweden	1986-1987	6.6	6½	Gas Wildcat
Cajon Pass	S California	1987-1988	3.5	6¼	Geologic Exploration
KTB	SE Germany	1987-1994	9.1	6½	Geologic Exploration + Tech. Development
Soultz-sous-Forêts GPK	NE France	1995-2003	5.3	9⅝	Enhanced Geothermal
SAFOD	Central California	2002-2007	4 (3)#	8¾	Geology Exploration
Basel-1	Switzerland	2006	5	8½	Enhanced Geothermal

* borehole diameter at total depth

\# true vertical depth



(Beswick 2008)



Developments in Deep Drilling

- Rig capacity
- Safety performance
- Top-head drive & automated pipe handling
- Directional drilling (vertical & horizontal)
- Measurement-while-drilling
- Coiled tubing & tools
- Improved electric wireline & tools
- "Managed pressure" drilling

Deep Borehole Disposal Isolation Strategy

Questions:

- How do hypersaline, ancient brines form in the crystalline basement?
- Why do they persist for so long?
- What does ancient age tell us about potential contaminant transport times to the biosphere?

Possible Origins of Hypersaline Crystalline Basement Brine:

- Marine (need some concentration or augmentation process to concentrate)
- Evaporite dissolution (has distinctive high Cl/Br ratio, and salt beds may be far away or low in the geologic section)
- Connate fluids (sedimentary pore fluids that are residues of evaporite precipitation)
- Cryogenic (requires previous marine transgression at the time of brine formation)
- Rock-water interaction
  - H_2O consumption by mineral alteration
  - Fluid inclusions as source for chloride

Interpretations of brine origin are site specific and uncertain…

but brine formation has occurred over geologic time scales, and its occurrence is ubiquitous, so it is evidently stable.

Groundwater Surveys

- Some Recent Studies:
  - J. Lippmann, et al. 2003. “Dating ultra-deep mine waters with noble gases and 36Cl, Witwatersrand Basin, South Africa.” GCA 67(23), pp. 4597–4619.
  - Gascoyne, M. 2004. “Hydrogeochemistry, groundwater ages and sources of salts in a granitic batholith on the Canadian Shield, southeastern Manitoba.” Applied Geochem. 19, pp. 519–560.
  - Greene, S., et al. 2008. “Canadian Shield brine from the Con Mine, Yellowknife, NT, Canada: Noble gas evidence for an evaporated Palaeozoic seawater origin mixed with glacial meltwater and Holocene recharge.” GCA 72, pp. 4008–4019.
  - Holland, G., et al. 2013. “Deep fracture fluids isolated in the crust since the Precambrian era.” Nature 497, pp. 357-362.
  - Kietavainen, R., et al. 2014. “Noble gas residence times of saline waters within crystalline bedrock, Outokumpu Deep Drill Hole, Finland.” GCA 145, pp. 159–174.
  - Concurrent studies by Bottomley, Lehmann, Bethke, Torgerson, Fritz, Frape, Davis, Moran, others
- Themes: groundwater model age from:
  - Long-lived environmental tracers (e.g., ^{81}Kr to > 10^6 yr)
  - Noble gas accumulation and isotopics (He, Ar; also Ne, Xe)
  - Fission product accumulation (^{36}Cl, ^{129}I)
- Supported by brine origin and evolution hypotheses based on:
  - Source fingerprinting and rock-water interaction (Cl/Br, Ca/Na, ^{2}H, ^{18}O, ^{6}Li/^{7}Li, ^{87}Sr/^{86}Sr, etc.)
- Characterization technology is evolving

Noble Gas Interpretation

$$Ng_{tot} = Ng_{eq\text{-}atm} + Ng_{excess} + Ng_{radogenic} + Ng_{fission} + Ng_{terrestrial} + Ng_{mantle}$$

$Ng_{eq\text{-}atm}$	Atmospheric equilibrium (e.g., ^{4}He, ^{3}He)
Ng_{excess}	From air entrained in recharge water
$Ng_{radogenic}$	Most important in situ source (e.g., ^{4}He from U, Th α decay; ^{3}He from $^{6}\text{Li}(n, \alpha)^{3}\text{H}(\beta–)^{3}\text{He}$; ^{40}Ar from ^{40}K decay)
$Ng_{fission}$	Products of spontaneous fission of natural U in situ (e.g., certain Kr and Xe isotopes)
$Ng_{nucleogenic}$	Reactions with neutrons from spontaneous fission of U (e.g., certain Ne isotopes)
$Ng_{terregenic}$	Crustal flux (combining different production mechanisms, mostly radiogenic)
Ng_{mantle}	Mantle flux

Torgerson. "Effects of shield brine on the safe disposal of waste in deep geologic environments." Advances in Water Resources 32, pp. 1352–1358.

Deep Borehole Field Test Borehole Sampling Objectives:

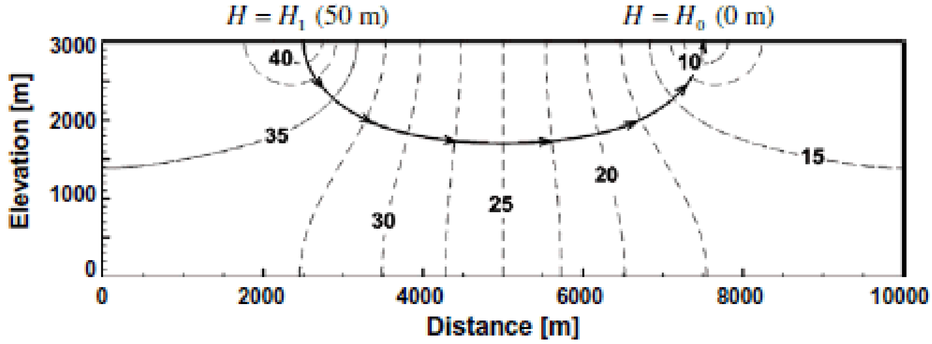
Analyte	Sample Requirement
Water stable isotopes (e.g., ^{2}H, ^{18}O)	1 mL
Drilling fluid tracer (e.g., fluorescein or iodide)	A few mL
Major anions/cations (e.g., Na^{+}, Cl^{-}, Ca^{2+}, SO_4^{2-})	10 mL
Trace elements (e.g., Li, Sr, U)	10 mL
Dissolved inorganic and total carbon	50 mL
Other isotopic ratios for dissolved species (e.g., Li, C, N, S, Sr, U)	100’s of mL
Radiogenic in situ tracers (e.g., ^{3}He, ^{4}He, ^{40}Ar)	Whole-rock samples, possibly waters
Cosmogenic tracers (e.g., ^{81}Kr)	100 L pumped to the surface
Scarce in situ fission products (e.g., ^{36}Cl, ^{129}I)	100’s of L pumped to the surface
Scarce terrigenic and in situ tracers (e.g., ^{3}He)	
Rare inert cases (e.g., Ne, Xe isotopes)	

Deep Borehole Field Test Borehole Sample Types:

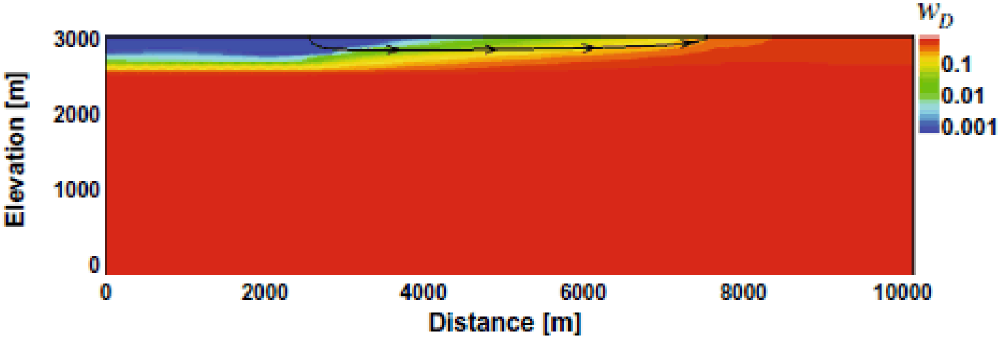
Fluid/Gas	Solids
Drilling fluid (surface samples, also gas separator)	Cuttings
Porewater (from core: centrifuged, squeezed, flushed)	Cores (up to 150 m)
Borehole fluid (wireline sampler)	Preserved cores (a few m)
Pumped groundwater (zone isolated by packers)	

Significance of Basement Brines to Waste Isolation

- **Density stratification → Mixing stability**
- **Verified by numerical studies for a homogeneous earth (Park et al. 2009)**



(a)



(c)

FRAC3DVS advective-dispersive simulation from Figure 6 of Park et al. (2009), comparing source-to-sink flowpaths ($\Delta H = 50$ m) for:

(a) uniform groundwater, and

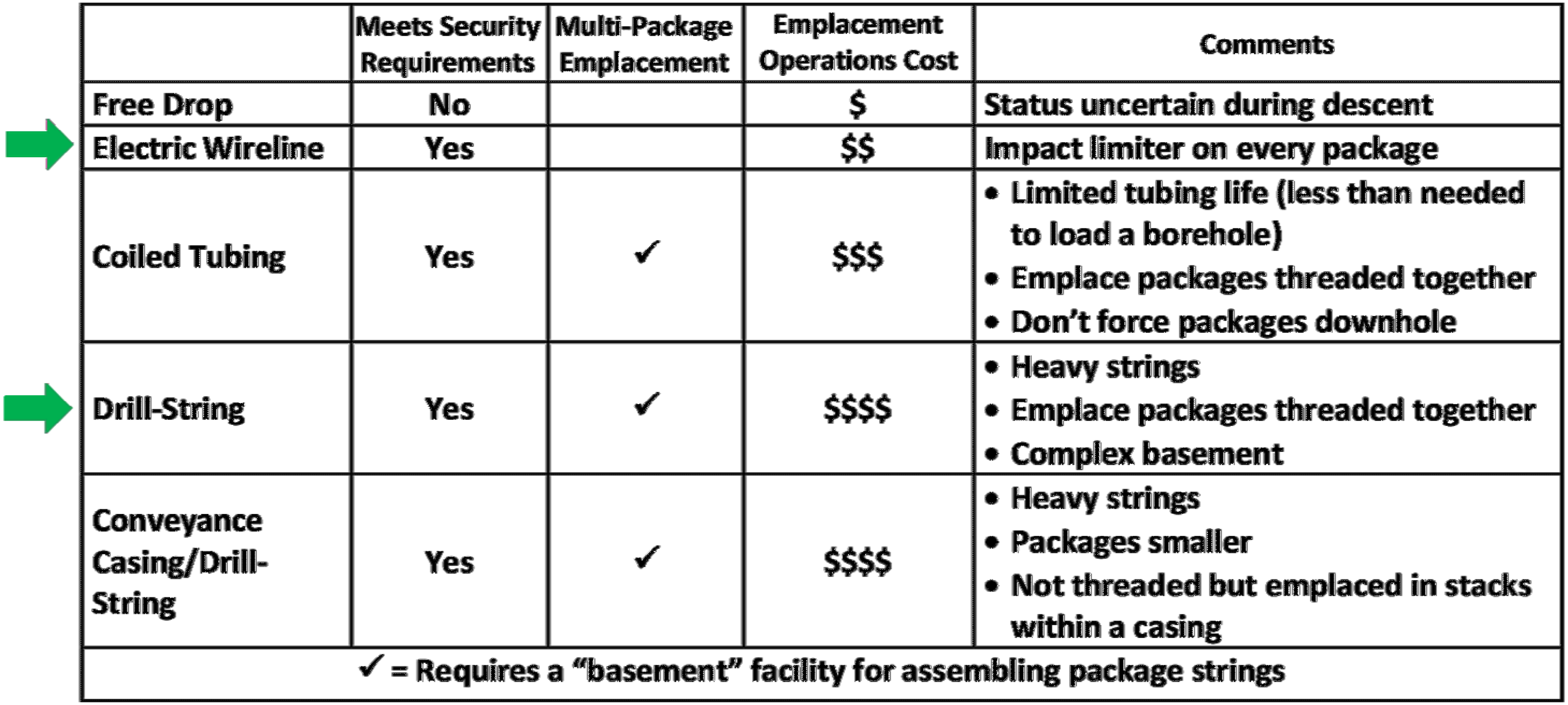
(c) stratified groundwater (i.e., $\rho = 1.2$ below 2500 m),

in a homogeneous earth.

Park et al. 2009. "Effects of shield brine on the safe disposal of waste in deep geologic environments." Advances in Water Resources 32, pp. 1352–1358.

- **Permeability decrease with depth**
  - Stober & Bucher 2007. "Hydraulic properties of the crystalline basement." Hydrogeol. Jour. 15, pp. 213–224.
  - Manning & Ingebritsen 1999. "Permeability of the continental crust: Implications of geothermal adata and metamorphic systems." Rev. Geophys. 37, pp. 127-150.

Alternative Emplacement Methods

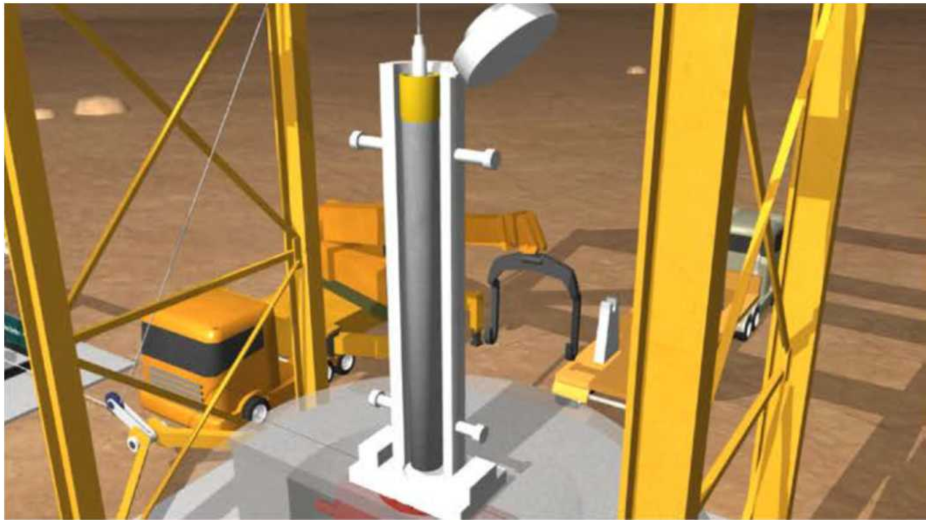


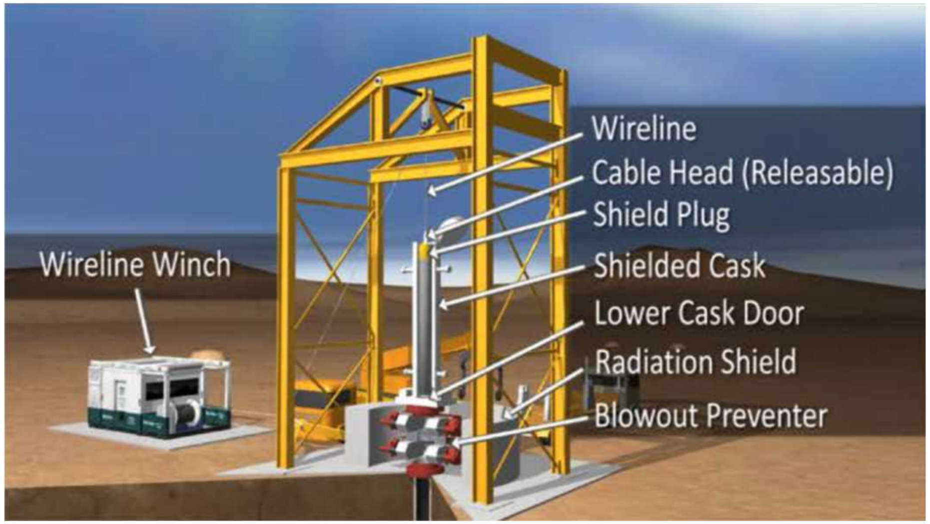
	Meets Security Requirements	Multi-Package Emplacement	Emplacement Operations Cost	Comments
Free Drop	No		$	Status uncertain during descent
➡ Electric Wireline	Yes		$$	Impact limiter on every package
Coiled Tubing	Yes	✓	$$$	• Limited tubing life (less than needed to load a borehole) • Emplace packages threaded together • Don't force packages downhole
➡ Drill-String	Yes	✓	$$$$	• Heavy strings • Emplace packages threaded together • Complex basement
Conveyance Casing/Drill-String	Yes	✓	$$$$	• Heavy strings • Packages smaller • Not threaded but emplaced in stacks within a casing

✓ = Requires a "basement" facility for assembling package strings

Wireline Emplacement Option

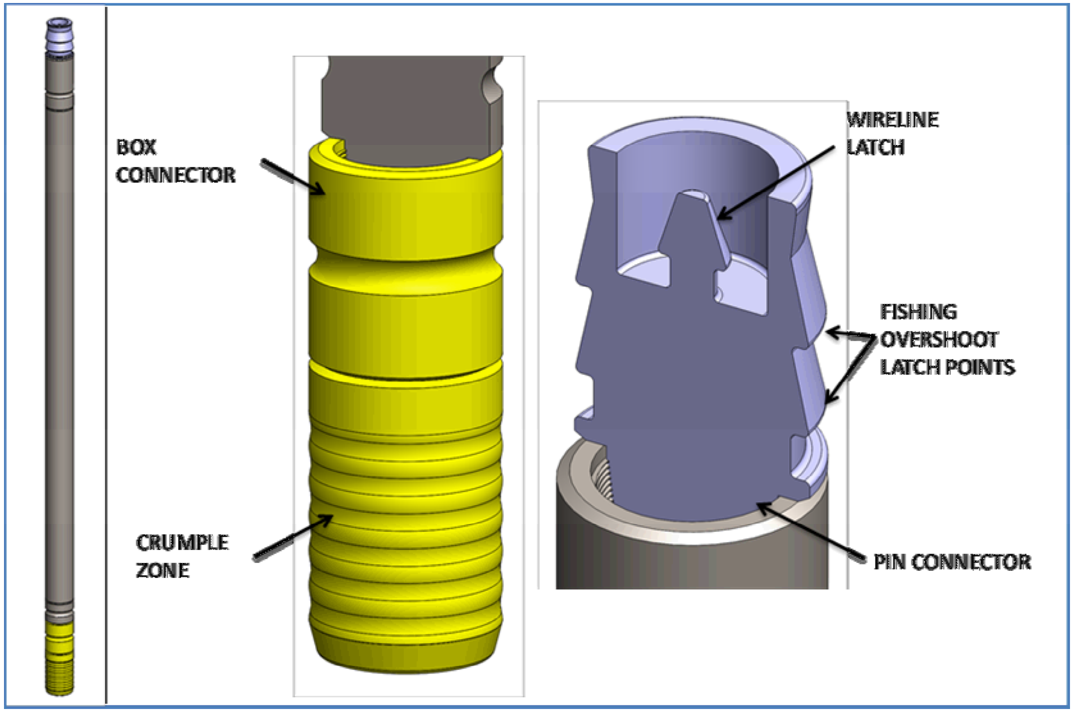
- **Packages lowered individually and stacked**
- **After ~40 packages are emplaced, set a cement plug to support more packages**





Innovative Engineered Safety Measures

- Waste packages with redundant metal-metal or welded closure seals
- Impact limiters
- Package release mechanism
- Functional safety system to mitigate human errors (ISO 12100)



- Methods to monitor potential borehole disturbance (e.g., casing collapse) during operations
- State-of-the-art concepts for shielded waste package handling at the surface