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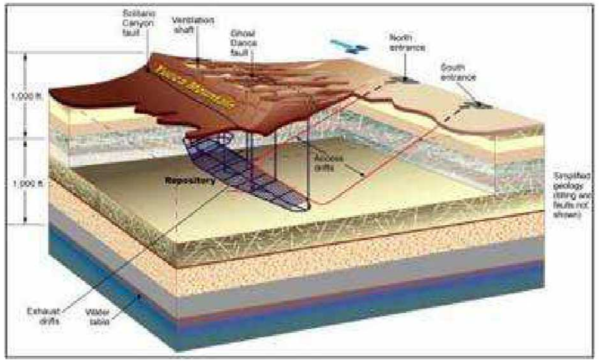

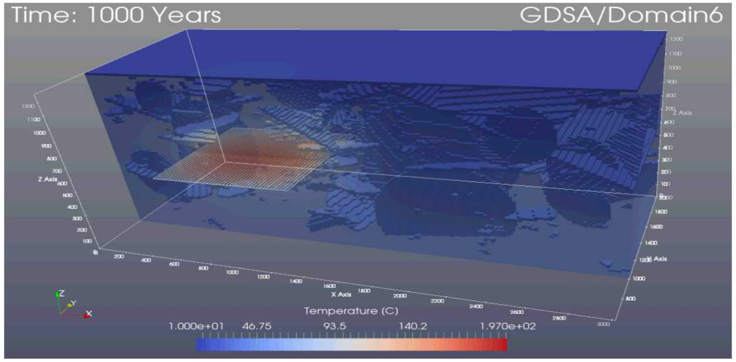

US Department of Energy (DOE) Work in Nuclear Waste Disposal: Status and Crystalline Rock R&D

DRAFT

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Applied Systems Analysis & Research
Sandia National Laboratories

1st Meeting of Crystalline Club
Prague, Czech Republic
December 5, 2017

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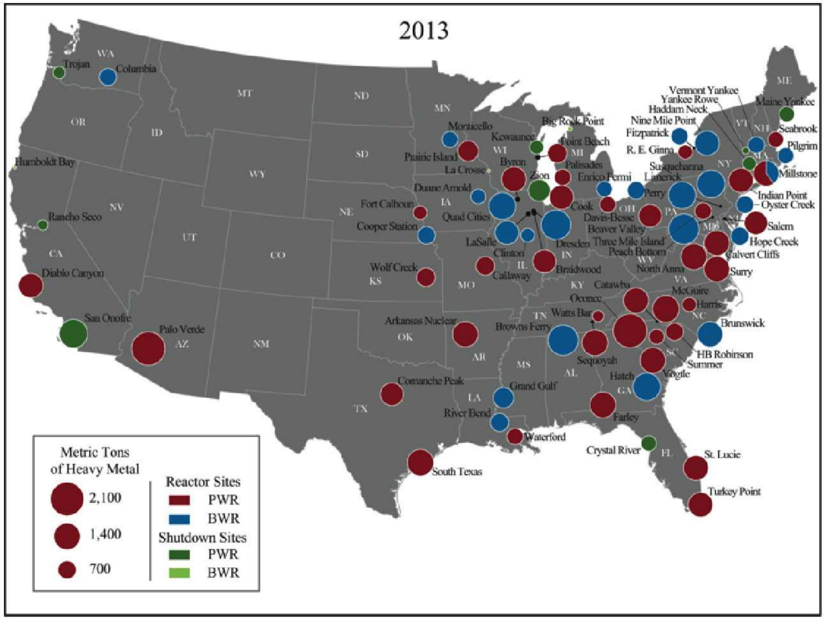
Outline

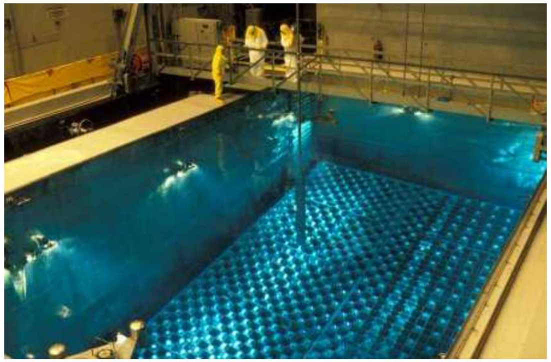
- Status of the US program
- R&D needs

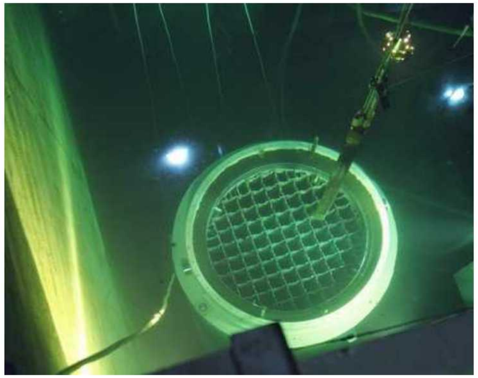
US Inventory: Commercial SNF

Commercial Spent Nuclear Fuel (SNF)

- In temporary storage at 75 reactor sites in 33 states
- US pools have reached capacity limits and utilities have implemented dry storage
- Some facilities have shutdown and all that remains is “stranded” fuel at independent spent fuel storage installations (ISFSIs)







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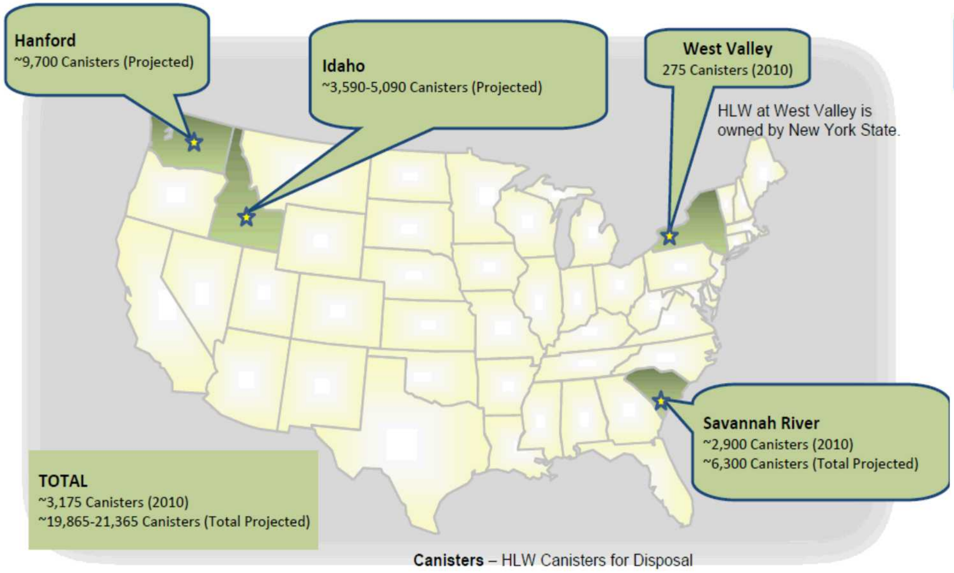
Slide content courtesy of Peter Swift, SNL

US Inventory: DOE-Managed SNF & HLW

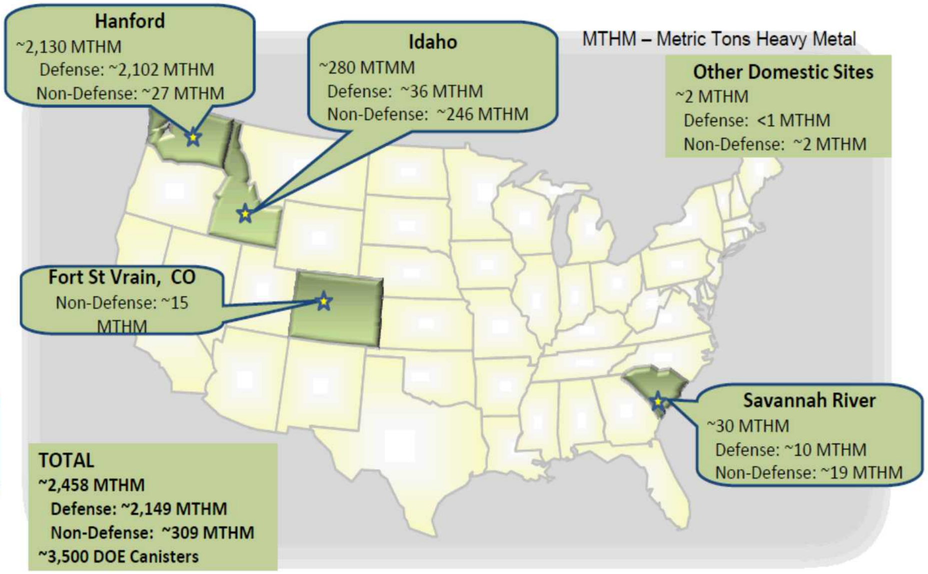
DOE-managed SNF and High-Level Radioactive Waste (HLW)

- In temporary storage at 5 sites in 5 states

DOE-Managed HLW
~20,000 total canisters (projected)



DOE-Managed SNF
~2,458 Metric Tons

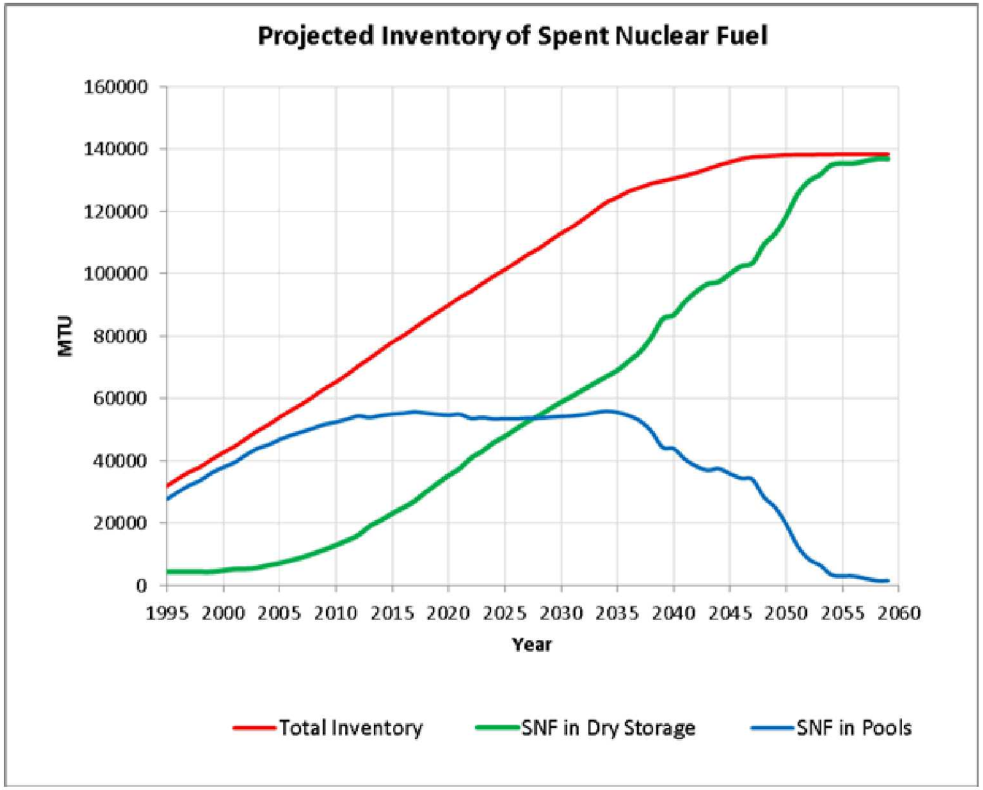


Source: Marcinowski, F., "Overview of DOE's Spent Nuclear Fuel and High-Level Waste," presentation to the Blue Ribbon Commission on America's Nuclear Future, March 25, 2010, Washington DC.

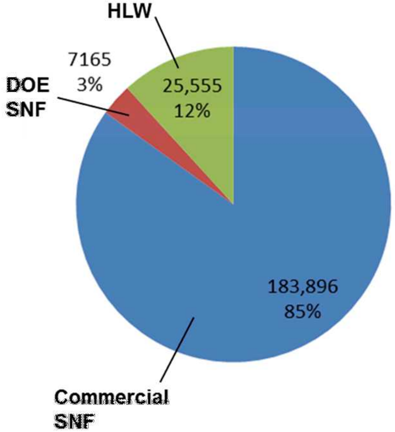
Slide content courtesy of Peter Swift, SNL

US Projections of SNF and HLW

Projection assumes full license renewals and no new reactor construction or disposal



Projected Volumes of SNF and HLW in 2048



Volumes shown in m^3, assuming constant rate of nuclear power generation and packaging of future commercial SNF in existing designs of dual-purpose canisters

Approx. 80,150 MTHM (metric tons heavy metal) of SNF in storage in the US today

- 25,400 MTHM in dry storage at reactor sites, in approximately 2,080 cask/canister systems

Approx. 2,200 MTHM of SNF generated nationwide each year

- Approximately 160 new dry storage canisters are loaded each year in the US

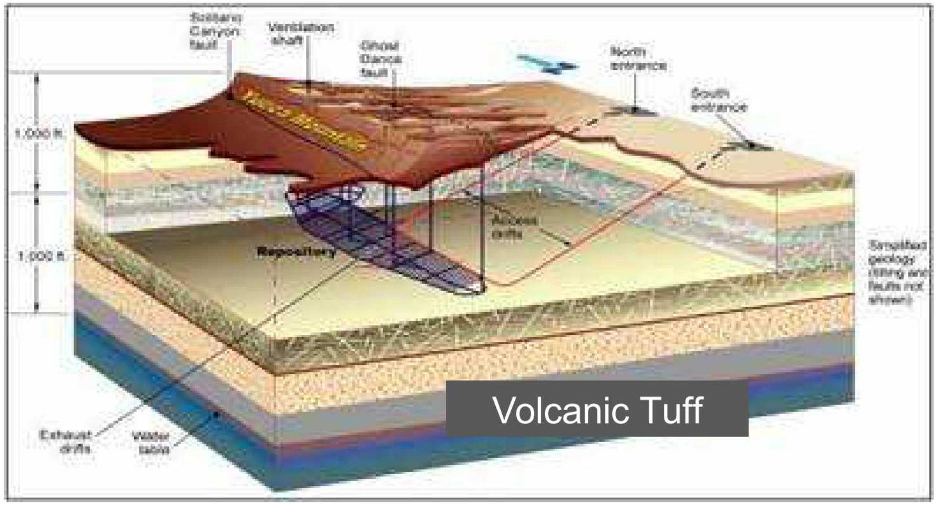
Slide content courtesy of Peter Swift, SNL

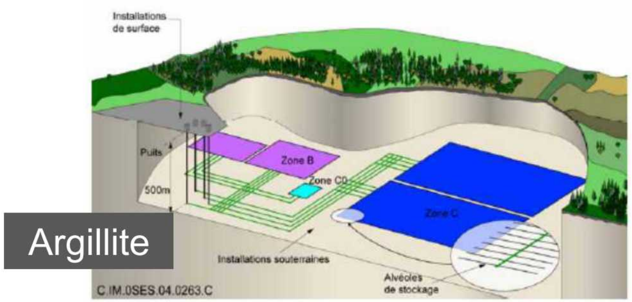
Deep Geologic Disposal of SNF and HLW in US

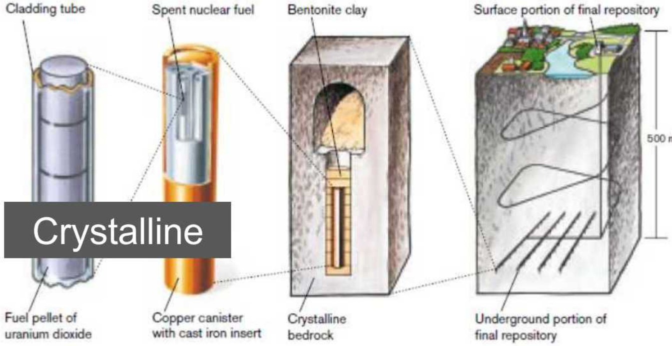
"Geological disposal remains the only long-term solution available."

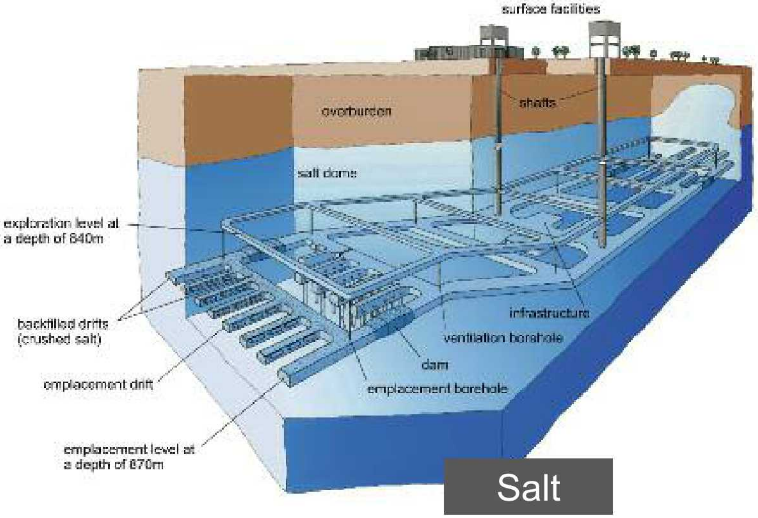
National Research Council, 2001

- Yucca Mountain Project (suspended)
- Several possible host rocks in US



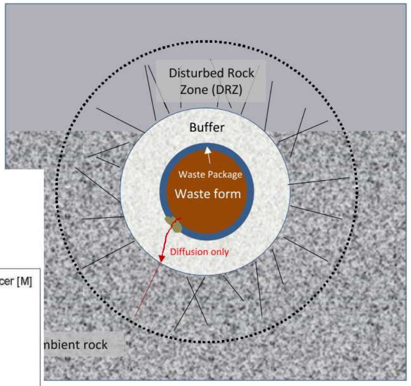


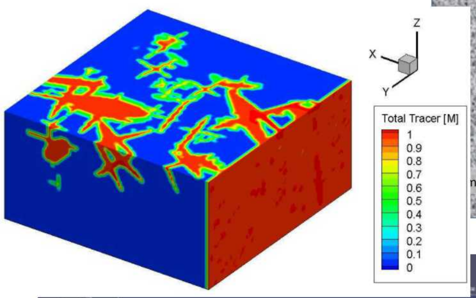


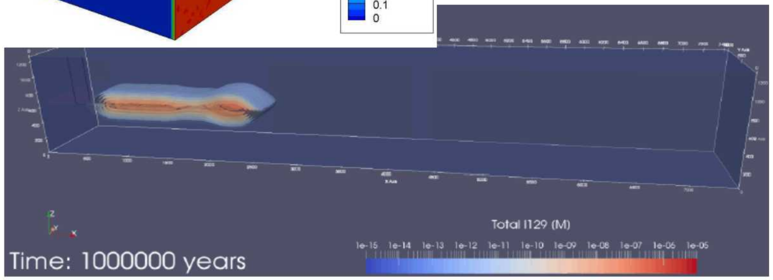


US DOE Office of Nuclear Energy

- ***Spent Fuel and Waste Science and Technology (SFWST)***
  - R&D Campaign (2010 – 2017)
- Mission
  - *To identify alternatives and conduct scientific research and technology development to enable storage, transportation and disposal of used nuclear fuel and wastes generated by existing and future nuclear fuel cycles*
- Mission work
  - Storage and transportation R&D
    - Dry casks, pools, extended storage, container degradation, resilience
  - Disposal R&D
    - Crystalline disposal R&D
    - Argillite disposal R&D
    - Salt disposal R&D
    - Deep borehole R&D (no longer pursuing)
    - Generic disposal system analysis
    - International R&D
    - Dual-purpose canisters (DPCs)

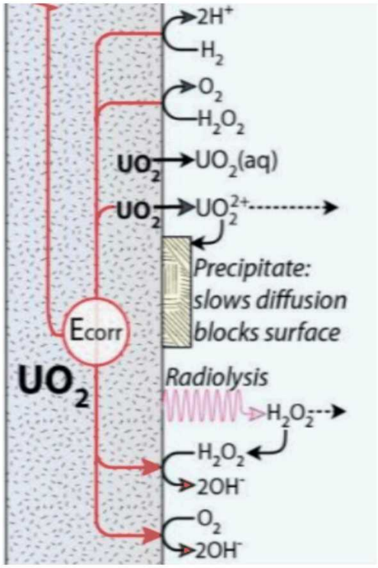




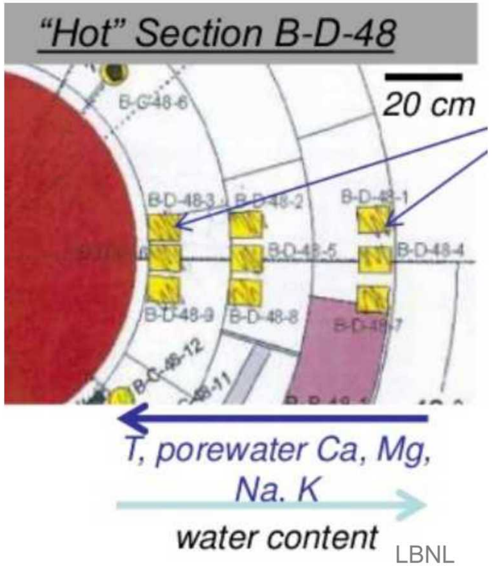


US DOE Disposal R&D

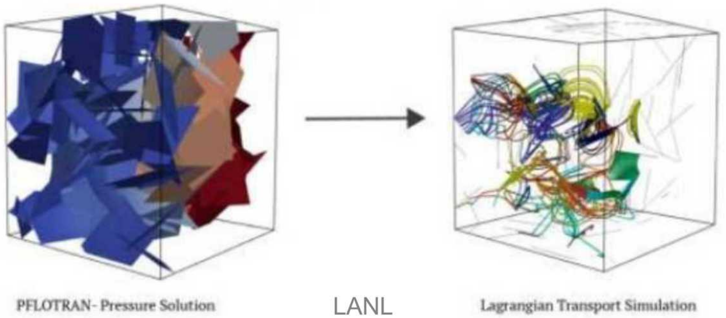
- National labs doing R&D relevant to crystalline:
  - Argonne (ANL), Lawrence Berkeley (LBNL), Lawrence Livermore (LLNL), Los Alamos (LANL), Pacific Northwest (PNNL), Sandia (SNL)



ANL, PNNL

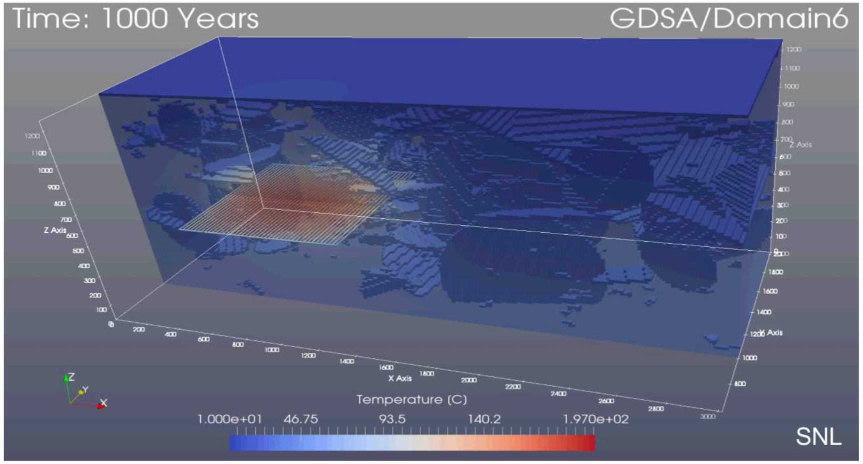


LBNL



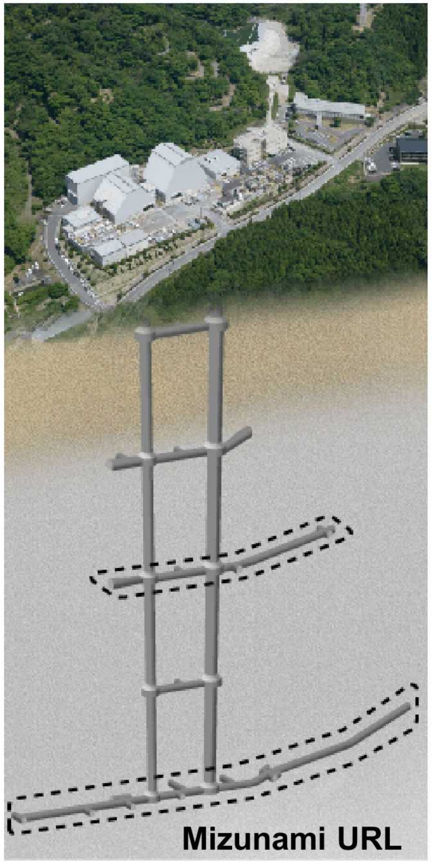
Thermodynamic Data

LLNL, LANL, SNL



US Multinational Project Participation

- DECOVALEX Project (Development of coupled models and their validation against experiments)
  - Process model comparison for data collected at underground research laboratories (URLs)
- Colloid Formation and Migration (CFM) Project
  - Grimsel Test Site (GTS), Switzerland (crystalline)
- FEBEX Dismantling Project – *Grimsel Test Site (GTS)*
  - Engineered barrier system (EBS) materials evolution after 18 years of heating
- Mont Terri Project – *Mont Terri URL, Switzerland (clay)*
  - Thermal-hydrologic-mechanical (THM) behavior of EBS materials
- SKB Task Forces – *Äspö Hard Rock Laboratory (HRL)*
  - Flow and transport of solutes, EBS behavior
- GREET – *Mizunami URL, Japan (crystalline)*
  - Groundwater recovery experiment
- KAERI Underground Research Tunnel *(KURT)*
  - Republic of Korea (crystalline), hydrogeological properties
- HotBENT – *Grimsel Test Site (GTS)*
  - Heater tests with different EBS materials and temperatures
- NEA/OECD
  - Thermochemical Database Project, Salt Club, Clay Club, Crystalline Club



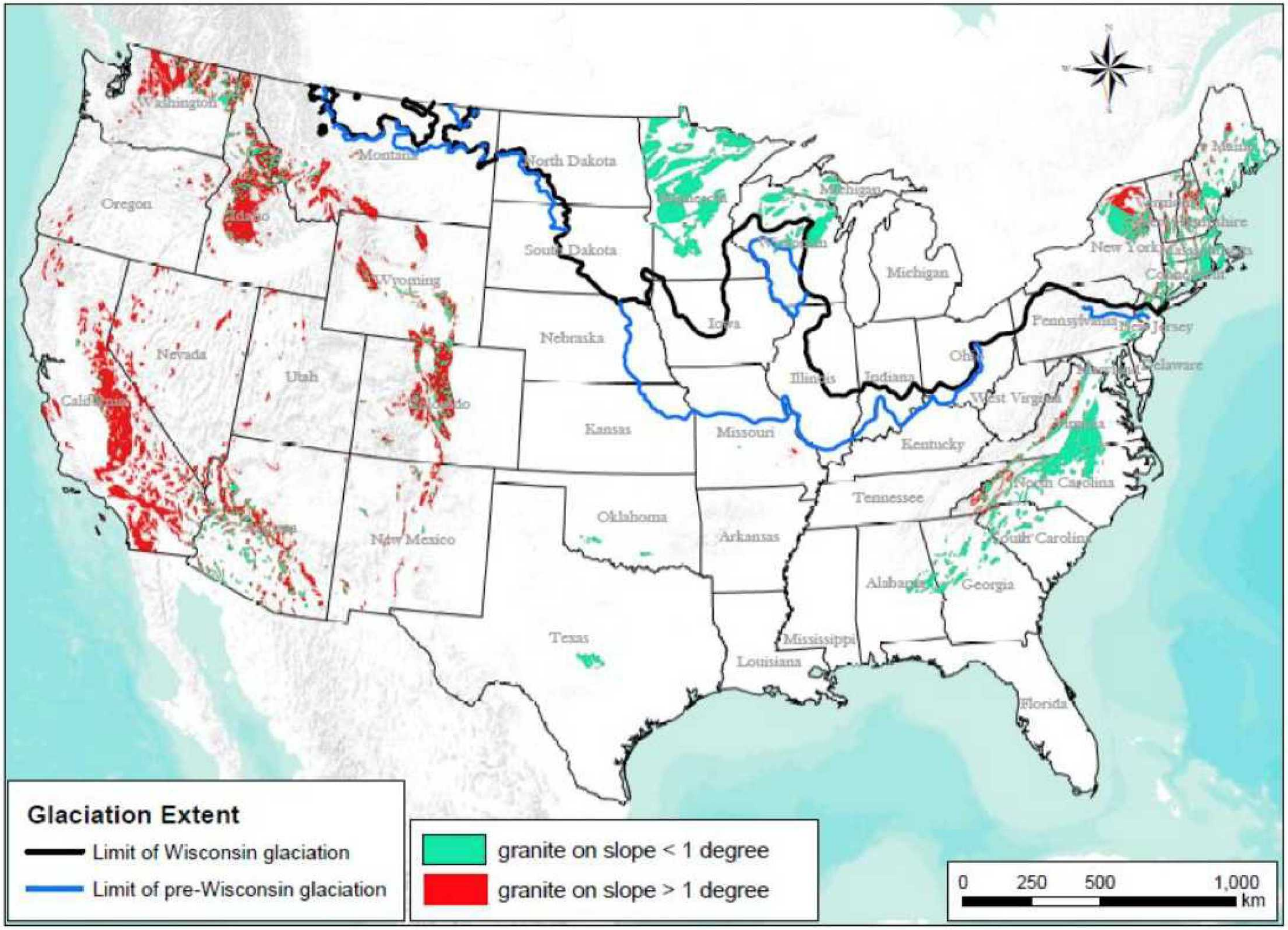
US Bi-Lateral Collaborations

- US – Republic of Korea
  - KURT – KAERI Underground Research Tunnel
  - JFCS – Joint Fuel Cycle Study
- US – German Salt Collaboration
  - Salt THM behavior
- US – Sweden COSC Collaboration (ICDP)
  - Crystalline rock hydrogeologic characterization
- US – China
  - BCNECAP – Bilateral Civil Nuclear Energy Cooperative Action Plan
- Memorandum of Understanding
  - DOE – Spain (ENRESA)
  - DOE – France (ANDRA)
  - DOE – Japan (JNEAP)
  - DOE – Belgium

KURT
KAERI underground research tunnel

icdp
INTERNATIONAL CONTINENTAL SCIENTIFIC DRILLING PROGRAM

Crystalline Rock in US

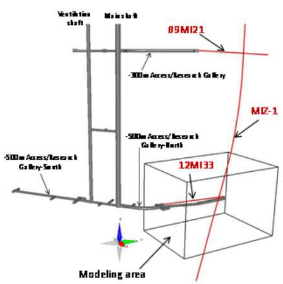


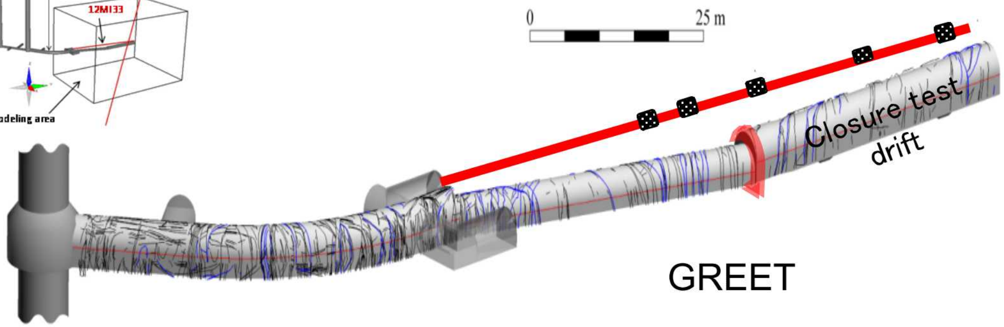
Wang et al. (2014, Figure 2-13)

- Locations of outcrops and near-surface sub-crops
- Extent of past glaciation

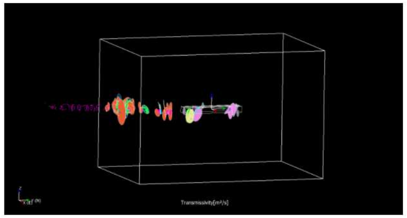
Crystalline Rock Characterization R&D

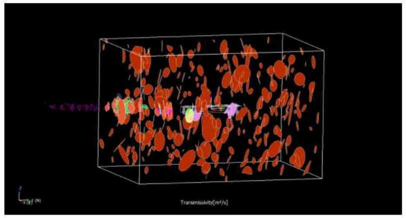
- ***Fracture flow, transport, fracture properties, water composition***
  - KAERI Underground Research Tunnel (KURT)
  - Colloid Formation and Migration (CFM) Project (Grimsel)
  - Groundwater Flow and Transport of Solutes (GWFTS) (Äspö)
  - DECOVALEX
    - Bedrichov Tunnel fracture flow & transport, Czech Republic, DECOVALEX-2015
    - Groundwater recovery experiment (GREET), Mizunami URL, DECOVALEX-2019





GREET



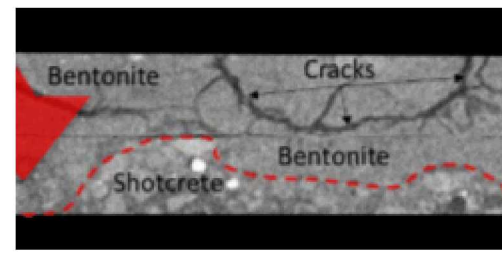


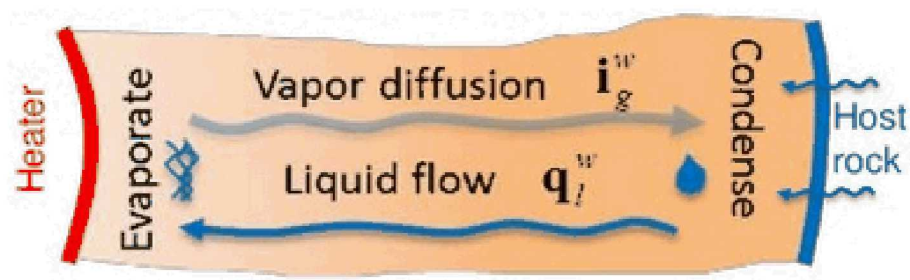
Bedrichov Tunnel

Crystalline EBS Process R&D

- ***EBS material evolution, coupled THMC* processes, transport through EBS***
  - Reactive transport from waste form to host rock
  - Compilation of steel corrosion rate data, Eh-pH dependency
  - Material alteration, heater tests, swelling, re-saturation, gas generation
    - FEBEX dismantling project (Grimsel)
    - Full-scale emplacement heater test (Mont Terri)
    - DECOVALEX
    - SKB Task Force (Äspö)
    - HotBENT (Grimsel)

Bentonite With Corrosion Rind



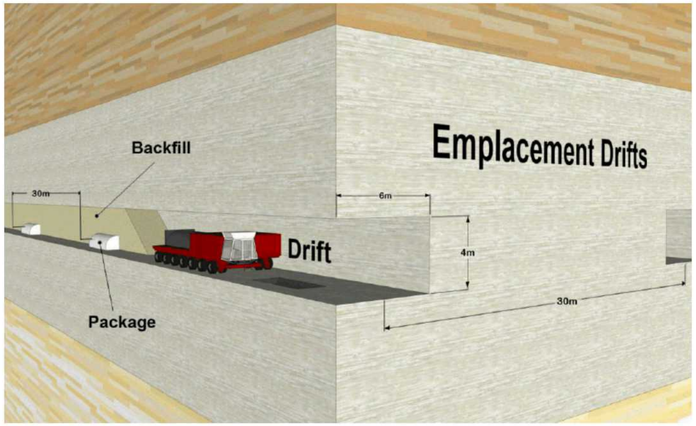


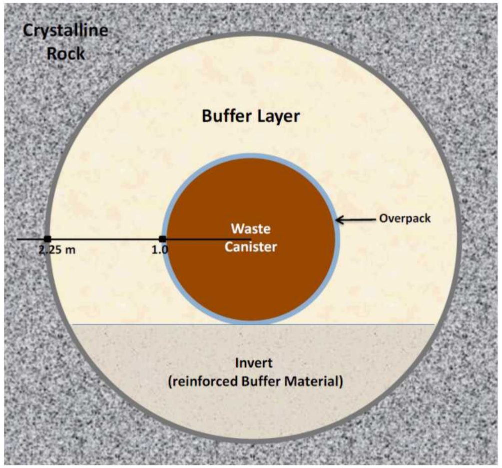
TOUGH-FLAC modeling of bentonite THM evolution, LBNL

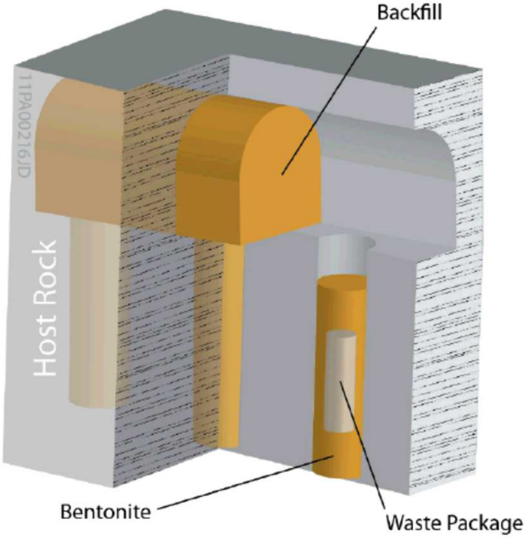
* THMC = thermal-hydrologic-mechanical-chemical

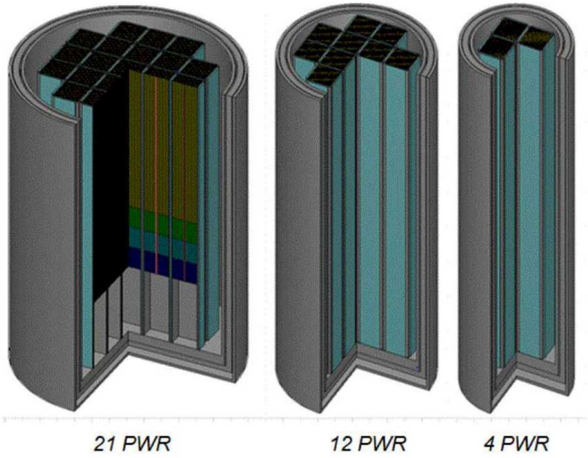
Crystalline Repository Design R&D

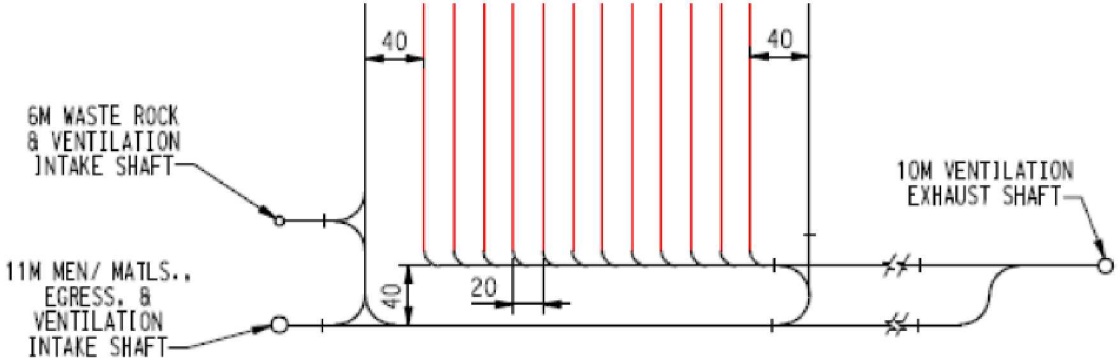
- ***Drift spacing, waste inventory, waste package (WP) material, WP placement, WP heat, buffer/backfill, seals, DPCs***





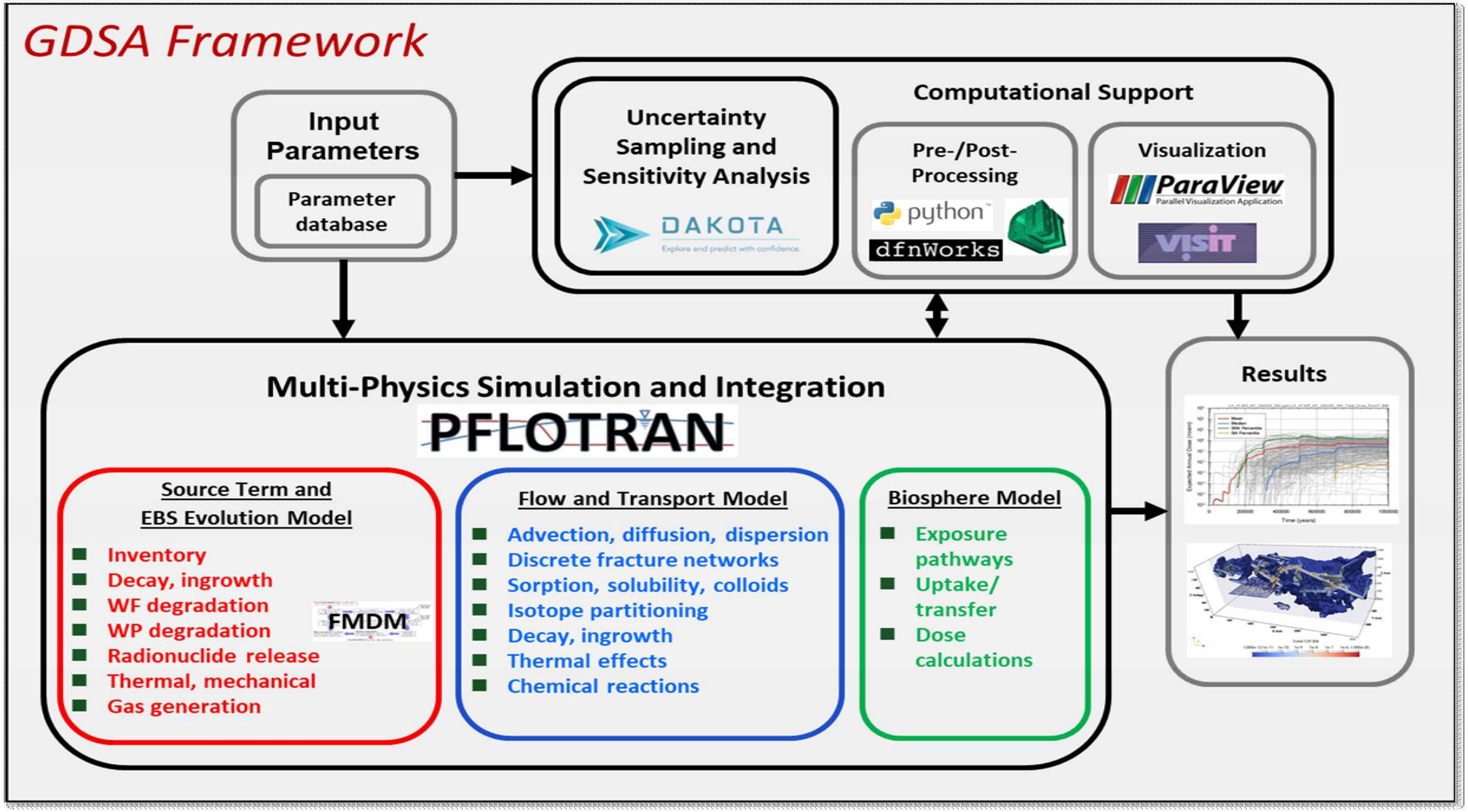






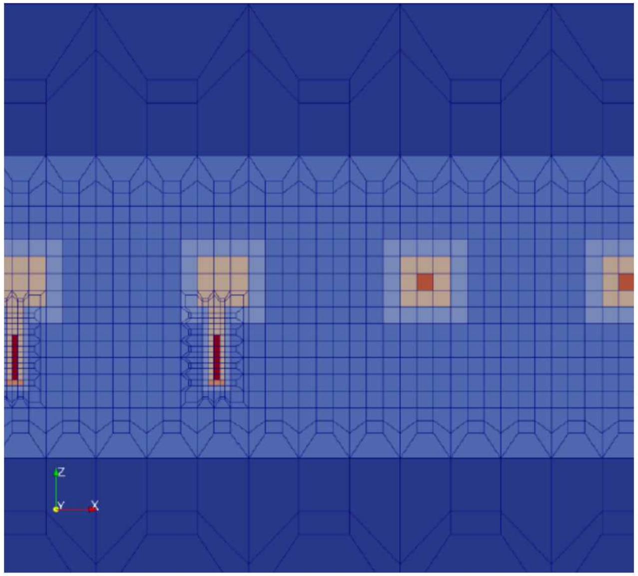
Safety Assessment – Crystalline

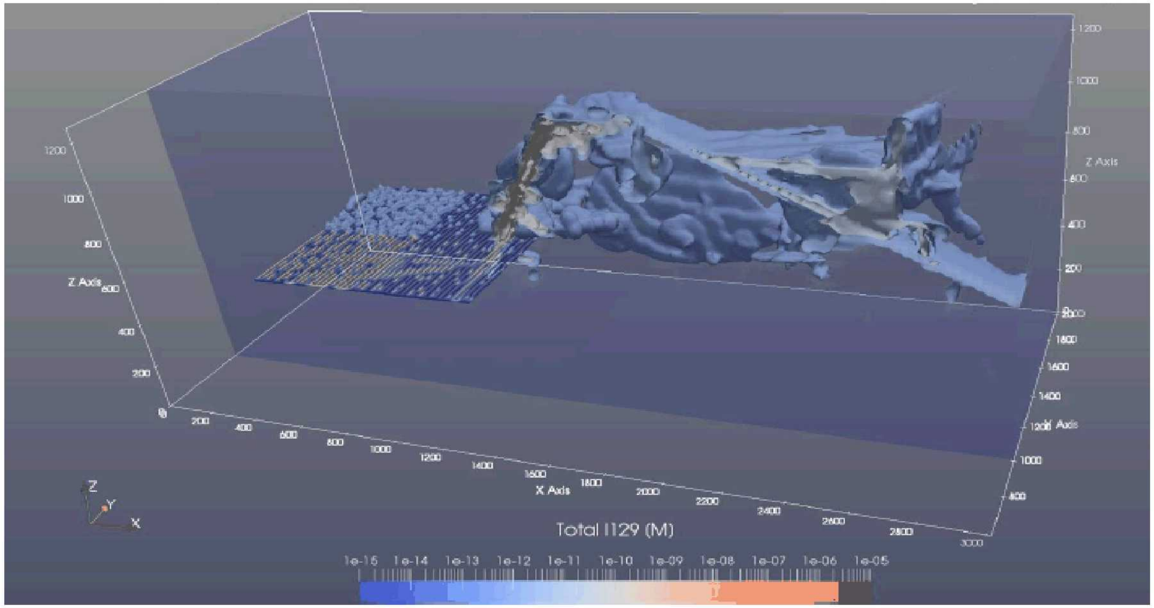
- ***GDSA Framework*** – Geologic disposal safety assessment framework for probabilistic performance assessment (PA)
  - Open source, massively parallel, freely available (pa.sandia.gov)

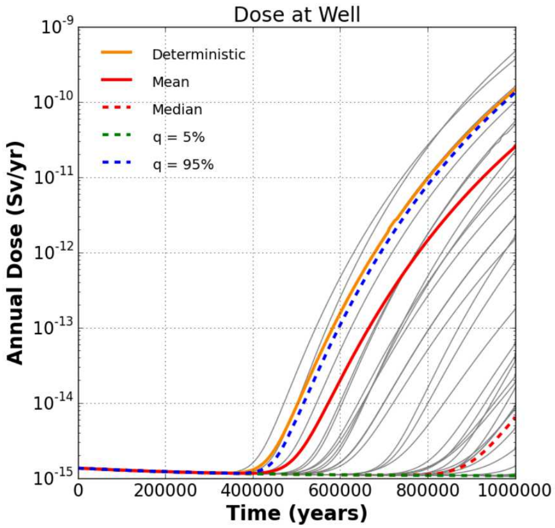


Safety Assessment – Crystalline

- ***Advanced FEP (Features, Events, and Processes) Database/Matrix***
  - Adapt to crystalline; screen (include/exclude)
- ***GDSA Framework Simulations***
  - Coupled THMC processes, dose calculation
  - Uncertainty quantification
  - Probabilistic sensitivity analysis



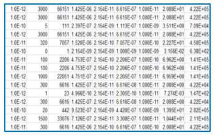




Data Challenges – Crystalline

Sandia National Laboratories

- Host rock characterization
  - Fractures – networks, density, distributions, connectivity, properties, evolution over time
  - Groundwater – composition, age
  - Sorption
  - Colloids
- EBS and near field
  - Damaged rock zone (DRZ) – extent, fracture properties
  - THMC evolution of the near field (buffer, backfill)
  - Waste package corrosion rates
  - Cladding performance, waste form degradation
  - Sorption
  - Colloids



Design Questions – Crystalline

- Repository design criteria
  - Limits on fractures, fracture flow, earthquakes
    - E.g., emplacement rejection criteria for boreholes/drift segments based on fractures encountered during excavation
  - Peak temperature limits
- Repository layout
  - Drift/WP spacing
  - WP placement (in-drift, in-floor, horizontal boreholes)
- Materials
  - WP materials
  - Buffer/backfill
  - Sealing (DRZ, drifts, shafts)

Modeling Challenges – Crystalline

- Process modeling
  - Fracture and matrix flow, water and heat
    - Honor observed fractures and fracture distributions
  - THMC evolution of the near field (buffer, backfill, DRZ)
    - Re-saturation of repository horizon, material evolution, fracture evolution
  - Waste package corrosion, failure, and performance after failure
  - In-package chemistry, cladding performance, waste form degradation
  - Radionuclide transport
    - Advection, dispersion, sorption, colloids, precipitation/dissolution
- Include/improve process models in PA code (*GDSA Framework*)
  - To improve simulation of coupled processes
- Simulate crystalline repository designs using PA code
  - To assess uncertainties, identify important FEPs, and direct future R&D

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