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SAND2015-8753PE

DOE Deep Borehole Field Test: Site Characterization and Design Requirements

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International Technical Workshop on Deep Borehole Disposal of Radioactive Waste
U.S. Nuclear Waste Technical Review Board
Washington, D.C., October 20-21, 2015

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Presentation Outline

- **Deep Borehole Field Test (DBFT) Team**
- **Deep Borehole Disposal (DBD) Concept Geologic Conditions**
  - Hydrogeologic information at depth
  - Geochemical information at depth
- **Assessing the DBD Concept Feasibility**
- **Site Characterization Approaches**
  - Geohydrologic, Geochemical, Geomechanical
- **Use of DBFT Characterization Data**
- **Waste Packaging, Emplacement and Seals Testing (E. Hardin)**

Site Evaluation, Characterization, and Data Integration Team Members

- **DOE NE-53**
  - Tim Gunter, Federal Program Manager
  - Lam Xuan, Program Lead
- **SNL – DBFT Project Technical Lead**
  - Bob MacKinnon, Manager
  - Geoff Freeze, Project Lead and Safety Assessment
  - David Sassani, Site Evaluation and Data Integration Lead
  - Kris Kuhlman, Site Characterization Lead
  - Ernie Hardin, Test Package/Emplacement Engineering Lead
- **DBFT Laboratory Participants**
  - LANL – Regional geology, geoscience, site characterization
  - LBNL – Geoscience, site characterization
  - ORNL – Surface site characteristics, GIS (OR-SAGE)
  - INL – Web visualization/interface for geoscience data
  - PNNL – Engineering design support

Deep Borehole Disposal Concept – Safety and Feasibility Considerations

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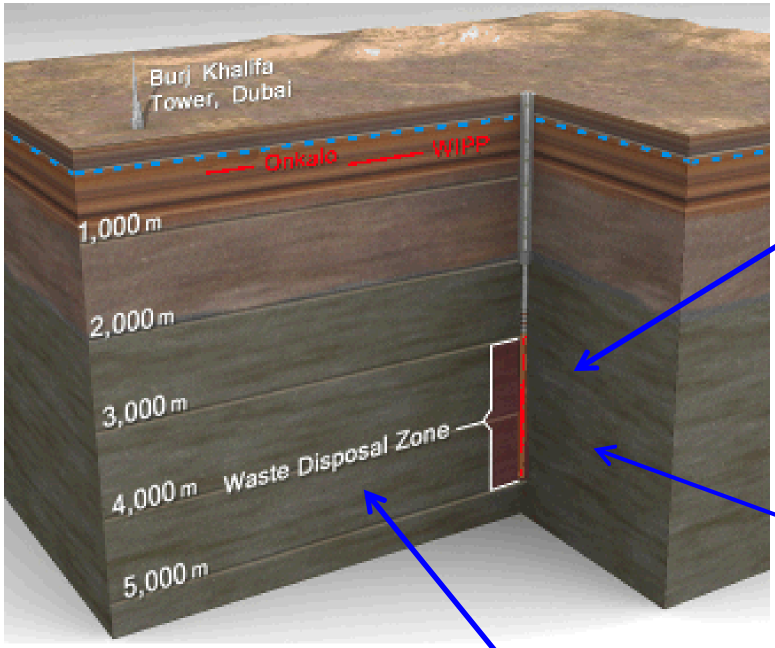
Long-Term Waste Isolation (hydrogeochemical characteristics)



Waste emplacement is deep in crystalline basement

- At least 1,000 m of crystalline rock (seal zone) overlying the waste disposal zone
- Crystalline basement within 2,000 m of the surface is common in many stable continental regions

Crystalline basement can have very low permeability – limits flow and transport

Deep groundwater in the crystalline basement:

- Can have very long residence times – isolated from shallow groundwater
- Can be highly saline and geochemically reducing – enhances the sorption and limits solubility of many radionuclides
- Can have density stratification (saline groundwater underlying fresh groundwater) – opposes thermally-induced upward groundwater convection

Deep Borehole Disposal Concept: Unfavorable Geologic Conditions

- **Geologic conditions that are undesirable for the deep borehole disposal concept and waste isolation:**
  - Interconnected high-permeability zone(s) (e.g., shear zone, fracture) from the waste disposal interval to the surface or shallow aquifer
  - High degree of heterogeneity in crystalline basement
  - At depths of greater than 3 km (i.e., in disposal interval):
    - *Young meteoric groundwater*
    - *Low-salinity, oxidizing groundwater*
    - *Economically exploitable natural resources*
    - *Significant upward gradient in fluid potential (over-pressured conditions)*
  - High geothermal heat flow
- **Additionally, high differential horizontal stresses are undesirable for borehole completion and disposal operations**
- **Absent these unfavorable features**
  - Potential scenarios for radionuclide release to the biosphere include
    - *thermally driven groundwater flow (from waste heat), or simply diffusive flux, through the borehole seals and/or along the disturbed rock zone annulus*

DBD Concept: Preferred Geologic Conditions

- **Geochemical Considerations**
  - Reduced, or reducing, conditions in the geosphere (rock and water system)
    - *Crystalline basement mineralogical (and material) controls*
      - Steels in borehole will provide reducing capacity (H_2 source)
  - Rock dominated system at depth
    - *Fluid composition deep in crystalline basement*
      - Major elements – brine at depth
      - Stable isotopes, radiogenic isotopes, noble gases indicating long-term isolated nature of fluids
  - Subset of waste forms and radionuclides are redox sensitive
    - *Lower degradation rates*
    - *Lower solubility-limited concentrations*
    - *Increased sorption coefficients*
  - Stratification of salinity – increasing to brine deep in crystalline basement
    - *Density gradient opposes upward flow*
    - *Reduces/eliminates colloidal transport*

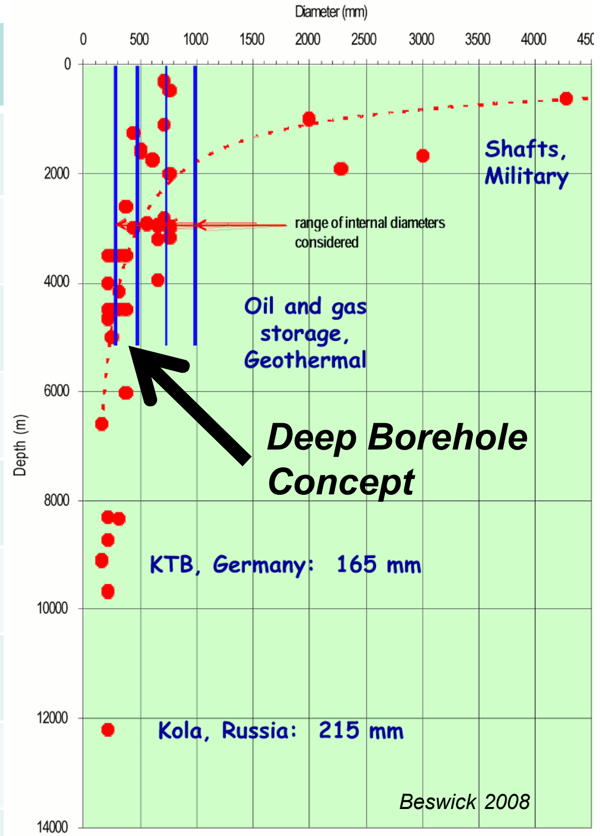
DBD Concept: Preferred Geologic Conditions (Continued)

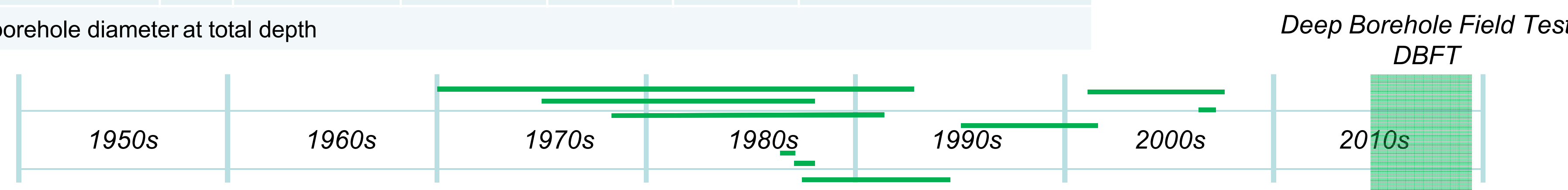
- **Geohydrological Considerations**
  - No large-scale connected pathways from depth to aquifer systems
    - *No through going fracture/fault/shear zones that provide fast paths*
    - *No structural features that provide potential connective pathways*
      - Seeking lower heterogeneity in crystalline basement
  - Low permeability of crystalline basement at depth
  - Evidence of ancient, isolated nature of basement groundwater
    - *Salinity gradient increasing downward to brine at depth*
      - Limited recharge/connectivity with surface waters/aquifers
      - Provides density resistance to upward flow
    - *Major element and isotopic indications of compositional equilibration with rock*
      - Crystalline basement reacting with water to affect major elements indicating rock-dominated fluid composition
      - Ancient/isolated groundwater from isotopes, noble gases indicating long-term isolated nature of fluids – minimal recharge

Deep Crystalline Drilling

Site	Bores	Location	Years	Depth [km]	Diam* [in]	Purpose
Kola SG-3	1	NW USSR	1970-1992	12.2	8½	Geologic Exploration + Technology Development
Fenton Hill	3	New Mexico	1975-1987	3, 4.2, 4.6	8¾, 9⅞	Enhanced Geothermal
Urach-3	1	SW Germany	1978-1992	4.4	5½	Enhanced Geothermal
Gravberg	1	Central Sweden	1986-1987	6.6	6½	Gas Wildcat in Siljan Impact Structure
Cajon Pass	1	California	1987-1988	3.5	6¼	San Andreas Fault Exploration
KTB	2	SE Germany	1987-1994	4, 9.1	6, 6½	Geologic Exploration + Technology Development
Soultz-sous-Forêts GPK	3	NE France	1995-2003	5.1, 5.1, 5.3	9⅝	Enhanced Geothermal
SAFOD	2	Central California	2002-2007	2.2, 4	8½, 8¾	San Andreas Fault Exploration
Basel-1	1	Switzerland	2006	5	8½	Enhanced Geothermal

*borehole diameter at total depth





Planned Activities to Evaluate Feasibility of Deep Borehole Disposal Concept

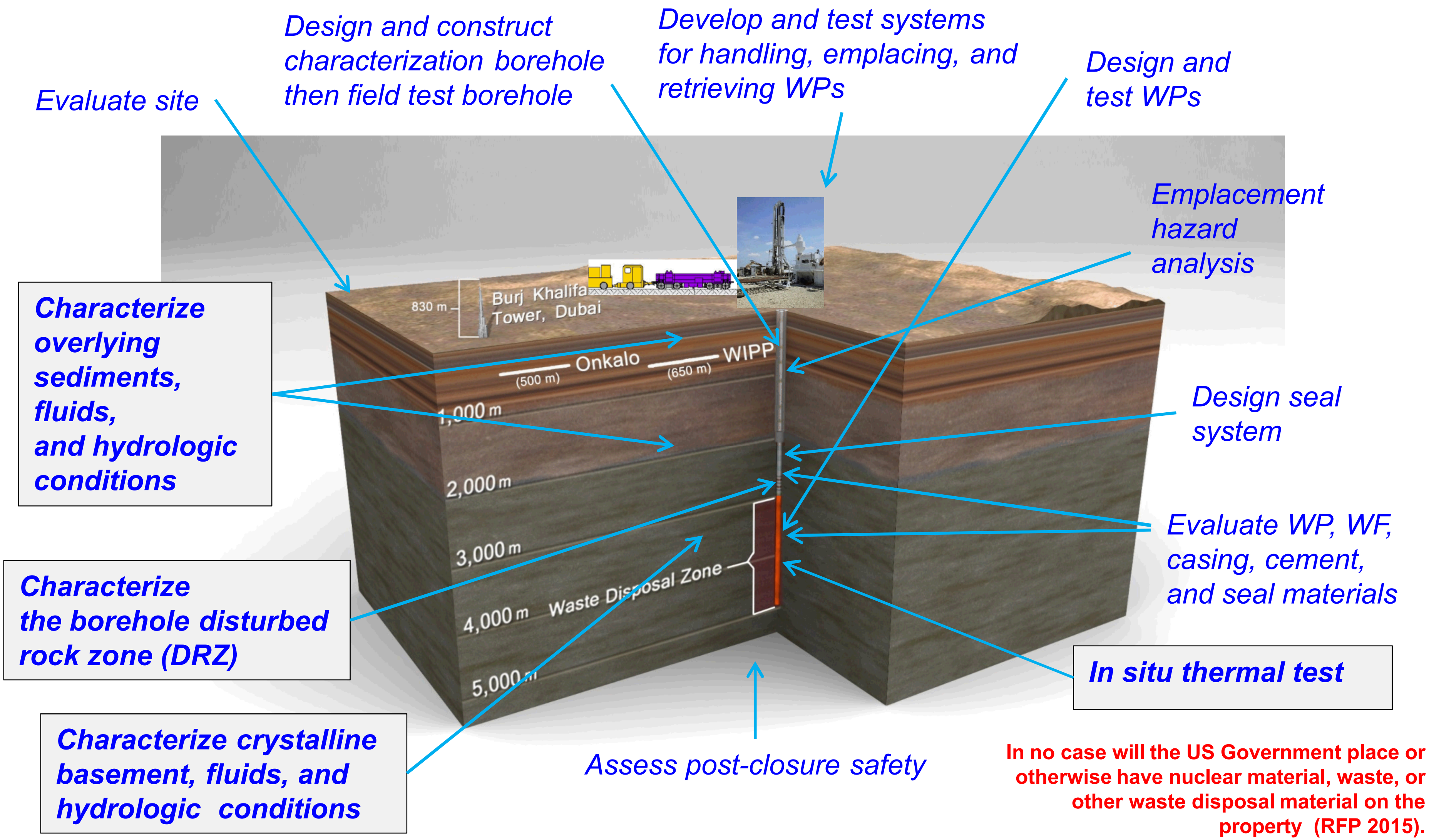
- **Select a suitable site**
- **Design, drill, and construct the characterization borehole (CB) to requirements**
- **Collect data in the CB needed to characterize crystalline basement conditions and confirm, with acceptable uncertainty, expected hydrogeochemical conditions**
- **Design, drill, and construct the field test borehole (FTB) to requirements**
- **Design and develop surface handling and emplacement systems and operational methods for safe canister/WP handling and emplacement**
- **Verify through hazard analysis that handling and emplacement operations canister/WP handling and emplacement have sufficiently low risk**

Planned Activities to Evaluate Feasibility of Deep Borehole Disposal Concept (Cont'd)

- Demonstrate safe surface handling, and emplacement and retrieval operations in the FTB
- Conduct laboratory studies of engineered materials under representative downhole conditions to provide a technical basis, with acceptable uncertainties, for predicting evolution of the system
- Conduct subsystem analyses and a post-closure safety assessment, including quantification of uncertainties, and demonstrate understanding of key processes and safety of the concept
- Conduct a cost analysis verifying acceptable costs of concept implementation
- Synthesize above elements into a comprehensive and transparent evaluation of the feasibility of the Deep Borehole Concept

Objectives of the Deep Borehole Field Test

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



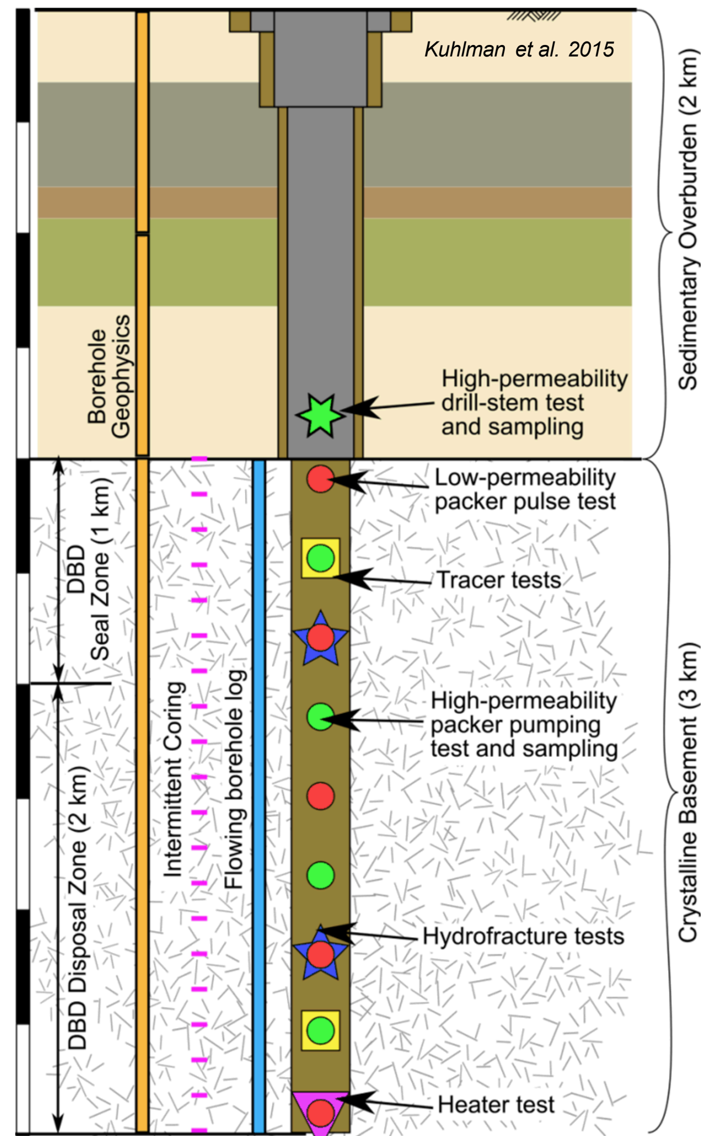
In no case will the US Government place or otherwise have nuclear material, waste, or other waste disposal material on the property (RFP 2015).

Deep Borehole Field Test

- **Characterization for DBFT is *different from*:**
  - **Mined waste repositories**
    - ***More geologic isolation – less "site mapping"***
    - ***Single-phase fluid flow***
    - ***Less steep pressure gradients***
  - **Oil/gas or mineral exploration**
    - ***Crystalline basement vs sedimentary rocks***
    - ***Low-permeability***
    - ***Avoid mineralization***
    - ***Avoid overpressure***
  - **Geothermal exploration**
    - ***Low geothermal gradient***

Characterization Borehole: Profile Data

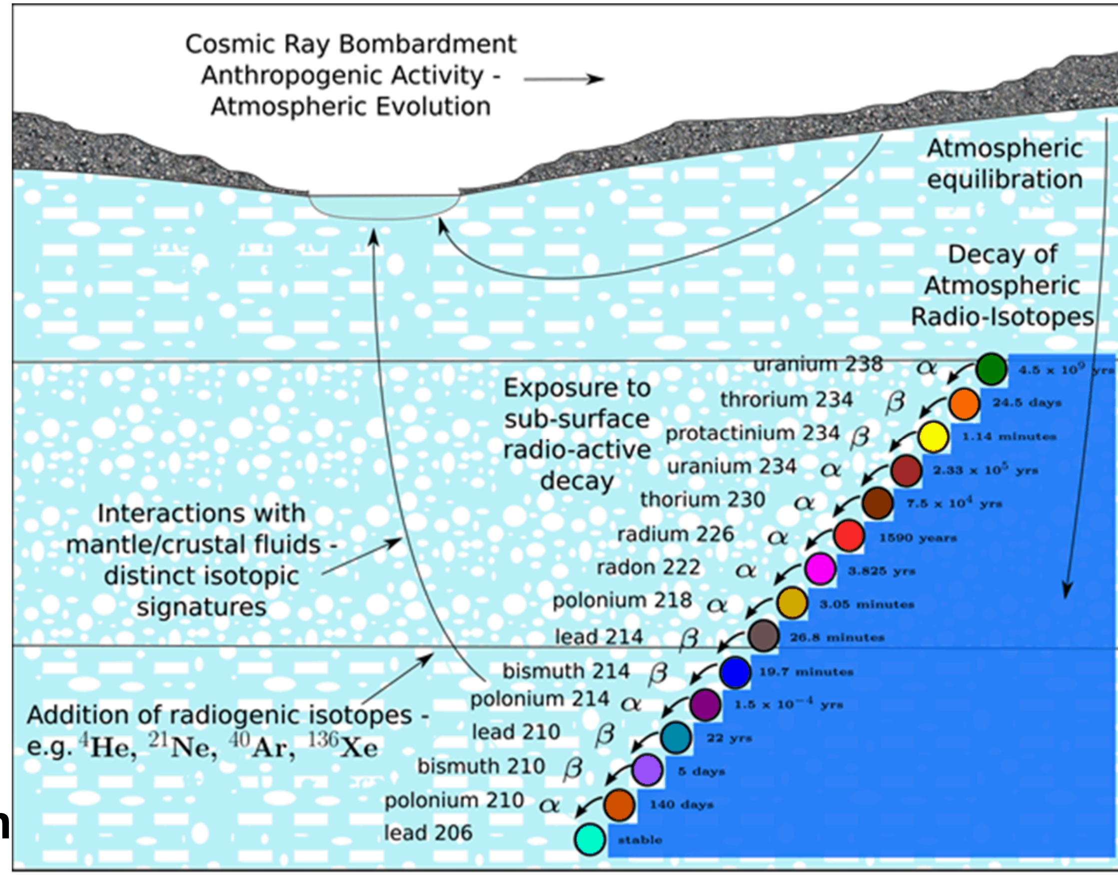
- Borehole Geophysics
- Coring/Cuttings/Rock Flour
  - Mineralogy/petrology
  - Fluid samples from cores
    - *Bulk composition (salinity; rock equilibration)*
- Sample-based Profiles
  - Fluid density/temperature/major ions
  - Pumped samples from high-*k* regions
  - Samples from cores in low-*k* regions
- Drilling Parameters Logging
  - Mud fluids/solids/dissolved gases
  - Torque, weight-on-bit, etc.
- Testing-Based Profiles
  - Static formation pressure
  - Formation hydraulic/transport properties
  - *In situ* stress (hydrofrac + breakouts)



Environmental Tracers

- **Vertical Profiles**
  - **Noble gases (He, Ne, etc.)**
  - **Stable water isotopes**
    - *Oxygen; hydrogen*
  - **Atmospheric radioisotope tracers (e.g., ^{81}Kr, ^{129}I, ^{36}Cl)**
  - **$^{238}U/^{234}U$ ratios**
  - **$^{87}Sr/^{86}Sr$ ratios**
- **Long-Term Data**
  - **Water provenance**
  - **Flow mechanisms/isolation**

Minerals → pores → fractures (evaluate the "leakiness")



(After Kuhlman, 2015)

Fluid Sample Quality + Quantity will be a Focus!

Repeatability between drill-stem testing, packer & core samples?

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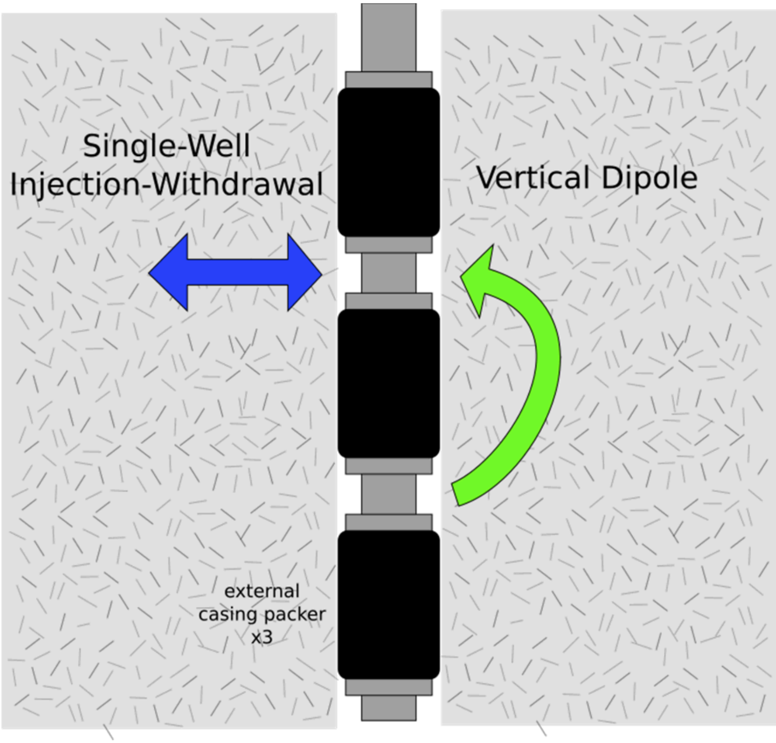
Hydrogeologic Testing

- Hydrologic Property Profiles
  - Static formation pressure
  - Permeability / compressibility
    - *Pumping/sampling in high k*
    - *Pulse testing in low k*
- Borehole Tracer Tests
  - Single-well injection-withdrawal
  - Vertical dipole
  - Understand transport pathways
- Hydraulic Fracturing Tests
  - σ_h magnitude
- Borehole Heater Test
  - Surrogate canister with heater in the crystalline basement



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Deep Borehole Field Test Characterization Data Inform the Post-Closure Safety Assessment

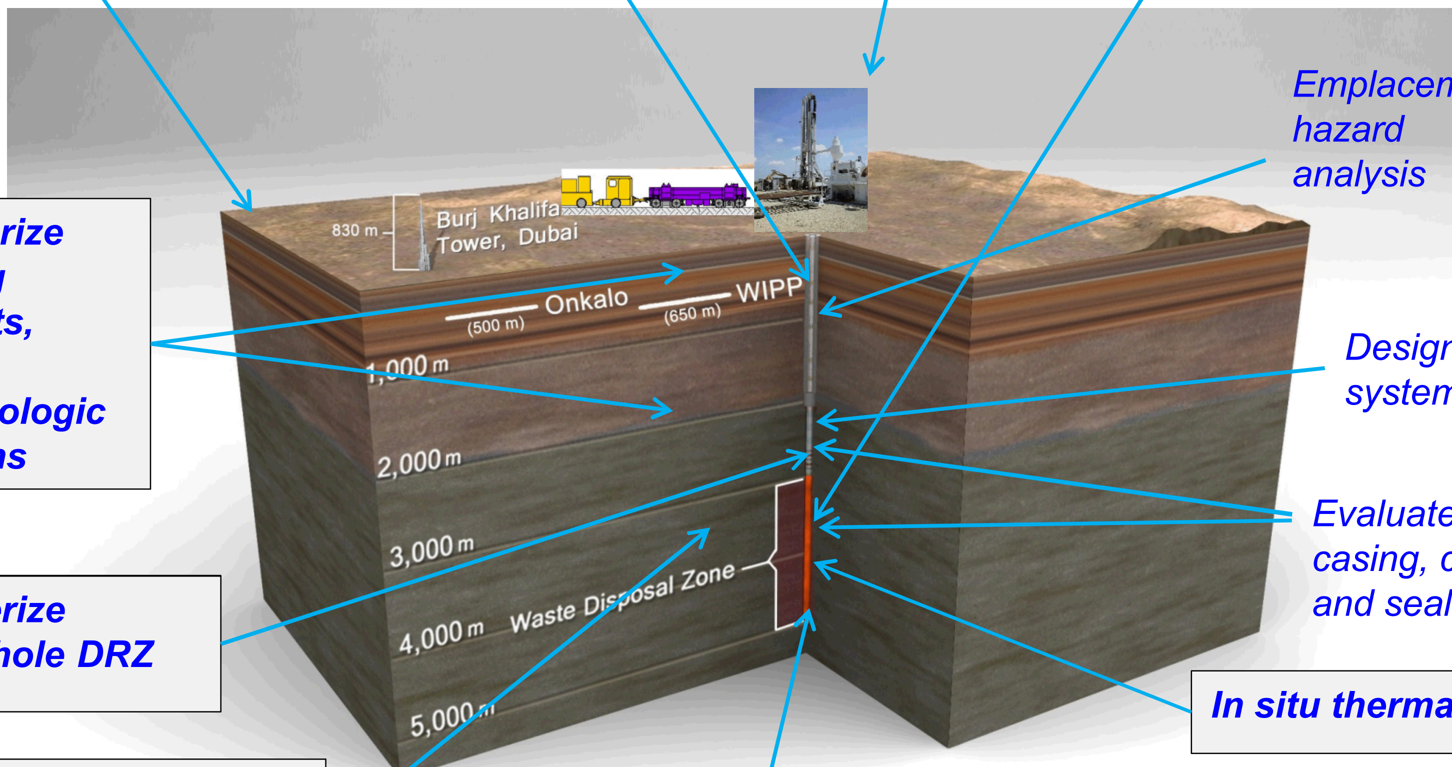
Evaluate site

Design and construct characterization borehole then field test borehole

Develop and test systems for handling, emplacing, and retrieving WPs

Design and test WPs

Emplacement hazard analysis



Characterize overlying sediments, fluids, and hydrologic conditions

Design seal system

Evaluate WP, WF, casing, cement, and seal materials

Characterize the borehole DRZ

In situ thermal test

Characterize crystalline basement, fluids, and hydrologic conditions

Assess post-closure safety

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Objectives of the Deep Borehole Field Test

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

Evaluate site

Design and construct characterization borehole then field test borehole

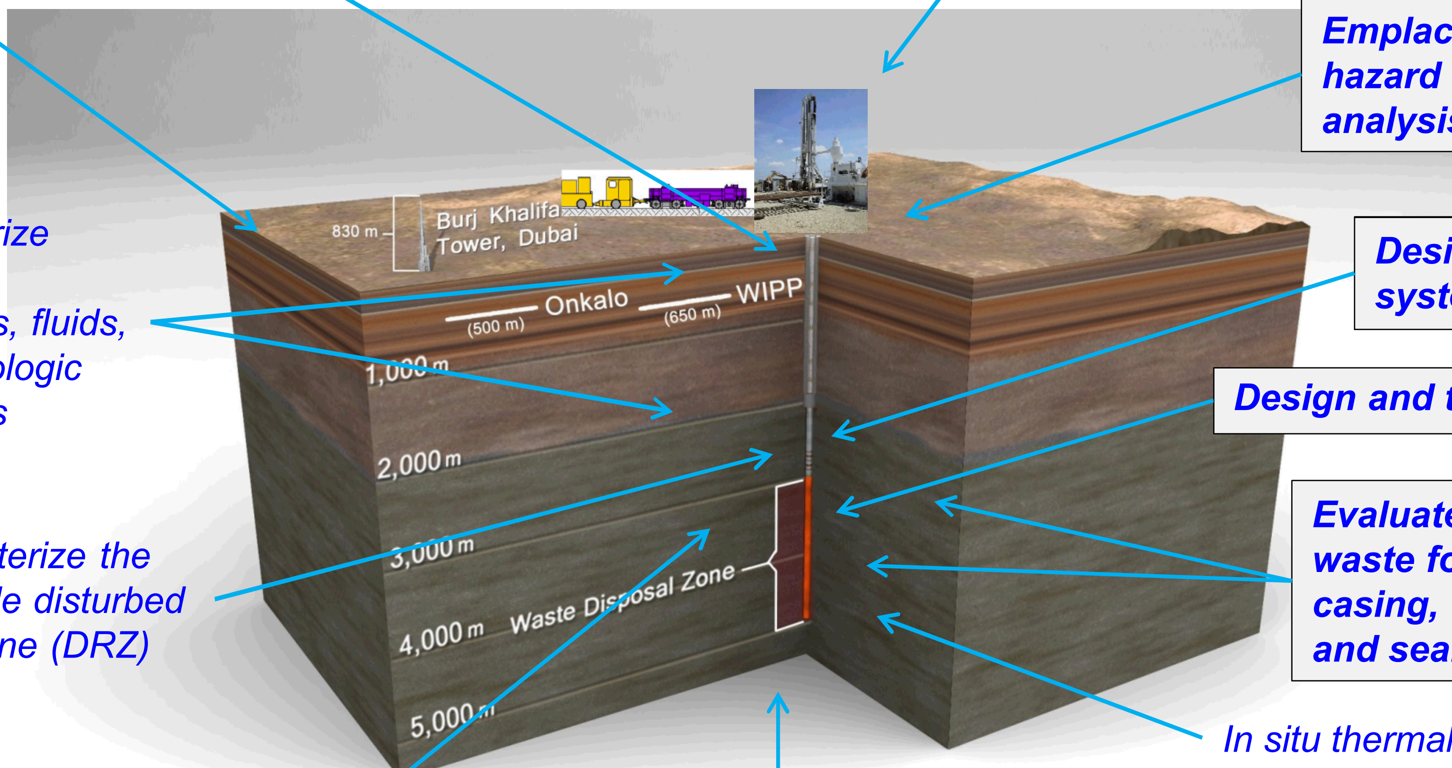
Develop and test systems for handling, emplacing, and retrieving waste packages (WPs)

Emplacement hazard analysis

Characterize overlying sediments, fluids, and hydrologic conditions

Design seal system

Design and test WPs



Characterize the borehole disturbed rock zone (DRZ)

Evaluate WP, waste form, casing, cement, and seal materials

In situ thermal test

Characterize bedrock, fluids, and hydrologic conditions

Assess post-closure safety

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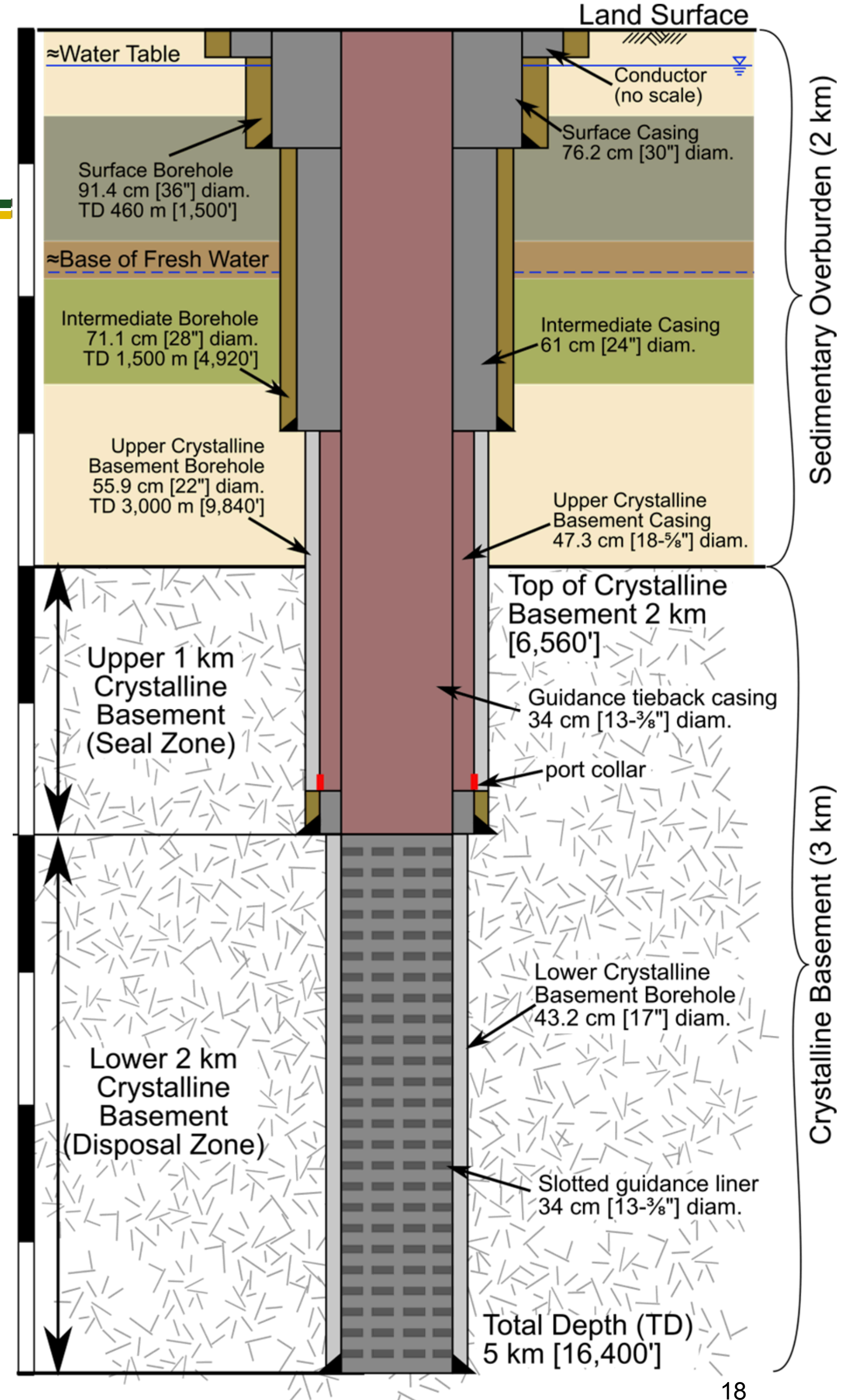
■ Field Test Borehole

- Disposal borehole diameter/plan
- Demonstrate emplacement and test canisters
- Casing removal
- 17-inch diameter at a few km depth in hard rock is not uncommon for geothermal

(Companion figure to the Characterization Borehole, Slide 13.)



DBFT Waste Packaging, Emplacement and Seals Testing - Outline

1. Deep Borehole Field Test (DBFT) objectives
2. Handling and emplacement system options
   - Previous test: Spent Fuel Test–Climax
   - Wireline emplacement
   - Drill-string emplacement
3. Test (waste) package concepts and analysis
4. Cost-risk study for emplacement concept selection
   - Preclosure risk insights
   - Recommendation: wireline emplacement
5. Conceptual design questions
6. Sealing technology R&D

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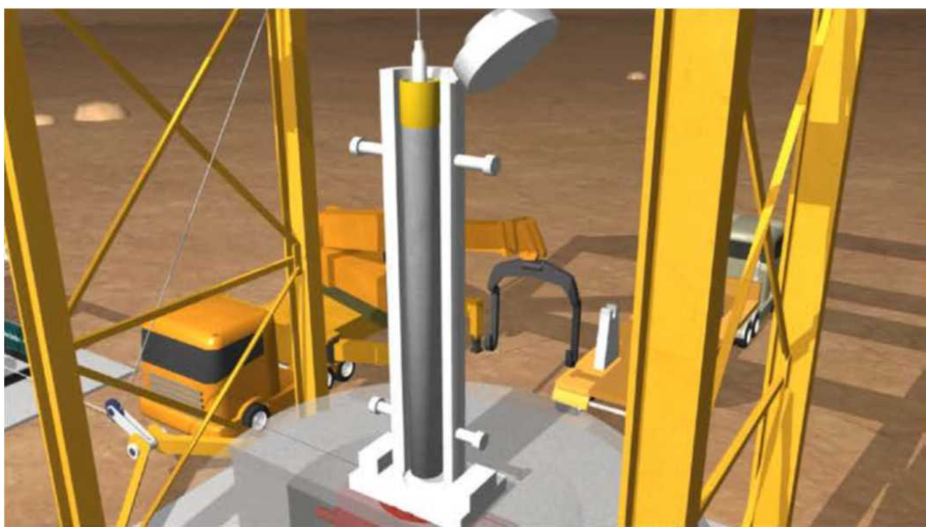
Spent Fuel Test – Climax (1978-1983)

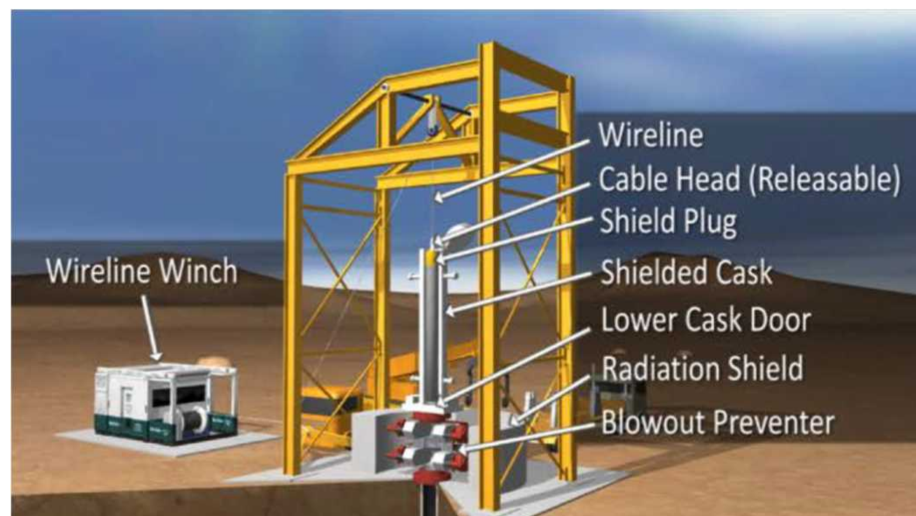
Waste package containing irradiated commercial reactor fuel assembly being lowered through shipping cask into borehole, leading to Climax Mine

Wireline Emplacement Concept: Surface Arrangement

- **Blow-out preventer (BOP) shield**
- **Packages lowered one-at-a-time**
- **After up to 40 packages are emplaced, set a cement plug to support more packages**

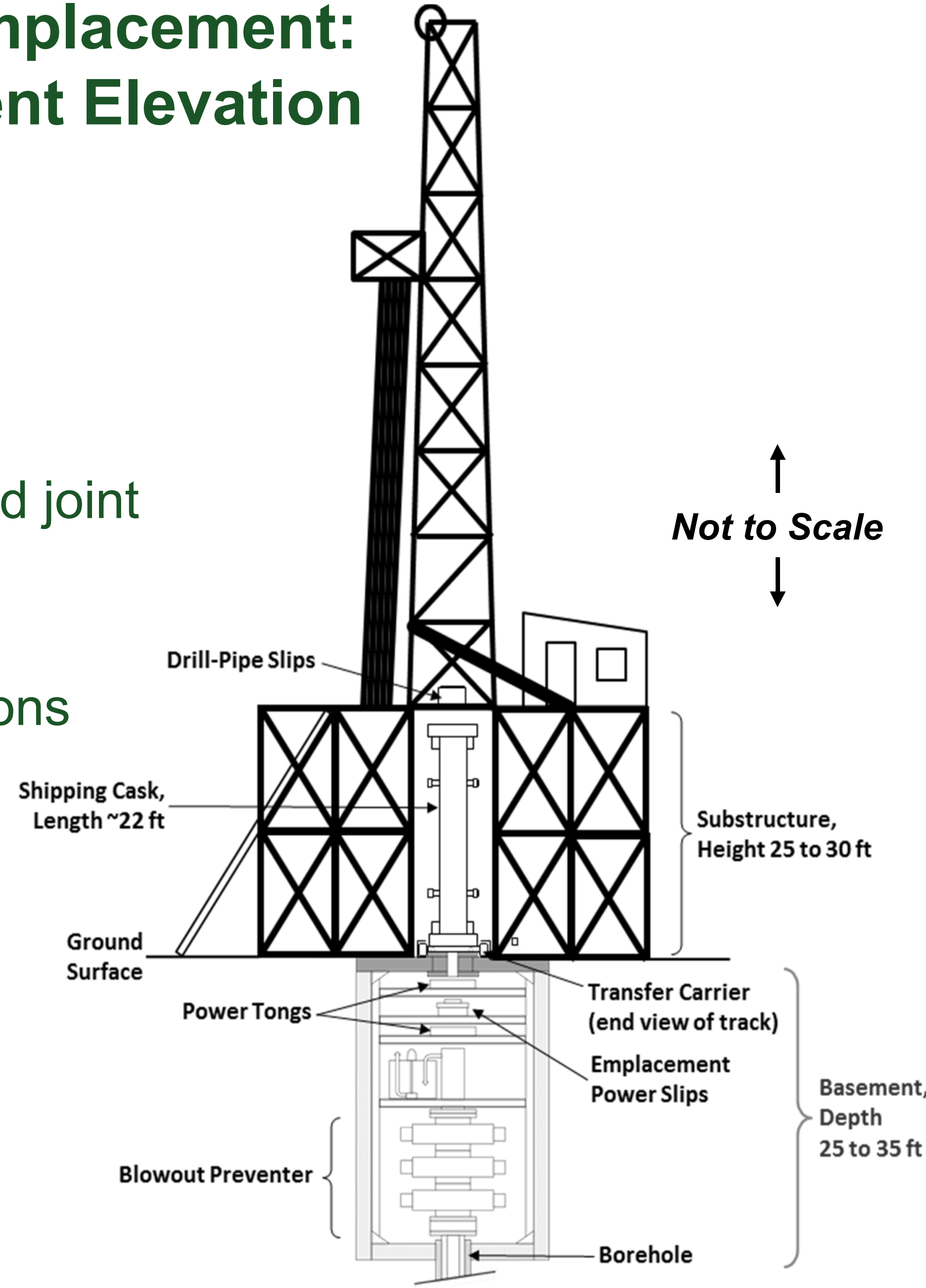
Video





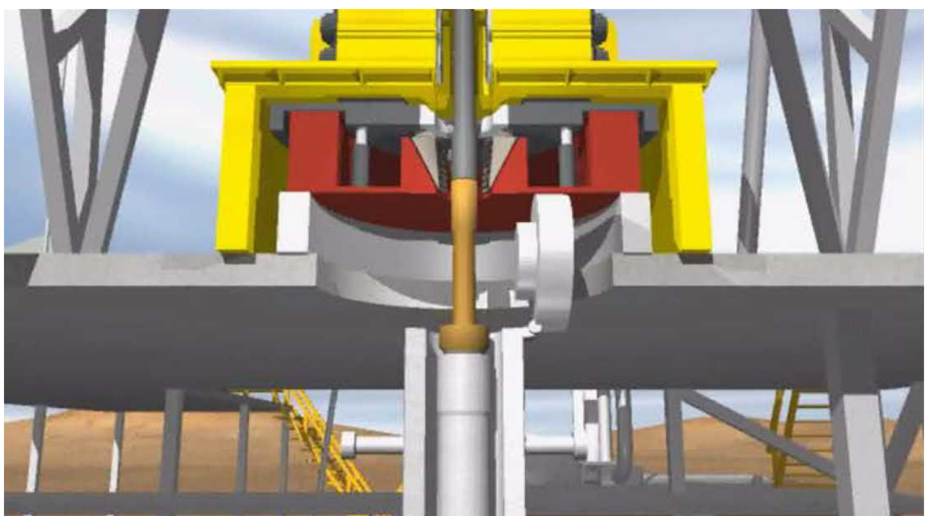
Drill-String Emplacement: Rig & Basement Elevation

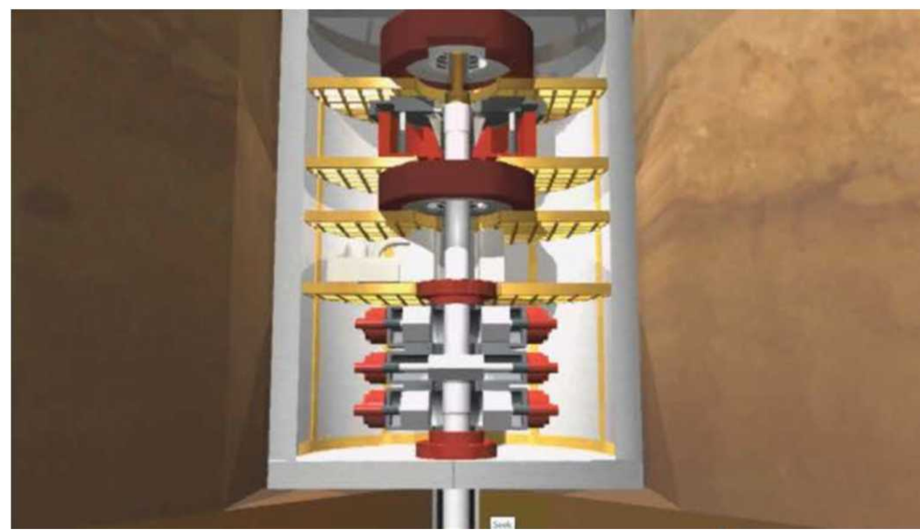
- **Rig capacities:**
  - Triple pipe stands (90 ft)
  - >500,000 lb working load
  - Automatic pipe handling and joint makeup
- **Shielded shipping cask:**
  - Length ~22 ft, weight ~30 tons
- **Upper and lower cask doors**
- **Transfer carrier**
- **Subgrade basement**
  - Power slips/tongs
  - Mud surge control
  - Blowout preventer



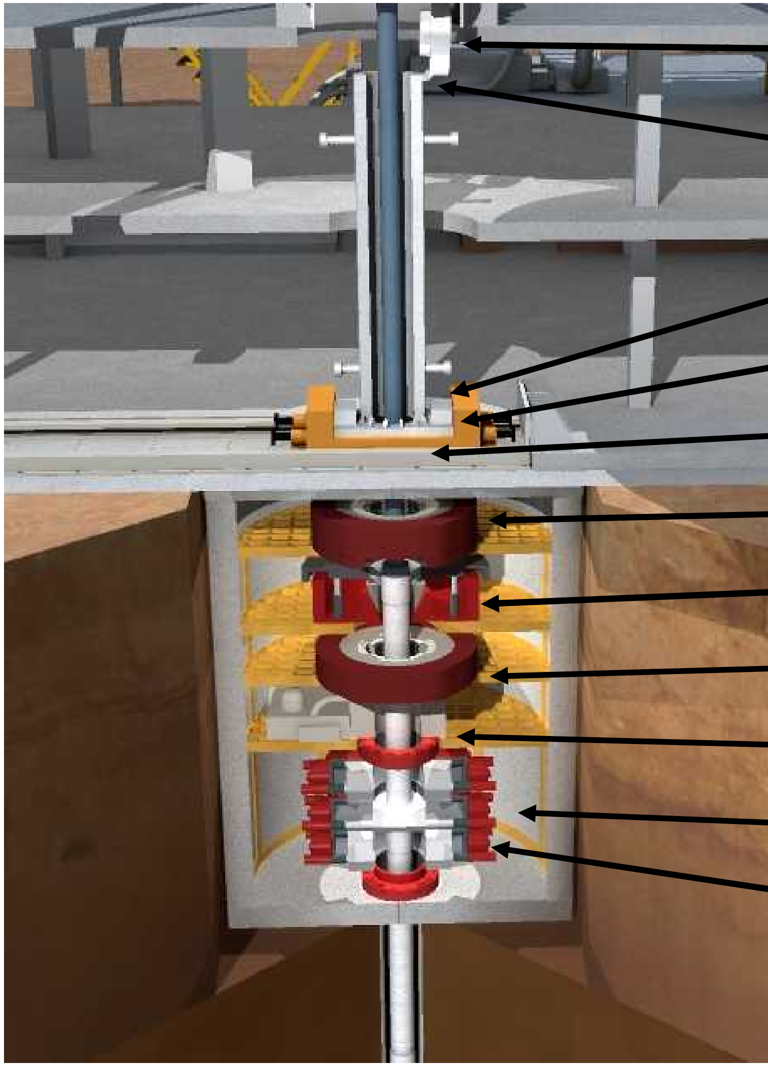
Drill-String Emplacement Concept: Equipment Arrangement

- Double-ended cask
- Transfer carrier to wellhead
- Up to 40 packages are assembled in a string, and emplaced
- Cement plug is placed to support more strings





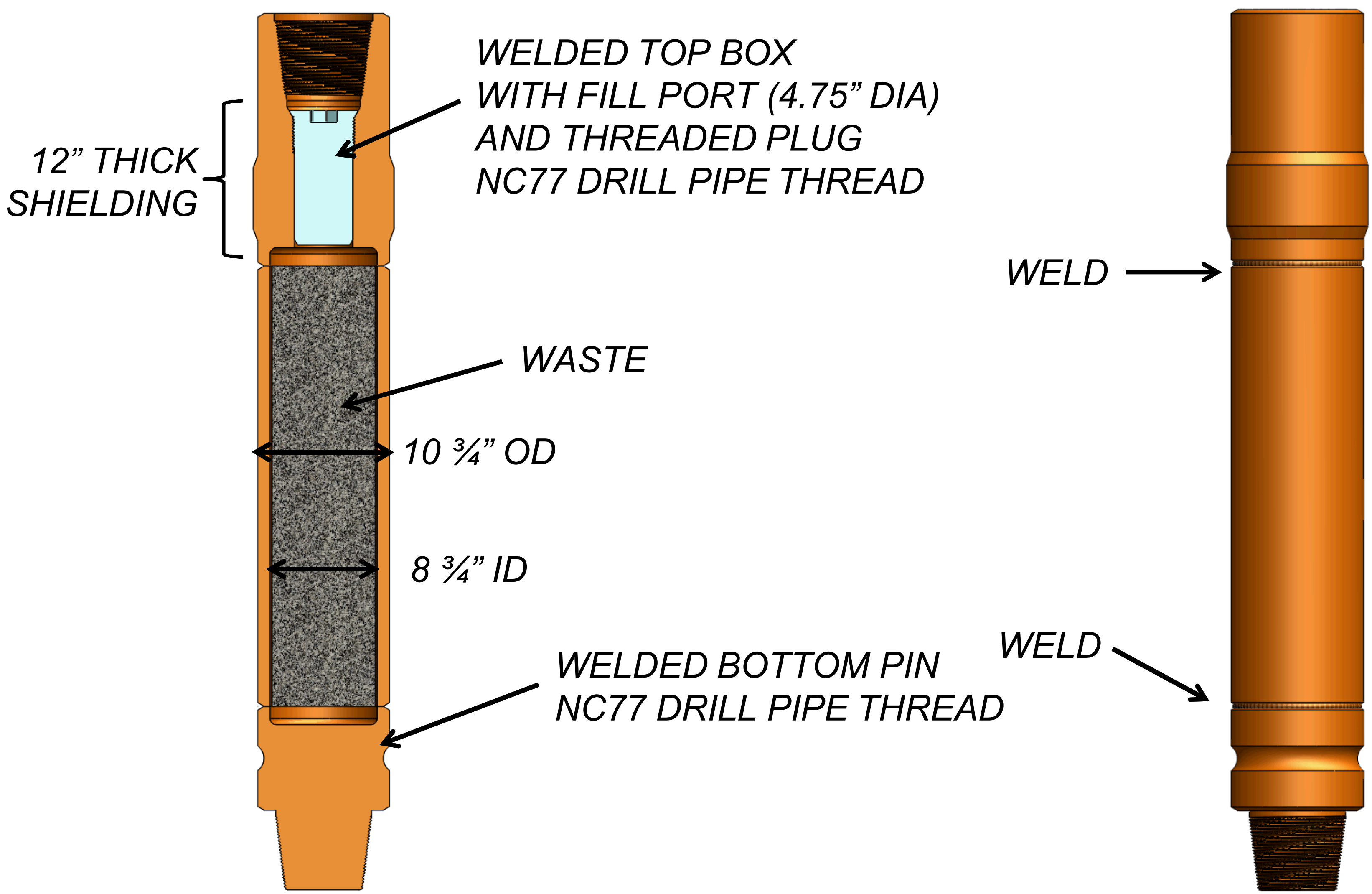
Cask and Shielded Basement Arrangement



- Upper hinged door
- Range-limiting restraints (not visible)
- Rotation restraints (not visible)
- Lower sliding doors
- Shield door (not visible)
- Upper tongs (torque)
- Power slips (weight-bearing)
- Lower tongs (counter-torque)
- Mud-transfer equipment
- "Elevator" ram (slips backup)
- Blowout preventer stack

Video

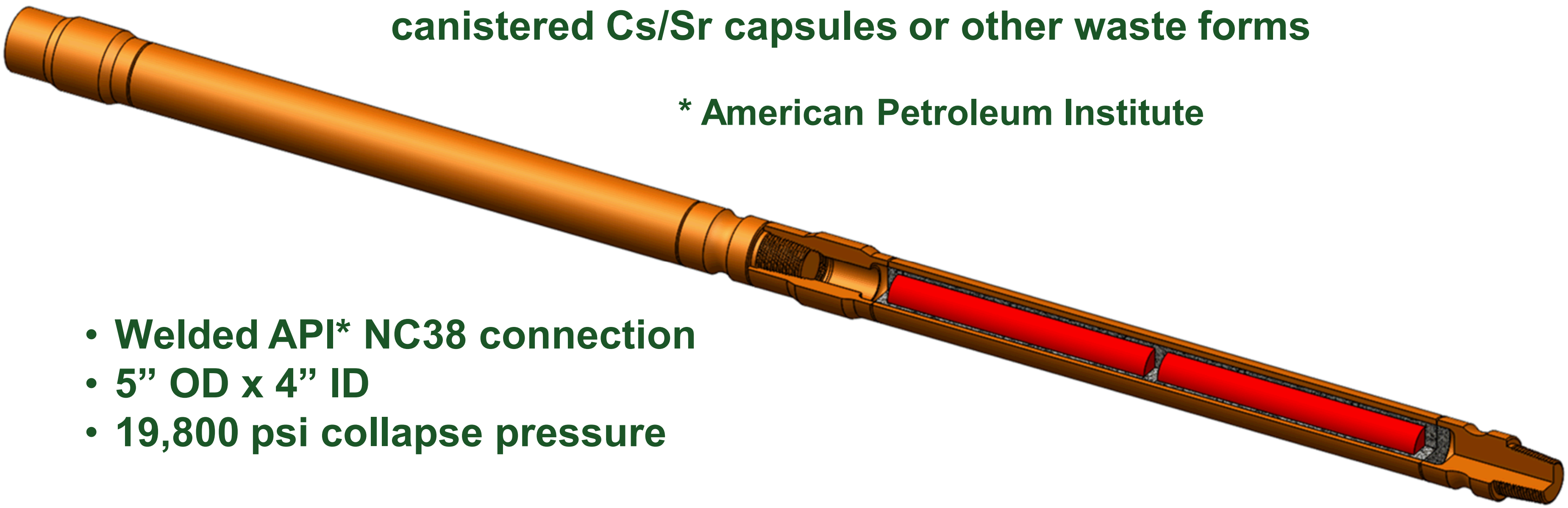
Packaging Concept for Bulk Waste



Packaging Concept (Small) for Cs/Sr Capsules

- Material: API* P110 (hardened/tempered, ≥ 110 ksi yield)
- Fabrication: machined, friction welded
- Sealing: threaded plug, metal-metal seal, welded cover
- Also proposed: internal-flush overpacks for pre-canistered Cs/Sr capsules or other waste forms

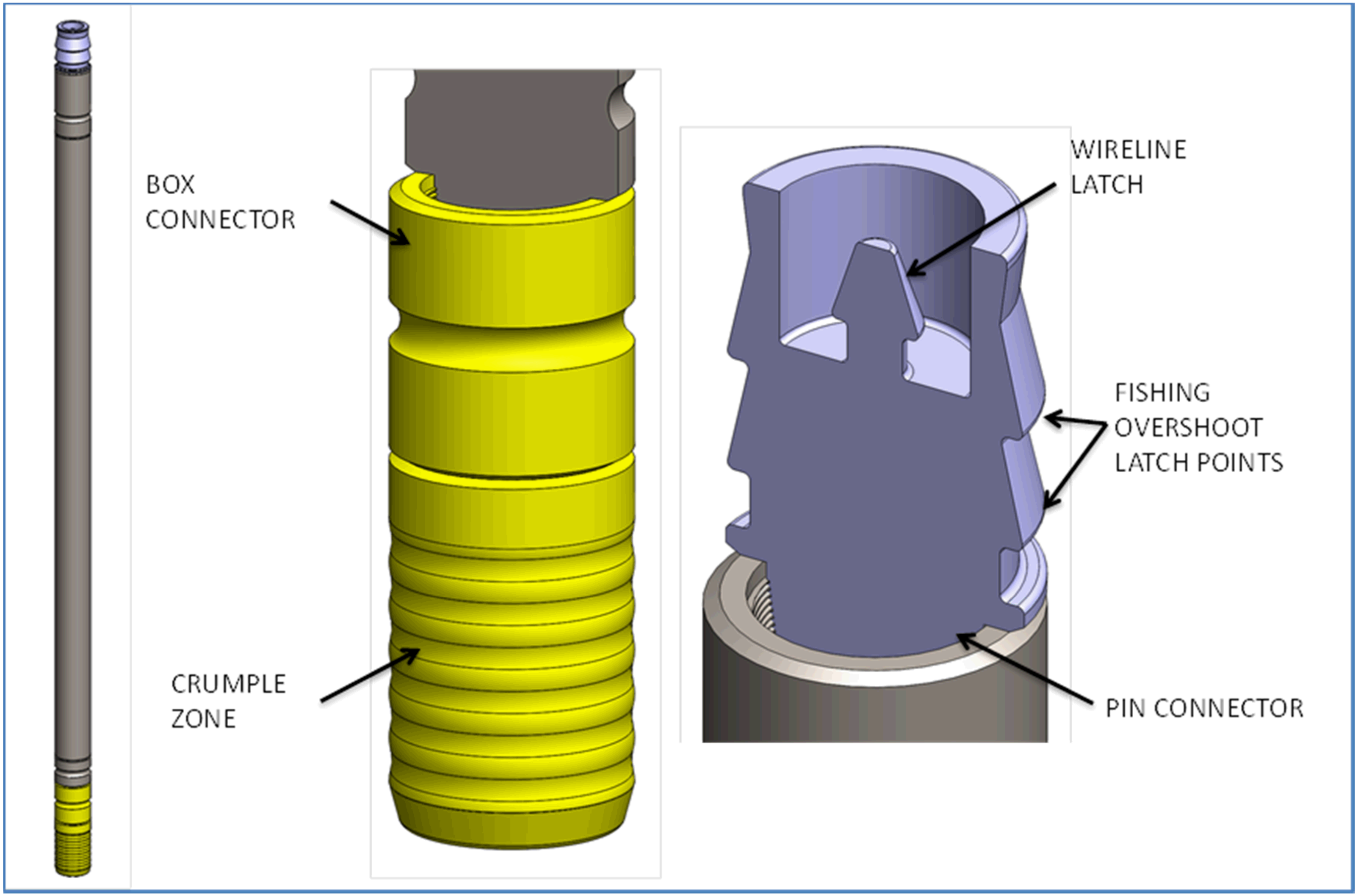
* American Petroleum Institute



- Welded API* NC38 connection
- 5" OD x 4" ID
- 19,800 psi collapse pressure

Number of capsules per package adjustable up to 8 (→18.5-ft overall length)

Upper and Lower Subs Attached to Each Package, for Wireline Emplacement



Safety of Disposal Operations

- **Deep Borehole Field Test vs. Potential Future Disposal System**
  - DBFT will have ***zero radiological risk***
- **Accident Prevention During Emplacement Operations**
  - DBFT conceptual design: safety analysis that discriminates between alternative concepts
- **Example Types of Emplacement Accidents (disposal system)**
  - Single canister drop in borehole (zero consequence?)
  - Pipe string + waste package string drops in borehole
  - Pipe string drops onto packages
  - Waste packages stuck → Fishing
  - External hazards (seismic, extreme weather)

What is the safest emplacement method, given the possible range of accidents/off-normal events?

Cost-Risk Study for Emplacement Concept Selection

- **Recommend Emplacement Method for Disposal, Apply to DBFT Demonstration**
- **Assumptions**
  - **Prototypical disposal system**
    - ***One borehole***
    - ***400 packages in stacks of 40 with cement plugs separating***
    - ***Average one package emplaced per day***
  - **Occupational hazards are low and don’t discriminate emplacement options (oilfield experience)**
  - **Worker radiological exposures would be low, and don’t discriminate emplacement options (industry experience with nuclear material handling)**
  - **Functional safety design approach (e.g., ISO 12100, *International Organization for Standards*)**

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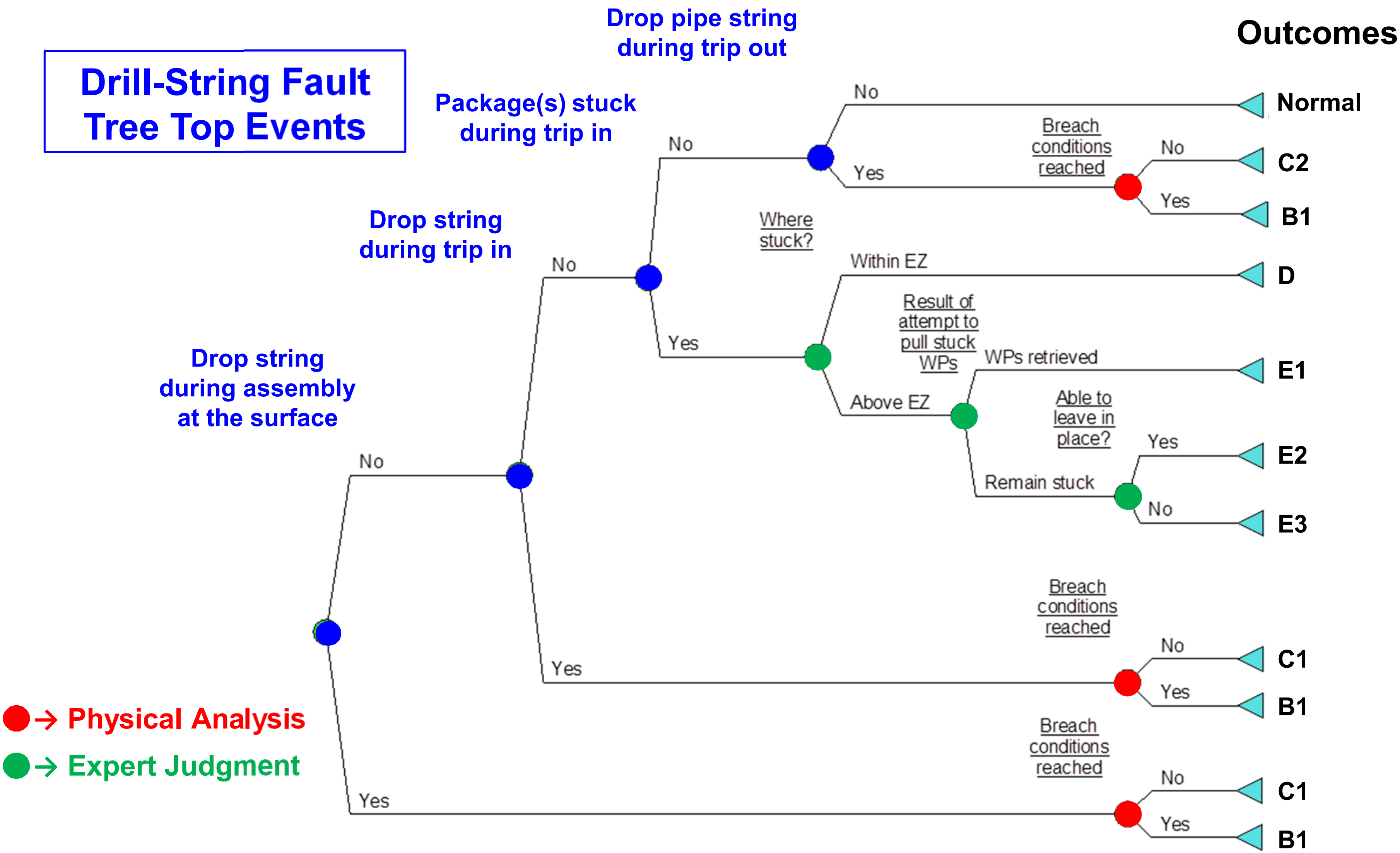
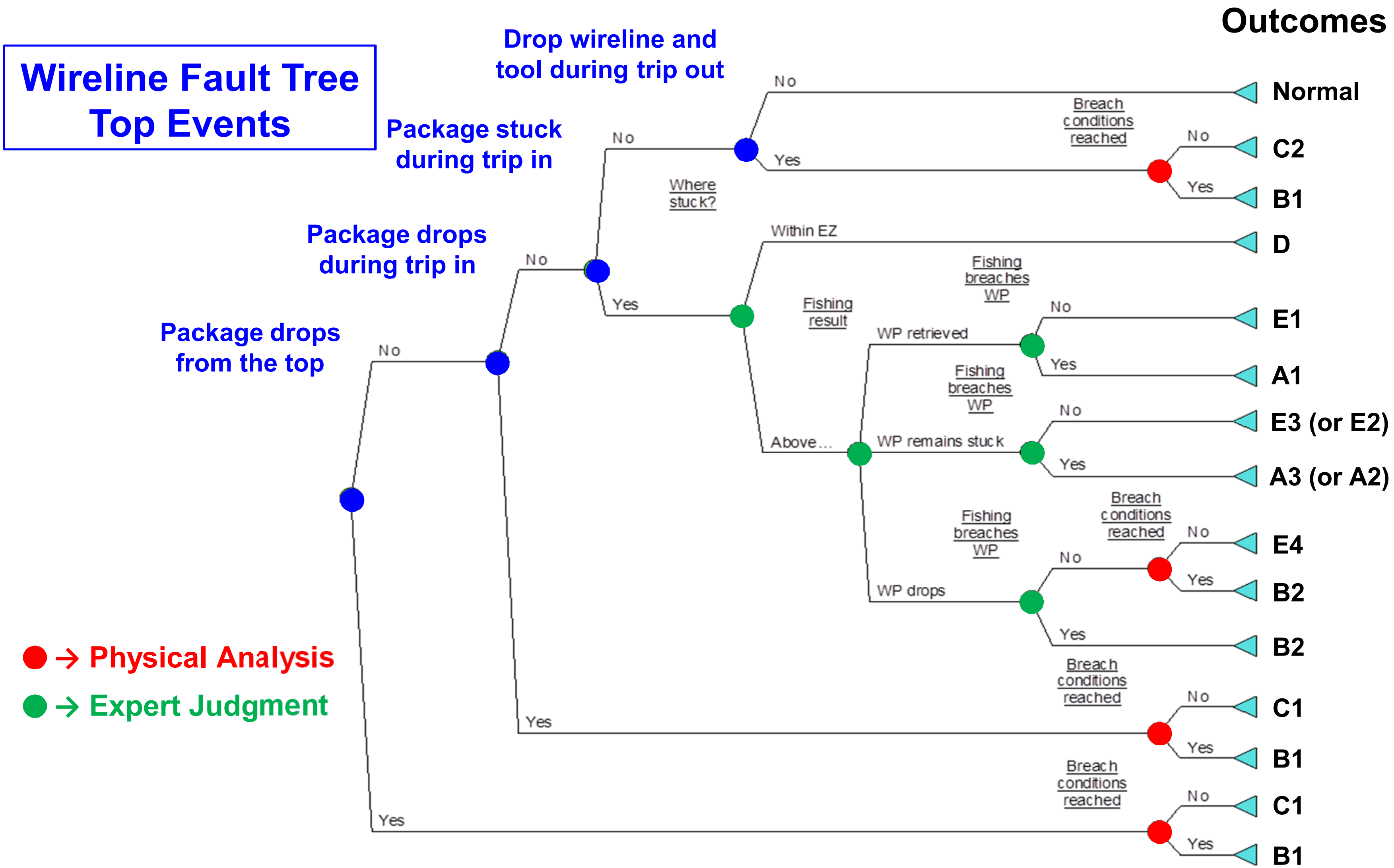
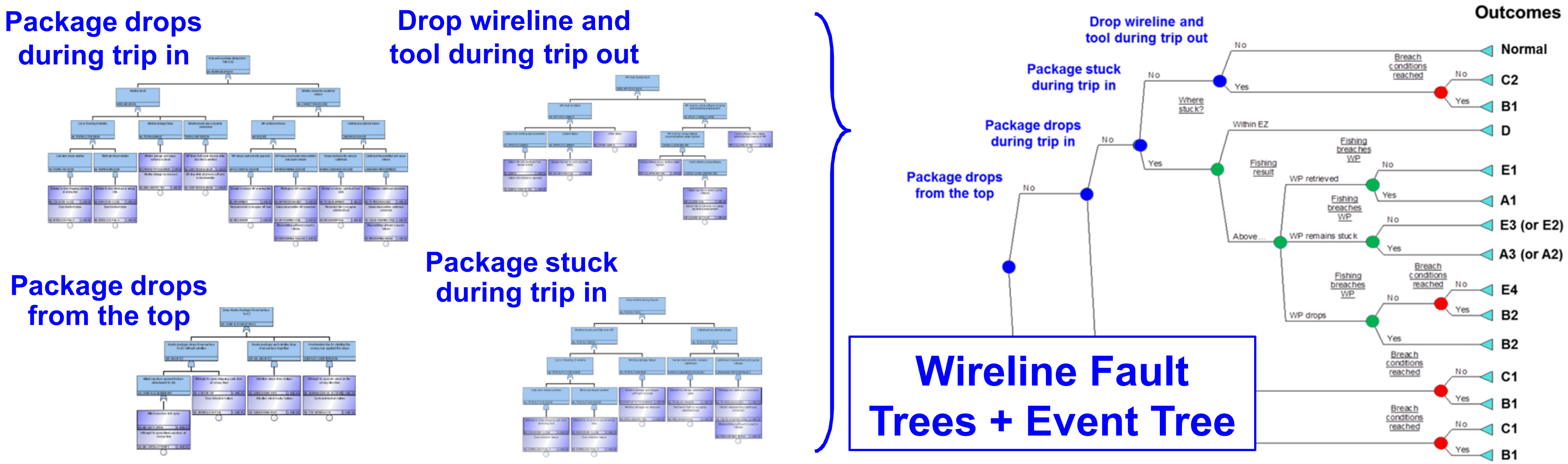
Cost-Risk Design Study: Event Tree for Drill-String Emplacement

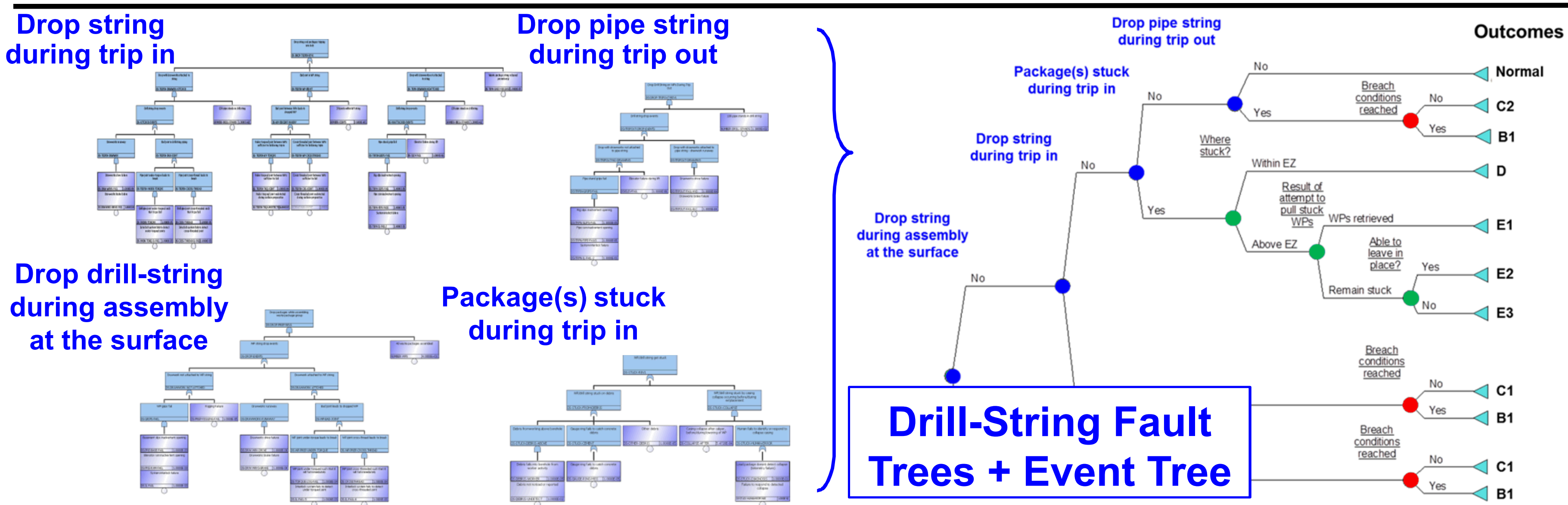


Cost-Risk Design Study: Event Tree for Wireline Emplacement



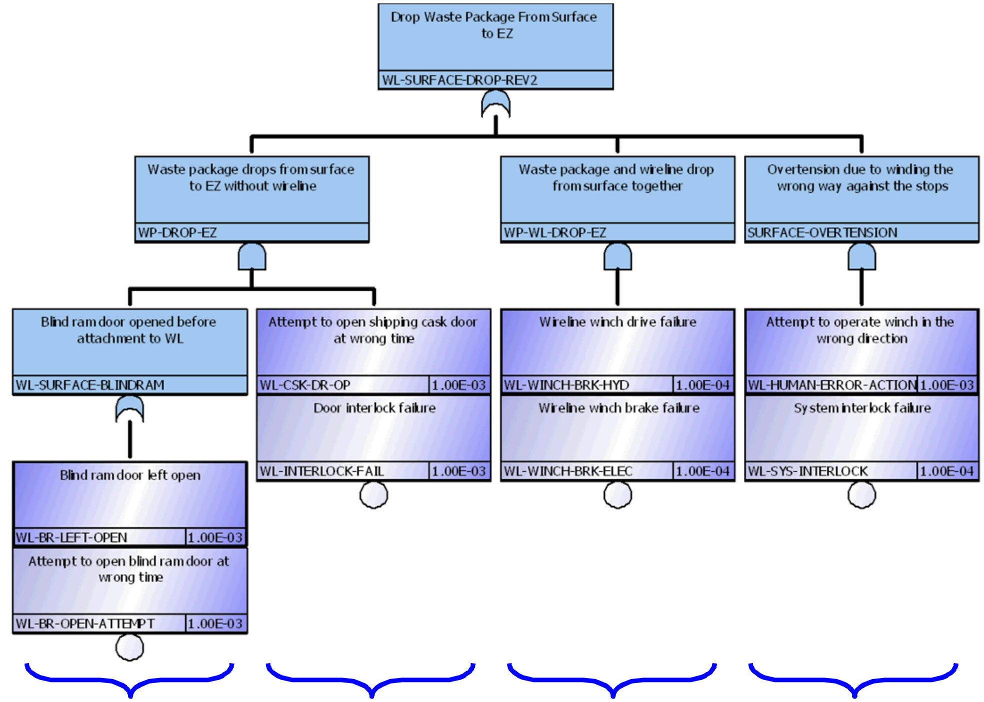
Cost-Risk Design Study: Cost–Risk Model





Example Fault Tree: Wireline/Package Drops from the Top

- **Top Event**
- **Logic Structure**
  - AND & OR gates
- **Basic (lower) Events**
  - Types of events (assigned probabilities)
    - *Human "diagnosis" error (10^{-2})*
    - *Human action error (10^{-3})*
    - *Active equipment (10^{-4})*
    - *Passive equipment (10^{-5})*
- **Example**
  - Top Event: Drop one package from the surface while staging for wireline emplacement



Human errors: Blind ram left open OR Open at wrong time

AND Open cask doors at wrong time AND Interlock failure

Winch hydraulic failure AND Winch brake failure

Human error (winch operation) AND Interlock failure

Expert Panel Participants

Convened to engage expertise in key subject areas, specifically to review and update preliminary input on engineering concepts, hazard analysis, and cost.

- **External Panelists:**
  - John Finger – Drilling engineering consultant
  - Mark MacGlashan – Wireline consultant
  - Nelson Tusberg – Head of Engineering, Leitner-Poma Ltd.
  - Frank Spane – Geoscientist, PNNL
  - Sven Bader – AREVA engineer
  - Scott Bear – AREVA engineer
- **SNL Panelists:**
  - Doug Blankenship – Manager, Geothermal Dept.
  - Courtney Herrick – WIPP engineer
- **Supporting Resources:**
  - Ernest Hardin – SNL (project lead)
  - Karen Jenni – Insight Decisions, LLC (analyst and facilitator)
  - Andrew Clark – SNL (risk analyst)
  - John Cochran/SNL (emplacement concepts, costing)
  - Jiann Su/SNL (waste packaging concepts)
  - Steve Pye – Drilling engineering consultant
  - Dave Sevougian (hazard analysis)
  - Paul Eslinger/PNNL (hazard analysis)
- **Observers:**
  - Allen Croff/NWTRB Member

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Risk Insights from Design Study

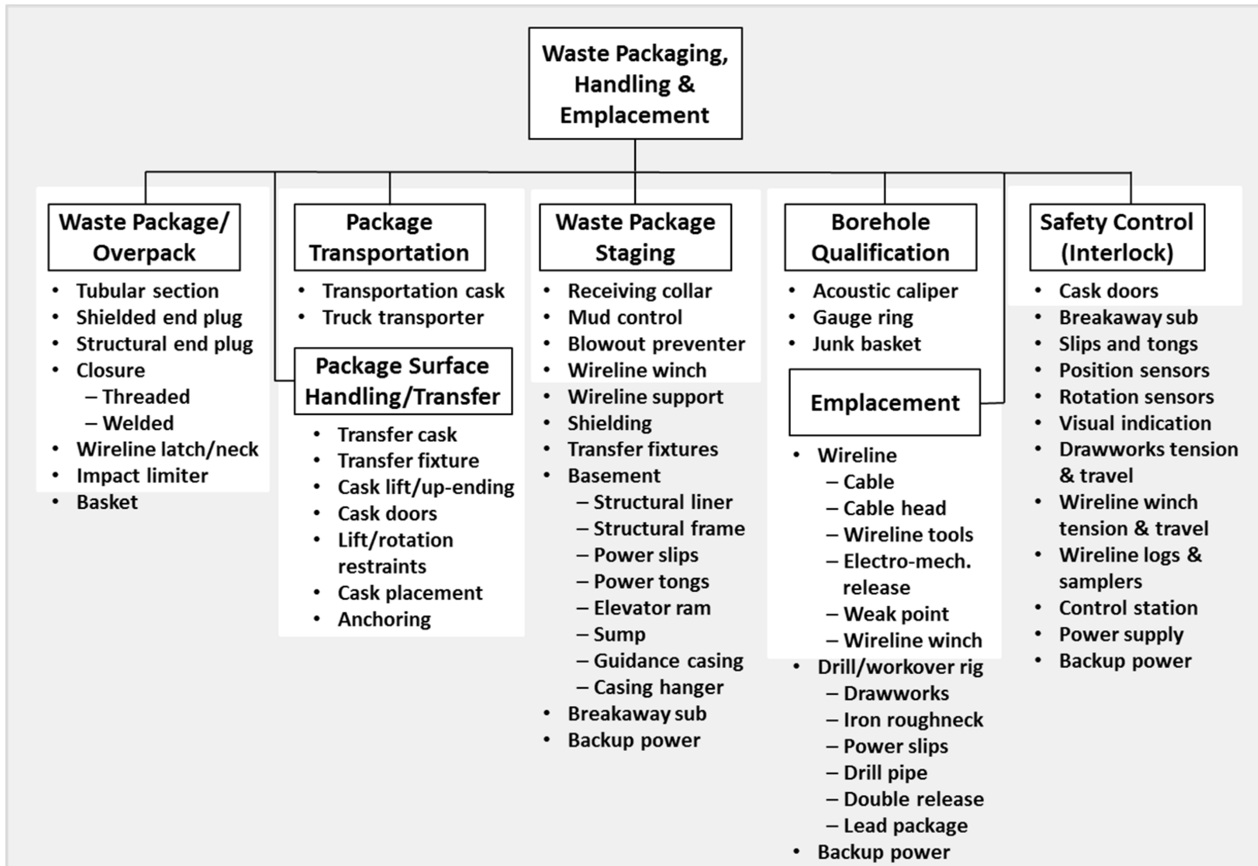
- Preliminary Results for DBFT Demonstration Emplacement Mode Selection
- Note: Operational safety analysis for a disposal facility would be conducted under applicable Title 10 regulations and DOE Orders.

	Results	
	Wireline	Drill-String
Probability of incident-free emplacement of 400 WPs	**96.81%**	**99.22%**
Outcome Probabilities		
Probability of a radiation release (Outcomes A1–A3, B1 & B2)	1.29E-04	7.04E-03
Probability of a failure that does not cause radiation release but terminates disposal operations (Outcomes D & E1–E4)	8.45E-03	8.00E-04
Probability of a failure that leads to extra costs and delays, but does not terminate disposal operations (Outcomes C1 & C2)	2.33E-02	0.00E+00*
Approximate total cost if successful ($ million)	**22.6**	**40.0**
Expected cost ($ million), weighted normal + off-normal	**22.8**	**42.0**

* No delay (and minimal extra cost) because rig is already on site, and some disposal capacity is sacrificed.

Recommendations from Comparative Cost-Risk Analysis

- Recommend that the DBFT Demonstrate Wireline Emplacement
- Use Functional Safety Principles to Control Risk
- Use Risk Insights to Down-Select Features for the DBFT → → →



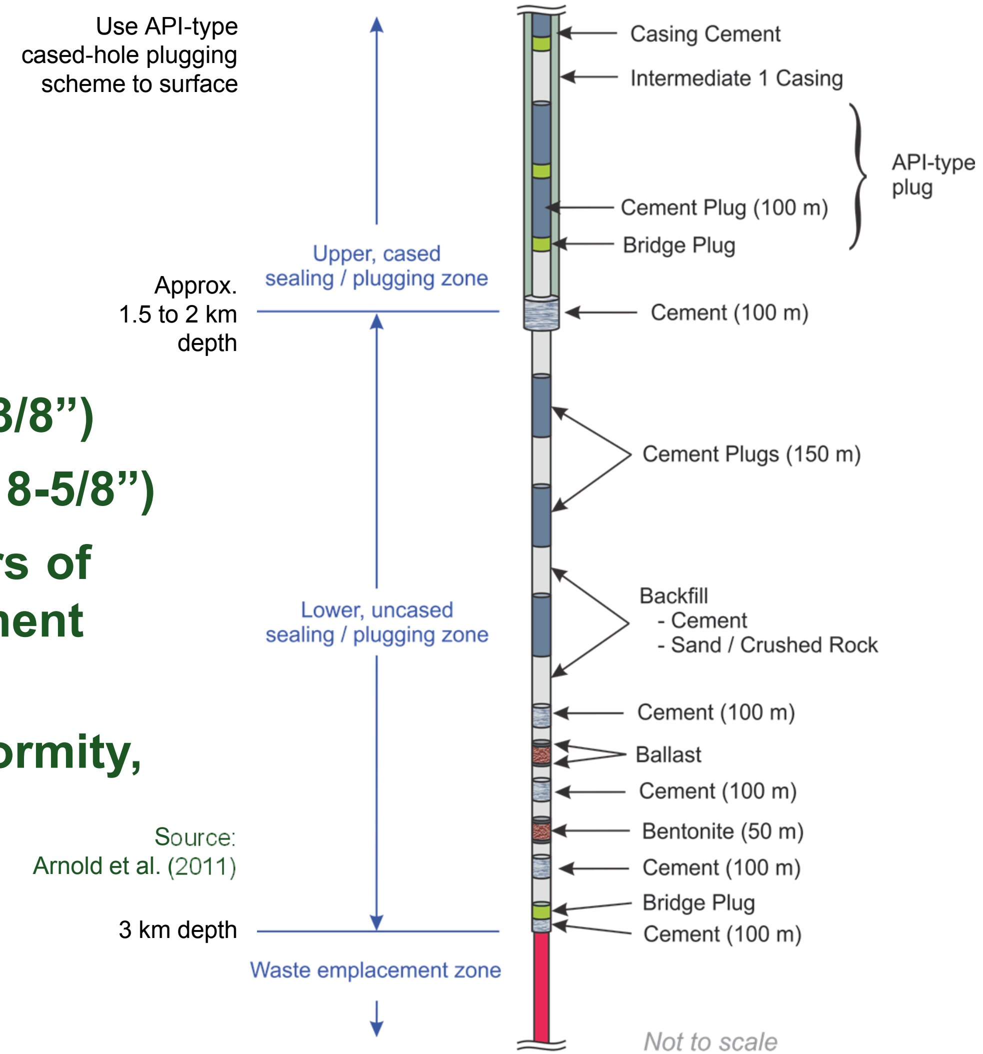
Some Remaining Conceptual Design Questions

- Deep Borehole Field Test
  a) Basement interval completion and emplacement fluid
  b) Factor of safety, and test package metallurgy
  c) Test package terminal sinking velocity
  d) Impact limiter design and performance
  e) Package release mechanism
- Disposal System (in addition to above)
  a) Multi-purpose cask vs. transporation + transfer casks
  b) Emergency equipment repairs in radiation environments
  c) Functional safety control (interlock) system
  d) Engineered measures to prevent packages getting stuck
  e) Waste package drop resistance (dry, surface)

Reference Concept for Disposal Borehole Completion and Sealing

- **Disposal Zone**
  - Cemented guidance casing
  - Emplacement fluid
  - Bridge plugs
- **Sealing/Plugging Zone**
  - Remove guidance tieback (13-3/8”)
  - Remove intermediate casing (18-5/8”)
  - Seal/plug with alternating layers of compacted bentonite clay, cement plugs, and cemented backfill
  - Extend upward across unconformity, into the overburden
- **Overburden Interval**
  - API* type plug, fully cemented

*American Petroleum Institute

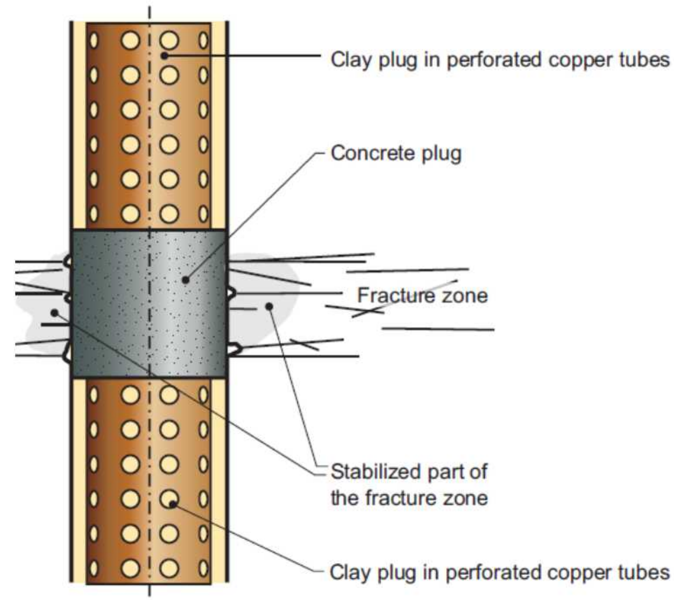


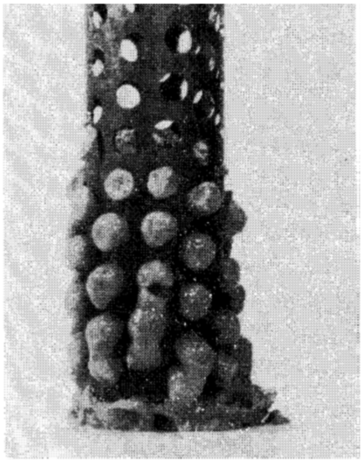
U.S. DEPARTMENT OF ENERGY
Nuclear Energy

Sealing Materials and Methods General Outline

- **Sealing ***
  - Smectites, illites, zeolites
  - Emplacement methods
- **Cement ***
  - Material properties and longevity
  - Emplacement methods and setting time
- **Fused Borehole Plug**
- **Rock Melting**
  - Low permeability plug
  - Controlled annealing of host rock

Following 35+ years R&D for sealing investigation boreholes and repository shafts





Laboratory immersion 24 hr

(Pusch, R. *Borehole sealing with highly compacted Na bentonite*. SKB TR-81-09)

Sealing Technology Studies Underway

- **DOE Small Business Innovation Research & Technology Transfer**
  - RESPEC: Rock melt borehole sealing system – Electric heater (2015-2017)
  - Olympic Research: Thermally formed (thermite) plugs for deep borehole plugging and sealing (2013-2016)
  - Impact Technologies LLC/Air Force Research Lab: Deep borehole applications of millimeter wave technology (2014-2016)
  - Cimentum, Inc.: Unique cement for cementing and grouting in deep boreholes for waste disposal (2015-2016)
- **Sandia Partner Labs and Subcontracts**
  - University of Sheffield, UK: Deep borehole field test and borehole seal design and performance criteria (Sept. 2015 – Sept. 2016)
  - Korean Atomic Energy Research Institute (KAERI): Borehole sealing investigations collaboration (2015+)
  - Los Alamos National Laboratory: High-temperature and -pressure investigations of smectite stability
  - Participation in DOE's Subsurface Technology and Engineering Research, Development, and Demonstration (SubTER) program

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