SAND2014-19600C

Exceptional service in the national interest

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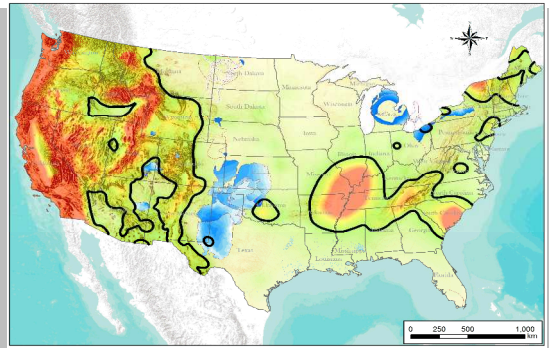

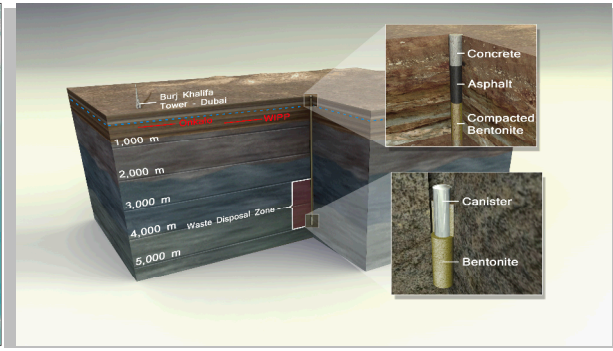

Status of the Used Nuclear Fuel Disposition Program in the United States

Kevin McMahon
Sandia National Laboratories

JAEA Spent Fuel Workshop
December 17-18, 2014
Tokyo, Japan

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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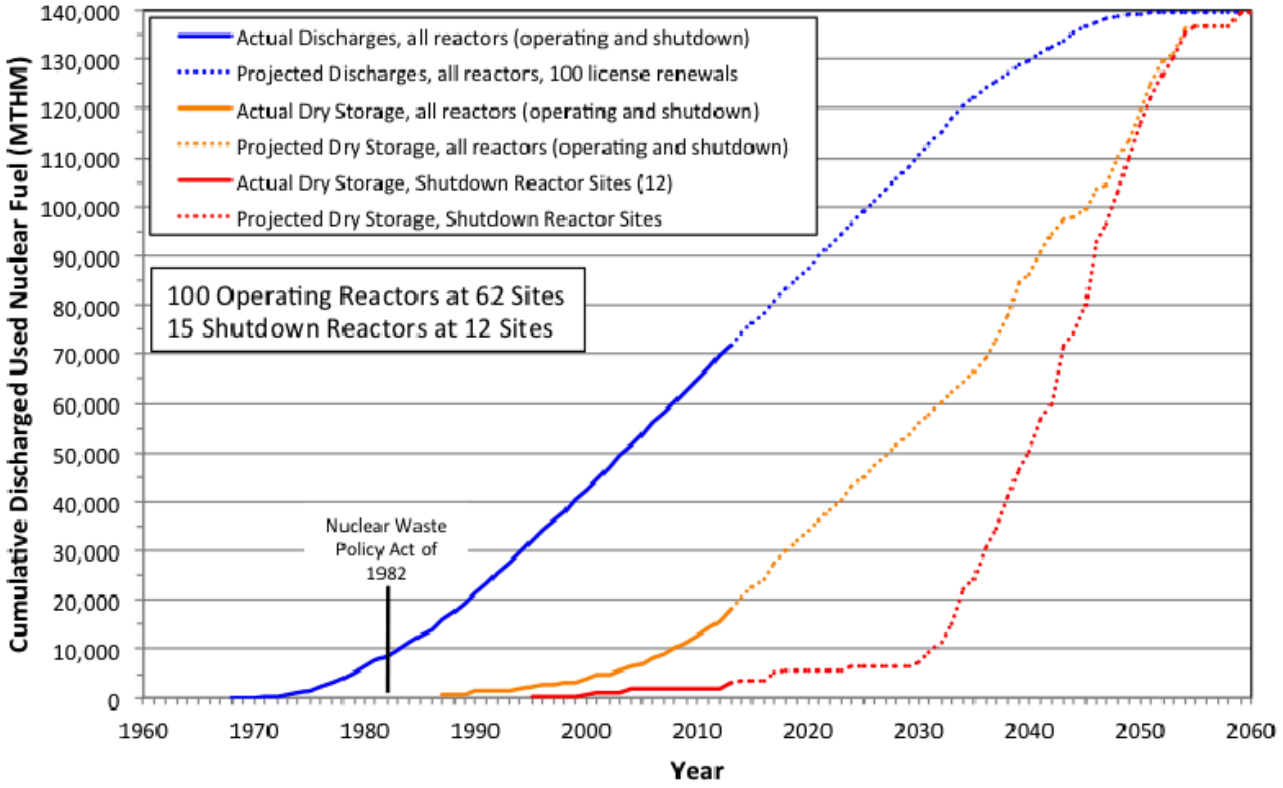
Outline

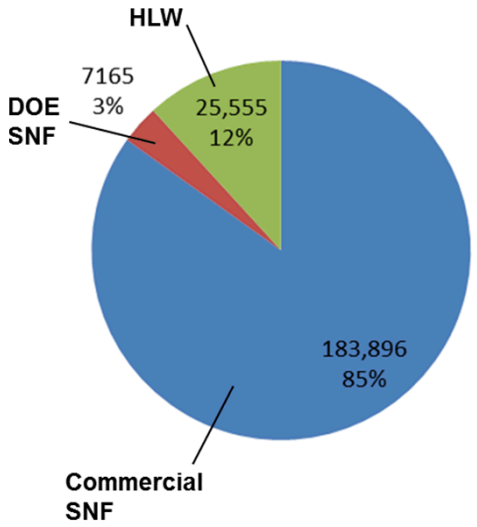
- United States Department of Energy (US DOE) Strategy
  - *Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste, 2013*
- Used Fuel Disposition (UFD) Campaign
  - Campaign Objectives
  - Mission & Challenge
  - Research & Development (R&D) Path Forward
  - Campaign Structure
- UFD Strategic Focus
  - Storage and Transportation
  - Disposal Research
  - External Collaborations
- Conclusions

Historical and Projected Spent Nuclear Fuel (SNF) and High-Level Radioactive Waste (HLW) in the United States



Historical and Projected Commercial SNF Discharges

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

UFD Campaign Objectives

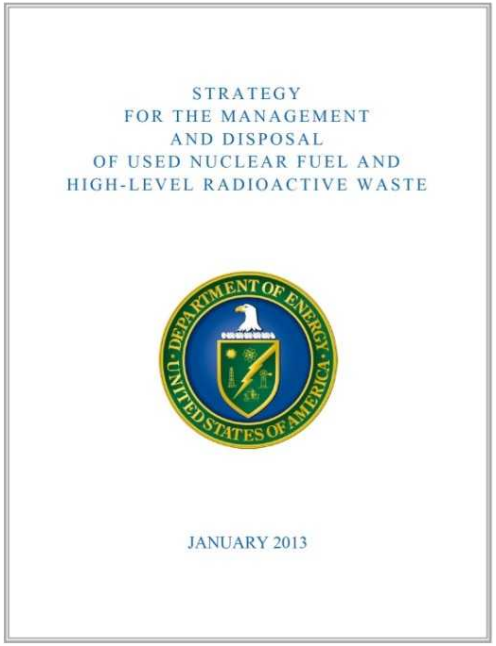
- Support the implementation of a full-scale NRC-licensed confirmatory storage demonstration facility, in collaboration with industry
- Develop the technical basis necessary to support eventual transportation of used nuclear fuel, including high-burnup fuel
- Collaborate with the Nuclear Fuel Storage and Transportation Planning Project to implement integrated storage, transportation, and disposal concepts

Support the Administration's 2013 *Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste***

http://energy.gov/downloads/strategy-management-and-disposal-used-nuclear-fuel-and-high-level-radioactive-waste

**US DOE Response to the *Blue Ribbon Commission on America's Nuclear Future*

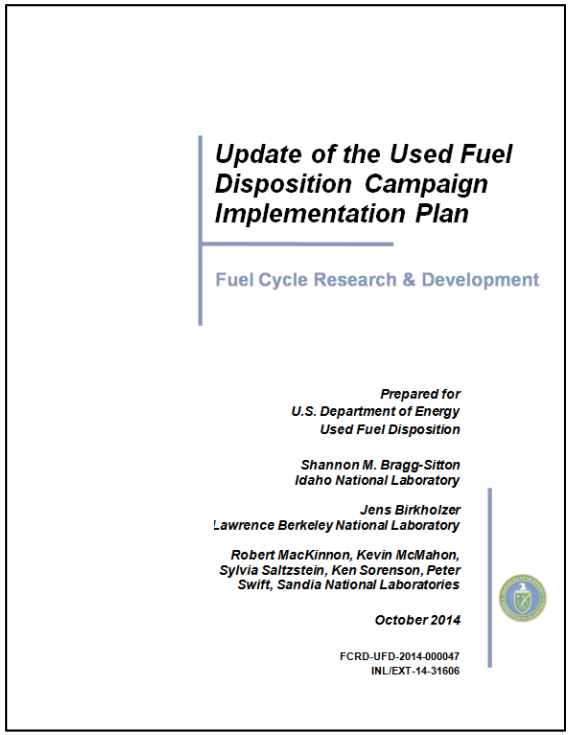
http://www.brc.gov



UFD Campaign Mission and Challenge

Campaign 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

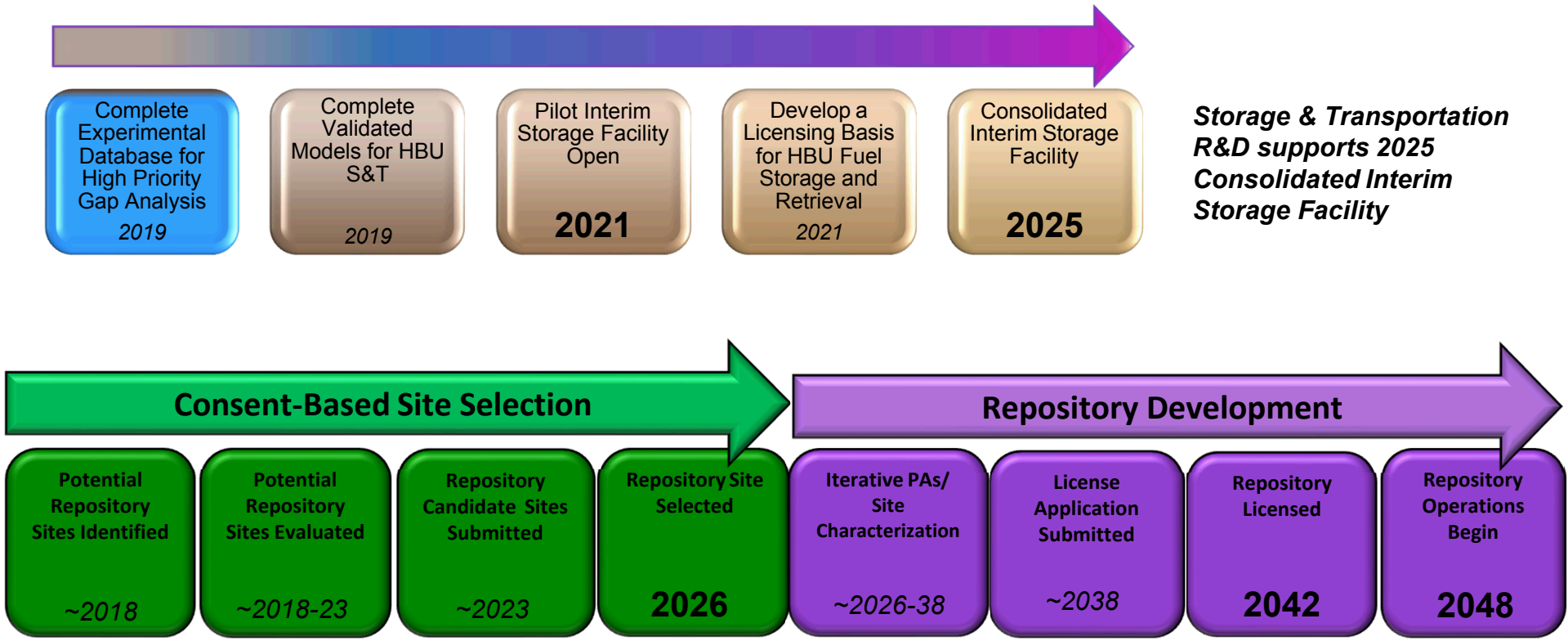
Campaign challenge: to provide a sound technical basis for supporting the current DOE strategy for managing the back end of the nuclear fuel cycle, including the identification and evaluation of safe and secure options for storage, transportation, and permanent disposal of radioactive wastes resulting from existing and future fuel cycles.



Update of the Used Fuel Disposition Campaign Implementation Plan
FCRD-UFD-2014-0000474, October 2014

UFD R&D Campaign Path

Supports DOE Waste Management Strategy

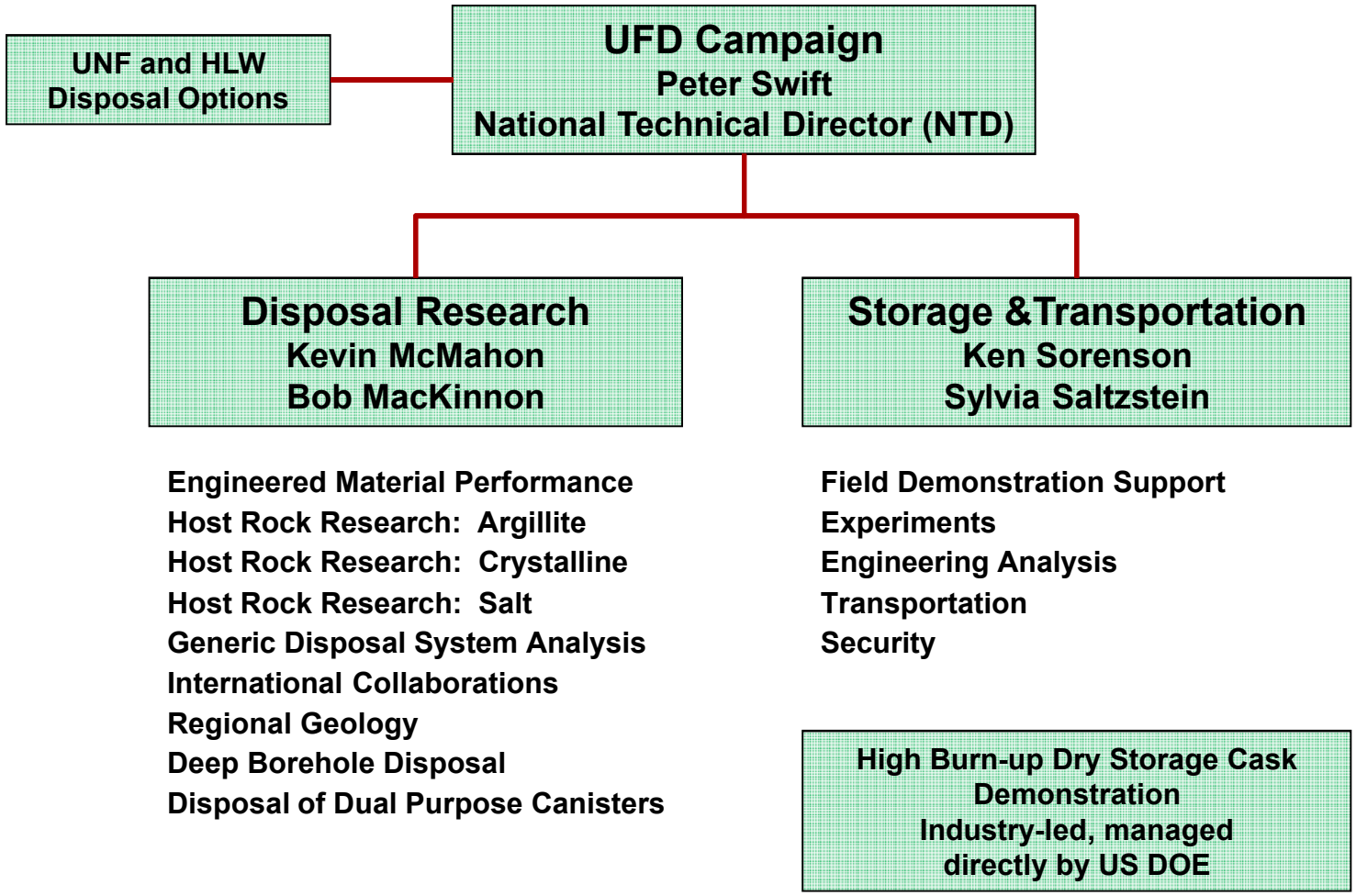


Storage & Transportation R&D supports 2025 Consolidated Interim Storage Facility

Approximate target dates (in *italics*) needed to meet milestones (in bold) set out in the 2013 DOE *Strategy*

Disposal R&D supports 2026 Repository Site Selection and 2042 Repository Licensing

UFD Campaign Structure



UFD Campaign Strategic Focus:

Storage and Transportation R&D

Prepare for extended storage and eventual large-scale transport of used nuclear fuel (UNF) and high-level waste

- Develop the technical basis for:
  - Extended storage of used nuclear fuel
  - Fuel retrievability and transportation after extended storage
  - Transportation of high-burnup used nuclear fuel

Storage and Transportation Research

Major FY14 Accomplishments

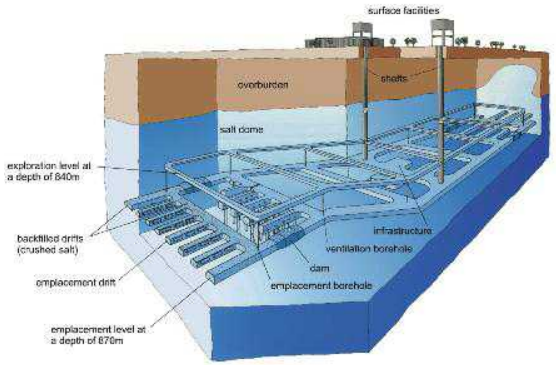
Sandia National Laboratories

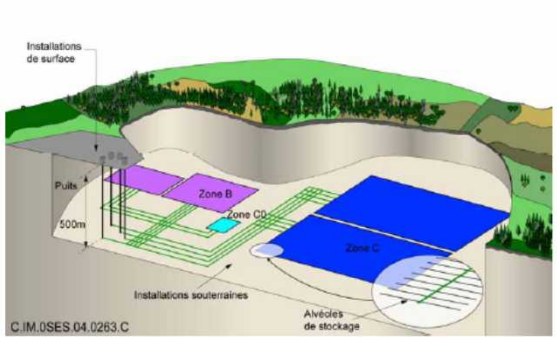
- Supported the industry storage cask demonstration
  - Support for finalization of the EPRI Test Plan
  - R&D in support of non-destructive evaluations of the demonstration cask
  - Selection and eventual placement of assemblies and thermal instrumentation
  - Support planning for cask lid design, licensing issues, and approval of final design
- Completed cladding bend test on irradiated Zirc-4 and M5 cladding
  - Results showed that the irradiated fuels can withstand millions of bending cycles at potentially higher than representative loading levels before breaking
  - Results indicate that pellet-clad interaction (PCI) provides added strength to high burnup used fuel.
- 50 mile over-the-road truck test to confirm Normal Conditions of Transport (NCT) loadings on used fuel
  - Results further confirm that stresses and strains seen by the fuel and assembly are well below those where damage is predicted
  - Coupled with the cladding bend tests, early indications look promising that high burnup embrittled fuel will withstand NCT
- Obtained salt and dust samples from operating dry storage canisters in marine and inland locations
  - Results show less salt than expected, but enough to be of concern
- Updated technical gap and prioritization report
  - Addresses new and emerging R&D issues (e.g., higher prioritization on canister SCC)
  - Validates original technical gap and prioritization reports

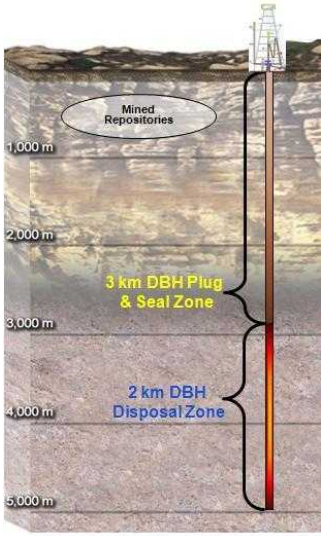
UFD Campaign Strategic Focus:

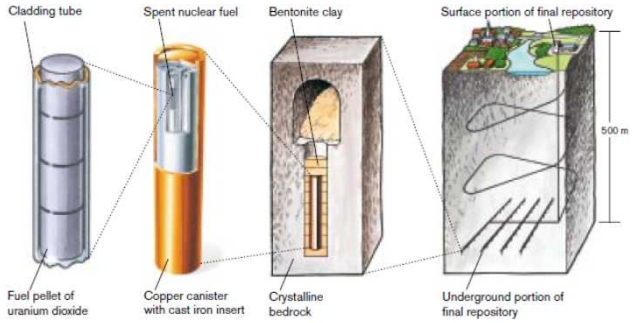
Disposal R&D

- Provide a sound technical basis for multiple viable disposal options in the US
- Increase confidence in the robustness of generic disposal concepts
- Develop the science and engineering tools needed to support disposal concept implementation









Three mined repository options (crystalline rocks, argillite rocks, and salt)
One geologic disposal alternative: deep boreholes in crystalline rocks

Disposal Research

Major FY14 Accomplishments

- Completed *Evaluation of Options for Permanent Geologic Disposal of Used Nuclear Fuel and High-level Radioactive Waste in Support of a Comprehensive National Nuclear Fuel Cycle Strategy*
  - Conclusion: multiple disposal options are feasible for all existing and currently projected waste forms except untreated sodium-bonded fuels, for which more information is needed
- Multiple international collaborations are ongoing and are an integral part of UFD's disposal R&D
- Updated analyses of dual-purpose canister (DPC) disposal alternatives indicate that DPC direct disposal could be technically feasible, at least for certain disposal concepts
- Identified RD&D needs for evaluating feasibility of deep borehole disposal of small HLW waste forms, providing the foundation for planning a deep borehole field test

UFD Campaign

External Collaborations

- Collaboration among other US DOE Fuel Cycle Technology Campaigns
  - Full collaboration and shared resources with Nuclear Fuels Storage and Transportation Planning Project (NFST)
  - Support for Fuel Cycle Options Campaign
  - Close interactions with Material Recovery/Waste Form Campaign
    - Waste form modeling work transitioning from MR/WF to UFD in FY14
- Collaboration with US DOE-Environmental Management (EM)
  - Salt disposal research (joint activities with EM Carlsbad Field Office)
- Industry (Advisory and Assistance Contracts)
  - Areva, Shaw/Westinghouse, GE Hitachi, EnergySolutions, Enercon, CH2M Hill
- DOE/Industry Storage Demonstration Collaboration initiated FY13
- EPRI (GET EXACT ACRONYM DEFINITION)
  - Extended Storage Collaboration Program (ESCP) (with NRC and international groups)

UFD Campaign

Nuclear Energy University Program (NEUP) Collaborations

- DOE NE University Programs
  - 2010: 1 NEUP grant relevant to UFD, in storage (U. of Michigan)
  - 2011: 3 NEUP grants relevant to UFD: 2 storage, 1 disposal
    1 Integrated Research Project in storage R&D
  - 2012: 9 NEUP grants relevant to UFD: 6 storage/transportation, 3 disposal
  - 2013: 7 NEUP grants relevant to UFD: 3 storage, 2 transportation, 2 disposal
  - 2014: 2 Integrated Research Projects in storage R&D
- Other university collaborations (Massachusetts Institute of Technology, University of Oklahoma, University of Nevada Las Vegas, University of Sheffield United Kingdom)

UFD Campaign

Concluding Remarks and Issues

- Will the current R&D Portfolio achieve near-term objectives?
  - For Storage and Transportation R&D: Yes
    - Storage demonstration project is still in very early stages
  - For Disposal R&D: yes, but only for generic concepts
    - Significant accomplishments are within reach in disposal R&D
      - E.g., increased confidence in engineered barrier designs, robust natural system performance, improved system-level modeling framework
    - Field demonstration of deep borehole disposal is achievable
- Will the current R&D Portfolio achieve the long-term strategic goals?
  - For Storage and Transportation R&D: uncertain
    - Commitment to storage demonstration and RD&D must be sustained for many years
  - For Disposal R&D: yes, but only with resolution of national policy issues
    - R&D is needed, but is not sufficient to address disposal issues

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Backup Slides

UFD Storage and Transportation R&D
Selected FY14 Accomplishments

Storage and Transportation R&D Guided by the 2012 Gap Analysis:

Work focused in the red areas.

System Component	Issue	Importance of R&D
Cladding	Annealing of Radiation Effects	Medium
	Oxidation	Medium
	H_2 effects: Embrittlement	High
	H_2 effects: Delayed Hydride Cracking	High
	Creep	Medium
Assembly Hardware	Stress corrosion cracking	Medium
Neutron Poisons	Thermal aging effects	Medium
	Embrittlement and cracking	Medium
	Creep	Medium
	Corrosion (blistering)	Medium
Canister	Atmospheric corrosion (marine environment)	High
	Aqueous corrosion	High

Source: Gap Analysis to Support Extended Storage of Used Nuclear Fuel, January 2012

Storage and Transportation R&D Guided by the 2012 Gap Analysis:

Work focused in the red areas.

System Component	Issue	Importance of R&D
Bolted Direct Load Casks	Thermo-mechanical fatigue of bolts/seals	Medium
	Atmospheric corrosion (marine environment)	High
	Aqueous corrosion	High
Overpack and Pad (Concrete)	Freeze/Thaw	Medium
	Corrosion of steel rebar	Medium

Cross-cutting or General Gaps

• ***Temperature profiles for fuel***	***High***
• ***Drying issues***	***High***
• ***Monitoring***	***High***
• ***Subcriticality***	***High***
• ***Fuel transfer options***	***High***
• ***Re-examine INL dry cask storage***	***High***

Identification of these data gaps are used to inform new initiatives for FY15

Source: Gap Analysis to Support Extended Storage of Used Nuclear Fuel, January 2012

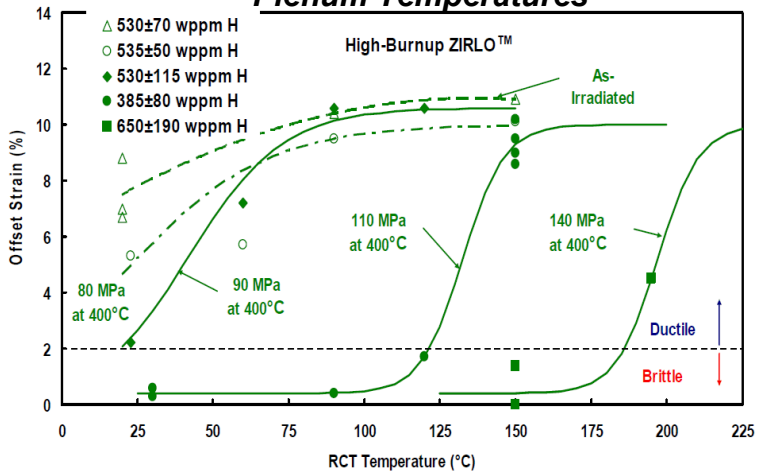
FY14 S&T Experiments:
High Burnup Fuel Cladding Material Properties

- Separate effects test to determine effects of hydrides, hydride reorientation, radiation damage, thermal annealing, and clad thinning on materials properties and performance.

- Hydrides and reorientation
  - Ring Compression Tests and determination of Ductile-Brittle Transition Temperature (ANL)
  - Cladding bend test and effects of fuel/clad bonding and pellet/pellet interfaces (ORNL)

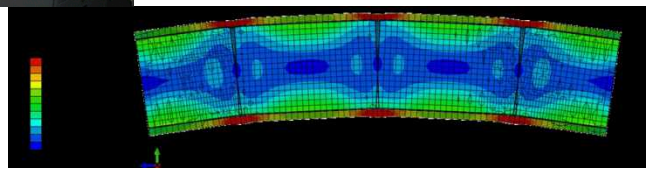
- Radiation damage and thermal annealing
  - Irradiate cladding in HFIR reactor at ORNL without all other effects.

DBTT data for Zirlo clad with Varying Internal Plenum Temperatures



Billone, Argonne National Laboratory, EPRI ESCP Meeting, Dec. 2013

Used fuel rod stiffness Experiments (in hot cell and out) and analyses of stress distribution



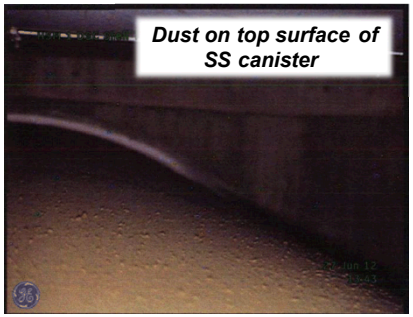
Jy-An, Wang; Oak Ridge National Laboratory, WM2014 Conference, March 2014

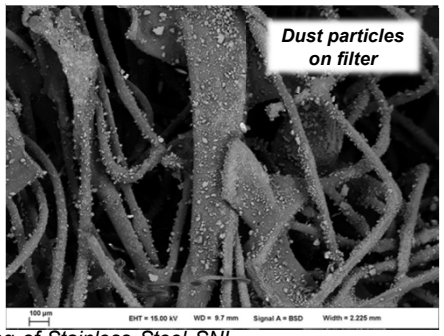
FY14 S&T Experiments:

Stainless Steel Canister Corrosion

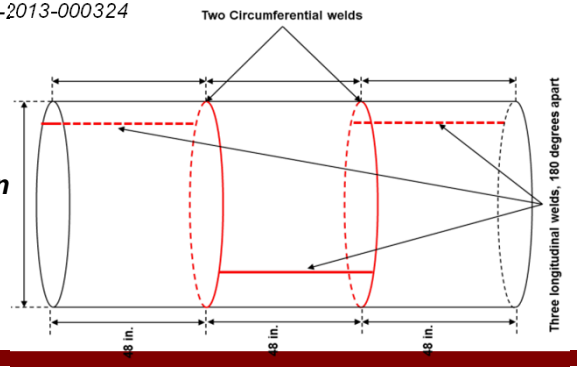
Purpose: Better understand canister degradation, support Aging Management Plans, and license extensions.

- Develop data to understand initiating conditions for corrosion conditions and progression of SCC-induced crack growth
- Obtain site data to assess atmospheric conditions and compare with initiating conditions.
- Procure a full scale (diameter) welded SS canister to investigate residual stresses due to plate rolling and welding.





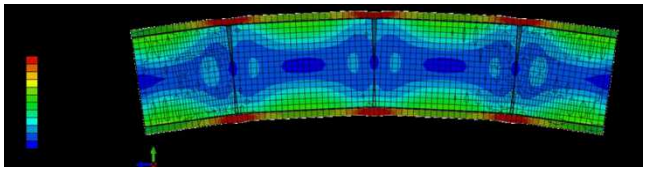
Enos, et al., Data Report on Corrosion Testing of Stainless Steel SNL Storage Canisters, FCRD-UFD-2013-000324



Conceptual design for full-scale (diameter) SS welded canister

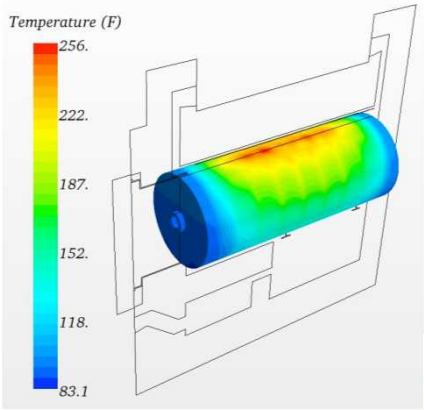
FY14 S&T Analysis

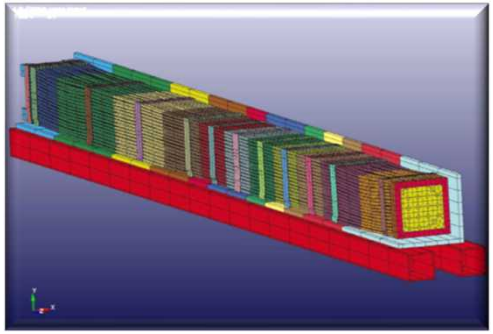
- Predictive modeling
  - Thermal Analysis (PNNL) to predict cool down, Ductile-to-Brittle Transition, deliquescence, etc.
    - HBU Demonstration fuel selection and cool down
    - Modern, high heat load, high capacity systems
    - In-service inspections validation data
  - Hybrid hydride reorientation model (SNL)
  - Structural uncertainty analysis at assembly and canister level (PNNL)
  - Finite element analysis validation and application to out-of-cell testing (ORNL)
- Thermal profile analyses
  - Detailed thermal analyses for 2-3 licensed dry storage systems (PNNL FY15)



Jy-An, Wang; Oak Ridge National Laboratory, WM2014 Conference, March 2014

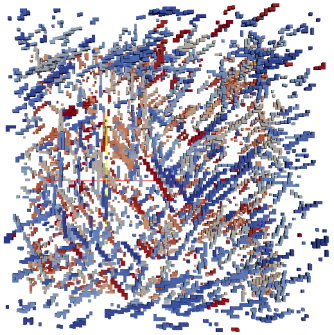
CFD Thermal Analysis of Dry Storage Casks
Suffield, et al, PNNL-21788

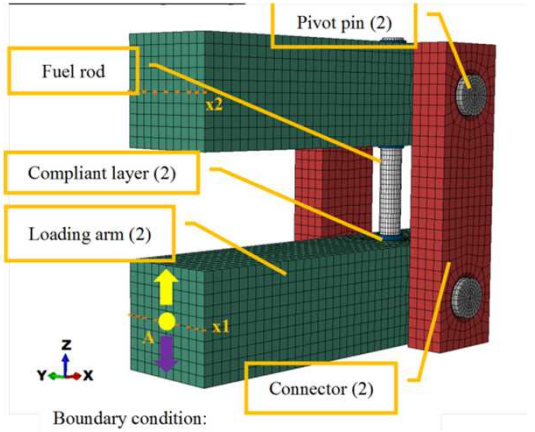




FE Models of Assembly
Klymyshyn, et al, PNNL, FCRD-UFD-2013-000168

Model for Simulation of Hydride Precipitation, Tikare et al, FCRD-UFD-2013-000251.

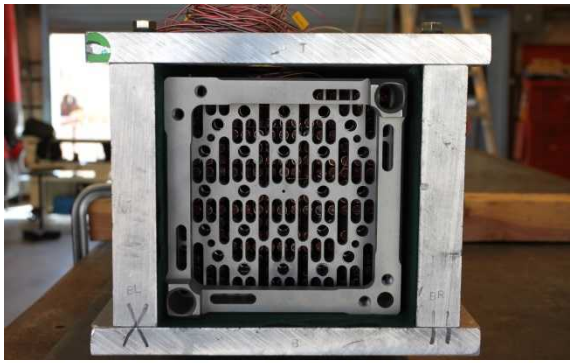


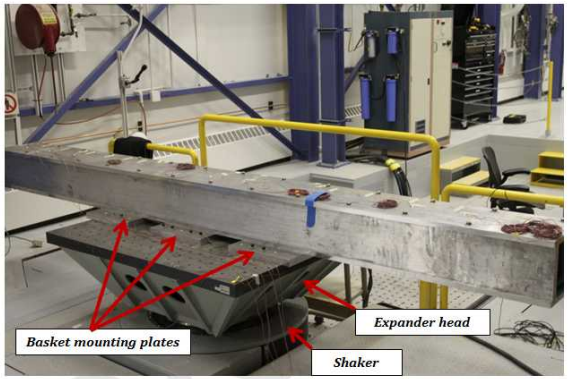


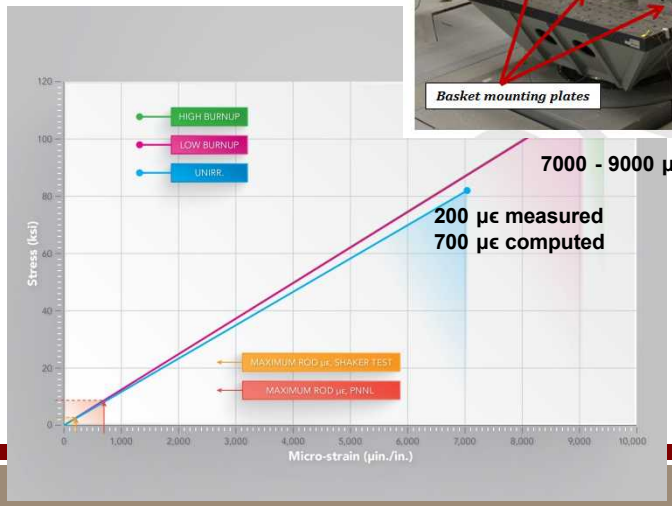
FE Model of Rod Bend Tests
Jy-An Wang et al, ORNL

Transportation:
Normal Conditions of Transport – Loading on Fuel Assemblies

- A surrogate assembly was subjected to a 50-mile over-the-road test on a real truck with representative weight
  - Data results were >10 times below yield strength
  - The strains measured in both were an order of magnitude lower than the elastic Zircaloy rod yield strength and well below the fracture toughness value for brittle behavior
  - Strains were commensurate with strains obtained from the FY13 shaker table test
- If high burnup fuel can maintain its integrity during transport, pressure will be taken off experimental R&D efforts associated with hydride effects on cladding strength and ductility.







Data collection and analysis for NCT loads on a surrogate fuel assembly

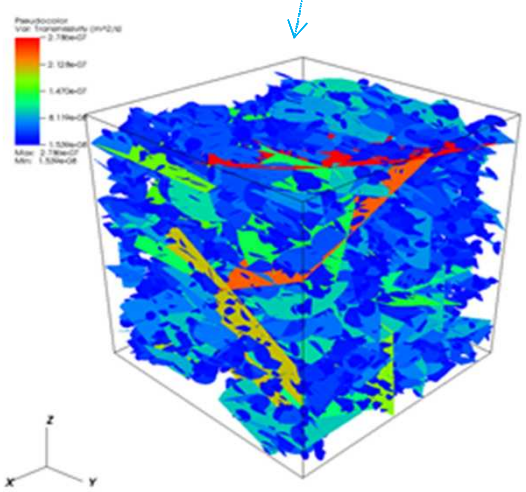
Sorenson, K., Determination of Loadings on Spent Fuel Assemblies During Normal Conditions of Transport, SAND2014-2043P.

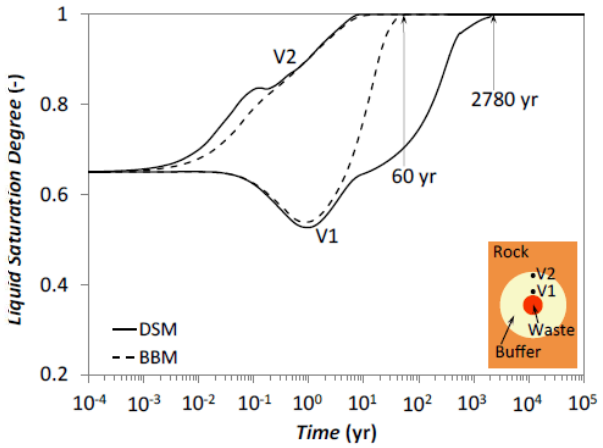
BACKUP SLIDES

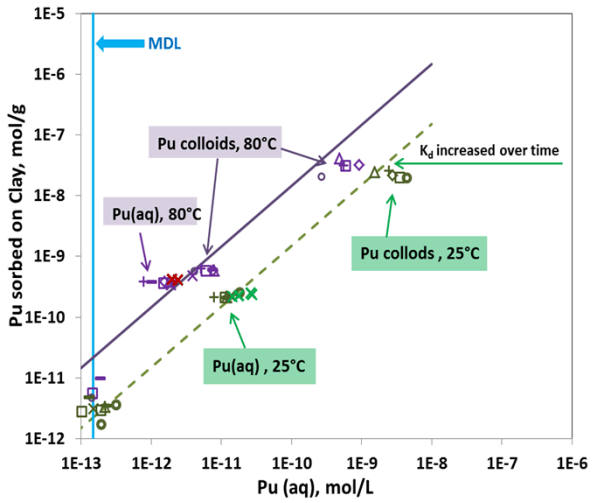
UFD Disposal Research
Selected FY14 Accomplishments

Example FY14 Accomplishments: Crystalline Disposal Research

- Generic reference case established for crystalline disposal media
- Capability of a discrete fracture network model demonstrated using fracture parameters from Swedish Forsmark site.
- Thermo-hydrologic-mechanical (THM) model has been applied to an engineered barrier system. ~3000 year delay of water saturation in bentonite is predicted.
- Significant progress has made in understanding radionuclide (e.g., Pu colloid) interactions with buffer and granitic materials. Thermal treatment of clay materials may enhance radionuclide retention.
- International collaborations in progress (e.g., DECOVALEX, KAERI, Sweden URL).



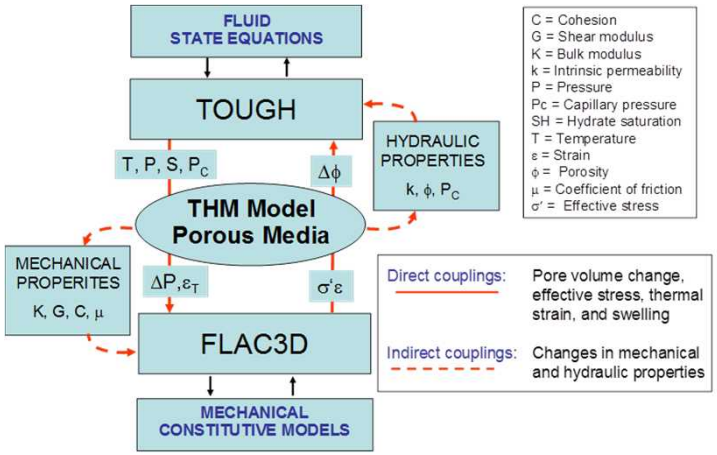


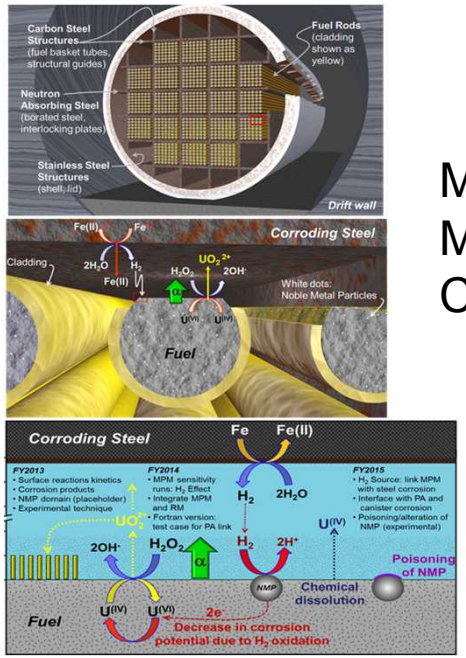


Argillite Host Rock Disposal

Examples of Model Development

- **THM coupled models for clay**
  - International Collaborations: THM Modeling of Underground Heater Experiments
- **Discrete Fracture Network (DFN) approach for fractures in argillite**
  - Excavation damaged zone (EDZ) and natural fracturing
  - Rigid-Body-Spring Network (RBSN) modeling approach for mechanical damage
- **Modeling and experimental investigations on barrier material interactions and stability**
- **ANL Mixed Potential Model (MPM) for used fuel matrix degradation**
  - Development towards integration with performance assessment (PA)



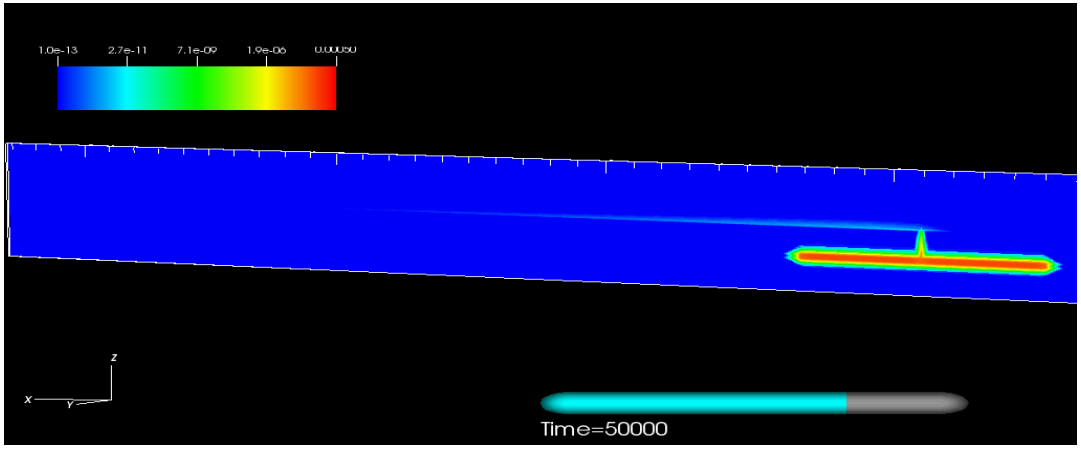


MPM Model Concept

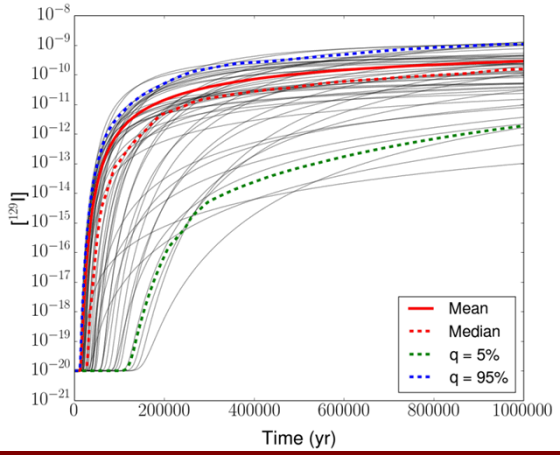
Example FY14 Accomplishments: Generic Disposal System Analysis

Probabilistic THC Simulations and Sensitivity Analyses

- Generic salt repository reference case with
  - spatially-varying waste degradation (160 individual waste packages)
  - decay heat and thermal effects
  - fluid flow, radionuclide mobilization and transport, and a coupled biosphere



- Sensitivity analyses from 100 realizations with 10 varying parameters



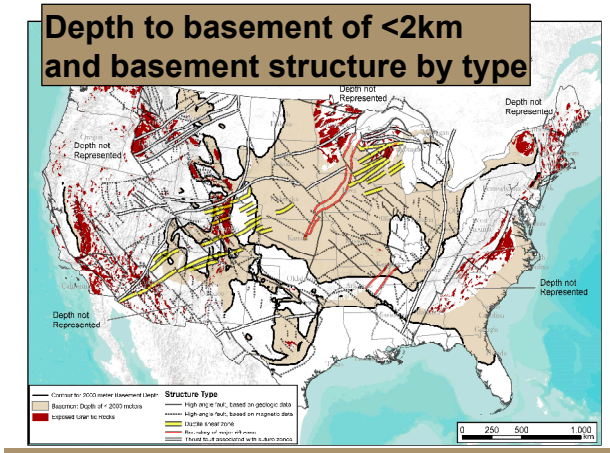
G. Hammond (SNL), G. Freeze (SNL), W.P. Gardner (SNL), P. Mariner (SNL), S.D. Sevougian (SNL)

Example FY14 Accomplishments: Disposal Research: Regional Geology

Sandia National Laboratories

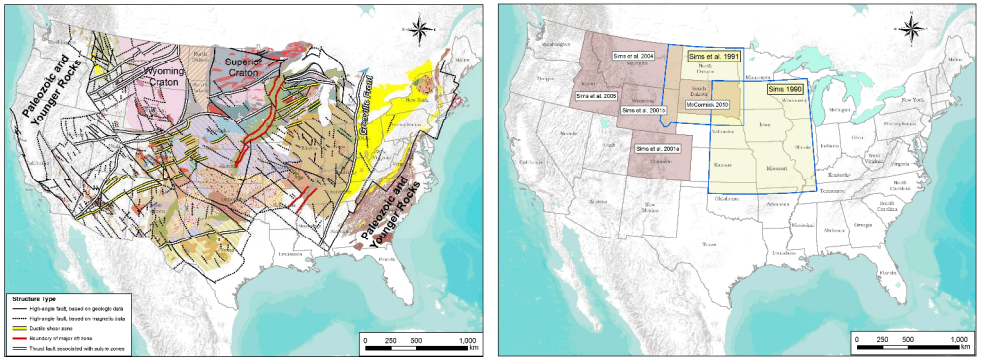
GIS database to support understanding of siting alternatives for the four UFD disposal options

- Created a national framework for broad consideration of siting alternatives for a deep borehole field test
  - Data at the national scale provide the overall framework to evaluate data at the sub-regional to local scale
  - Provides information on major terrane boundaries (structures) and alternative lithologies that would influence siting decisions



Basement structure from Sims et al. (2008); basement depth from SMU Geothermal Laboratory

- Planned and prototyped an interactive web mapping tool for the GIS database in collaboration with INL for implementation in FY15
- Supported other media-specific work packages that are developing the granite and argillite reference cases by providing information related to the geology, hydrology and depth or distribution of shale and crystalline rocks

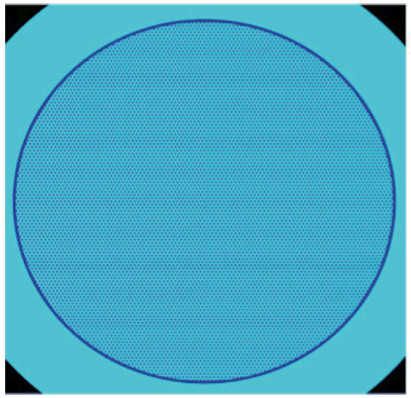


National-scale map of basement terranes and selected areas that include more detailed regional to state coverage
Left: data from Reed et al. (1993)

Frank Perry and Rick Kelley (LANL),
Pat Dobson and Jim Houseworth (LBNL)

Example FY14 Accomplishments: Disposal Research: Preliminary Study of DPC Direct Disposal Alternatives

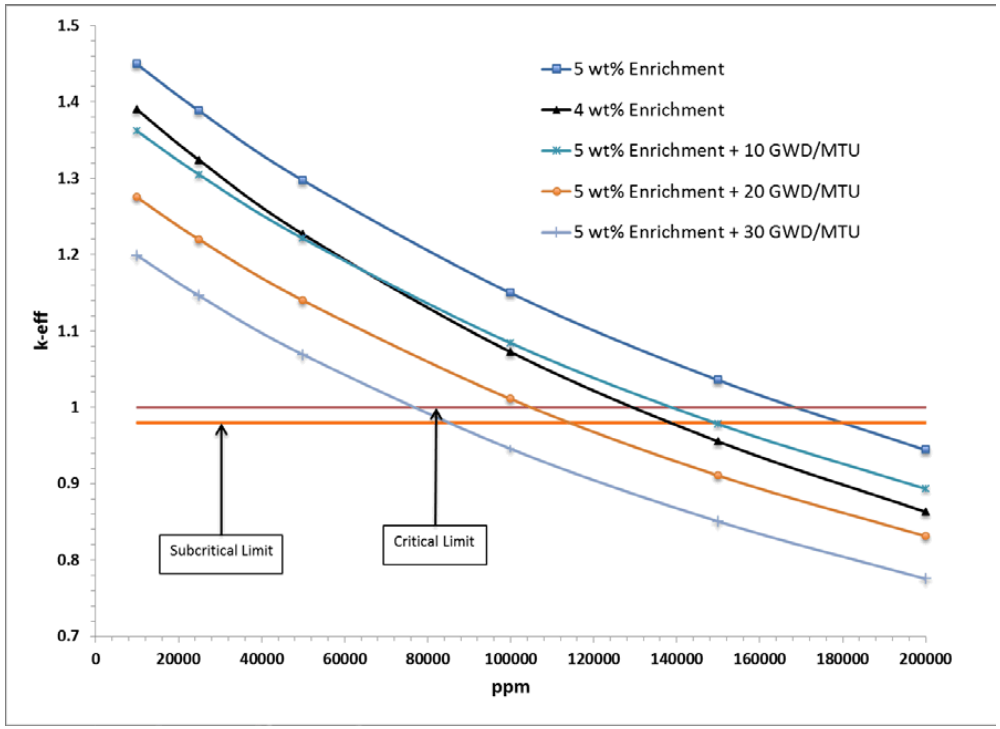
Postclosure Nuclear Criticality of SNF in Dual-Purpose Canisters Flooded with Chloride Brine and Degraded



Bounding-Type Configuration of Fuel Rods in a DPC

Hypothetical Neutron Multiplication Factor (keff) vs. Chloride Concentration

(NaCl saturation at 20°C gives 158,000 ppm chloride)



Conclusion: Groundwater salinity (^{35}Cl) could allow exclusion of postclosure criticality from performance assessment for direct disposal of most DPCs in a salt repository.

John Scaglione, Justin Clarity and Rob Howard (ORNL); Ernest Hardin (SNL)