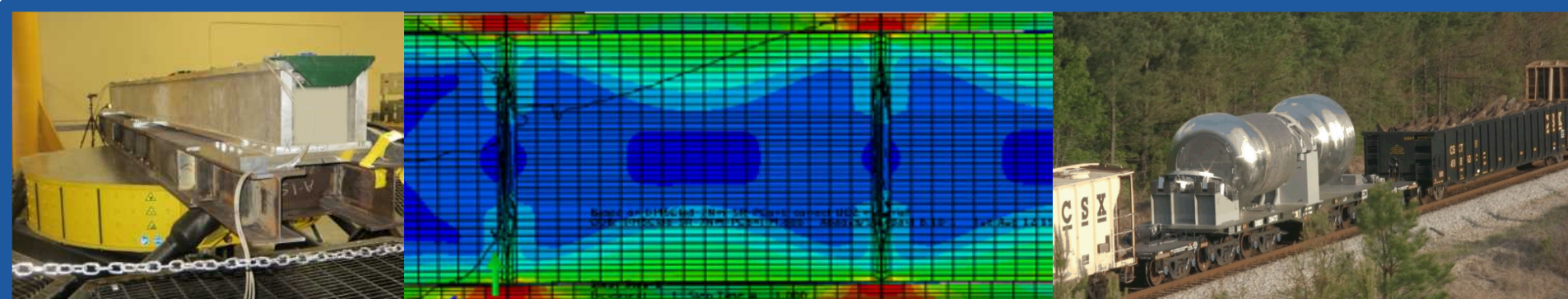




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SAND2017-3574C



“U.S. DOE Spent Nuclear Fuel Storage & Transportation R&D Activities”

Presented: ANS International High-Level Radioactive Waste Management Conference (IHLRWM 2017) – Charlotte, North Carolina

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Paul McConnell, Brady Hanson, Charles Bryan, John Scaglione***
Sandia National Laboratories

10 April 2017



R&D Goal & Presentation Objective

R&D GOAL

To provide data and analysis to support the enhancement of the technical basis for decisions regarding storage and transportation of spent nuclear fuel

PRESENTATION OBJECTIVE

To provide a brief overview of some current R&D in DOE Spent Fuel & Waste Disposition Science and Technology and show that the body of R&D points to a strong fuel system and lower external loads than previously thought



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1 SPENT FUEL INTEGRITY

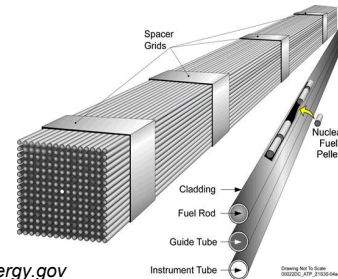


Photo: energy.gov

2 STORAGE SYSTEM INTEGRITY

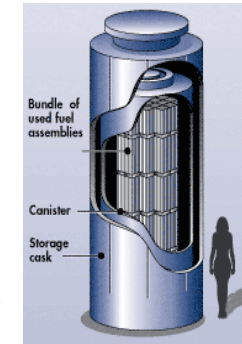
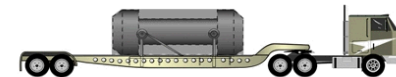


Photo: nrc.gov

3 SPENT FUEL TRANSPORTABILITY FOLLOWING EXTENDED STORAGE



energy.gov/pictures

4 THE BIG PICTURE



Collaboration Leverages Research Dollars & Enables a Diversity of Perspectives, Skills, & Ideas

■ US DOE (*primarily DOE-funded*)

- Office of Nuclear Energy, Spent Fuel & Waste Storage & Transportation
- Multiple national laboratories (ANL, INL, LANL, ORNL, PNNL, SRNL, SNL)

■ US NRC

- Office of Nuclear Materials Safety and Safeguards

■ Industry

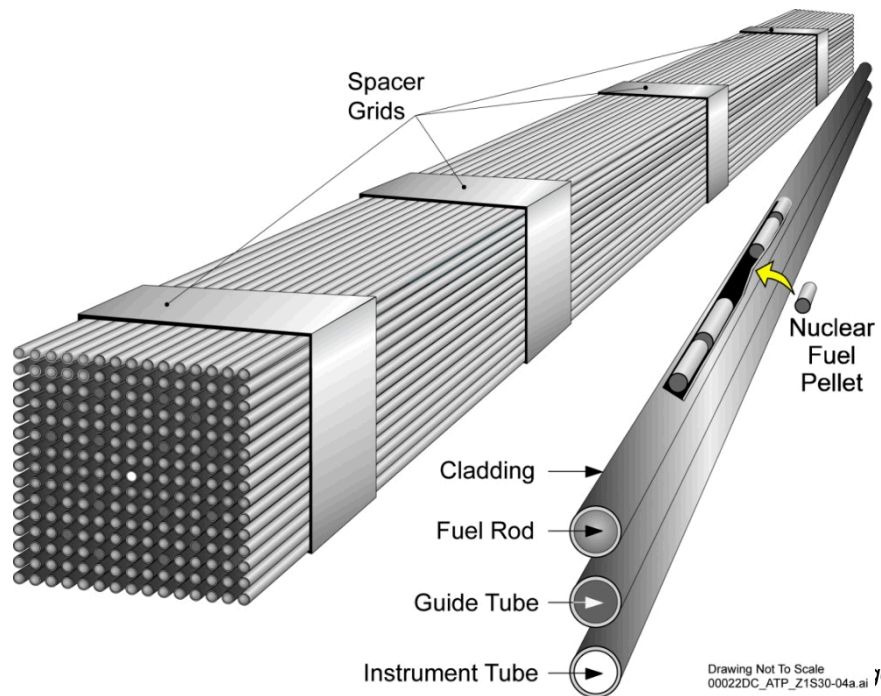
- Fuel and storage system vendors
- Site Operators
- Electric Power Research Institute (EPRI)
- Nuclear Energy Institute (NEI)

■ Universities (*primarily through DOE-NE University Programs*)

- Penn State, University of Illinois, University of South Carolina, University of Florida, South Carolina State University, Colorado School of Mines, North Carolina State, University of Mississippi, Oregon State University, University of Houston, Pepperdine, University of Utah, Utah State, Massachusetts Institute of Technology, Texas A&M University, University of Nevada at Reno, Northwestern, University of Michigan, University of California at Irvine

■ International Collaborations

- Japan, Spain, Germany, Korea, IAEA, Euratom



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1

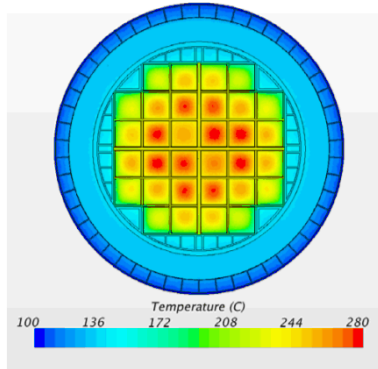
SPENT FUEL INTEGRITY



Understanding High Burn-up Cladding Performance

■ Ductile/Brittle Transition Temperatures

- Lower temperatures and lower rod internal pressures than previously assumed results in fewer radial hydrides
- Temperature where cladding loses significant ductility is thus lower than previously thought



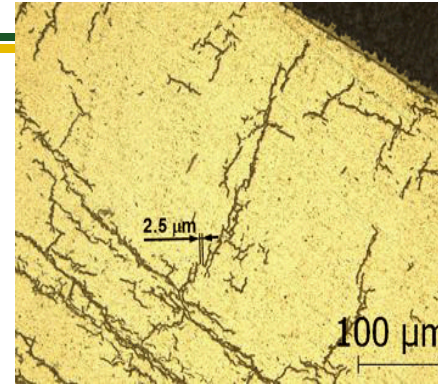
Maximum cladding surface temp. (°C) for each assembly in one type of licensed cask. (Fort, et al, 2016. PNNL)

■ Thermal analysis

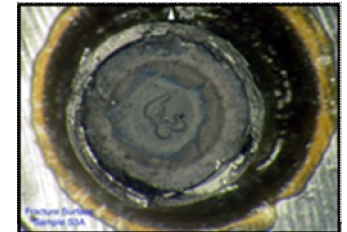
- More detailed modeling shows considerable margin between design basis loading and actual loading resulting in lower temperatures than previously thought

■ Strength and Fatigue

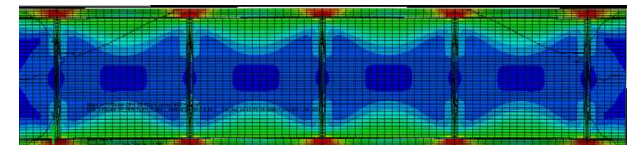
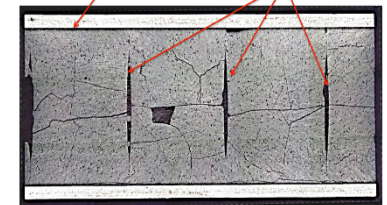
- Cyclic bending tests of irradiated fuel segments identify increases in strength due to pellet/clad and pellet/pellet bonding effects.



Circumferential and Radial hydrides in High Burn-up ZIRLO cladding subjected to peak temperatures of 350°C and 92 MPa hoop stress. (Billone, 2015. ANL)



Fuel rod segment before bend testing (Wang, et al., 2016. ORNL)



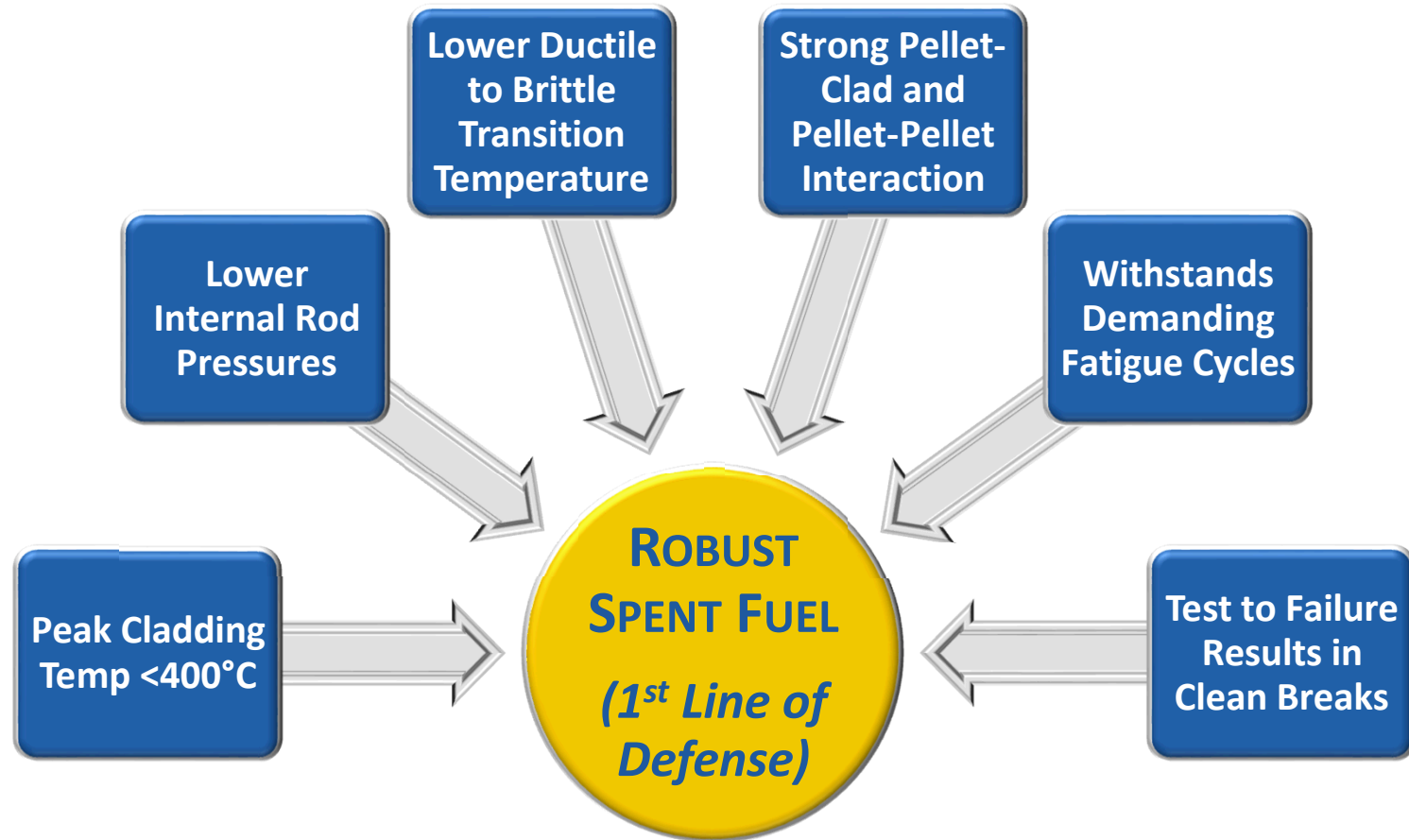
Modeled Stress distribution in fuel showing the fuel pellets supporting the clad due to cohesive bonding. (Wang, et al., 2014, ORNL)



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Current Tests & Analyses Indicate Spent Fuel More Robust than Previously Thought





Obtaining Data on High Burnup Cladding After 10 Years of Dry Storage

■ DOE/EPRI High Burnup Confirmatory Data Project

Goal: To provide confirmatory data for models, future SNF dry storage cask design, to support license renewals and new licenses for ISFSIs

■ Steps

- 1) Loading a commercially licensed TN-32B storage cask with high burn-up fuel in a utility storage pool (planned for 2017)
 - *Loading well-characterized fuel of four common cladding alloys*
 - *Instrumenting cask outfitted with thermocouples; gas samples taken before going to pad and periodically during storage*
- 2) Drying using industry standard practices
- 3) Storing at utility's dry cask storage site – 10 years
- 4) Transporting to lab to open
- 5) Testing rods to understand mechanical properties

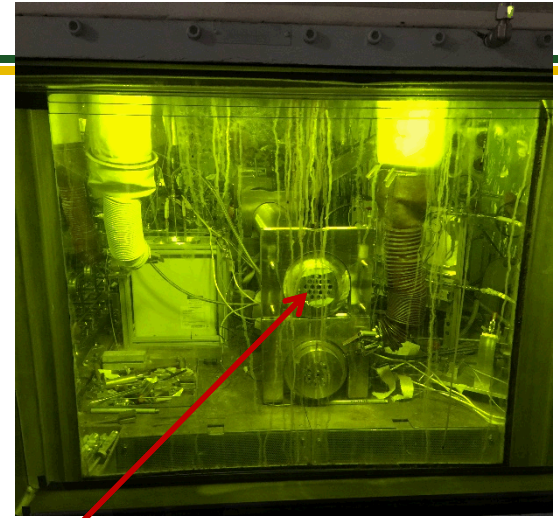


Prairie Island Dry Storage

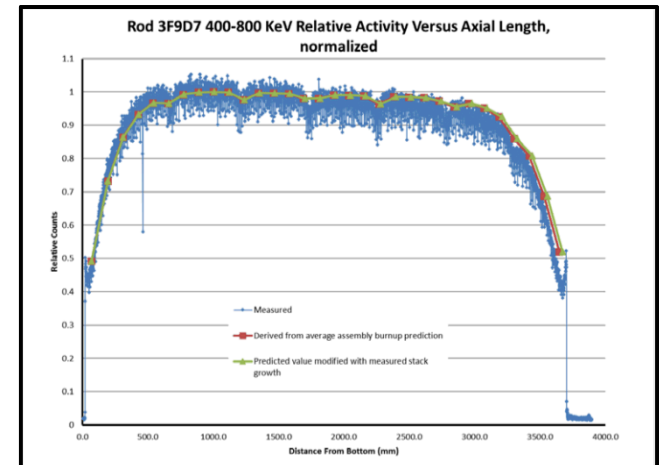


High Burnup Confirmatory Data Project – Obtaining *Baseline* Data

- 25 fuel rods with similar histories to those in the cask will be tested to document pre-storage properties.
- “Sister Rod” Acquisition & Testing
 - Areva and Westinghouse rods pulled in June and January 2015 from different assemblies
 - 9 AREVA M5® rods
 - 12 Westinghouse Zirlo® rods
 - 4 Westinghouse Zircaloy-4
 - 2 Low-tin
 - 2 Standard
 - All 25 sister rods currently at Oak Ridge National Laboratory undergoing nondestructive analysis
 - Non-destructive tests began in FY17; destructive tests planned to begin in FY18
 - 14.5 rods at ORNL
 - 10 rod equivalents at PNNL
 - 0.5 rod equivalents at ANL



25 Sister Rods in ORNL Hot Cell
Photo: Saltzstein, SNL

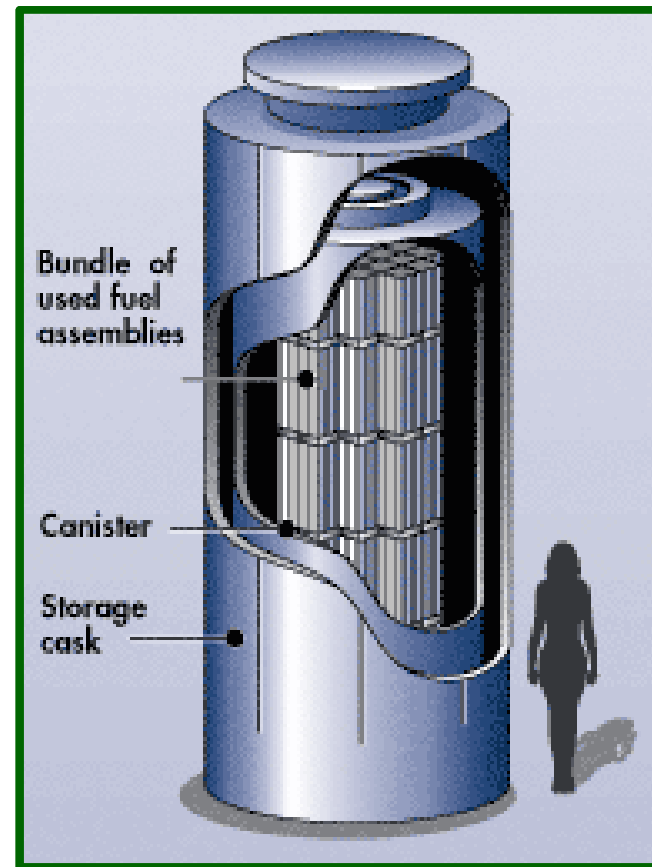


Sister rod gamma scan results to determine the axial burnup profile and identify pellet locations (Montgomery R, 2016).



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2 STORAGE SYSTEM INTEGRITY

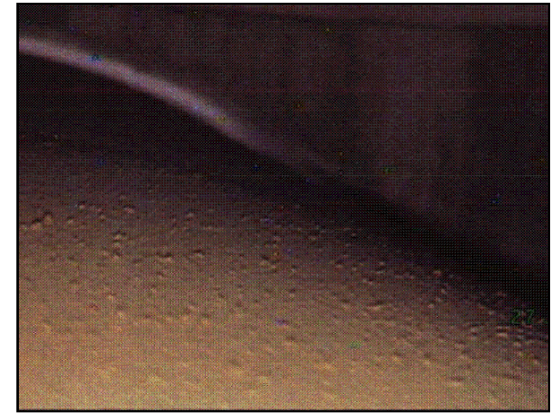


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Understanding Canister Performance:

Primary Concern – Stress Corrosion Cracking (SCC) Requiring 3 Concurrent Conditions



Dust on canister surface at Calvert Cliffs (EPRI 2014)



Photo of dry canister weld. Photo: SNL

Mock-up Canister
Photo: Enos, SNL





Understanding Canister Performance:

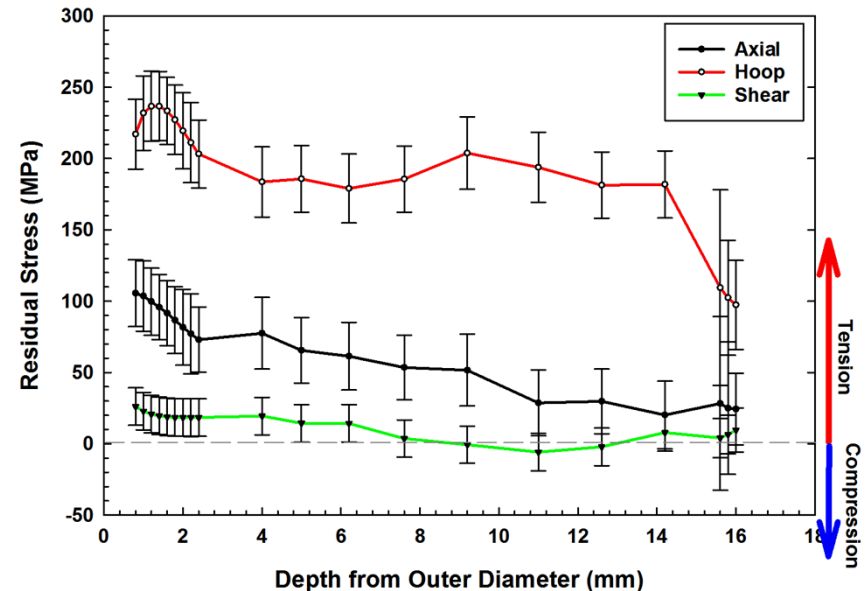
Is there Tensile Stress Through the Canister Wall?

Canister Mockup WRS measurement results

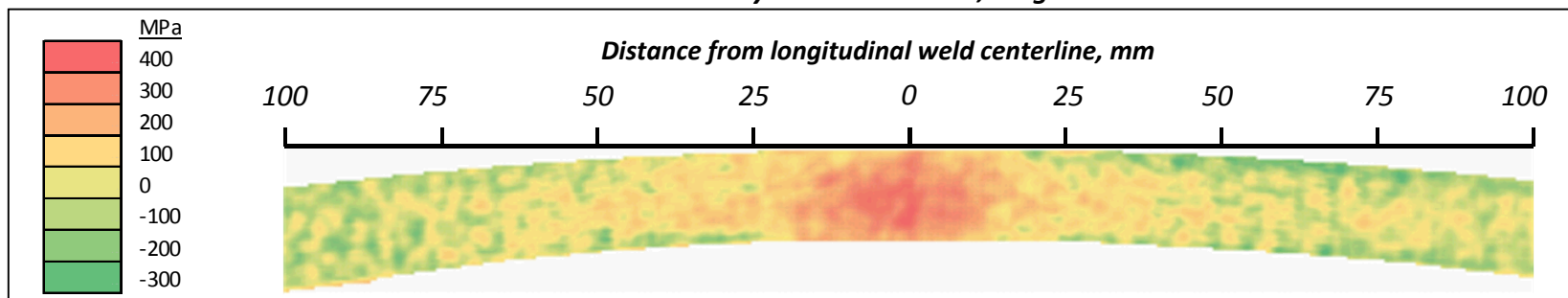
- DHD and contour mapping results are consistent.
- High through-wall tensile stresses measured in all weld types and in all HAZ. Highest tensile stresses are parallel to welds, but tensile stresses also occur perpendicular to welds.
- Highest tensile stresses (up to 600 MPa) measured at simulated weld repairs.

Enos D. and Bryan C., 2016. Final Report: Characterization of Canister Mockup Weld Residual Stresses, FCRD-UFD-2016-000064, U.S. DOE.

Residual stresses measured by deep-hole drilling (DHD) method, circumferential weld HAZ



Residual stresses measured by contour method, longitudinal weld





Understanding Canister Performance: *Can a Corrosive Environment Form?*

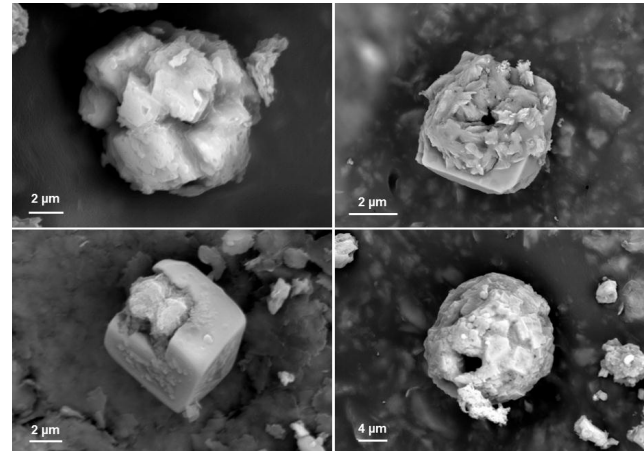
DOE/EPRI sampling efforts at Calvert Cliffs, Hope Creek, Diablo Canyon, and Maine Yankee. Potentially corrosive chloride salts found in some areas. Need additional sampling to determine (1) deposited salt compositions as a function of geographical location; (2) salt loads and compositions as a function of canister surface location and surface temperatures.

Dust Sampling at the Diablo Canyon ISFSI



Photos: Bryan, SNL

Sea-salt aerosols found in canister surface dusts.



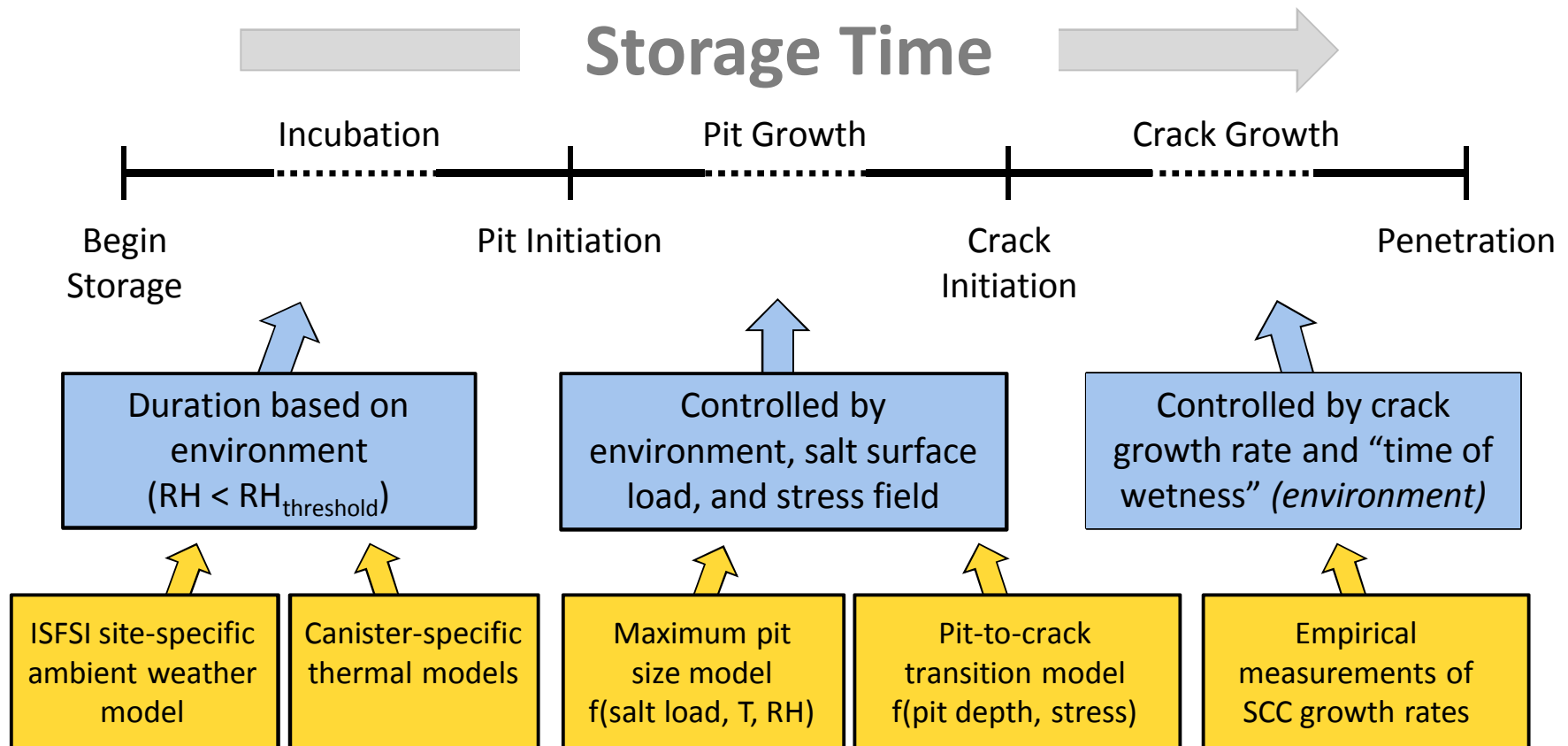
Are deliquescent brines stable on the heated canister surface?

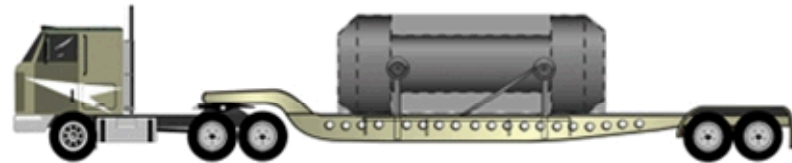
Previous work: ammonium- and chloride-containing brines are not stable on heated surfaces, rapidly degassing until one or the other component is consumed. This makes presence of chloride-rich brines at inland sites with ammonium-rich continental salts unlikely. Current work: evaluating the stability of brines formed by sea-salt deliquescence at elevated temperatures.



Understanding Canister Performance: *Probabilistic Modeling of Canister SCC*

SNL Probabilistic SCC model divides timeline for canister failure into three periods and develops models for the dominant processes in each.





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3 SPENT FUEL TRANSPORTABILITY FOLLOWING EXTENDED STORAGE



Transporting Spent Nuclear Fuel:

How do Stresses on Fuel During Normal Conditions of Transport Compare to Failure Limits?

Three series of tests using a surrogate PWR assembly

- 1) Truck data on a vertical acceleration shaker table
- 2) Over-the-road truck test
- 3) Truck and rail data on a commercial seismic shaker with six degrees of motion

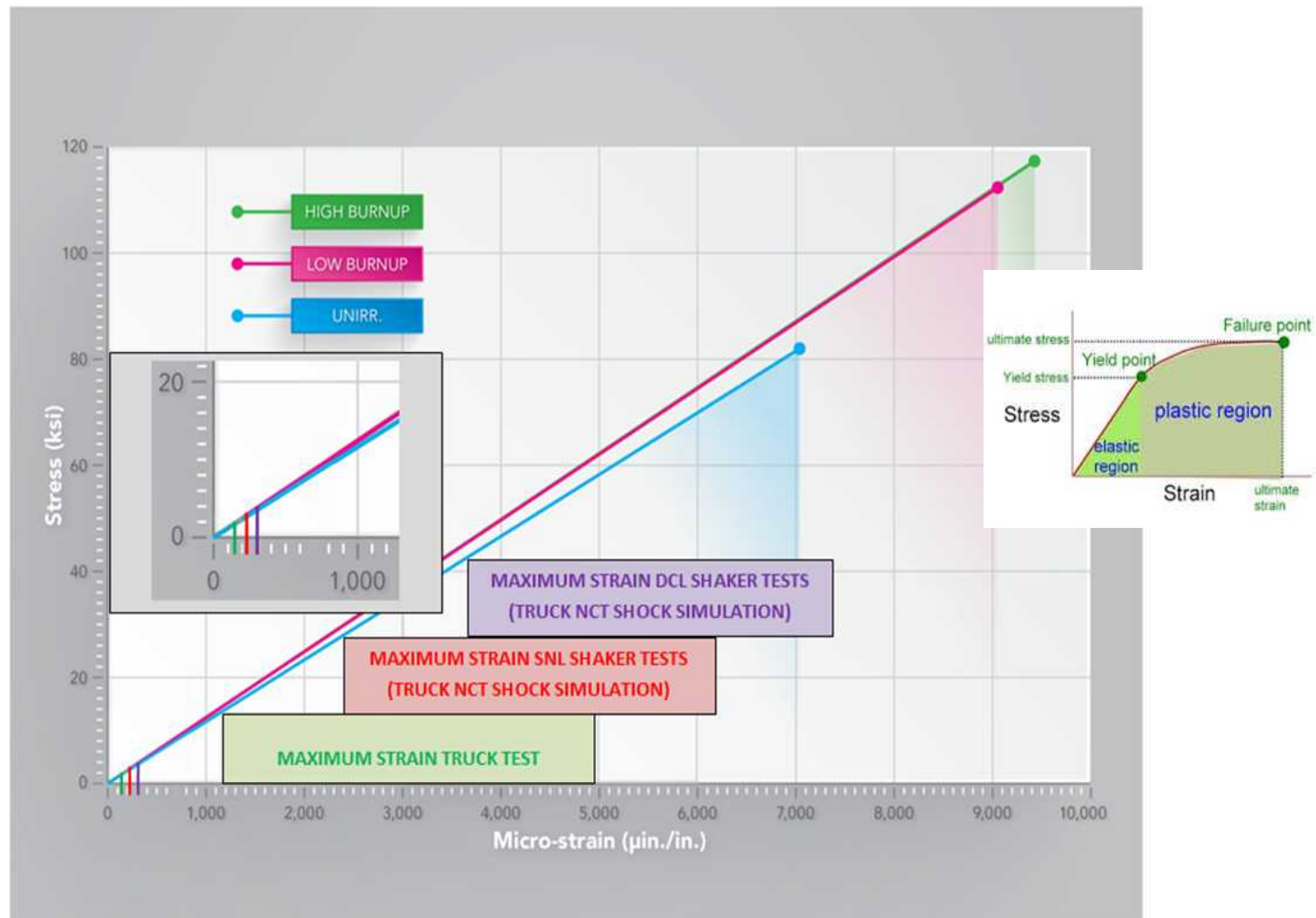


McConnell et al, 2016, SNL and PNNL



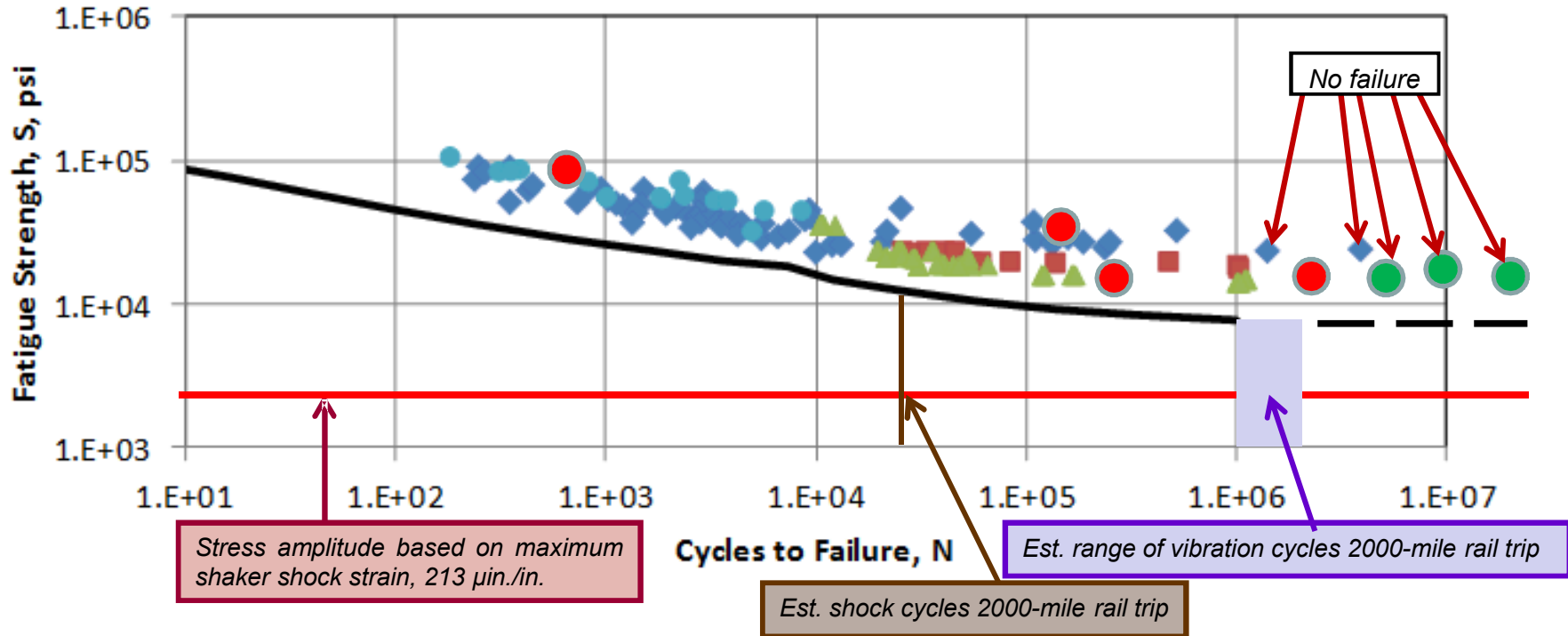
Transporting Spent Nuclear Fuel:

How do Stresses on Fuel During Normal Conditions of Transport Compare to Failure Limits?





Transporting Spent Nuclear Fuel: *Could Vibrations or Shocks Result in Fatigue Failure?*



Fatigue design curve (—): O'Donnel and Langer, "Fatigue Design Basis for Zircaloy Components," Nucl. Sci. Eng. 20, 1, 1964. (cited in NUREG-0800, Chapter 4)

Data plot courtesy of Ken Geelhood, PNNL
The large circles are ORNL HBR data

CONCLUSIONS

The realistic stresses fuel experiences due to vibration and shock during normal transportation are far below yield and fatigue limits for cladding. We only have limited rail data, which most likely will be the prevailing transportation mode.



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However, these tests...



...are only simulations of the
configuration of actual

UNF transport mode.





Collaboration Leverages Research Dollars & Enables a Diversity of Perspectives, Skills, & Ideas

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■ Industry

- Fuel and storage system vendors
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- Nuclear Energy Institute (NEI)

■ Universities (*primarily through DOE-NE University Programs*)

- Penn State, University of Illinois, University of South Carolina, University of Florida, South Carolina State University, Colorado School of Mines, North Carolina State, University of Mississippi, Oregon State University, University of Houston, Pepperdine, University of Utah, Utah State, Massachusetts Institute of Technology, Texas A&M University, University of Nevada at Reno, Northwestern, University of Michigan, University of California at Irvine

■ International Collaborations

- Japan, Spain, Germany, Korea, IAEA, Euratom



So, We Are Performing a More Realistic Test

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- **Equipos Nucleares (ENSA) has provided an ENUN 32P rail cask, basket, and cradle for an international test program**
 - The ENUN 32P is similar to an existing NRC-licensed cask currently in use in the USA
- **Testing to be conducted by DOE laboratories**
- **These tests are significantly different than the previous tests:**
 - instrumented surrogate assemblies will be...
 - *within a rail-cask basket...*
 - *within an actual rail cask which will be on...*
 - a heavy-haul truck, then
 - two different ships, and then
 - a railcar



ENUN 32P basket.
Photo courtesy of
ENSA

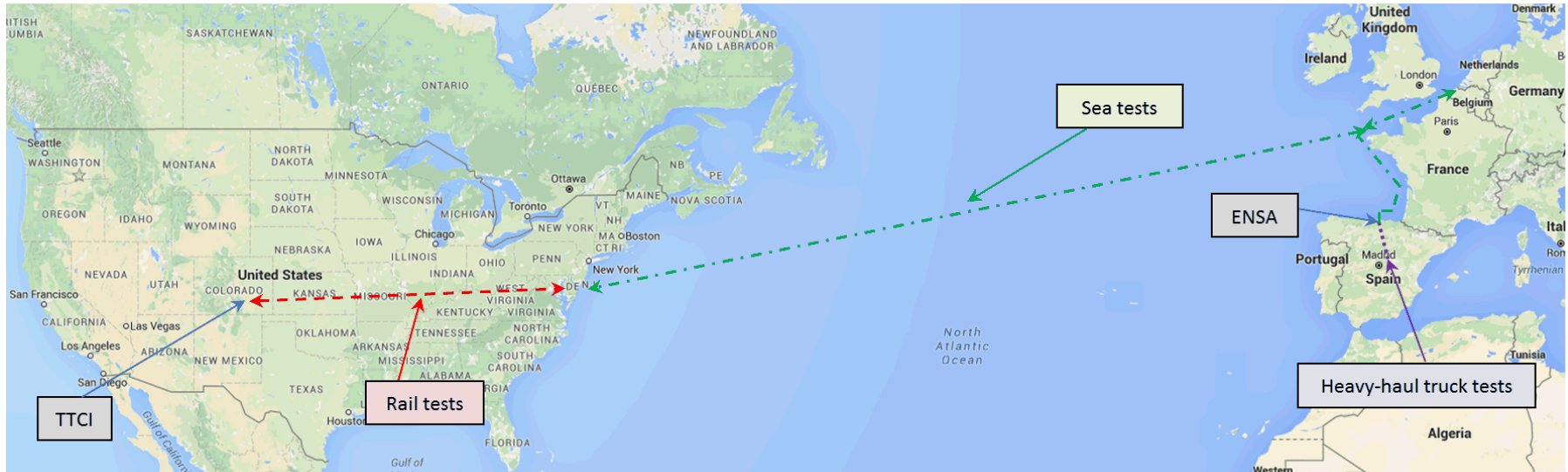


ENUN 32P Cask.
Photo courtesy of
ENSA





Proposed Routing of Cask



- 1) Heavy-haul truck from within Spain ~ June 14, 2017
- 2) Coastal sea shipment from Santander to a large northern European port ~ June 27
- 3) Ocean transport from Europe to an eastern U.S. port (e.g., Baltimore)
- 4) Commercial rail shipment from East Coast to Pueblo ~July 12
- 5) Testing at the Transportation Technology Center, Inc.
- 6) Return trip to ENSA will be the same

Data will be collected throughout all legs of the transport as well as the transfers between legs



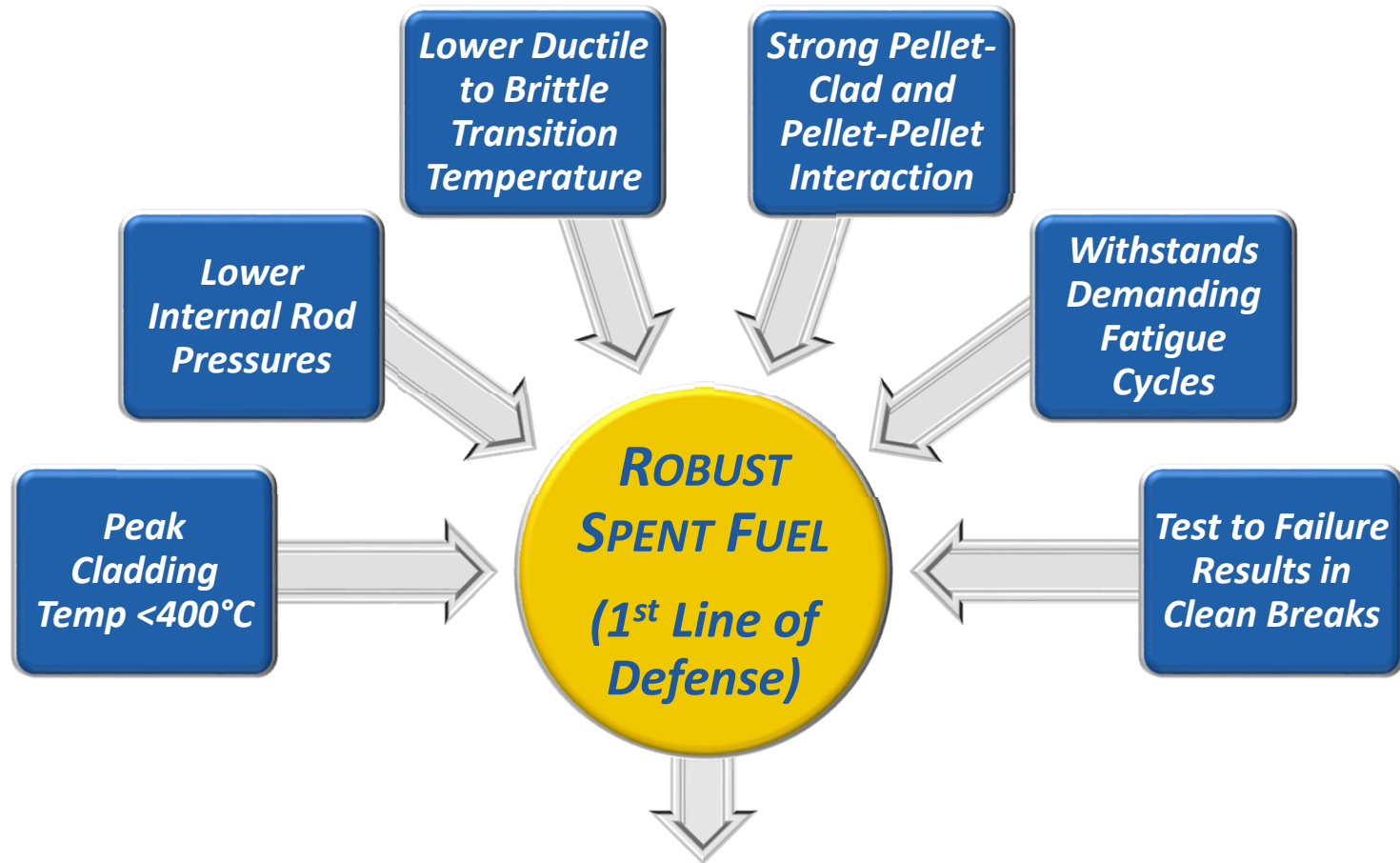
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4 THE BIG PICTURE



Current R&D Indicates SNF is Robust: *Loads Expected During Handling/Transport < What We Previously Thought*



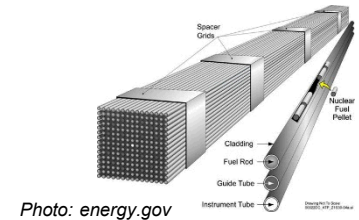
The realistic stresses fuel experiences due to vibration and shock during normal transportation are below yield and fatigue limits for cladding



Observations from Current Storage & Transportation R&D

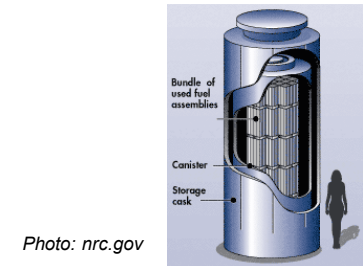
1) Spent fuel integrity

- Current tests and analyses indicate that spent fuel is robust.
- The DOE/EPRI High Burnup Confirmatory Data Project will obtain data after 10 years of dry storage to confirm current test and analysis results.



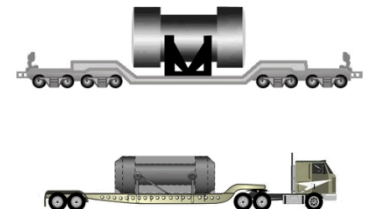
2) Storage system integrity

- Stress corrosion cracking of canisters may be a concern in some environments. More work is needed in analysis and detection.
- Monitoring and Aging Management practices at storage sites will be important to confirm storage system performance during extended service.



3) Spent fuel transportability following extended storage

- The realistic stresses fuel experiences due to vibration and shock during normal transportation are far below yield and fatigue limits for cladding.





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- Billone, M., “Effects of Lower Drying-Storage Temperatures on the DBTT of High-Burnup PWR Cladding,” FCRD-UFD-2015-000008. U. S. Department of Energy, Office of Used Nuclear Fuel Disposition, August 2015.
- Hanson, B., “High Burnup Fuel, Associated Data Gaps, and Integrated Approach for Addressing the Gaps,” presentation to the U.S. Nuclear Waste Technical Review Board, February 17, 2016, Knoxville, TN.
- Wang, J.-A., Wang, H., Jiang, H., Bevard, B., Howard, R., “FY14 Status Report: CIRFT Testing Results on High Burnup UNF ” FCRD-UFD-2014-000053. U. S. Department of Energy, Office of Used Nuclear Fuel Disposition, September 2014.
- Enos, D.G. , Bryan, C.R., Norman, K.M , “Data Report on Corrosion Testing of Stainless Steel SNF Storage Canisters,” FCRD-UFD-2013-000324, SAND2013-8314. U. S. Department of Energy, Office of Used Nuclear Fuel Disposition. September 2013.
- McConnell, P., “Sandia Shaker Table and Over-the-Road Vibration Studies,” presentation to the U.S. Nuclear Waste Technical Review Board, February 17, 2016, Knoxville, TN.
- Wang, J.-A., H. Wang, H. Jian, Y. Yan, B. Bevard, “CIRFT Testing of High Burnup used Nuclear Fuel from PWR and BWRs,” presentation to the U.S. Nuclear Waste Technical Review Board, February 17, 2016, Knoxville, TN.
- Enos, D.G., and Bryan, C.R. , 2016. “Understanding the Risk of Chloride Induced Stress Corrosion Cracking of Interim Storage Containers for the Dry Storage of Spent Nuclear Fuel: Residual Stresses in Typical Welded Containers.” SAND2015-8668 C. Conference Paper, NACE 2016, Vancouver, BC.
- Bryan, C. and Enos, D. (2014). Results of Stainless Steel Canister Corrosion Studies and Environmental Sample Investigations. FCRD-UFD-2014-000055, U.S. Department of Energy, 102 p.