SAND2013-9322C

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Used Nuclear Fuel Disposition R&D Campaign Overview

Peter Swift
National Technical Director
Used Fuel Disposition R&D Campaign

2013 Fuel Cycle Technologies Annual Review Meeting
November 5-7, 2013

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Outline

- **The Campaign Overview**
  - Background
  - Mission and Goals
  - Organization of the R&D Activities
  - Selected accomplishments for FY13
  - Summary of activities planned for FY14
- **Introduction to the following Used Fuel Disposition R&D presentations**
  - Quantification of Cation Sorption to Engineered Barrier Materials Under Extreme Conditions (NEUP Project 11-3180)
    - Brian Powell, Clemson University
  - Increased Bentonite Stability, or "How I learned to Stop Worrying and Love the Interlayer Cations
    - Michael Cheshire, Los Alamos National Laboratory
  - Ductile-to-Brittle Transition Temperatures for High-Burnup PWR Fuel Cladding Alloys
    - Michael Billone, Argonne National Laboratory
  - Preliminary Report on Dual-Purpose Canister Disposal Alternatives
    - Ernest Hardin, Sandia National Laboratories
  - Status of the High-Burnup Cask Demonstration Project
    - Ned Larson, DOE Office of Used Nuclear Fuel Disposition R&D
  - Integrated Research Project: Fuel Aging in Storage and Transportation (FAST): Accelerated Characterization and Performance Assessment of the Used Nuclear Fuel Storage System
    - Sean McDeavitt, Texas A&M University.

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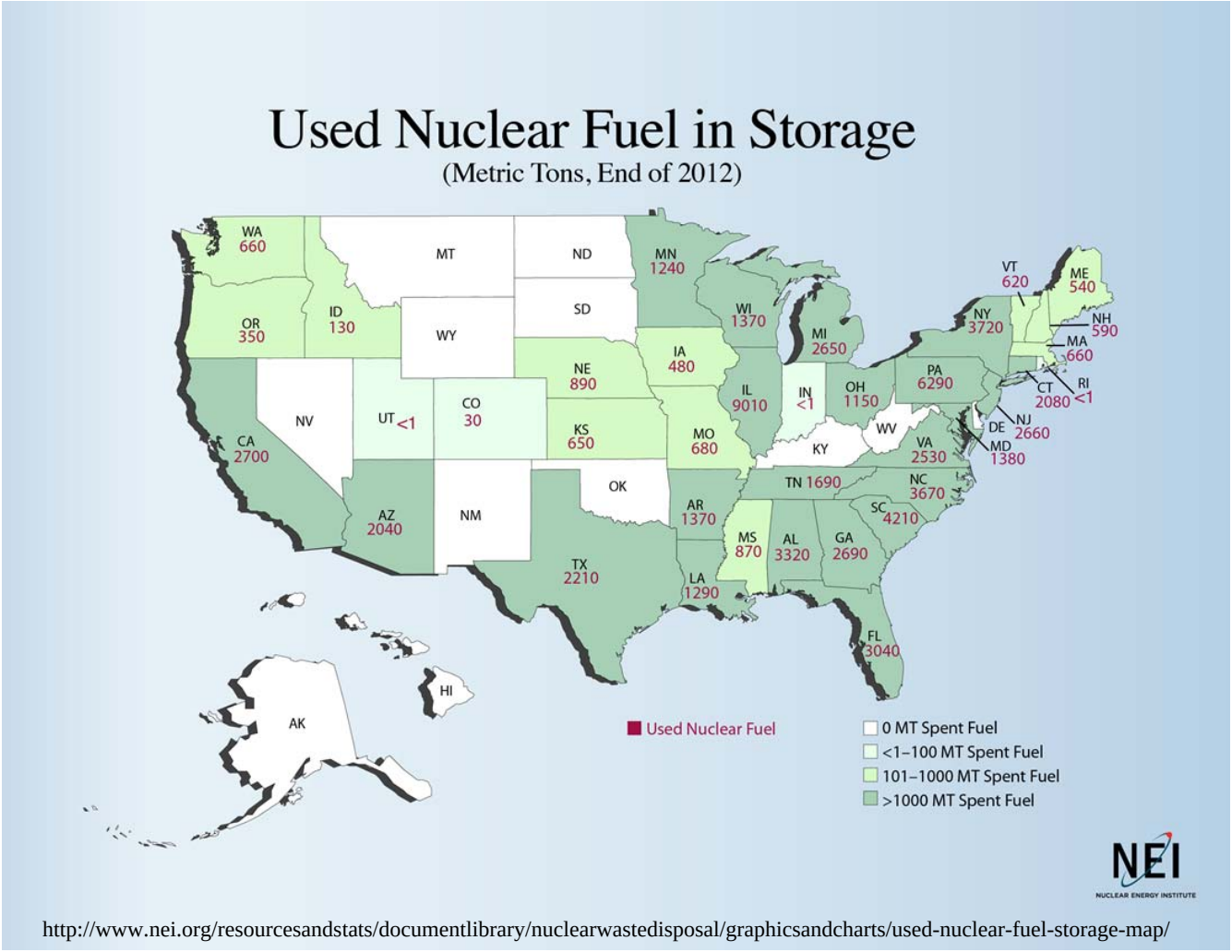
Where Used Nuclear Fuel is Today



http://www.nei.org/resourcesandstats/documentlibrary/nuclearwastedisposal/graphicsandcharts/used-nuclear-fuel-storage-map/

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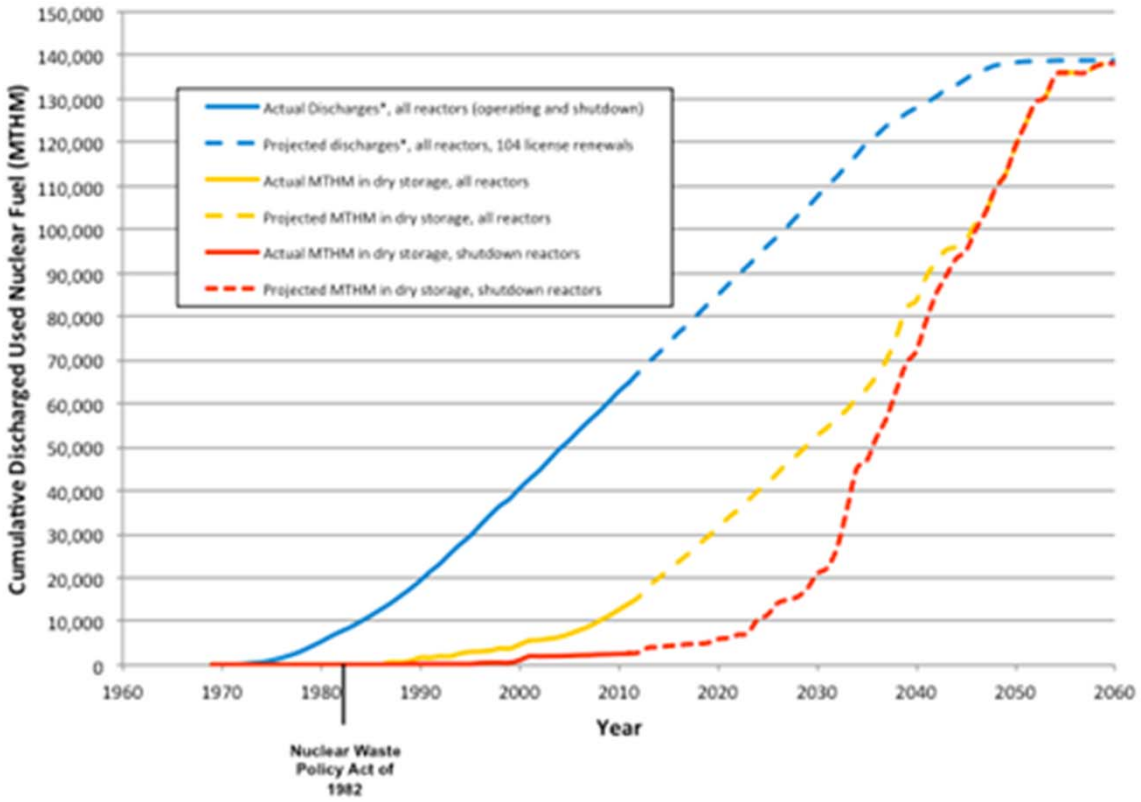
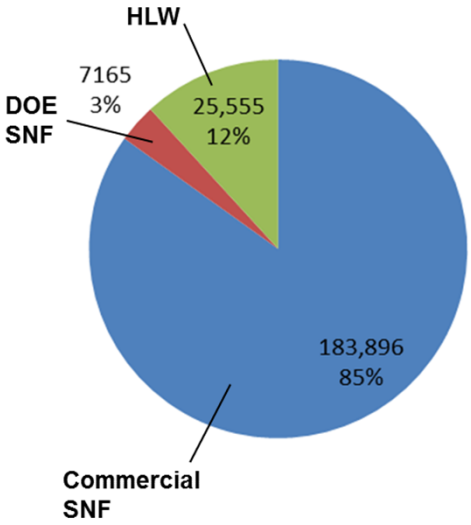
Historical and Projected Spent Nuclear Fuel (SNF) and High-Level Radioactive Waste (HLW) in the United States



Source: *Based on actual discharge data as reported on RW-859s through 12/31/02, and projected discharges, in this case for 104 license renewals

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

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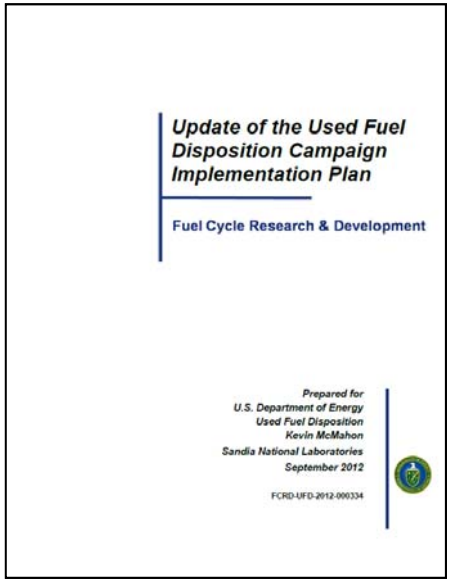
UFD Mission

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 implementation of a new national policy 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-2012-000334, September 2012

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UFD Campaign 2009-Present

- FY09 Planning meeting at Argonne National Laboratory, June 2009
- FY10 R&D funding at $7.1 M
  - Disposal R&D, modest level of effort on Storage R&D, no Transportation R&D
- FY11 R&D funding at $23.8 M
  - Nine national laboratories participating in UFD
  - Significant R&D program in Storage, including Transportation
  - Disposal R&D not site specific
- FY12 R&D budget baseline at $22.8 M, end-of-year actual ~$37 M
  - Some elements of FY12 work scope not established until fourth quarter
- FY13 R&D budget baseline at $23.5 M, end-of-year actual $32.5M
- FY14 R&D budget planning target at $15.4M, with $4.4M carryover

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Used Fuel Disposition Campaign External Collaborations

- **Collaboration among 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 Separations/Waste Form Campaign
    - Waste form modeling work transitioning from Seps/WF to UFD in FY14
- **Collaboration with DOE-EM**
  - Salt disposal research (joint activities with DOE-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**
  - Separate presentation by Ned Larson
- **EPRI**
  - Extended Storage Collaboration Program (ESCP) (with NRC and international groups)
- **International Collaborations**
  - Korea, China, Taiwan, Japan, France, Switzerland, Sweden, Czech Republic, multinational working groups

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Used Fuel Disposition Campaign External Collaborations (cont.)

- **International activities**
  - Participation in international Underground Research Laboratories in Europe and Korea
  - Bilateral agreements on disposal R&D with Korea, Japan, China
  - MOU for salt R&D with Germany
  - IAEA working groups in storage and transportation
  - Collaboration with Germany and Japan on extended performance of bolts and seals for bolted storage casks
- **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
    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
- **Other university collaborations (U. of Wisconsin, MIT, U. of Oklahoma, UNLV, University of Sheffield UK)**
- **National Laboratory LDRD programs**
  - E.g., modeling of natural tracers in groundwater (SNL)

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Organization of R&D in the Used Fuel Disposition Campaign

UFD Campaign
Peter Swift
National Technical Director (NTD)
Shannon Bragg-Sitton, Deputy NTD

Disposal Research
Kevin McMahon
Bob MacKinnon

Engineered Barrier Systems
Natural Systems
Salt R&D
Deep Borehole Disposal
Generic System Modeling
Advanced System Modeling
ST&D Interface Analysis
International Collaborations
Regional Geology
Inventory Projections
LLW Disposition
Thermal Load Management & Design
UNF and HLW Disposal Option Evaluation

Storage &Transportation
Ken Sorenson
Sylvia Saltzstein

S&T Experiments
Transportation
Security
R&D Investigations
Engineering Analysis
Field Demonstration

Used Fuel Disposition Campaign		
	FY 2013 Actual	FY2014 Planned
Storage and Transportation Research	$12,400,000	$7,674
Disposal Research	$17,500,000	$7,048
Crosscut Activities	$2,600,000	$678
Total	**$32,500,000**	**$15,400**

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Campaign 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

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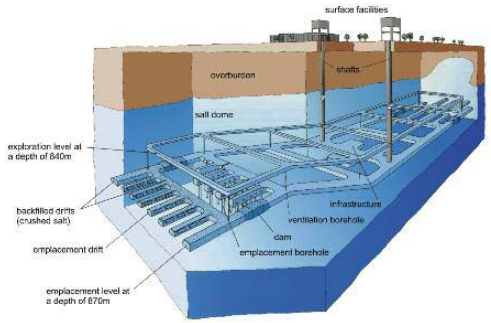
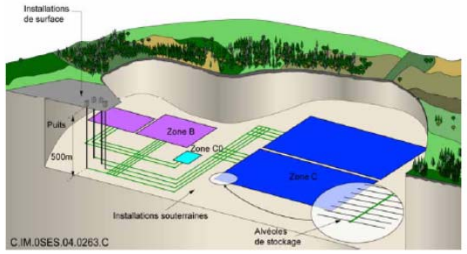
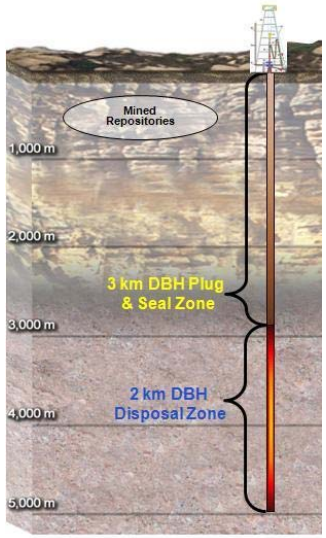
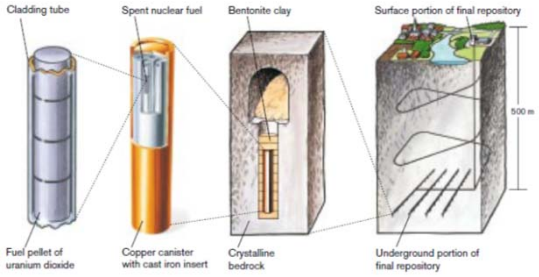
UFD Campaign Focus: Disposal R&D

- **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**









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Specific UFD Campaign Objectives Near Term (2013-2015)

- Conduct testing to determine high-burnup UNF cladding properties and long-term stainless steel canister corrosion performance
- Develop analytic basis for representing hydride behavior in UNF cladding
- Develop a technical basis for licensing transportation systems designed to transport high-burnup UNF
- Develop the scientific basis for multiple geologic options for permanent disposal of UNF and high-level radioactive waste, including computational models supported by experiments

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UFD Strategic Objectives Long Term (2015-2025)

- Collaborate with industry to field a full-scale NRC-licensed storage demonstration facility with monitoring and inspection capabilities to assess long-term performance
- Conduct high priority separate effects tests on storage system safety components that align with the confirmatory demonstration (e.g., full-assembly material property data, closure system degradation behavior, concrete performance)
- Collaborate with industry and NFST to support the eventual transport of UNF
- Collaborate with industry and NFST to develop and implement integrated storage, transportation, and disposal concepts that ensure safe, secure, and timely storage, transportation and disposal of waste

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Major FY13 Accomplishments

- Completed analysis of the existing U.S. inventory of used nuclear fuel (UNF), including both commercial and DOE-managed fuels, concluding that ~98% of the existing UNF could be committed for permanent disposal without precluding future options including potential recycling of future UNF
- Completed preliminary analyses on dual-purpose canister (DPC) disposal alternatives. The preliminary results indicate that DPC direct disposal could be technically feasible, at least for certain disposal concepts
- Completed embrittlement and ductile-to-brittle transition temperature (DBTT) testing of high burnup PWR cladding alloys. This data helps to inform the modeling work described in the next bullet
- Developed a modeling capability to perform preliminary deterministic evaluations of moderate-to-high burnup used nuclear fuel (UNF) mechanical performance under normal conditions of storage (NCS) and normal conditions of transport (NCT)

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Selected FY13 UFD Deliverables

- ***Categorization of Used Nuclear Fuel Inventory in Support of a Comprehensive National Nuclear Fuel Cycle Strategy*, October 2012, FCRD-UFD-2013-000232**
- ***Generic Deep Geologic Disposal Safety Case Report,* January 2013, FCRD-USED-2013-000146 Rev 1**
- ***Hydride Rim Formation in Unirradiated Zircaloy*, April 2013, FCRD-UFD-2013-000151**
- ***Fuel Assembly Shaker Test for Determining Loads on a PWR Assembly under Simulated Normal Conditions of Truck Transport*, June 2013, FCRD-UFD-2013-000190**
- ***Preliminary Report on Dual-Purpose Canister Disposal Alternatives*, August 2013, FCRD-UFD-2013-000171**
- ***Experimental and Modeling Investigation of Radionuclide Interaction and Transport in Representative Geologic Media,* September 2013, FCRD-UFD-2013-000314**
- ***Brine Migration Experimental Studies for Salt Repositories*, September 2013, FCRD-UFD-2013-000204**
- ***Engineered Barrier System Model Development and Evaluation*, September 2013, FCRD-UFD-2013-000312**
- ***Draft Evaluation of Options for Permanent Geologic Disposal of Spent Nuclear Fuel and High-Level Waste in Support of a Comprehensive National Nuclear Fuel Cycle Strategy*, September 2013, FCRD-UFD-2013-000371**
- ***Used Nuclear Fuel Loading and Structural Performance Under Normal Conditions of Transport – Demonstration of Approach and Results on Used Fuel Performance Characterization*, September 2013, FCRD-UFD-2013-000325**
- ***Data Report on Corrosion Testing of Stainless Steel Storage Canisters*, September 2013, FCRD-UFD-2013-000324**
- ***Data Report on Ring Compression and DBTT Tests for PWR Cladding*, September 2013, FCRD-UFD-2013-000401**

- **Total of 24 L2 milestones completed in FY13, all on time**

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UFD Storage and Transportation R&D FY13 Activities and FY14 Planning

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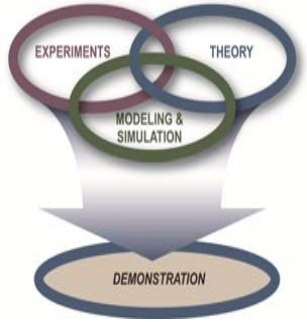
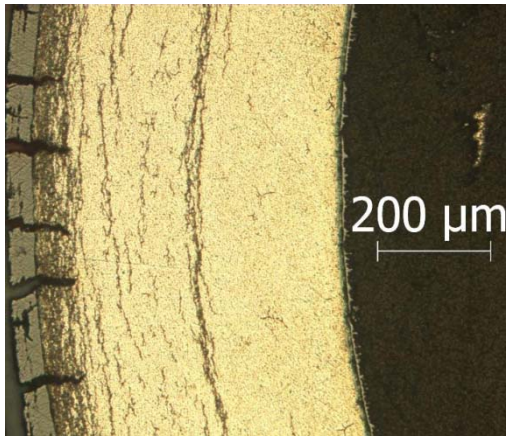
Storage and Transportation Objectives

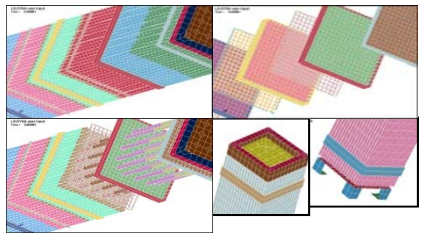
Overall Objectives:

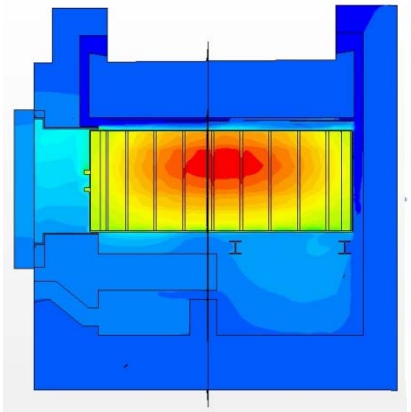
- Develop the technical bases to demonstrate used fuel integrity for extended storage periods.
- Develop technical bases for fuel retrievability and transportation after long term storage.
- Develop the technical basis for transportation of high burnup fuel.
- Support the DOE/EPRI Confirmatory Storage Demonstration Project [Note: this is a new objective]



Science based, Engineering driven







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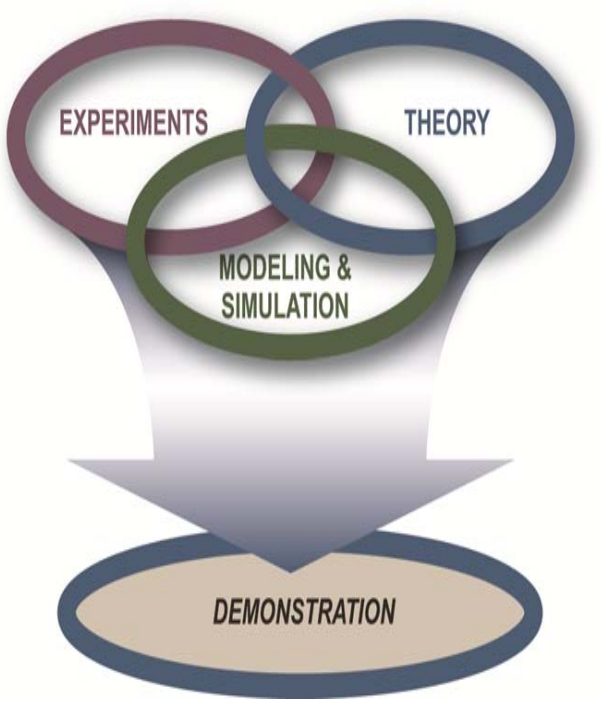
Storage and Transportation Major Control Accounts

Five major Control Accounts define the work

- Experiments
- Analysis
- Transportation
- Field Demonstration Support
- Security



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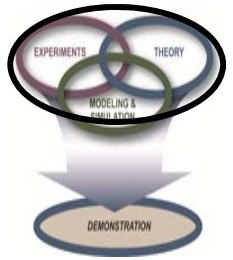
ST R&D Experiments: Noted FY13 Activities

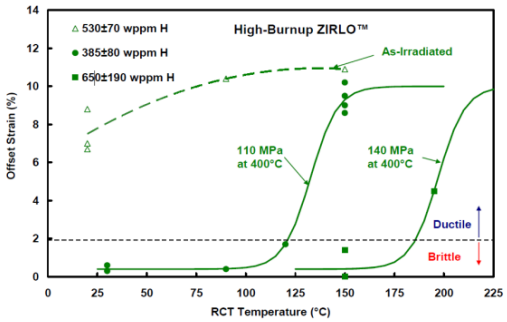


High burnup fuel cladding embrittlement/Ductile-brittle transition temperature (DBTT) testing

Billone, Burtseva, Han, Liu (ANL)

DBTTs of high burnup ZIRLO™ and M5® cladding in simulated drying storage conditions systematically lowered to ≤20° C.

Test Rodlets



DBTT Test Results for Zirlo Cladding

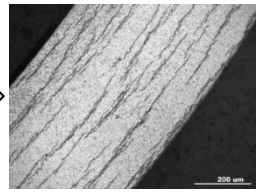
Hydrogen doping and HFIR Irradiation Testing

Howard, Yan ,Wang, Ott, Howard (ORNL)

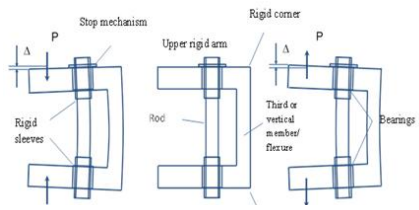
Post-irradiation examination of Zircaloy-4 and ZIRLO™ rods subjected to HFIR irradiation at known hydrogen concentrations and high temperatures. Testing will generate baseline data to benchmark hot-cell testing of actual high-burnup UNF cladding..

Hot cell bend tests on high burn-up UNF will evaluate fuel pellet interaction on clad fatigue performance.

As-irradiated Zircaloy Cladding



Hydrogen-doped Zircaloy Cladding



Irradiated Fuel rod bend and vibration test apparatus

Hydrogen Doping And Distribution

Shimskey, Lavender, MacFarlan, Eslinger (PNNL)

Demonstrated that it is possible to pre-hydride samples at low temperatures (<400° C) in pure H_2 and to form the desired hydride rim using this technique.

SS canister corrosion studies

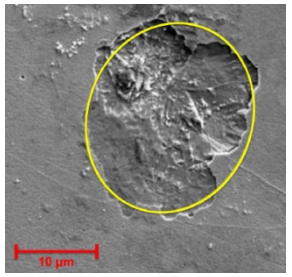
Enos, Bryan, Norman (SNL)

Experiments performed on 304 SS stainless steel show that localized corrosion can initiate and does not stifle, despite the limited mass of the corrosive species (chloride) present..

On-site inspection of Calvert Cliffs ISFSI

INL/SNL/PNNL

Calvert Cliffs EPRI filter: Ca-sulfate crystals – no chlorides



Crevice corrosion on stainless steel

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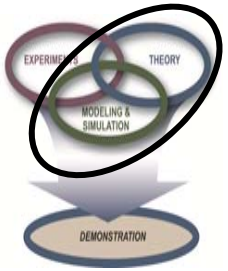
ST R&D Analysis: Noted FY13 Activities



Hydride Precipitation Modeling

Tikare, Weck, Glazoff (SNL)

All the basic microstructural evolution processes necessary to simulate δ−$ZrH_{1.5}$ nucleation and growth in a Zircaloy-4 microstructure were incorporated into the model and demonstrated with good qualitative agreement with experimental observations.

Uncertainty Quantification Method For Used Fuel

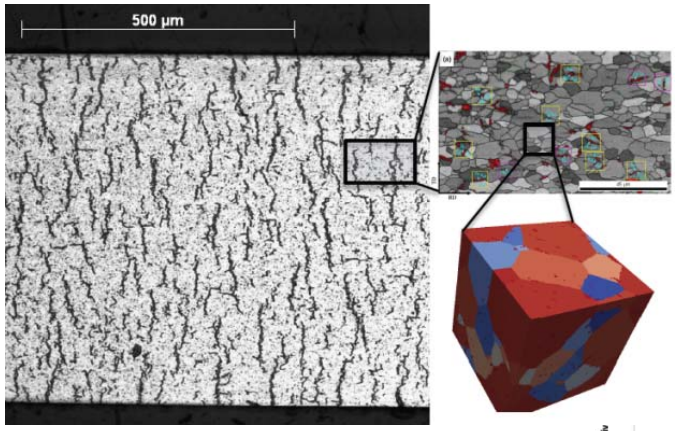
Gauld, Pigni, Williams, Ilas, Wieselquist, Wiarda (ORNL)

Method provides a technical basis for extrapolating uncertainties to regions where direct measurement data validation of the modeling tools are neither available nor possible (e.g., extended storage times).

Structural Sensitivity of Dry Storage Canisters

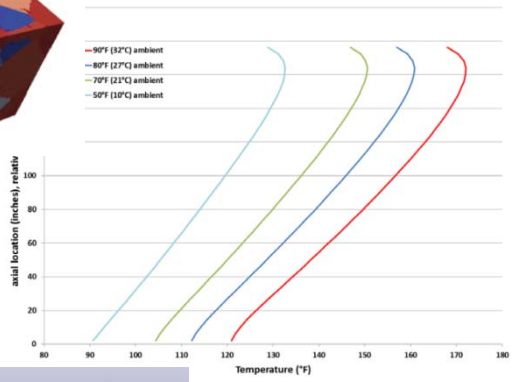
Klymyshyn, Karri, Adkins, Hanson (PNNL)

"Tip-over" of a vertical dry storage system offers a strong challenge to the containment boundary, and identifies a concern regarding the behavior of welded stainless steel joints under high-strain-rate conditions.

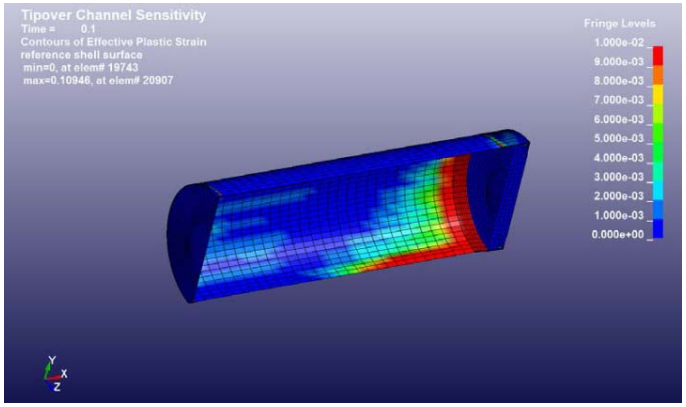


Hydride precipitation modeling

Hope Creek preliminary canister surface temperature analysis



Storage canister –tipover strains



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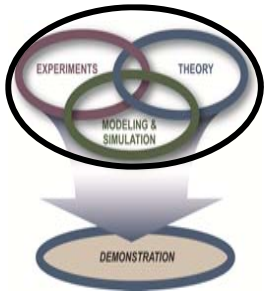
ST R&D Transportation: Noted FY13 Activities



Surrogate PWR Assembly Shaker Table Test

McConnell, Flores, Wauneka, Koenig, Ammerman, Bignell, Saltzstein, and Sorenson (SNL)

Measured strains on surrogate rods were very small relative to the elastic limit of unirradiated and irradiated Zircaloy-4

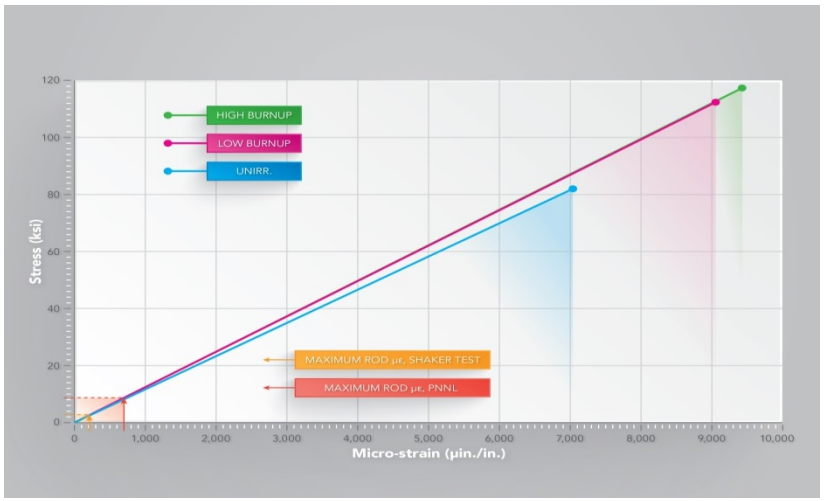
Surrogate PWR Assembly Shaker Table Test Analyses

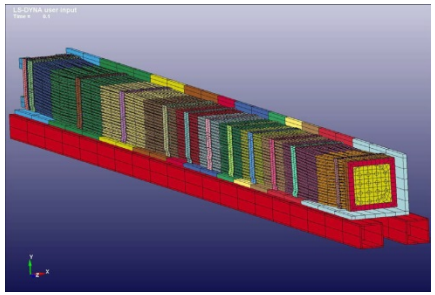
Klymyshyn, Sanborn, Adkins, and Hanson (PNNL)

Finite element model results of the surrogate PWR assembly subjected to SNL shaker test conditions closely matched the experimental results.

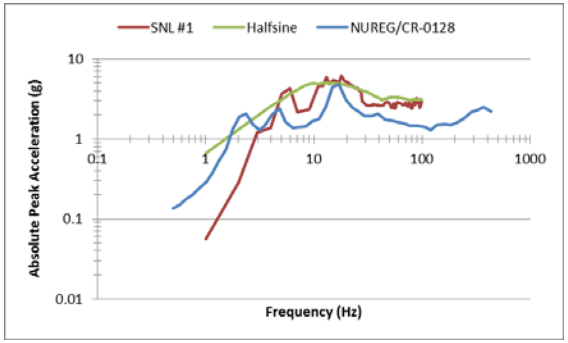
Surrogate PWR assembly

Surrogate PWR assembly on shaker table





Surrogate PWR assembly model



Elastic response: Experimental data and analyses indicate loadings are well below elastic limits

Acceleration plots:

- **Experimental data**
- **Analysis**
- **NRC input guidance**

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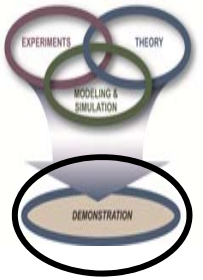
ST R&D Field Demonstration Support: Noted FY13 Activities



Viability of Existing INL Facilities for Dry Storage Cask Handling

Bohachek, Park, Wallace, Winston, and Marschman (INL)

It is possible to receive, open, inspect, remove samples, close, and reseal large, bolted-lid, dry storage casks at INL.

CPP 603 Facility

Strategy for Used Fuel Acquisition

Marschman and Rusch (INL)

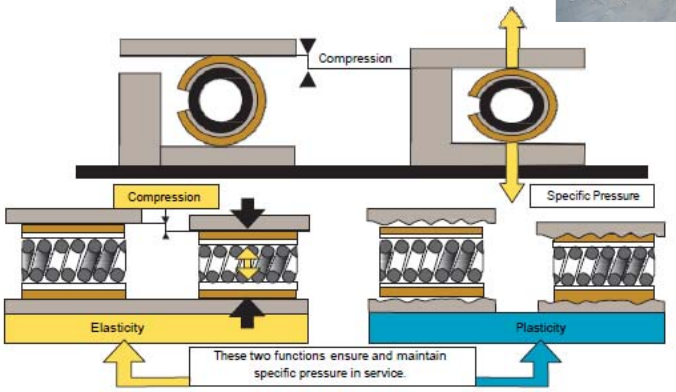
Acquiring fuel from reactor spent fuel pools is viable and there are shipping casks available for moving fuel from pools to laboratories for R&D purposes.

Figure V.3-5(a): Helicoflex seal

Managing Aging Effects on Dry Cask Storage Systems

Liu (ANL)

Develops technical bases for Ageing Management Plans



Helicoflex seal system aging considerations:

- **Relaxation**
- **Corrosion**

Support DOE/EPRI Storage Demonstration project

- Test plan review
- Monitoring and inspection support
- Fuel selection and basket configuration support

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ST R&D
FY14 Planned Activities

Experiments
- **Fuel Clad testing**
- **Stress Corrosion Cracking and SS Corrosion and Environmental Sample Investigations**

Analysis
- **Incorporate Hydride Model into Moose-Bison**
- **Thermal Profile analyses of in-situ industry storage systems identified for inspection**

Transportation
- **Results of Shock and Vibration testing**

Field Demonstration
- **Strategy For Fuel Pin Receipt, Characterization, Sample Allocation for the Demo Sister Pins**
- **Develop a UFD ST Program Plan**

Security
- **Continue to Assess the Regulatory Rule-making Process for S&T and Orphaned Sites.**

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UFD Disposal R&D
FY13 Activities and FY14 Planning

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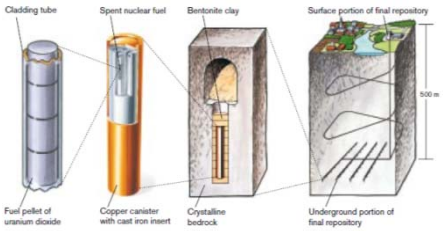
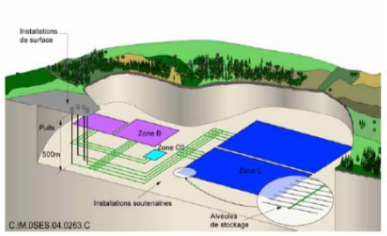
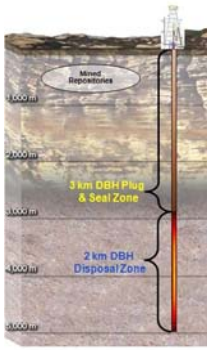
Disposal R&D Restructured for FY14

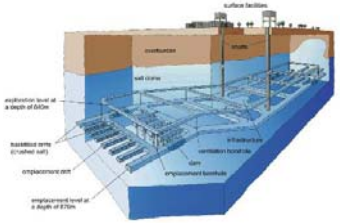
- **13 Disposal Control Accounts in FY13**
  - Engineered Barrier Systems
  - Natural Systems
  - Salt R&D
  - Deep Borehole Disposal
  - Generic System Modeling
  - Advanced System Modeling
  - ST&D Interface Analysis
  - International Collaborations
  - Regional Geology
  - Inventory Projections
  - LLW Disposition
  - Thermal Load Management & Design
  - UNF and HLW Disposal Option Evaluation

- **10 Disposal Control Accounts in FY14**
  - Engineered Material Performance
  - Argillite Disposal
  - Crystalline Disposal
  - Salt Disposal
  - Deep Borehole Disposal
  - Generic Disposal System Analysis
  - International Disposal Collaborations
  - Regional Geology
  - Disposal of Dual Purpose Canisters
  - UNF and HLW Disposal Option Evaluation









FY13 accomplishments discussed for a subset of activities

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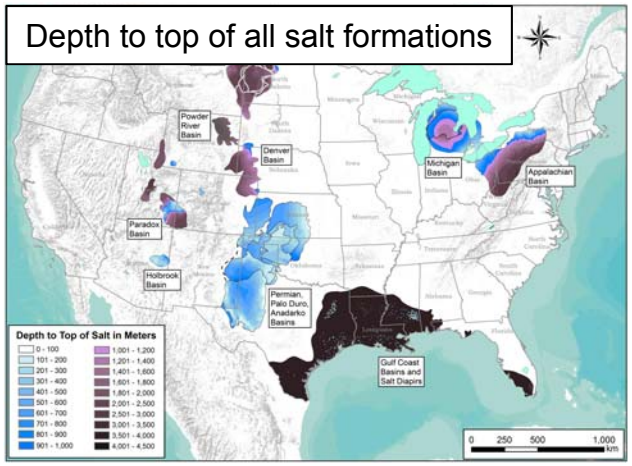
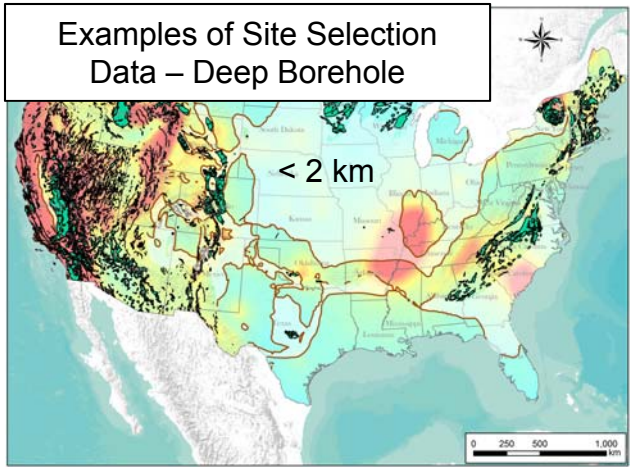
Example FY13 Accomplishments: Disposal Research: Regional Geology

- A working GIS database with the capability to visualize and spatially analyze the relationship between alternative host rocks and data pertaining to siting guidelines
- Populated formation-scale data for salt, shale, and crystalline rock
- Populated numerous data sets bearing on site selection guidelines for deep borehole demonstration
- Analyzed siting factors such as depth to formation for salt and shale
- Finalized an approach to build an interactive website for visualizing the distribution of alternative host rocks and siting options

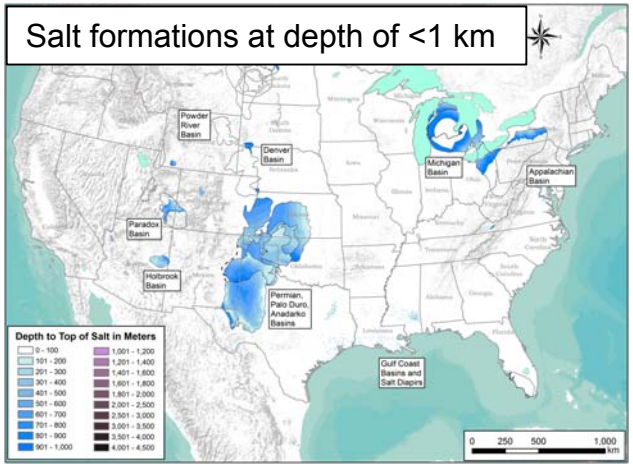
Depth to top of all salt formations



Examples of Site Selection Data – Deep Borehole



Salt formations at depth of <1 km



- Advantageous to locate borehole emplacement in regions of crustal stability with crystalline basement at a depth of < 2 km
- Database includes indicators of crustal stability such as location of Quaternary faults and seismic hazard, as well as data for depth to crystalline basement and distribution of exposed crystalline rocks

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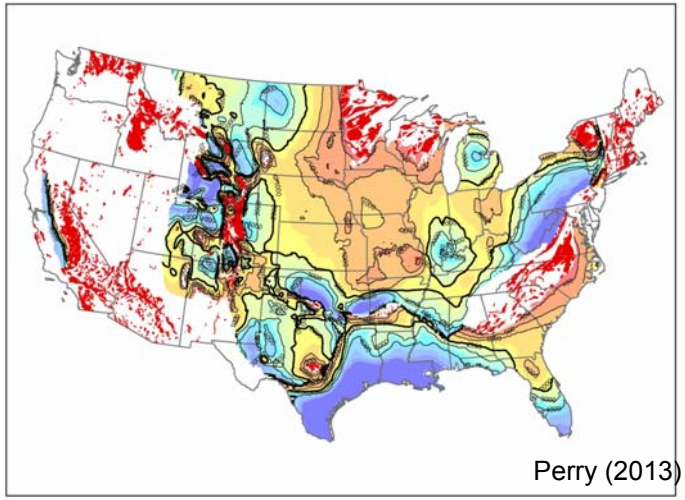
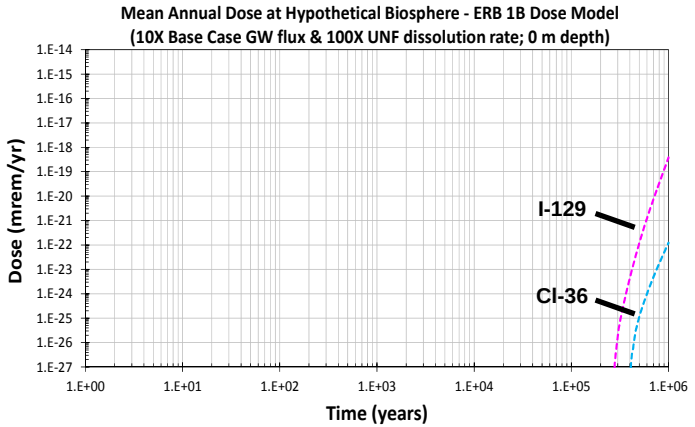
Example FY13 Accomplishments: Disposal Research: Deep Borehole Disposal

Site Selection Guidelines and Safety Assessment Developed

- Site selection guidelines developed for a full-scale deep borehole disposal demonstration project: *depth to crystalline basement, lithology, structural complexity, horizontal stress, geothermal heat flux, topographic relief and hydraulic gradient, Quaternary faulting and volcanism, and mineral resources potential*
- Updated thermal-hydrologic simulations and performance assessment (PA) modeling developed, including radionuclide diffusion from borehole into surrounding host rock
- Base-case PA model results show no radionuclide releases to the biosphere
- PA model with vertical flow rates increased 10X and waste form degradation rate increased 100X indicates negligibly small dose rate at 1,000,000 years



Perry (2013)



Bill Arnold, Pat Brady, Teklu Hadgu (SNL); Frank Perry (LANL)

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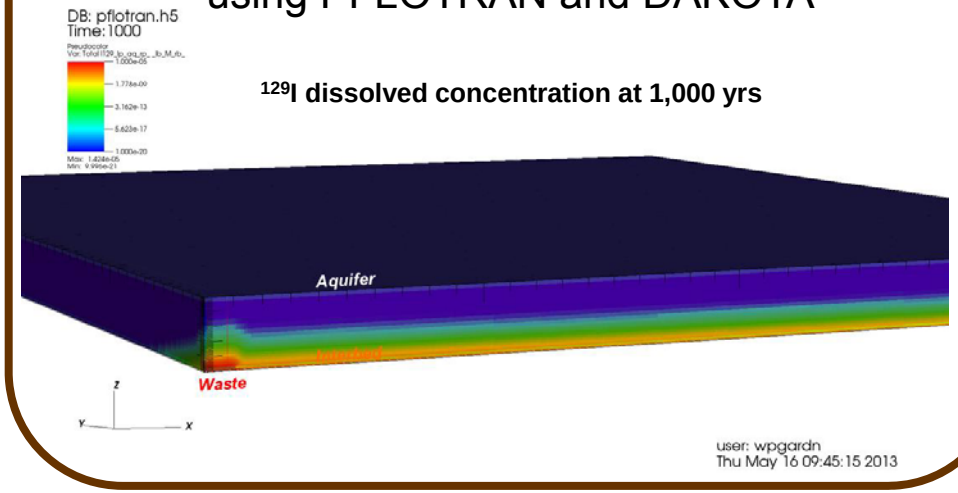
Example FY14 Work: Generic Disposal System Modeling

Enhanced Generic Disposal System Modeling

- Probabilistic high-performance-computing (HPC) based simulations of generic disposal systems that couple the THCM processes governing waste degradation and radionuclide transport in the engineered barriers, geosphere, and biosphere

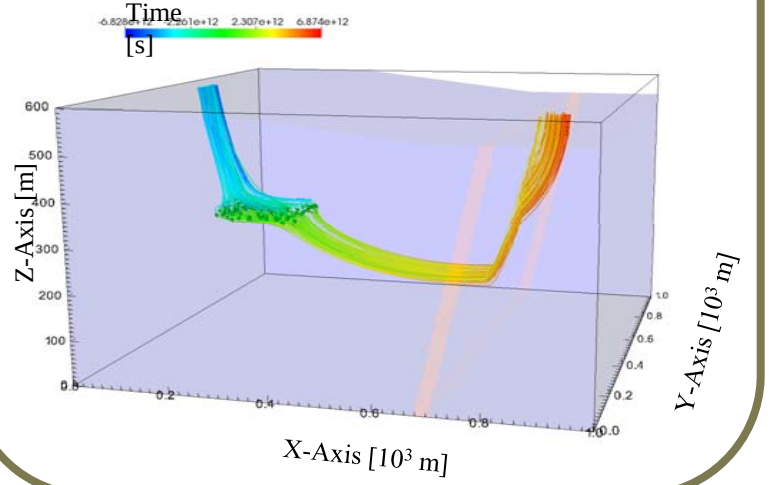
Generic Bedded Salt Repository

- Develop reference case properties
- Perform HPC-based simulations using PFLOTRAN and DAKOTA



Generic Granite Repository

- Develop reference case properties
- Perform HPC-based simulations using PFLOTRAN and DAKOTA



G. Freeze (SNL), P. Vaughn (SNL), S.D. Sevougian (SNL), P. Gardner (SNL), P. Mariner (SNL), S. Painter (LANL)

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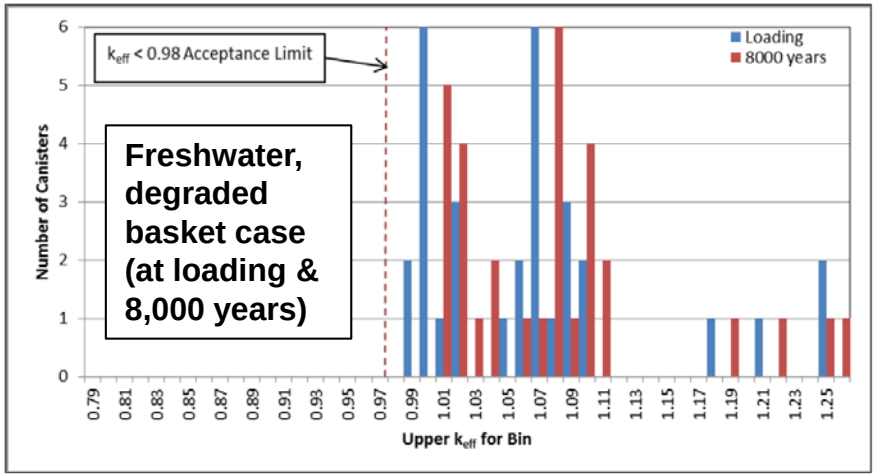
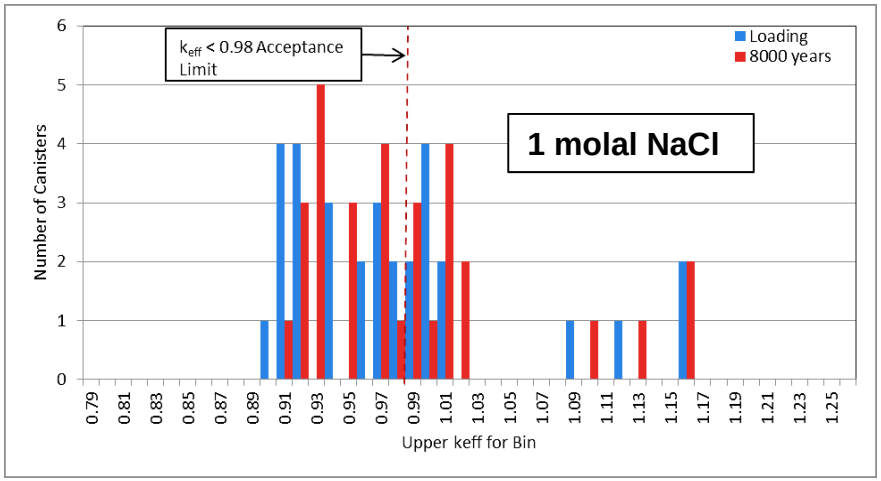
Example FY13 Accomplishments: Disposal Research: Disposal of Dual-Purpose Canisters

Postclosure Nuclear Reactivity of SNF in Degraded, Flooded Dual-Purpose Canisters

Conclusion: Groundwater salinity (seawater, deep groundwater, or salt brine in evaporite deposits) could significantly lower reactivity for degraded, flooded waste packages.

Example calculations performed at ORNL using SCALE, for 31 existing DPCs at the Maine Yankee site.





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

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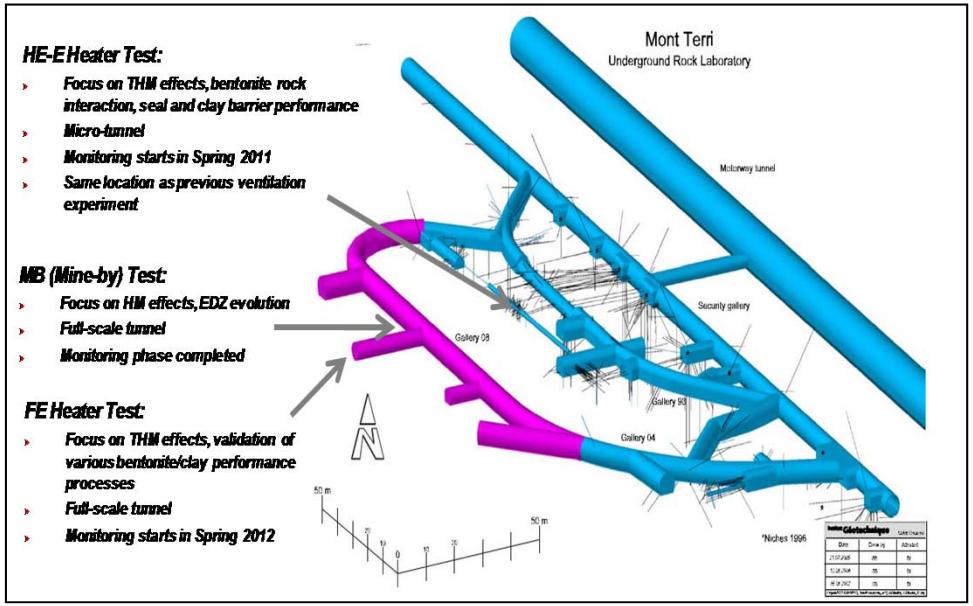
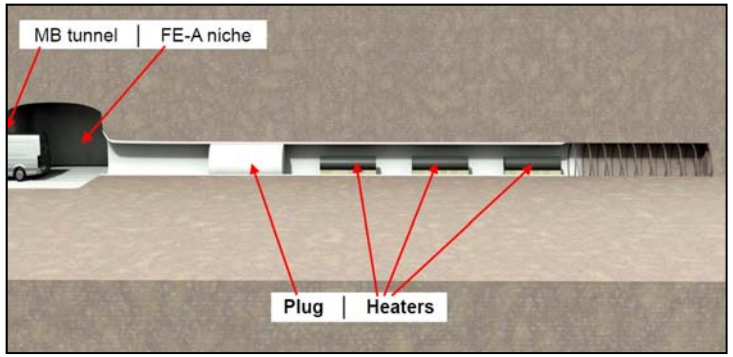
Example FY13 Accomplishments: International Collaborations in Disposal Research

- ***DOE has joined formal R&D agreements with ongoing programs in Europe and Asia***
- ***Several UFD funded collaborative R&D projects have been initiated within these R&D agreements***

- **Mont Terri: International underground research laboratory (URL) in clay in Switzerland**
  - ***DOE has access to data from all Mont Terri R&D, can participate in ongoing projects, and also has the opportunity to conduct new experiments***
- **Colloid Formation and Migration Project**
  - ***Colloid research at Grimsel granite URL in Switzerland***
- **DECOVALEX: (Development of Coupled Models and their Validation against Experiments)**
  - ***DOE has participated in the past. New phase of project began Spring 2012***
- **KAERI Underground Research Tunnel (KURT)**
  - ***Collaborative US/ROK experiments began this year***
- **Others**
  - ***SKB Task Forces, MoU***
  - ***ANDRA MoU***
  - ***Clay Club, Salt Club, BMWi***





J. Birkholzer, LBNL

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Disposal R&D
FY14 Planned Activities

- **Engineered Material Performance**
  - Waste form modeling (transition from Separations/Waste Form Campaign); UNF performance/radiolysis modeling
- **Argillite Disposal**
  - Modeling of barrier materials; clay interaction experiments
- **Crystalline Disposal**
  - Modeling of fluid flow and transport in fractured media, modeling and experimental investigations of clay buffer material
- **Salt Disposal**
  - Thermo-mechanical testing ,experimental and modeling analysis of brine chemistry, flow
- **Deep Borehole Disposal**
  - Reference designs for alternative waste forms, seals research, support for drilling demonstration project
- **Generic Disposal System Analysis**
  - Integrate updated subsystem models into system model architecture; selected reference case simulations
- **International Disposal Collaborations**
  - Support ongoing collaborations
- **Regional Geology**
  - Develop interactive GIS map application
- **Disposal of Dual Purpose Canisters**
  - Develop and evaluate disposal system concepts; postclosure criticality analyses; logistic analysis
- **UNF and HLW Disposal Options**
  - Complete ongoing tasks of identifying disposal options for existing inventory of SNF and HLW

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Used Fuel Disposition R&D 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 beyond near-term planning
- **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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