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Spent Fuel and Waste Science and Technology (SFWST)

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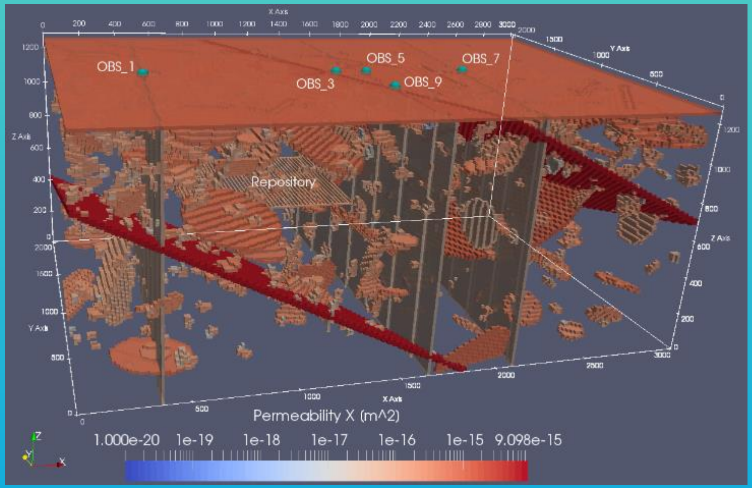

Overview of Engineered Barrier System (EBS) Function and Design in an Argillite Host Rock

U.S. Nuclear Waste Technical Review Board

Fact Finding Meeting

July 19, 2022

Ed Matteo

Sandia National Laboratories

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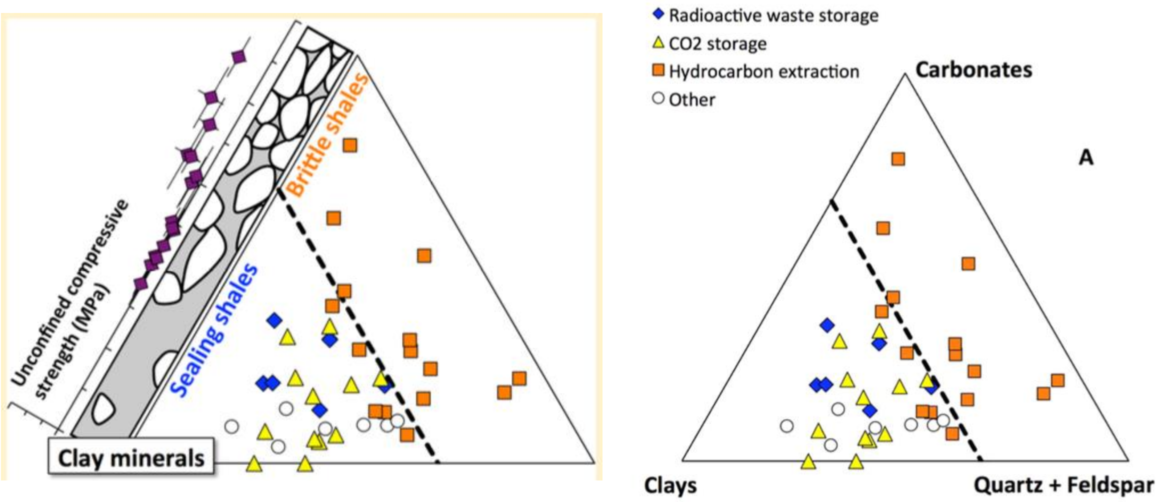
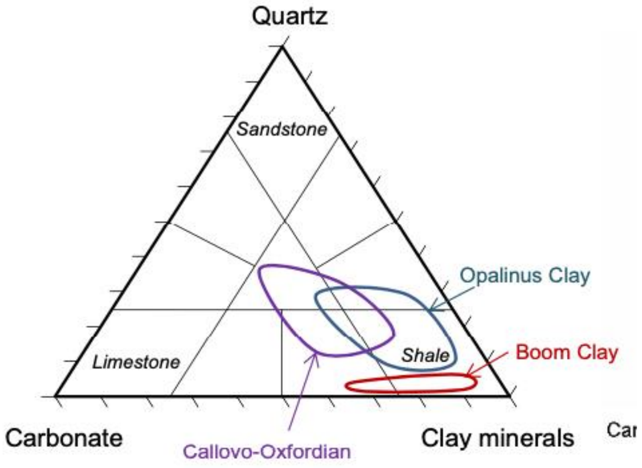
SAND2022-10290PE

Argillite Host Overview

- Argillite is a broad Rock Category
  - Sealing vs. Brittle Clay Rock defined in the literature, as point where Clay fraction is > = 1/3 (see dashed in top figures)
- High reliance on the natural system
  - Reducing chemical environment
  - Diffusion Dominated (for sealing argillites) in base case
  - But …there is typically a scenario for advective transport via the short-lived EDZ (which eventually self-heals) or otherwise through and/or around the Seal System (Hansen et al. 2010).



From Bourg 2015

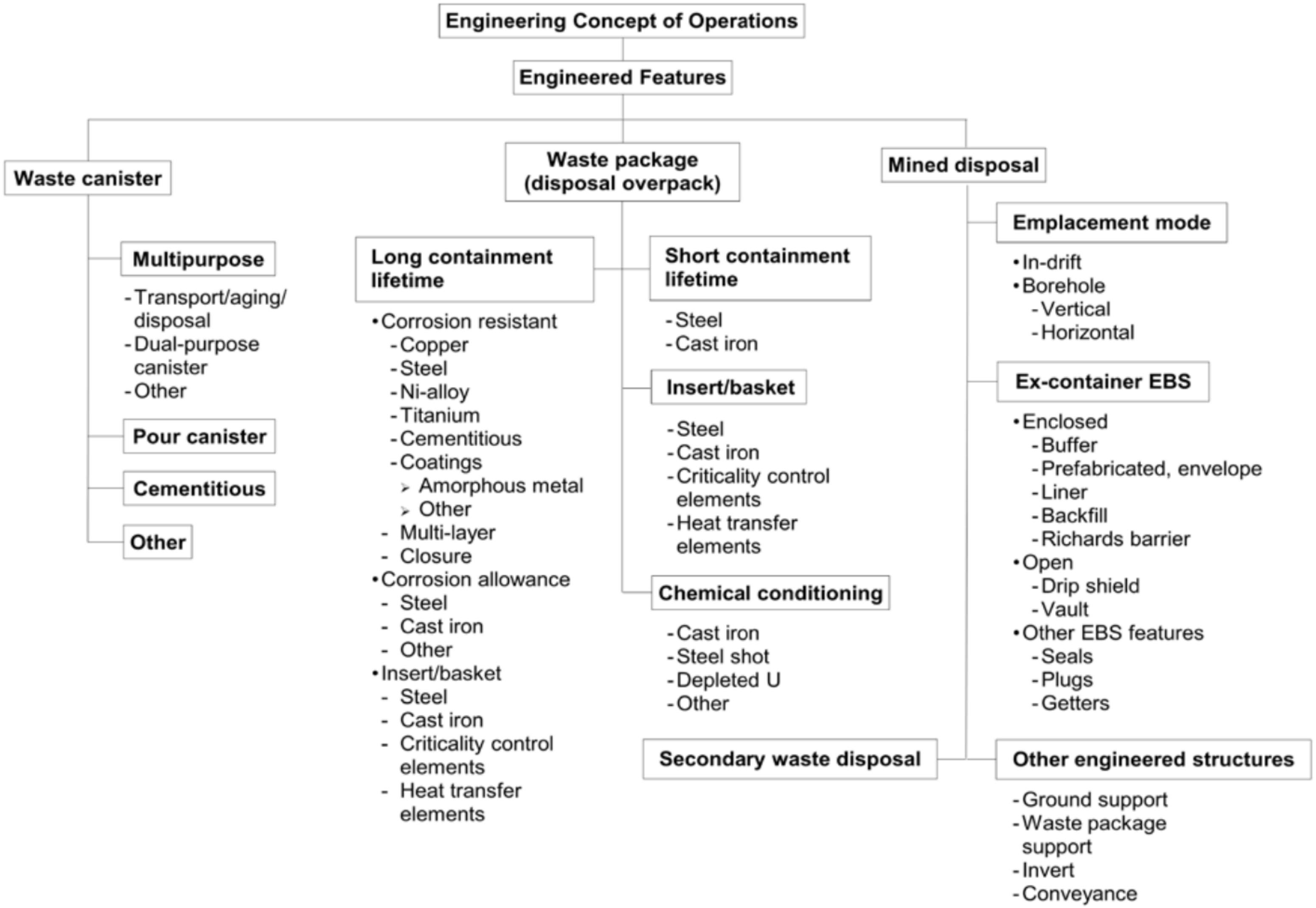


From Charlet et al. 2017

The EBS Design will be a function of Inventory and Geologic Setting

- Inventory – thermal output has key impacts on Repository Design
  - Who, What, Where of waste
- Geologic Setting
  - Host rock chemical and mechanical environment
- Engineering Decisions
  - Constructability
  - Emplacement
    - Drift and waste packing spacing (determined by thermal and geomechanical considerations)
    - Vertical vs. horizontal emplacement
    - Bentonite Buffer/backfill – pelletized vs. compacted vs. pre-fab
  - Materials selection
    - Overpack (e.g. corrosion allowance materials)
    - Buffer vs. backfill
  - Additional Engineered System Elements for Operational Safety (e.g. ground support)

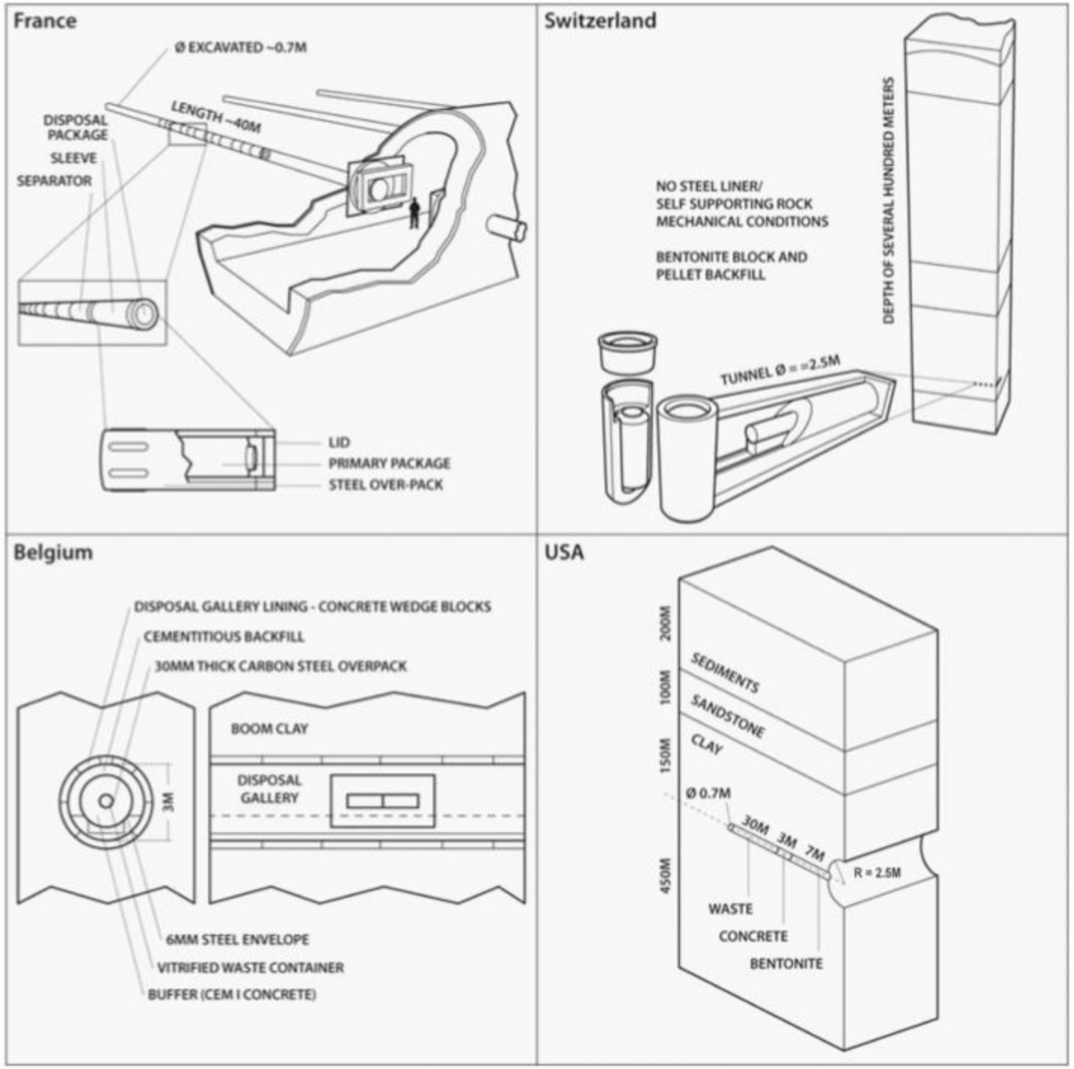
There are many Design Options for the Engineered System



From Hardin et al. 2011

Argillite type has a big impact on Repository Concept and EBS Design

- Degree of induration, i.e. mechanical integrity
- Sealing vs. Brittle (Bourg 2015)
  - Callovo-Oxfordian (COx) (ANDRA - France)
  - Opalinus Clay (NAGRA - Switzerland)
  - Boom Clay (ONDRAF - Belgium)

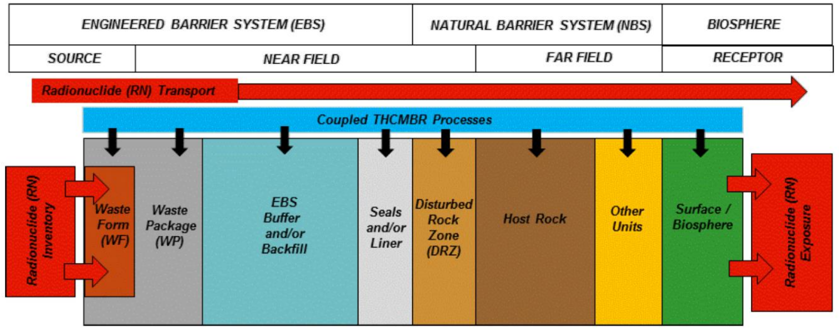


Sources: France: www.andra.fr; Switzerland: www.nagra.ch; Belgium: www.sckcen.be.

Though all are Argillites, the chemical and mechanical environments differ enough that the Design Concept have significant differences*

*ANDRA example case - shotcrete is removed in upper COx

Engineered Barrier System Components, 1/2



NOTE: THCMBR = thermal, hydrologic, chemical, mechanical, biological, and radiological.
Source: Freeze et al. 2013, Figure 2-1.

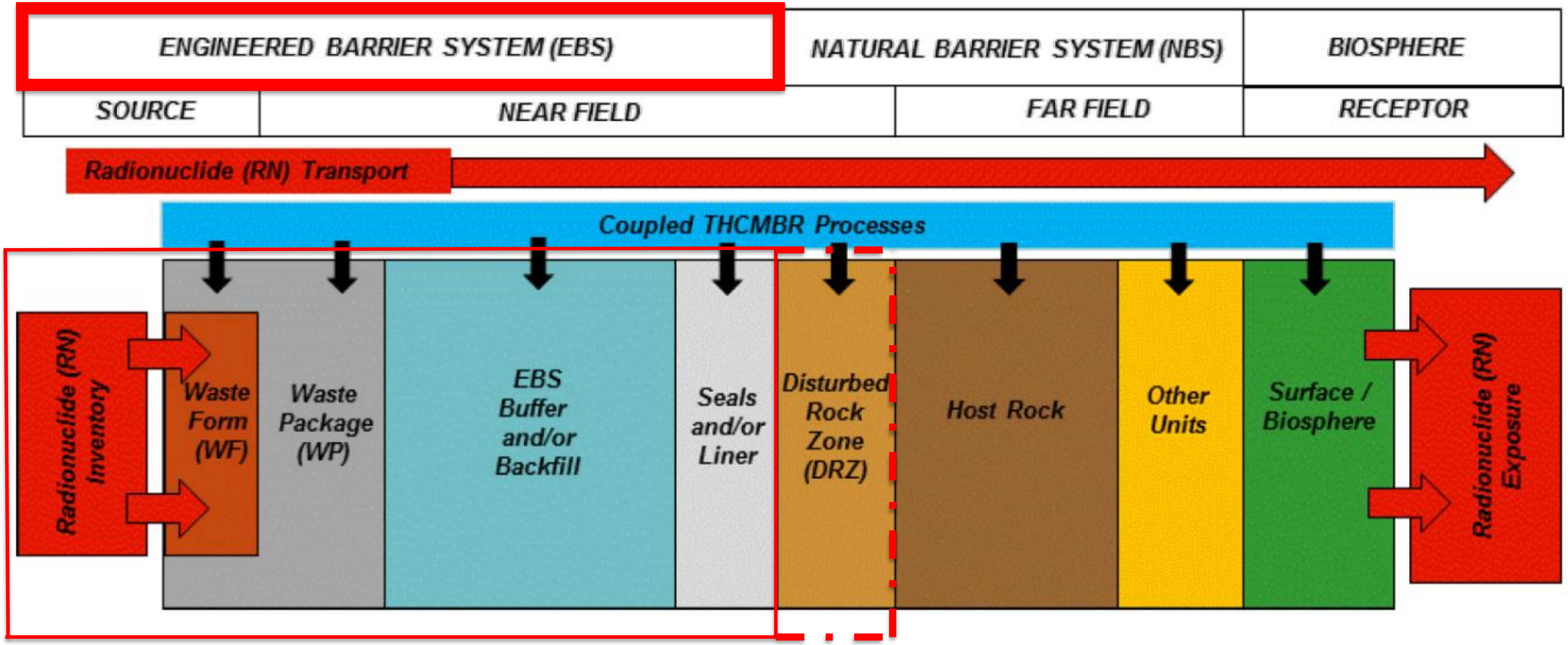
- Waste form
- Waste Canister/Overpack
- Buffer/Backfill
- Drift Seals
  - Access and Emplacement
- Shaft Seals
- Ground Support (generally needed in Argillite Hosts) – e.g. liner, rock bolts, etc.
- Excavation Damaged Zone (EDZ)

Seal System*

a/k/a Geotechnical Seals

*The Seal System functions to seal the drifts and shafts, and also takes into account the EDZ

Engineered Barrier System, 2/2

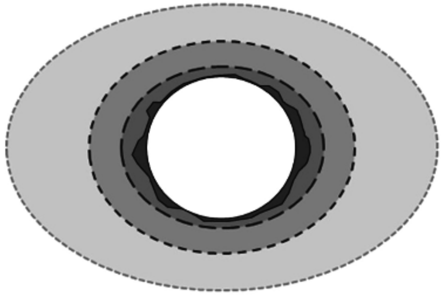


NOTE: THCMBR = thermal, hydrologic, chemical, mechanical, biological, and radiological.

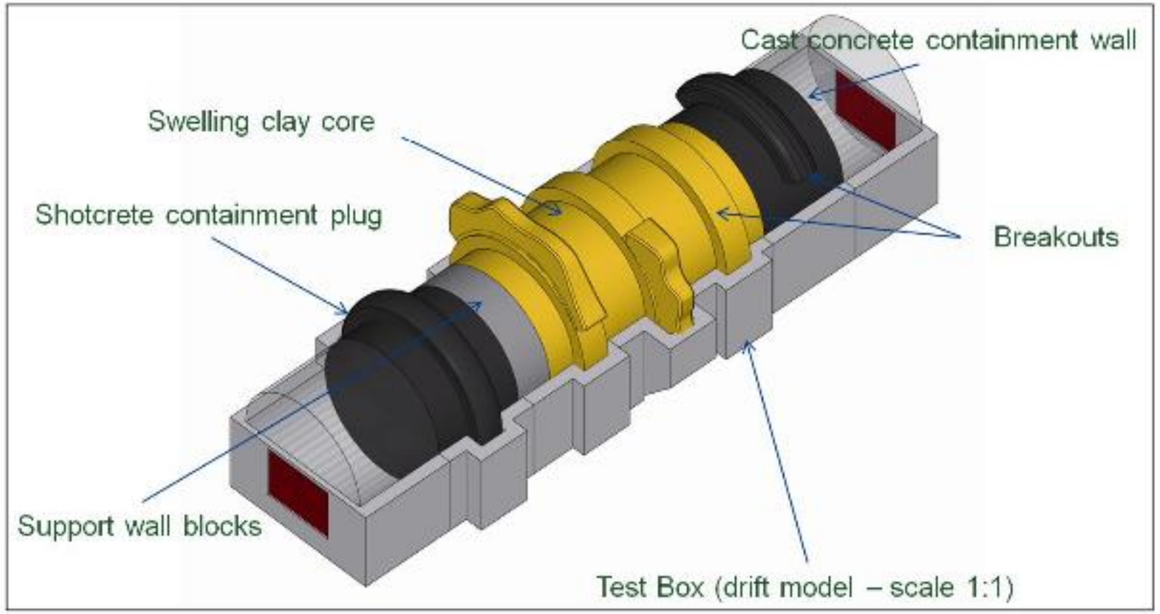
Source: Freeze et al. 2013, Figure 2-1.

Excavation Damage Zone (EDZ) and the Seal System

- A/k/a Damaged Rock Zone (DRZ)
- EBS Design must account for the EDZ and implement design features that prevent preferential transport along the fracture networks left behind from mining (Perras and Diederichs 2016)
- The EDZ features prominently into the design of the seal system, where break-outs and water stops are incorporated to interrupt potential transport pathways in the EDZ and/or at the Seal/Host interfaces
  - Liner – buffer/backfill
  - Liner- Host
  - Plugs – Host



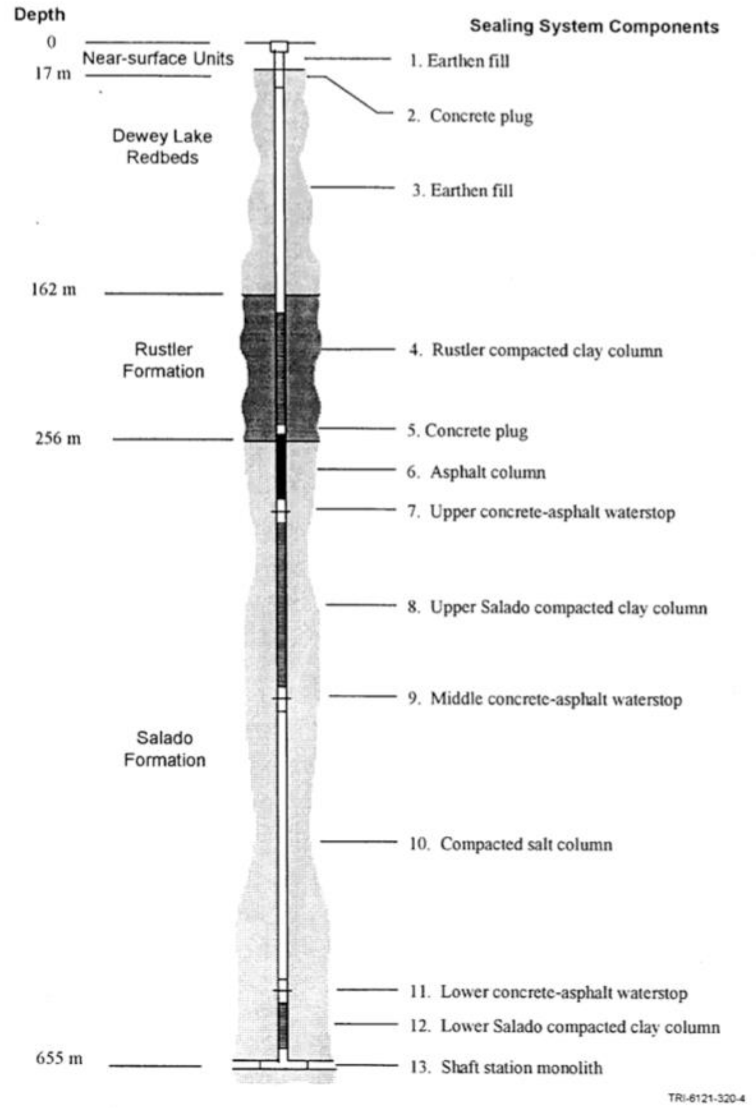
From Perras and Diederichs 2016



From DOPAS 2016 - Full Scale Seal Test conducted by ANDRA

Excavation Damage Zone (EDZ) and Shaft Seals

- In the Shaft, this also includes potential advective transport from disposal horizon to some other horizon that has potential to increase rate of transport to the biosphere
- Multi-barrier design, including “layers” composed of cementitious plugs, compacted swelling clay, backfill, and water stops.
- WIPP Shaft Seal Design often considered state-of-the-art of the multi-barrier design



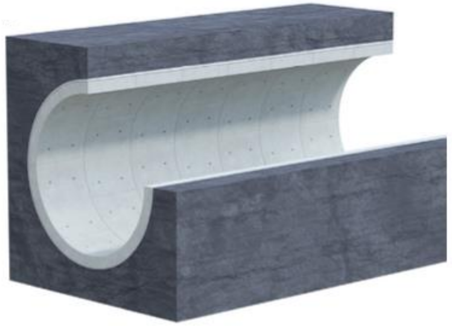
From Hansen and Knowles 1999

Cement Liners

- Provide Ground Support
- Performance Uncertainties arising from potential unknowns:
  - Preferential flow pathways formed by degradation/cracking of cement matrix (e.g. drying damage during the repository thermal period)
    - Cements are saturated materials in normal service environments
    - Fiber reinforcement is a potential remedy
  - Effect of cement alkalinity on near-field chemistry
    - Low pH cements (in actuality lower pH ~10-11) as a remedy
- Sourcing and/or variability of cementitious materials
  - Due to the CO2 intensity of Ordinary Portland Cement, industry may adopt novel replacements that have different chemistry
  - For example, future fly ash availability

Uncertainties due to time-dependent and coupled processes, which are difficult to fully capture via modelling

Conservative assumptions and/or simplified representations are typically made in the absence of robust chemo-mechanical models

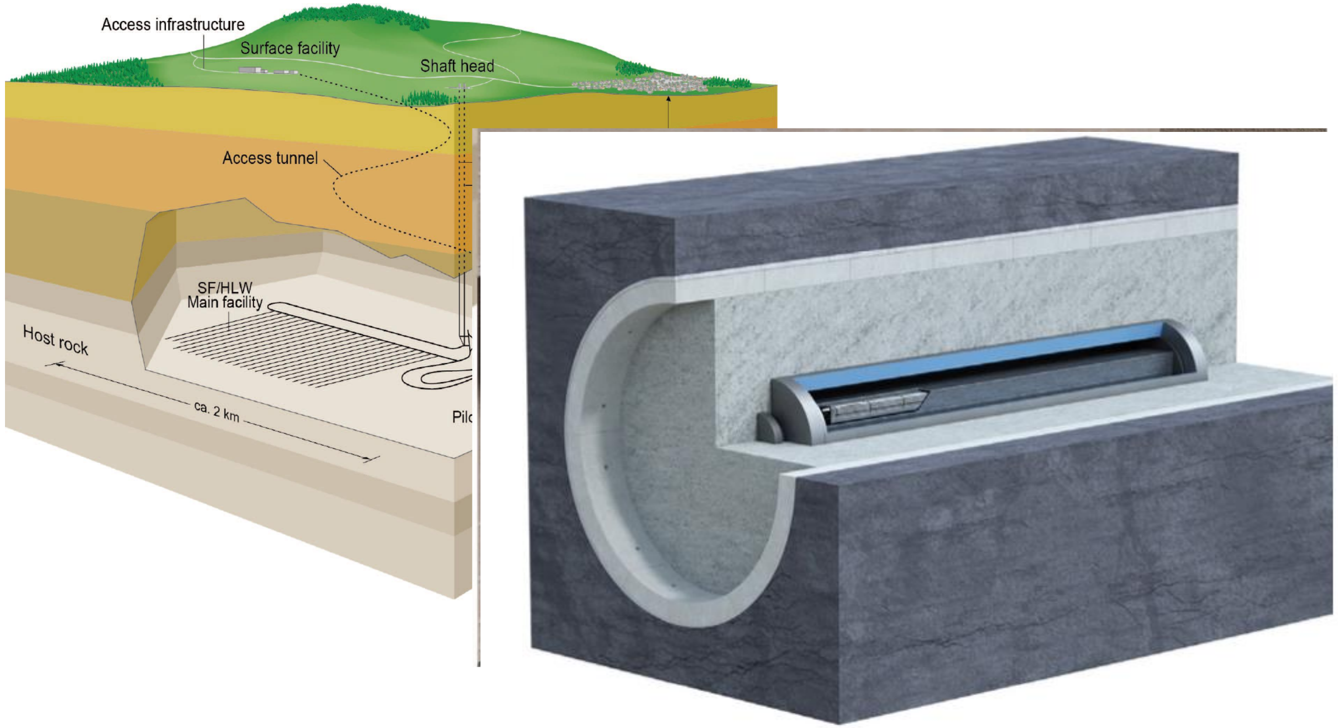


From NAGRA 2022

Source: Stein et al. 2020

Buffer/Backfill Functions, 1/2

- Bentonite or Cement
- Extends waste package lifetime and secures waste package in emplacement
- Helps conduct heat away from the waste package
- Functional barrier that can swell to fill gaps/voids and retains cationic radionuclide species
- Deters microbial activity



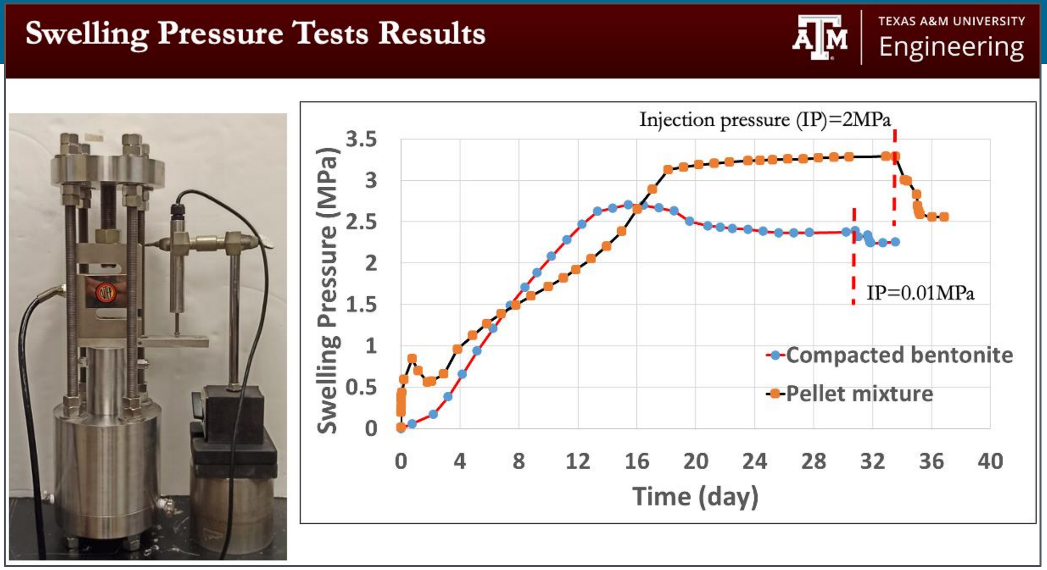
From NAGRA 2022

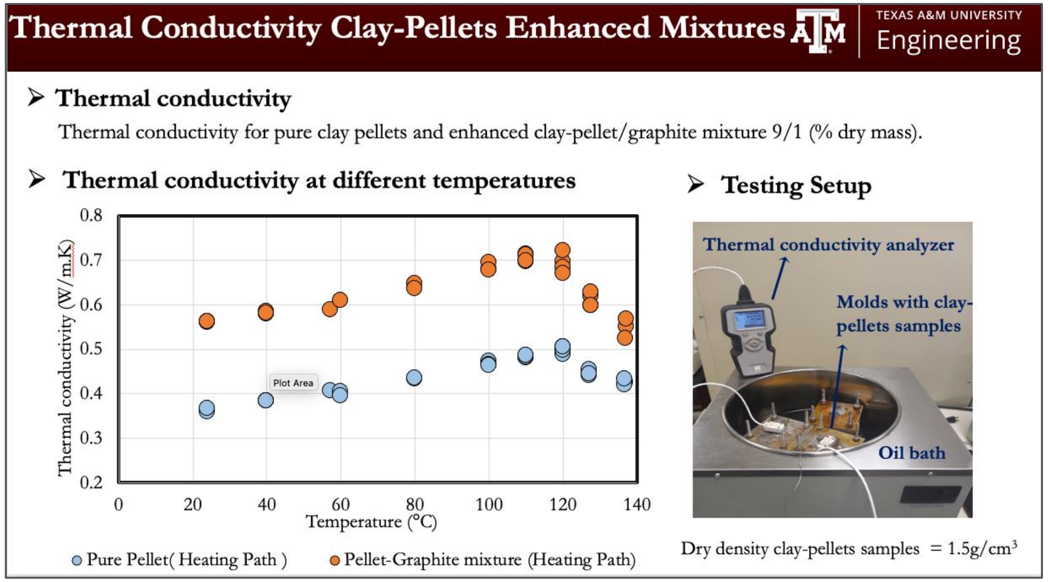
Buffer/Backill Functions, 2/2

- Favorable properties of Bentonite Buffer
  - **Self healing** with similar properties and compatibility to clay-bearing host
  - **Proven durability** in repository environment (clay formations have stability on geologic time scales and under repository conditions)
  - **Low permeability**, diffusion-dominated transport when intact (i.e., no fractures or channels)
  - **Swelling behavior** upon saturation
  - **Retention of cationic radionuclides**
- Bentonite Buffer Research crosscuts between Argillite and Crystalline Research Areas

Areas of Research Interest in the Design of Buffer/Backfill, 1/2

- High temperature effects (related to higher thermal output waste)
  - Lab and field scale tests to characterize effect of high temperatures (above 100 ˚C)
  - Swelling
  - Radionuclide retention
    - Sensitive to near field chemistry and temperature, both via complexation and sorption capacity
- Thermal conductivity
  - Additives to improve thermal conductivity
- Pelletized vs. Compacted Bentonite Buffer Emplacement
  - Homogenization - extent and rate of pellets or blocks
- Crosscuts with Nuclear Energy University Partnerships



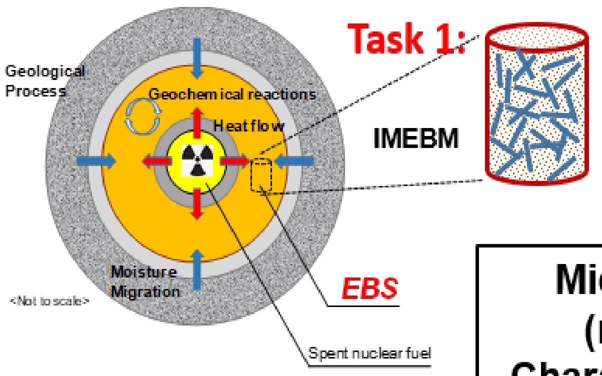


Graphics Courtesy of Prof. Marcelo Sanchez, Texas A&M University

Nuclear Energy University Partnership (NEUP) Project:

Multiscale and Multiphysical Testing-Modeling of Inorganic Microfiber-Reinforced Engineered Barrier Materials (IMEBM) for Enhancing Repository Performance

Engineered Barrier System



Task 2: Multiscale-Multiphysical Experiments (e.g., IMEBM rheological properties)

Task 3: Computational Modeling (e.g., Cracking modeling, THM modeling)

Task 4: Applicable IMEBM

Micro-scale (nm-µm) Characterization → Meso-scale (µm-cm) Experiment and Modeling → System-scale (cm~) Experiment and Modeling

University of Nebraska–Lincoln
College of Engineering
PI's: J. Eun and S. Kim

Texas A&M University
Civil & Env, Engineering
PI: Yong-Rak Kim

Sandia National Laboratories
PI's: Carlos Jove Colon
Yifeng Wang

Purpose: To develop inorganic, microfiber-reinforced engineered barrier materials **(IMEBM)** that are less permeable and more resistant to desiccation cracking and chemical degradation for a long term in the challenging geological environment of high-level radioactive waste repositories.

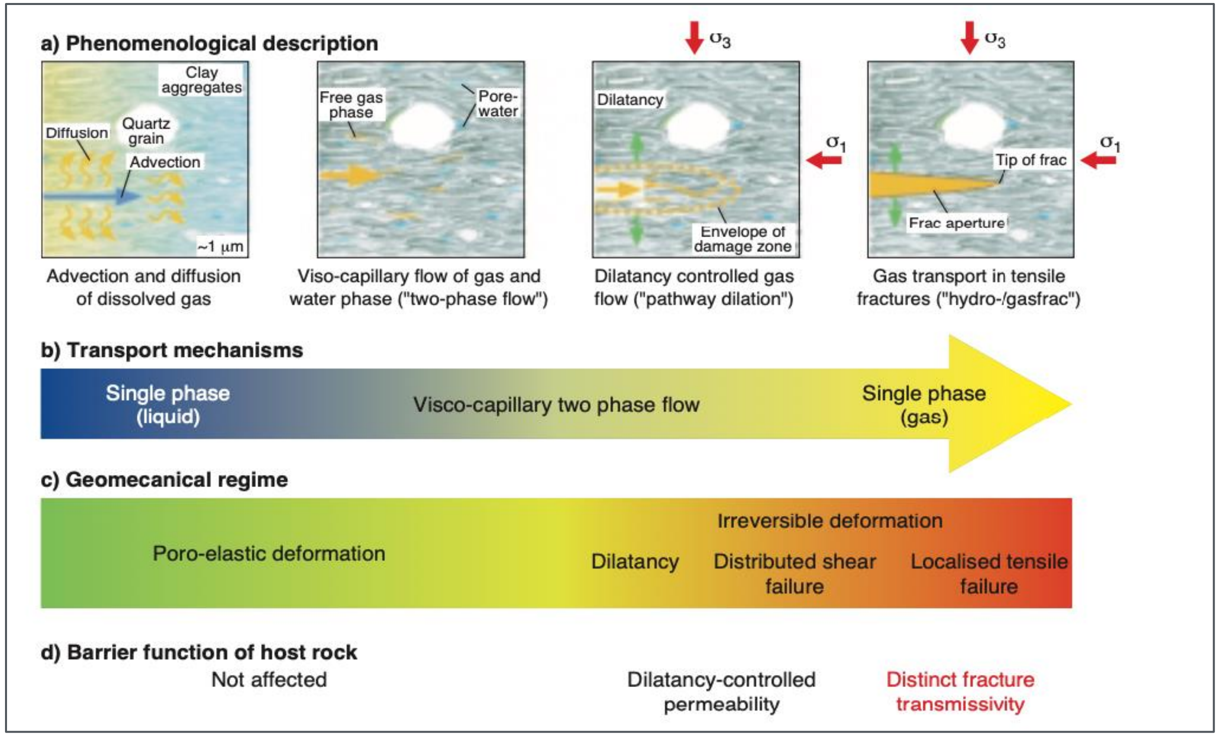
Objectives:

- (1) Develop and conduct an experimental program to identify the fundamental (THMC) and geometrical characteristics of IMEBM constituents (bentonite and fibers) and their interaction in multiple length scales (nm to cm) with the geological environment of the repository,
- (2) Develop multiscale-multiphysics computational models to simulate the laboratory testing program,
- (3) Integrate the experimentation with computational modeling to validate-calibrate the model and to propose an optimal set of variables for designing an improved engineered barrier material.

Source: J. Eun, DOE NEUP Quarterly report

Areas of Research Interest in the Design of Buffer/Backfill, 2/2

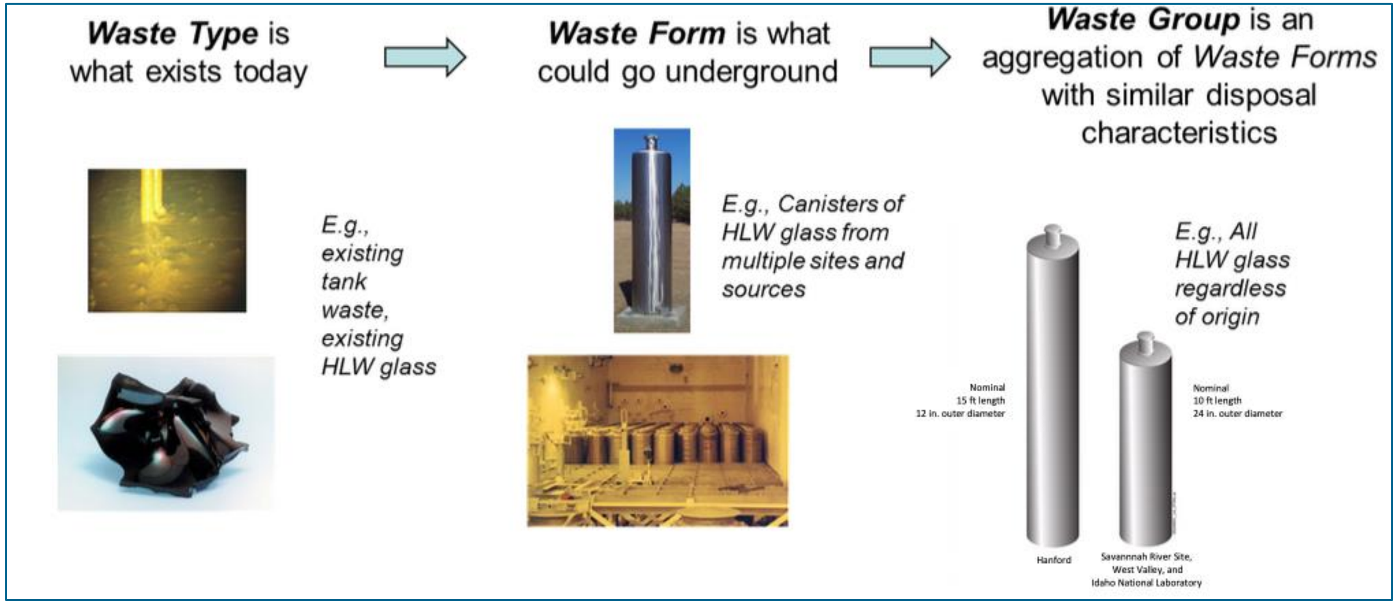
- Dry out and re-saturation damage
  - Will bentonite buffer crack and to what extent and at what rate will it heal upon re-saturation?
- Gas flow through bentonite
  - Channeling
  - Fracturing
- Buffer erosion (brittle Argillite)
- High performance sorbents and getters



Source: Marschall et al., 2005

Wasteform

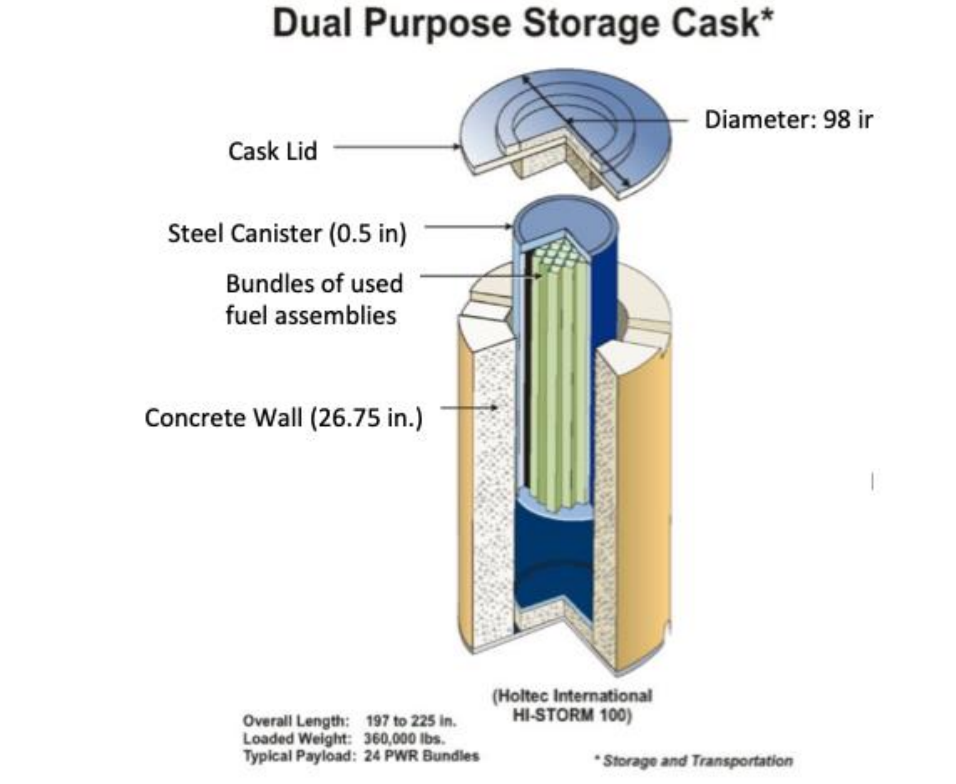
- Spent Nuclear Fuel Characteristics
  - Radionuclide inventories
  - Waste package loading
    - Effect of burn-up
  - Cladding
  - Criticality control via neutron adsorbers
  - In-package chemistry
- These are fixed variables that must be taken into account by Repository/EBS Design



From DOE 2014

Waste Package

- Overpack selection
  - Steel for sealing shale
  - Corrosion allowance material (e.g. copper) for brittle shale, where potential for fracture –mediated transport necessitates a long-lived waste package
- Multi-purpose canisters (e.g. Dual purpose canister)
  - Systems engineering challenge – is it more efficient and/or safer to emplace fewer larger, hotter waste packages vs a greater number of smaller, cooler waste packages
- Corrosion Rates?



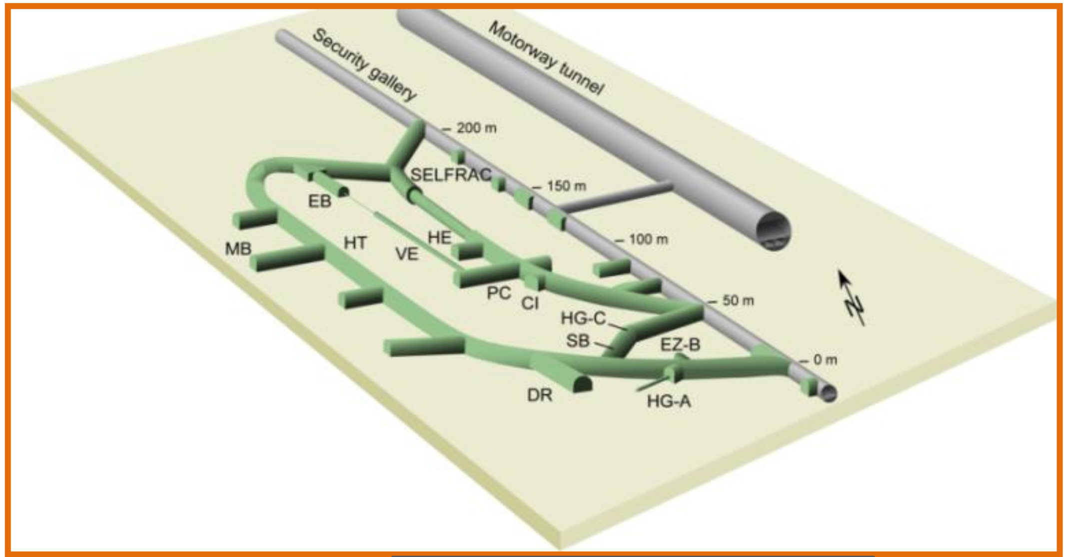
Source: modified from Easton 2011.

From DOE 2014

International Field Tests in Argillite provide Proof of Concept and improve understanding of complex processes

- Proof of concept
- Improve understanding of complex processes
  - Process model development
  - Provide critical data for development of computational representations of processes
- Demonstration Field Tests
  - Mt. Terri
    - For Example - FE : Full Scale Emplacement Heater Test demonstrates emplacement and provides a platform form for understanding/modelling processes in the near field, including waste package(heater), bentonite buffer, argillite host rock– link to DECOVALEX 2023 Tasks
    - Many, many others…EDZ, gas transport, sealing, etc.

Critical to the EBS Design Process



Mont Terri, Switzerland

Conclusions and Summary, 1/2

- Preliminary Repository Design Concept includes a preliminary EBS Design – both are based upon geologic setting and inventory
- Argillite is a broad rock type, which can vary widely in both chemical and mechanical characteristics
- Varying characteristics plus the possibility for higher thermal loads generates more potential EBS Design variations (rel. to crystalline and salt hosts), even in the preliminary design phase for a generic design concept.
- The function and some high level design considerations have been have presented and briefly discussed

Conclusions and Summary, 2/2

- Field Scale Tests and International Collaborations via Underground Research Lab investigations are crucial for:
  - Proof of concept for design concepts and/or important processes
  - Datasets that can be used to develop computational tools and process models for EBS performance
- The EBS Design, Computational tools, and Process Models can be critical in Geologic Disposal System Assessment by
  - By increasing predictive confidence, providing parameter values, and/or bounding constraints of parameter range.

References, 1/2

Bourg, I. *Environ. Sci. Technol. Lett.* 2015, 2, 10, 255-259

Charlet et al., *Advances in Water Resources 106 (2017) 39–59*

DOE 2014. FCRD-UFD-2013-000371, Revision 1 SAND2014-0187P (Vol. I); SAND2014-0189P (Vol. II)

DOPAS 2016. DOPAS Work Package 6 Deliverable D6.4: DOPAS Project Final Summary Report.

Hardin, E., J. Blink, H., Greenberg, M. Sutton, M. Fratoni, J. Carter, M. Dupont, and R. Howard, "Generic Repository Design Concepts and Thermal Analysis (FY11)", SAND2011-6202.

Hansen, F.D. and M. K. Knowles. Design and Analysis of a Shaft Seal System for the Waste Isolation Pilot Plant, SAND99-0904J, Sandia National Laboratories, Albuquerque, NM, 1999.

Hansen et al. , 2010. Shale disposal of US High-Level Radioactive Waste. SAND2010-2843, May 2010.

Marschall, P., Horseman, S., Gimmi, T., 2005. Characterisation of Gas Transport Properties of the Opalinus Clay, a Potential Host Rock Formation for Radioactive Waste Disposal, Oil & Gas Science and Technology - IFP International Workshop. Rev. IFP, Vol. 60 (2005), No. 1, 121-139.

NAGRA, Arbeitsbericht, NAB 22-16. Beacon / WP 1.3 / Final Assessment Repot, January 2022.

Perras, M. A. and M. S. Diederichs. Predicting excavation damage zone depths in brittle rocks. Journal of Rock Mechanics and Geotechnical Engineering 8 (2016) 60-74

References, 2/2

Stein, E., C. Bryan, D. Dobson, E. Hardin, C. Jové-Colón, C. M. Lopez, E. Matteo, S. Mohanty, M. Pendleton, F. Perry, J. Prouty, D. Sassani, and Y. Wang. Disposal concepts for a High-Temperature Repository in Shale. M3sf-21SN010304064, SAND202-12471 R, October 2020.

Wakeley, L. D. Grouts and Concretes for the Waste Isolation Pilot Project (WIPP). Mat. Res. Soc. Symp. Proc. Vol. 176, 1990.