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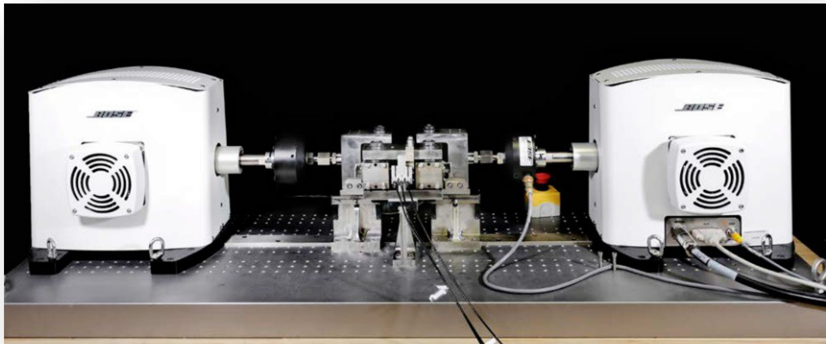
CIRFT Testing of High Burnup Used Nuclear Fuel from PWR and BWRs



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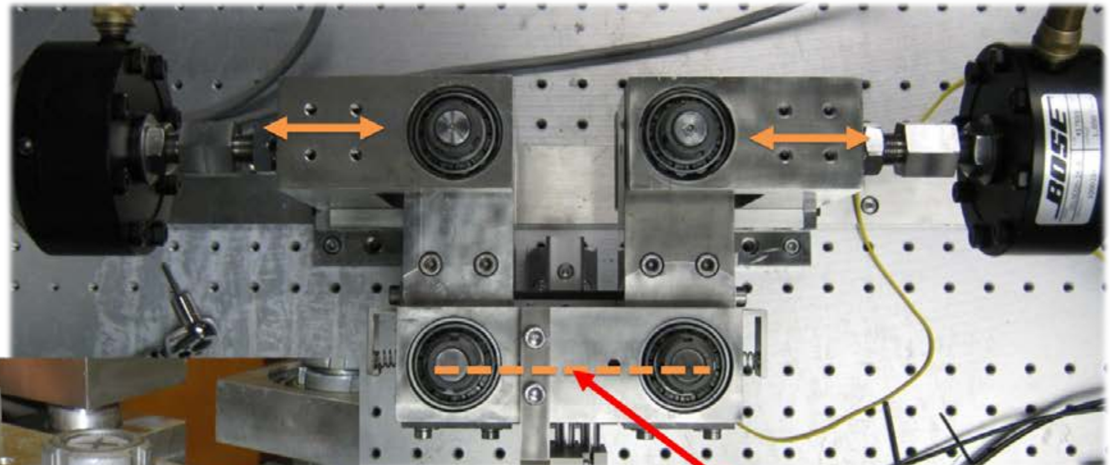
Oak Ridge National Laboratory (ORNL) is conducting testing to collect technical information to support transportation of spent nuclear fuel (SNF).

- **Research has been undertaken to:**
  - **Understand the mechanical properties of SNF to accurately evaluate issues related to the transportation of high-burnup fuel**
  - **Provide experimental data to support/validate modeling and integrity evaluations of SNF during transportation**
  - **Develop a validated methodology for predicting the effective lifetime of SNF under different vibration conditions**

To investigate the effects of vibration on SNF, a unique piece of test equipment was designed and built at ORNL, the Cyclic Integrated Reversible-Bending Fatigue Tester (CIRFT)

Design concept eliminates the need for a machined gage section and the testing of SNF in "as-found" condition.

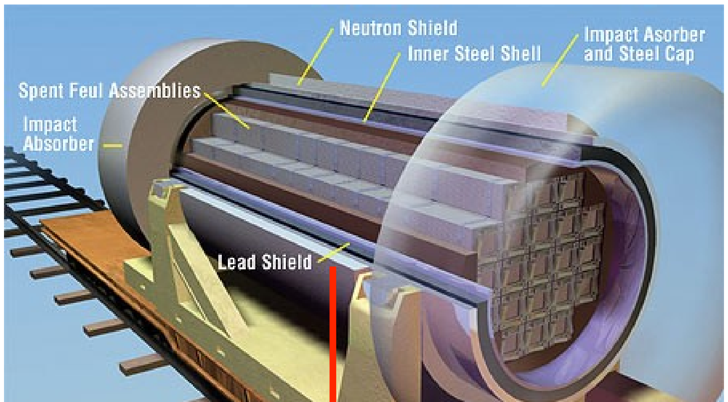


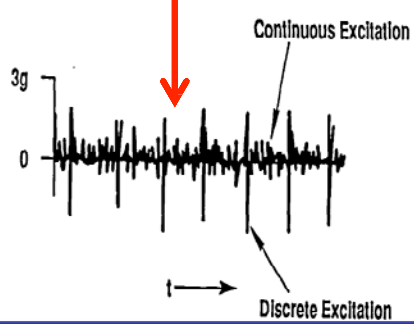
Sample location.
Push-pull force of linear motors translates to bending moment using unique U-frame design.

Real-time, direct monitoring with three linear variable differential transformer setup

Frictionless grip, in combination with roller bearing design, allows for lateral movement, eliminating an axial tensile loading during bending.

Random vibration provides the external loading driver to the SNF assemblies; internal vibration drivers could be transient shocks generated by basket & spacer grids and fuel rod interactions





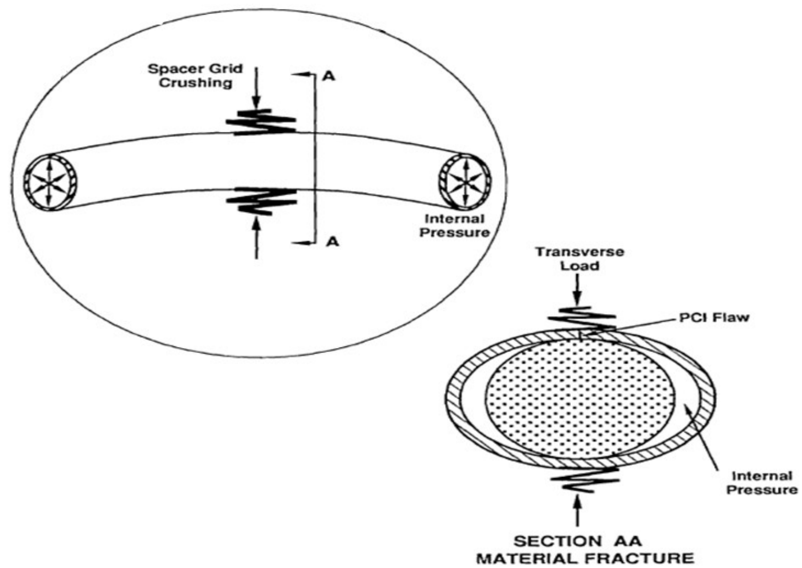


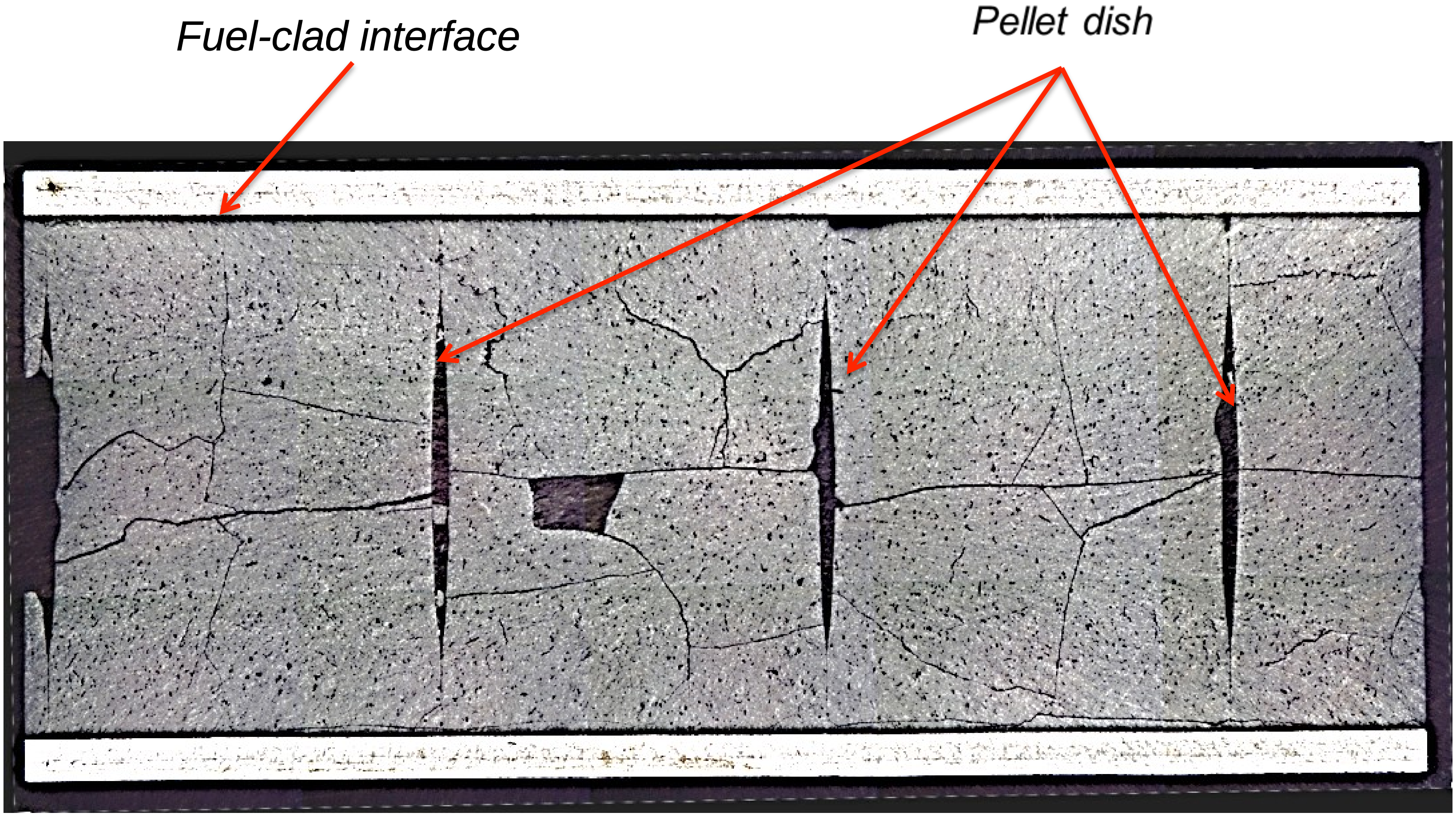
Figure III-28. Cladding Material Fracture Failure Mode

Acceleration-time history shows presence of discrete shock signals superimposed on continuous vibration

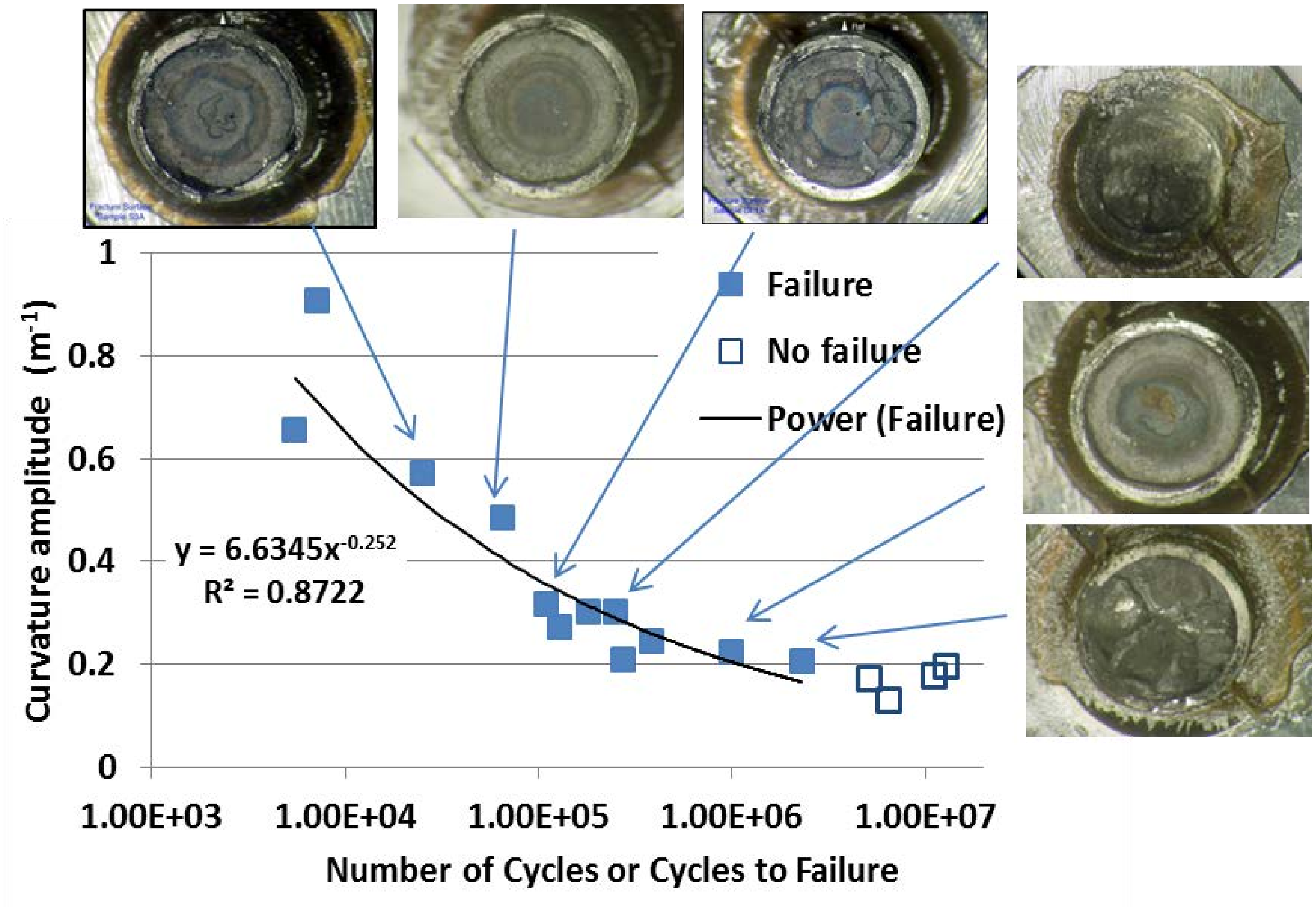
CIRFT testing provides important mechanical properties information on SNF to aid in understanding the potential effects of transport

- Provides experimental data on fuel/clad system fatigue endurance limits to support model validation
- Testing has been conducted on three types of cladding:
  - High-burnup pressurized water reactor (PWR) fuel (HB Robinson) – 23 tests
  - High burnup boiling water reactor (BWR) fuel (Limerick) – 15 tests
  - AREVA M5™ clad PWR fuel (North Anna & Catawba MOX) – 19 tests
  - Testing on sister rods is planned to begin in 2017
- Fuel has performed robustly under various loading conditions and under millions of vibration cycles below the fatigue threshold loading
  - Results are documented in: FY 2015 Status Report: CIRFT Testing of High-Burnup Used Nuclear Fuel Rods from Pressurized Water Reactor and Boiling Water Reactor Environments

PWR high-burnup SNF rod used for CIRFT testing reveals good bonding at fuel-clad interface and the remaining fuel pellet dish



High-burnup HBR PWR SNF fatigue data show a well-defined S-N curve with failure at the P-P interface



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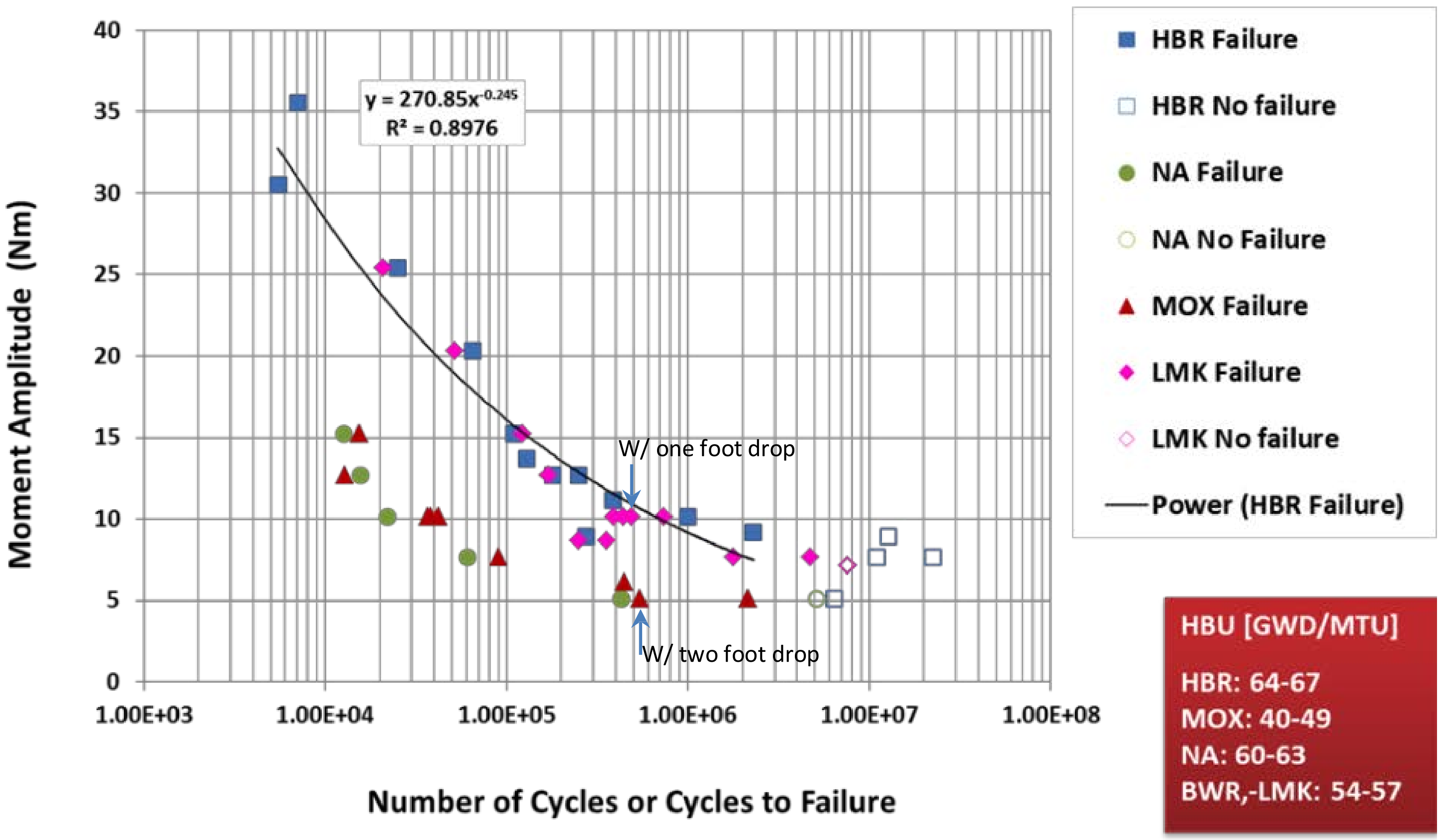
CIRFT fatigue test results reveal some data scatter due to different types/sizes and burnup of clads tested

***HBR**: HB Robinson (Zr-4), **LMK**: Limerick (Zr-2), **NA**: North Anna (M5™), **MOX**: MOX (M5™)*



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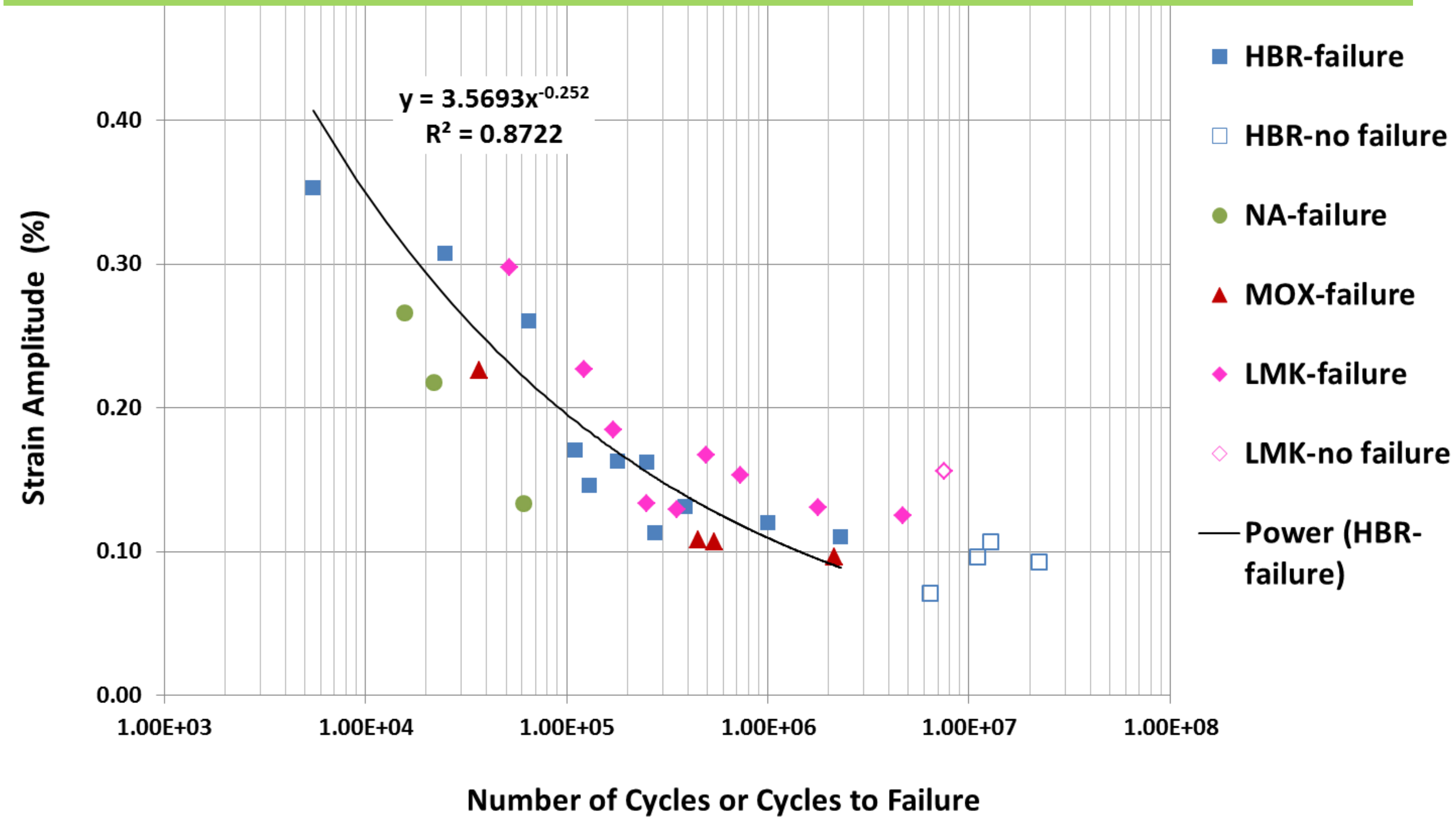
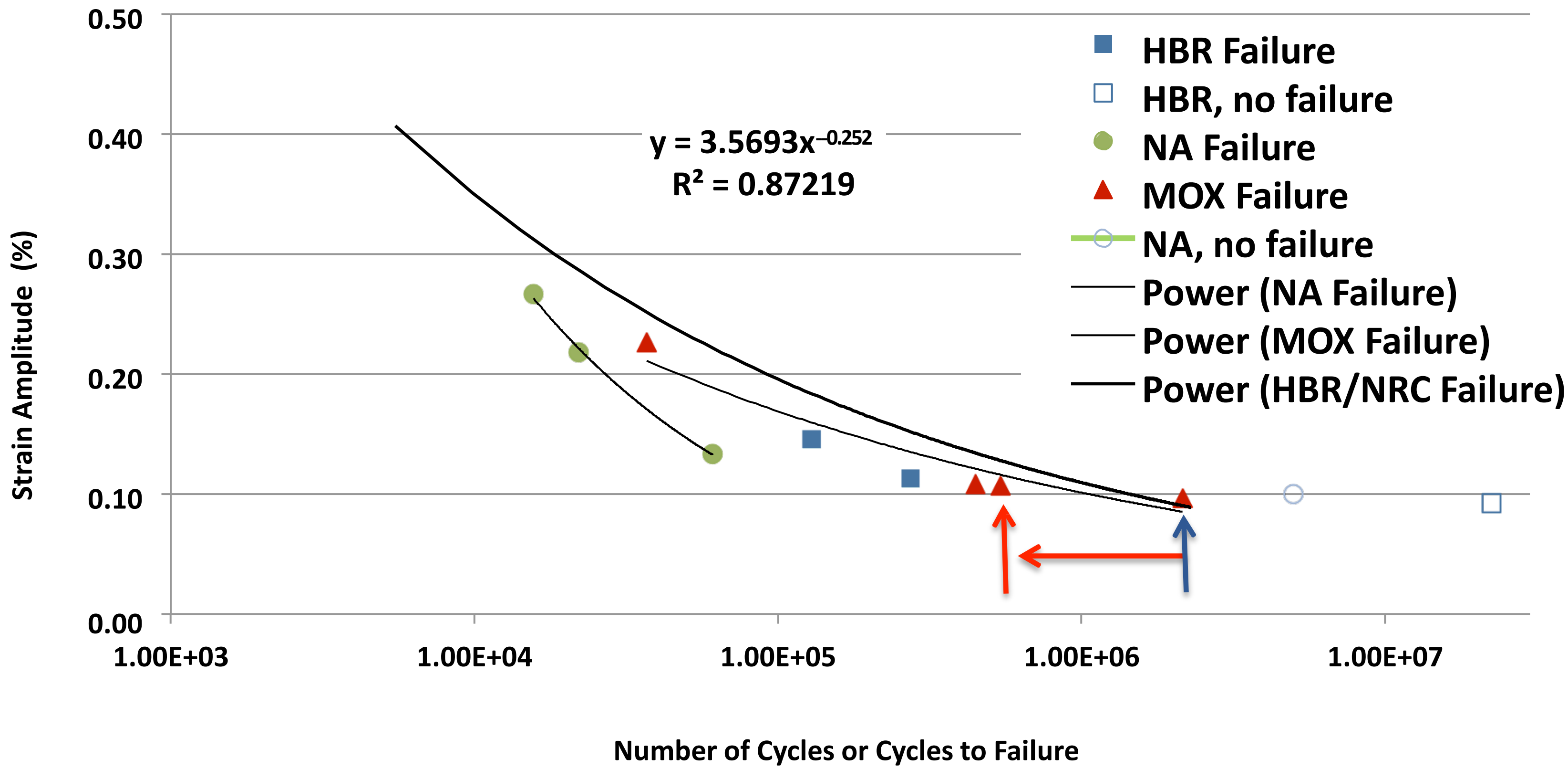
CIRFT strain vs. cycles-to-failure reflects less data scatter taking into account the clad sizes/types

***HBR**: HB Robinson (Zr-4), **LMK**: Limerick (Zr-2), **NA**: North Anna (M5™), **MOX**: MOX (M5™)*



A reduction in cycles-to-failure was noted when a drop-induced transient shock was induced



The data point with red arrows represents test data where the sample experienced a two-foot drop (twice); both MOX specimens were tested with the same dynamic loading of 5N m.

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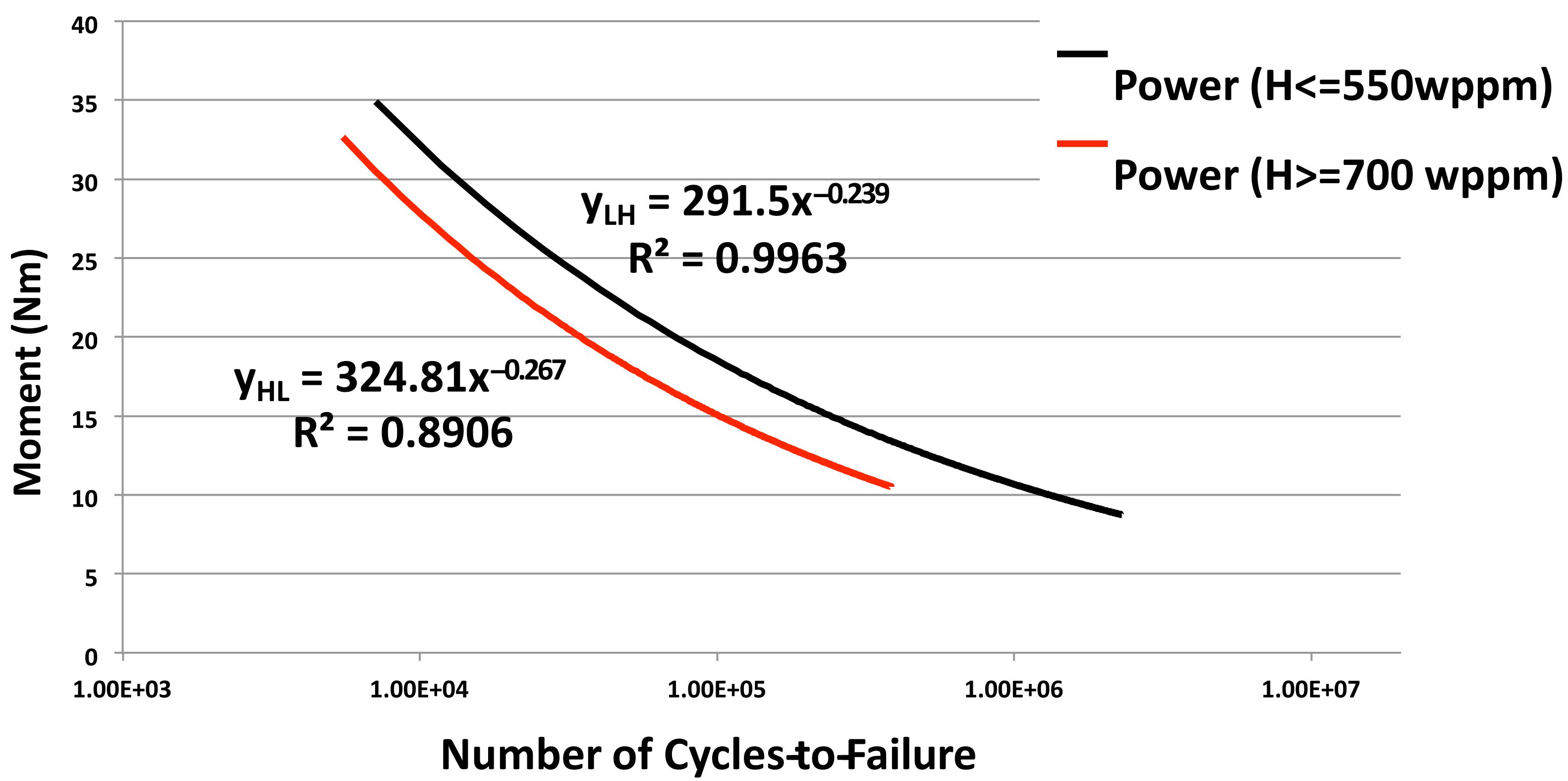
HBR SNF S-N data indicates a hydrogen content dependency

Hydrogen was estimated from oxide thickness; detailed hydrogen measurements are needed to further quantify any hydrogen-dependent failure mechanism



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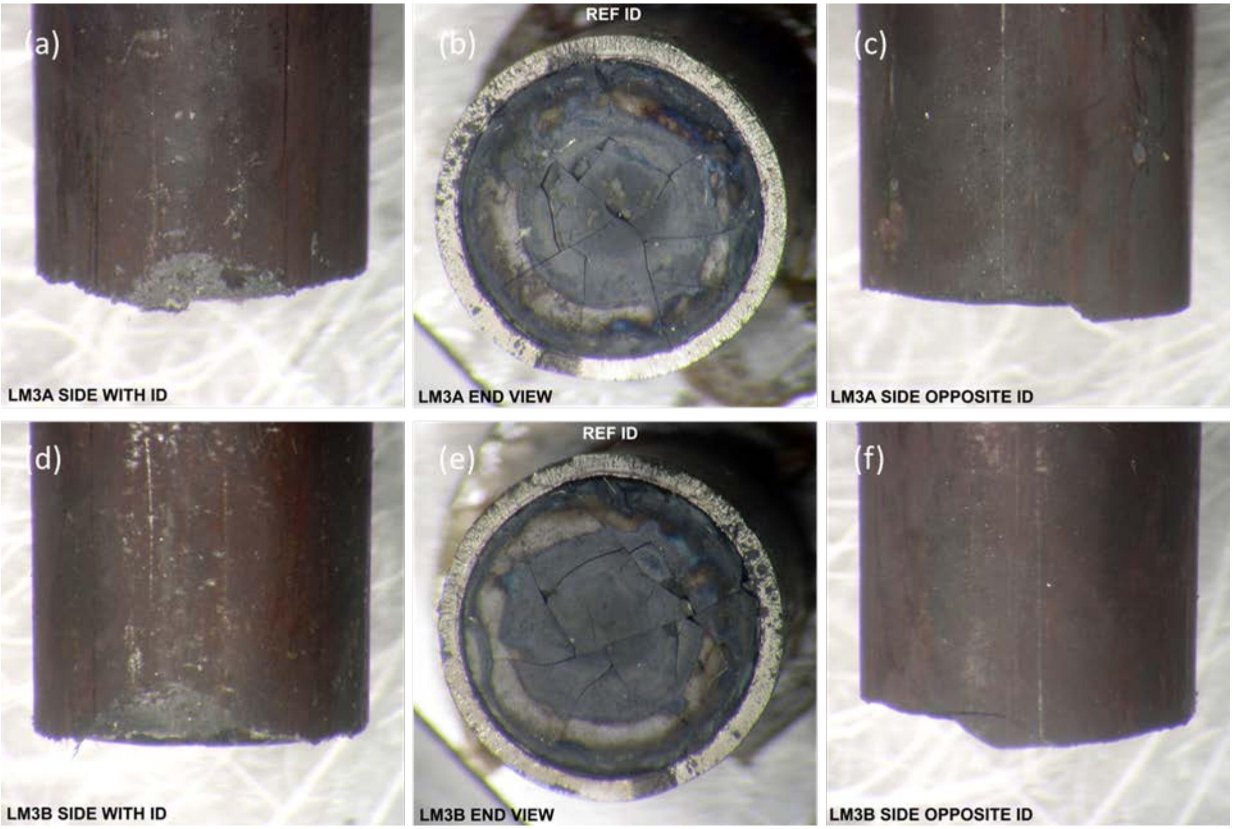
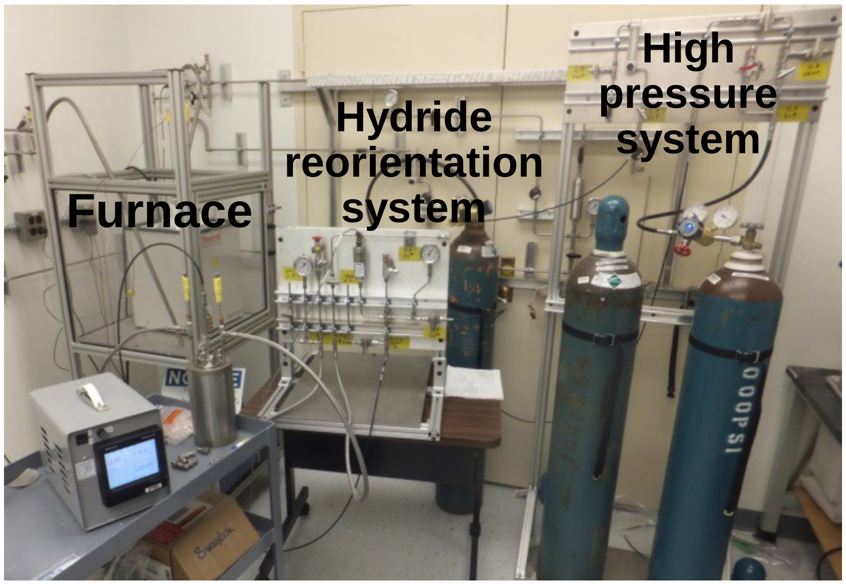
BWR CIRFT tested specimen failed at P- P interface

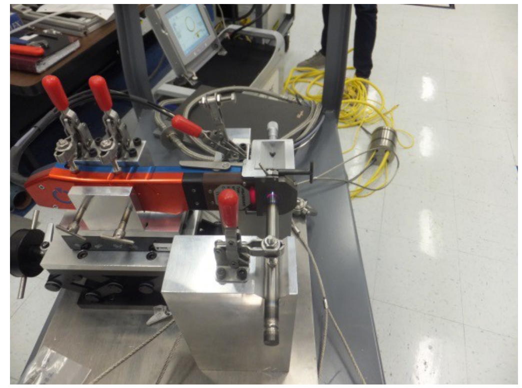


Fracture segments for LMK03/575B-A. (a) and (d) show the specimen ID side of the test segment; (b) and (e) show the mating fracture surface; and (c) and (f) show the opposite specimen ID side of the test segment.

Hydride reorientation system and associated equipment for in-cell hydride reorientation tests have been tested out of cell and have been moved in cell



- **The hydride reorientation test equipment was constructed and tested out of cell.**
- **Planned test temperature: 400°C**
- **The max. test pressure: 3500 psi (24MPa)**




Tubing weld system with a welded unirradiated Zry-4 sample


Oxide layer removal device with an oxide layer removed Zry-4 sample

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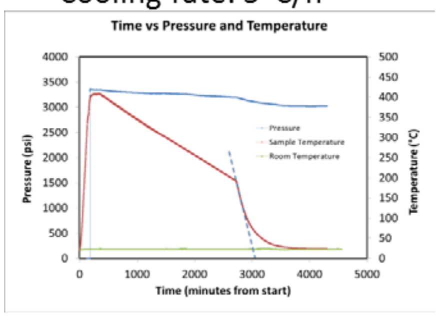
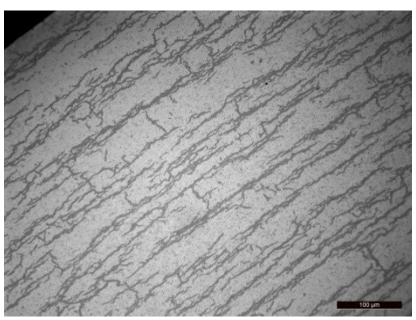
Out-of-Cell benchmark tests helped optimize reorientation test parameters

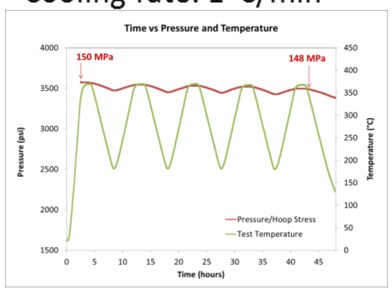
Produced a high ratio of radial hydrides for in-cell hydride reorientation tests with high-burnup HBR fuel segments.

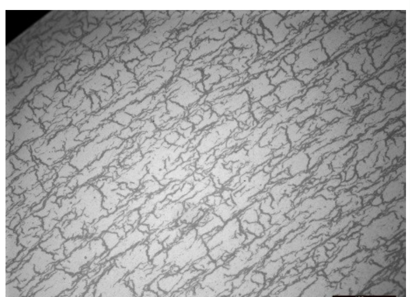
#1
1 thermal cycle
Hoop stress ≈ 150 MPa
Internal pressure≈3600 psi
400°C for 3 hours
Cooling rate: 5°C/h



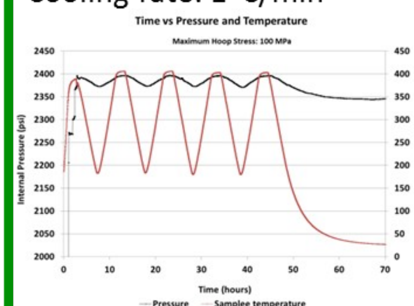


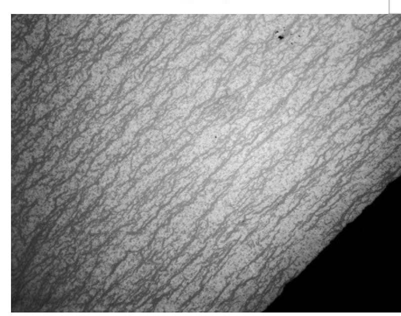
#2
5 thermal cycles
Hoop stress ≈ 150 MPa
Internal pressure≈3600 psi
400°C for 2 hours
Cooling rate: 1°C/min



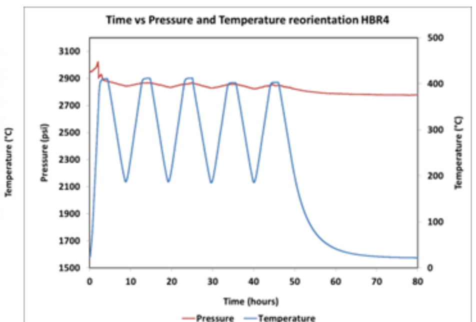


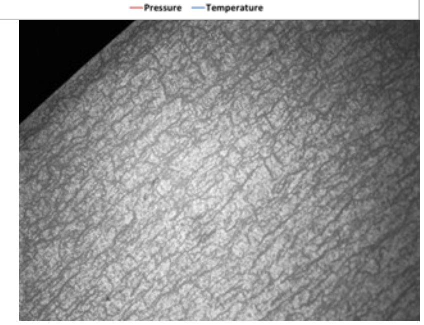
#3
5 thermal cycles
Hoop stress ≈ 100 MPa
Internal pressure≈ ≈2400 psi
400°C for 2 hours
Cooling rate: 1°C/min





#4
5 thermal cycles
Hoop stress ≈ 120 MPa
Internal pressure ≈2880 psi
400°C for 2 hours
Cooling rate: 1°C/min

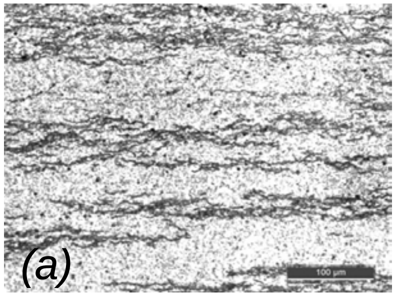


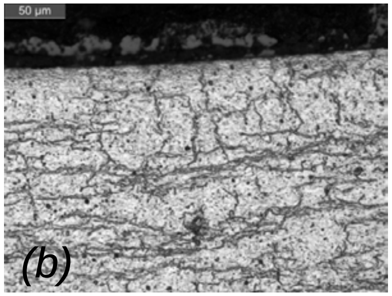


Test conditions to be used for in-cell testing

The first in-cell hydride reorientation demonstration has been successfully completed

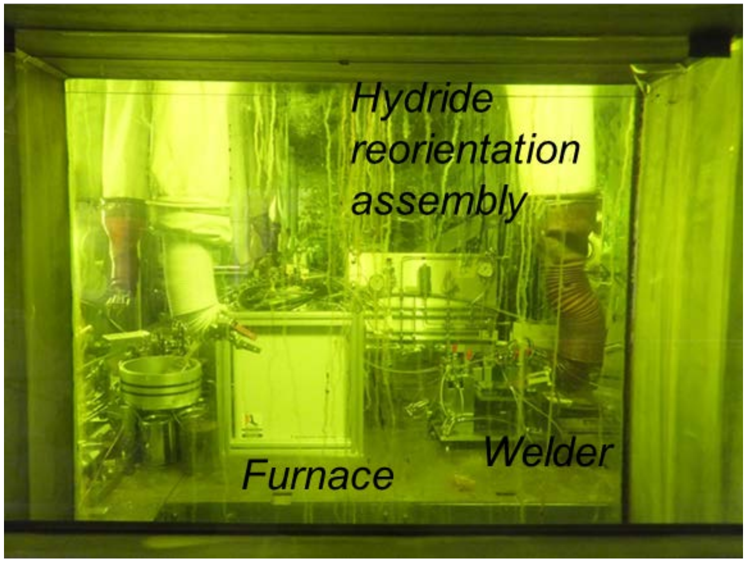
- The system was installed in the hot cell.
- All equipment functioned as expected.
  - Welder: tested with both unirradiated and irradiated cladding samples
  - High pressure system: tested at 3500 PSI at room temperature, as well as at elevated temperatures
  - Furnace system: tested on an unirradiated sample overnight
  - First in-cell reorientation demonstration (welding/ thermal cycling) was successfully completed on high burnup SNF at 400°C with a hoop stress ≈145 MPa (see Slide 12 for details of thermal cycles).

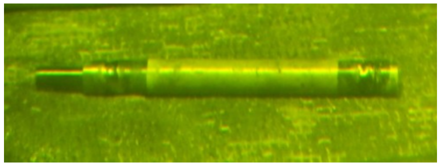




Micrographs showing (a) circumferential hydrides before the hydride reorientation test, (b) radial hydrides after the hydride reorientation test.

ORNL Hot Cell





4"-long HBR fueled specimen for welding

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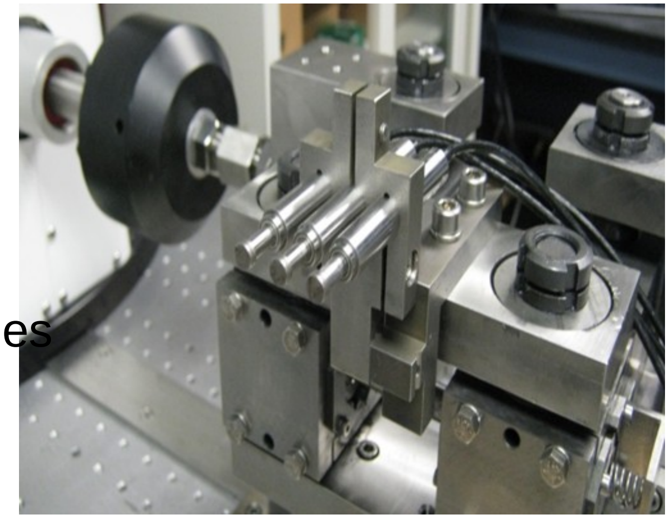
Modeling (FEA) provides insights into the CIRFT testing results



- Finite element analysis (FEA) has been performed to help understand the experimental test results
  - The FEA shows that a number of physical issues may affect SNF performance during transport, including:
    - Pellet length
    - Amount of hydrides in the cladding
    - Fuel burnup – as it affects pellet-to-clad bonding [pellet-to-clad bonding is potentially an important factor in SNF performance during transport]
    - Pellet – clad interaction
    - Fuel rod condition prior to vibration testing - the segment composite structure of a HBU rod introduces numerous stress concentration sites into a HBU rod system

Annealed SNF CIRFT testing is needed to allow an accurate comparison between HBU CIRFT data and HR CIRFT data

The hydride reorientation (HR) sample preparation has the potential to introduce a material bias into test results due to the followings:

- Induces a thermal annealing effect in the clad tubing structure;
- Heat source of HR samples is initiated from the clad outer surface (~400C), which may reduce clad compressive radial stress and generate a thermal gradient from clad to fuel
- In-situ pressurization of 3,500 psi pressure may reduce the radiation induced clad crimping effect (of 2,450 psi coolant pressure) and counter/decrease the radial compressive residual stress that occurs during clad irradiation;
- Combined effects of thermal annealing & clad pressurization could permanently change clad geometry (i.e. enlarge the clad inner wall radius) and reduce the pellet support to the clad.

Initial observations from CIRFT testing include:

- The fuel provides strength (flexural rigidity) to the fuel/clad system
- When the clad is fatigued to failure, failure occurs primarily at the pellet-pellet interface
- The fuel pellets retain their shape (dishing and chamfering is evident) and do not become fragmented – very little residue is released from rods that are broken into two pieces
- Considering the complexity and non-uniformity of the HBU fuel cladding system, it was significant to find that the strain to failure data for the SNF was characterized by a curve expected of standard uniform materials
- It was significant to find that the HBU HBR exhibited an endurance limit, if an endurance limit is defined by survival of >10^7 cycles
- At low loads, the PWR HBR fuel did not fail after >10M cycles

Other observations from the CIRFT testing:

- Pellet-clad-interaction includes P-C bonding efficiency
- Hydrogen concentration does affect SNF system strength
- The SNF system has significant stress concentrations and residual stress distributions
- It appears that transient shock accumulated damage may reduce the SNF fatigue lifetime
- In addition to the fatigue strength data, fracture toughness data of the SNF system is also essential to assist in the SNF vibration reliability study, especially in a high-rate loading arena

Future work will focus on detailed analysis of experimental data, testing of Sister rods (with and without heat treatments), and testing for higher intensity "jolts"

- Analyze previously obtained ORNL SNF test data
  - Evaluate the hydride reorientation and other CIRFT test results using FEA
  - Conduct post-irradiation examination (PIE) of hydride reorientation experiments
- Sister rod non-destructive tests including:
  - Visuals, profilometry, gamma scans, eddy current, surface temperature
- Sister rod destructive tests including:
  - Heat treatments to simulate drying, quench and long-term dry storage
  - MET,SEM/TEM, isotopics, hydrogen analysis
  - Mechanical properties testing