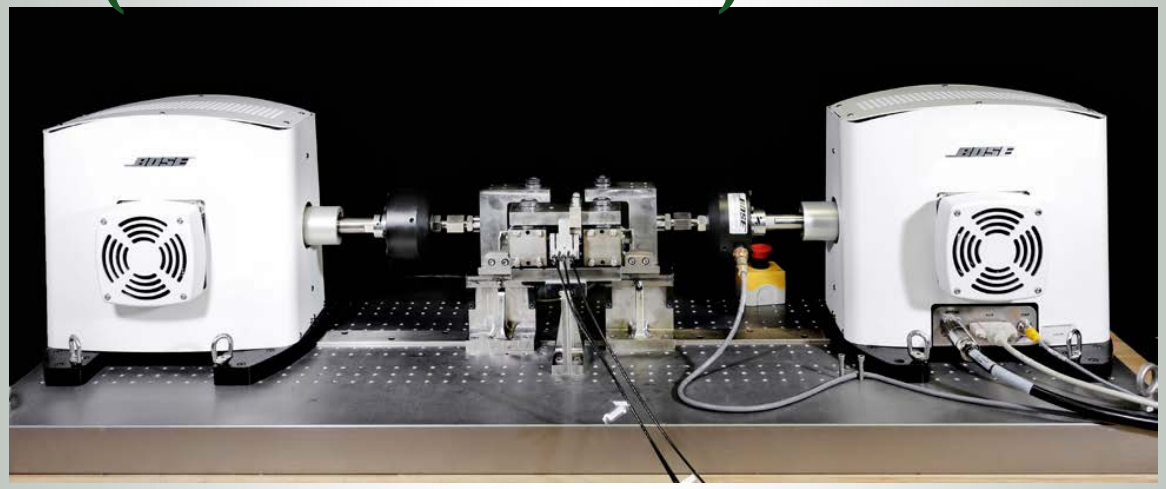
Used Fuel Disposition Campaign

INFORMATION LEARNED FROM CIRFT (SNF VIBRATION) TESTING



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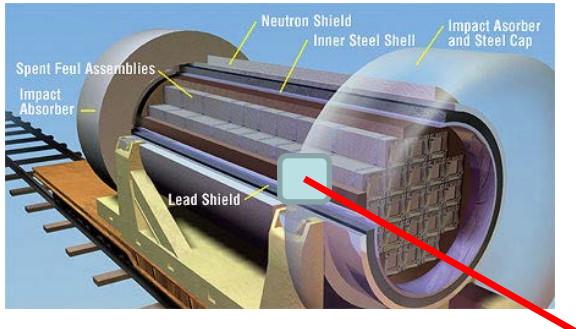
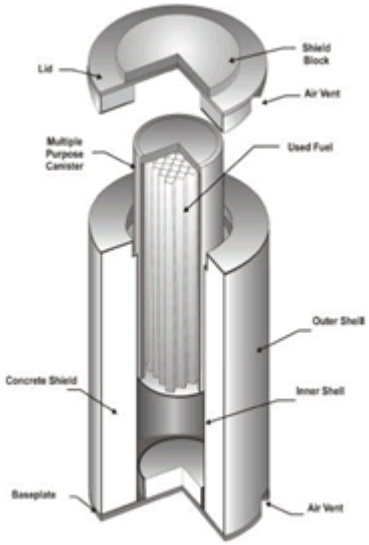
Used Fuel Disposition Campaign Program Review Meeting
June 10, 2015
Las Vegas, NV

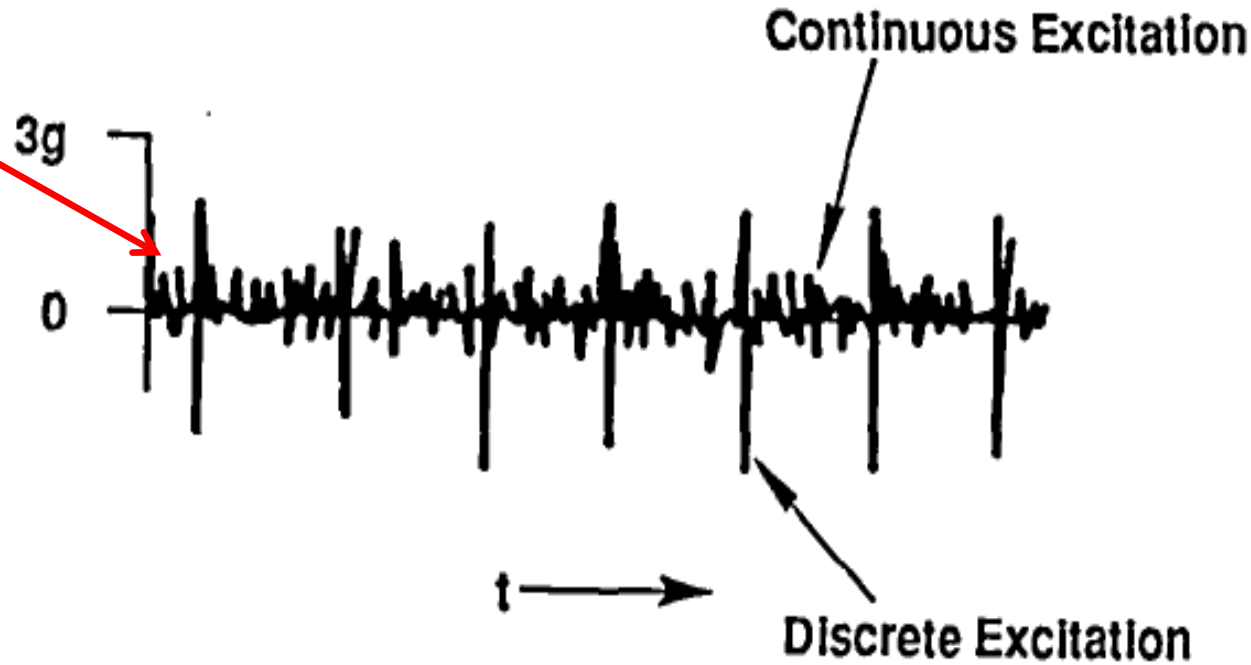
CIRFT testing is successfully closing a critical information gap in our clad material properties knowledge

- **Goal is to develop an understanding of the effects of transportation induced vibration on SNF**
  - Testing addresses the need for experimental information on fuel/clad system fatigue endurance limits to support modeling and licensing of used nuclear fuel during transport
- **Testing has been conducted on three types of cladding to date:**
  - high burnup PWR fuel (HB Robinson) – 21 tests;
  - high burnup BWR fuel (Limerick) – 11 tests;
  - Areva M5™ clad PWR fuel – 7 tests
- **Fuel has performed very well under various loading conditions and under millions of vibration cycles**

NCT Cask random vibration provides the external loading driver to SNF assembly

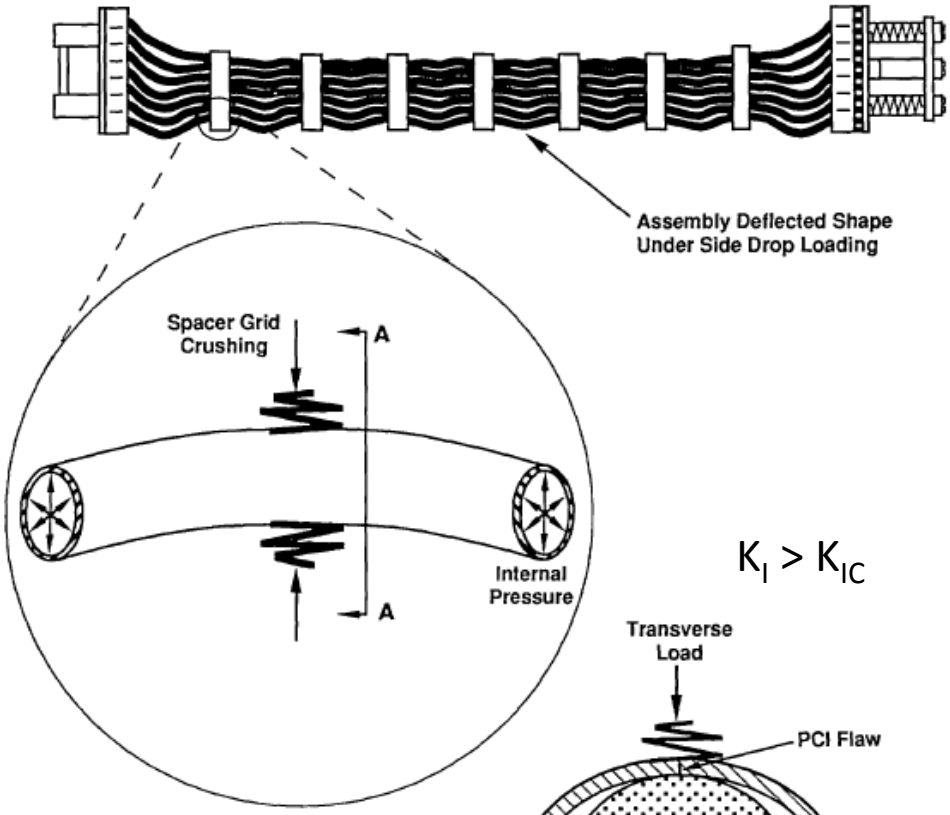




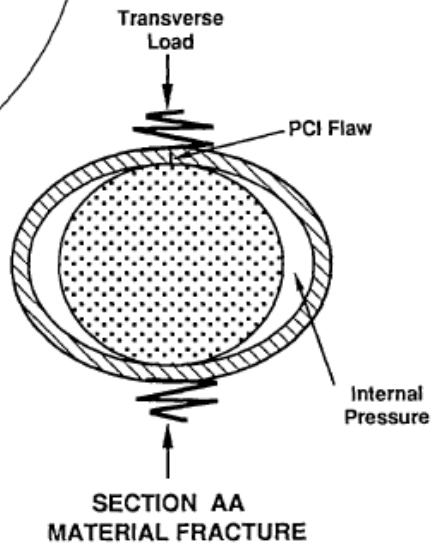


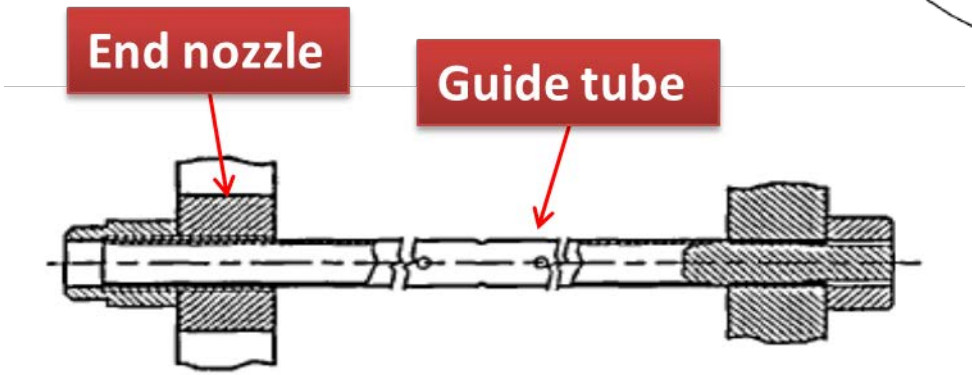
Acceleration-time history shows presence of discrete shock signals superimposed on continuous vibration

Internal vibration driver: Transient shocks generated by basket & fuel rods & spacer grids interactions



$K_I > K_{IC}$





Guide Tube Assembly - Details

Figure III-28. Cladding Material Fracture Failure Mode

CIRFT HBU HBR fuel inventory contains pins with a wide range of exposure history

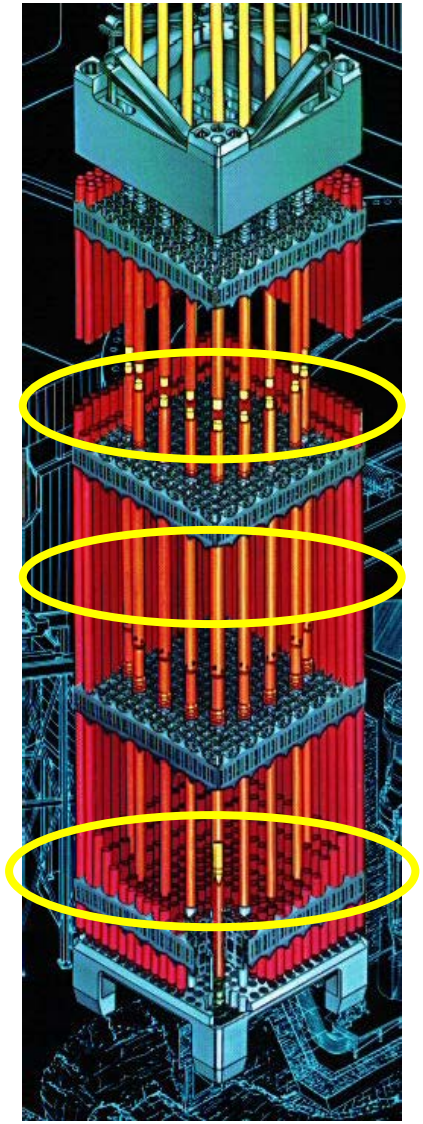
Fatigue 8.8 N-m

Cycles

<300 K

>11 M

~2 M



PWR Environment

Higher Temp/Higher oxide layer

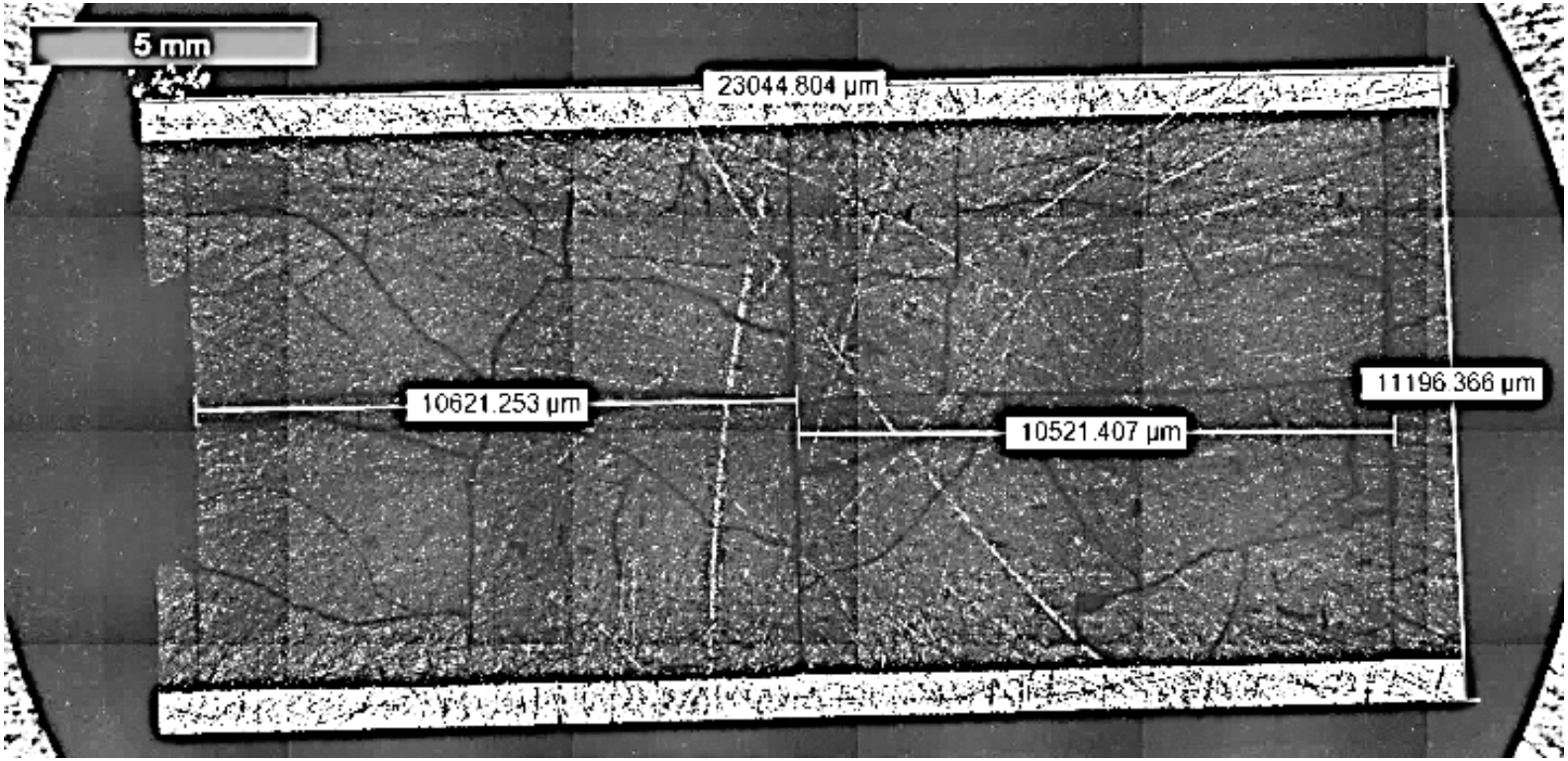
Higher Burn-up

Higher constraint/Lower burnup

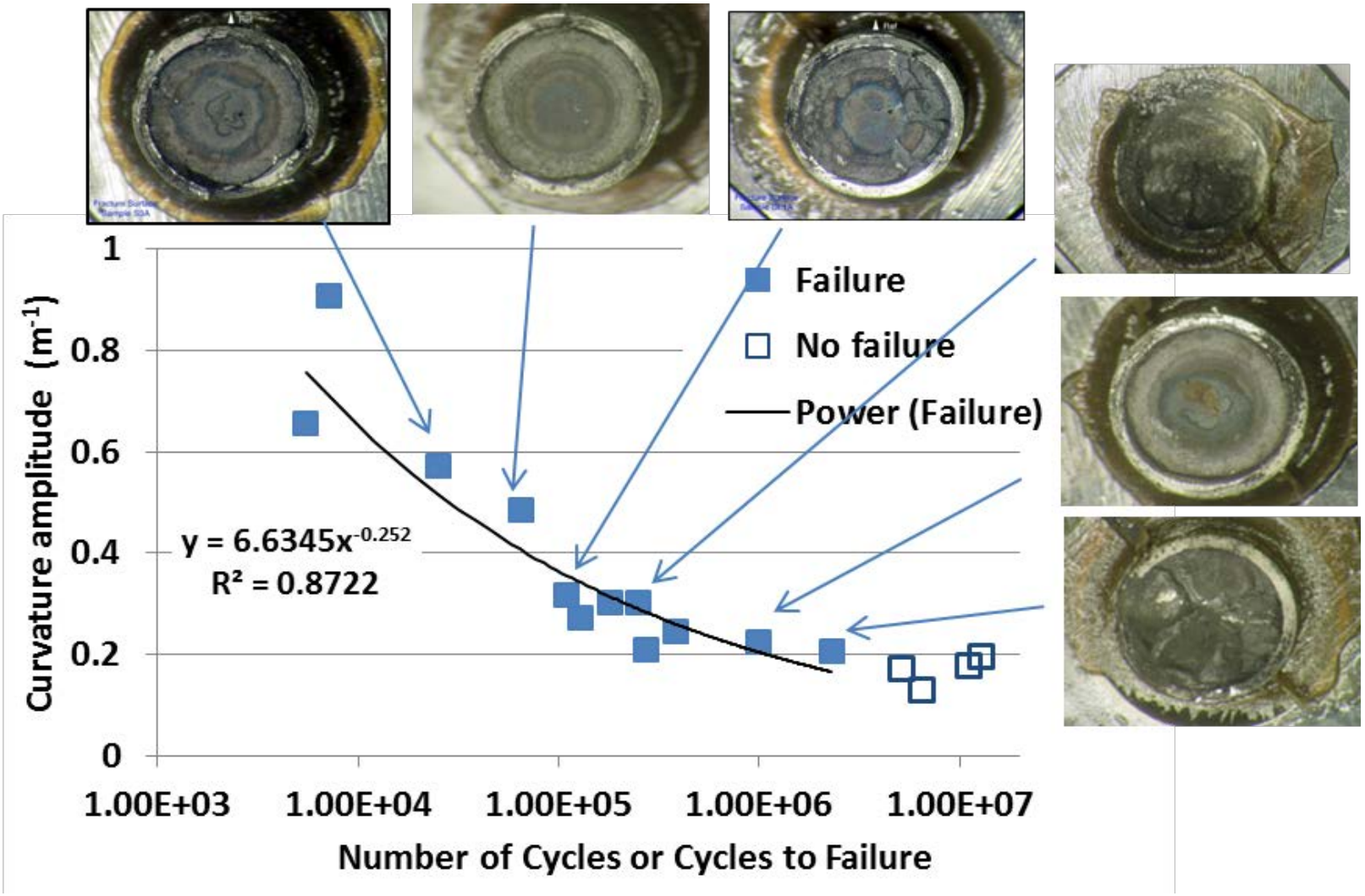
- Fuel type
- Clad type
- Fuel dimensions
- Temperature
- Burn-up
- Hydriding
- Mechanical interaction

PWR HBU SNF rod used for CIRFT testing reveals good bond at fuel-clad interface

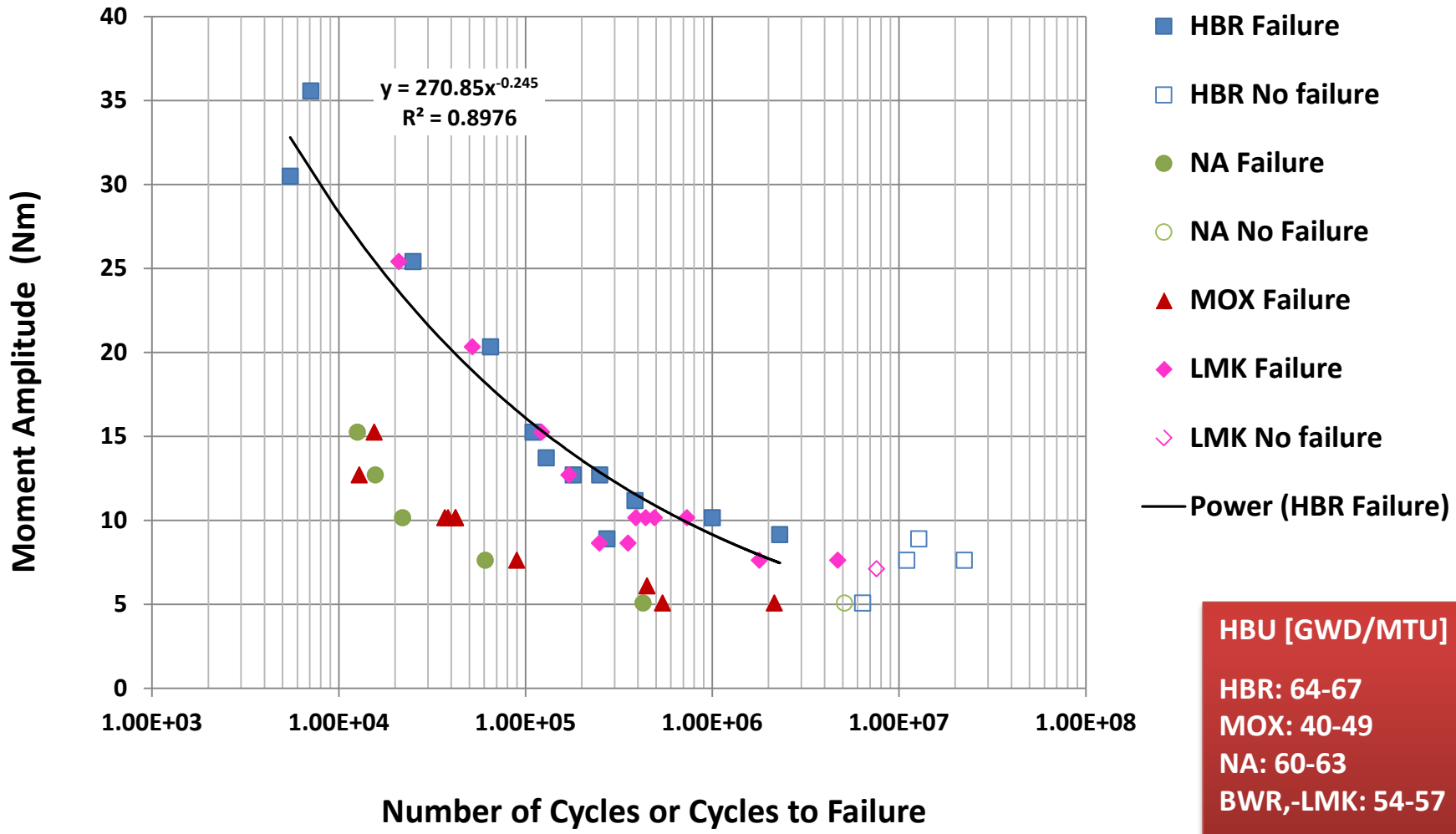
Limerick BWR SNF Rod has more fractured surface within pellets



HBU HBR SNF fatigue data shows a well defined S-N curve with failure at P-P interface



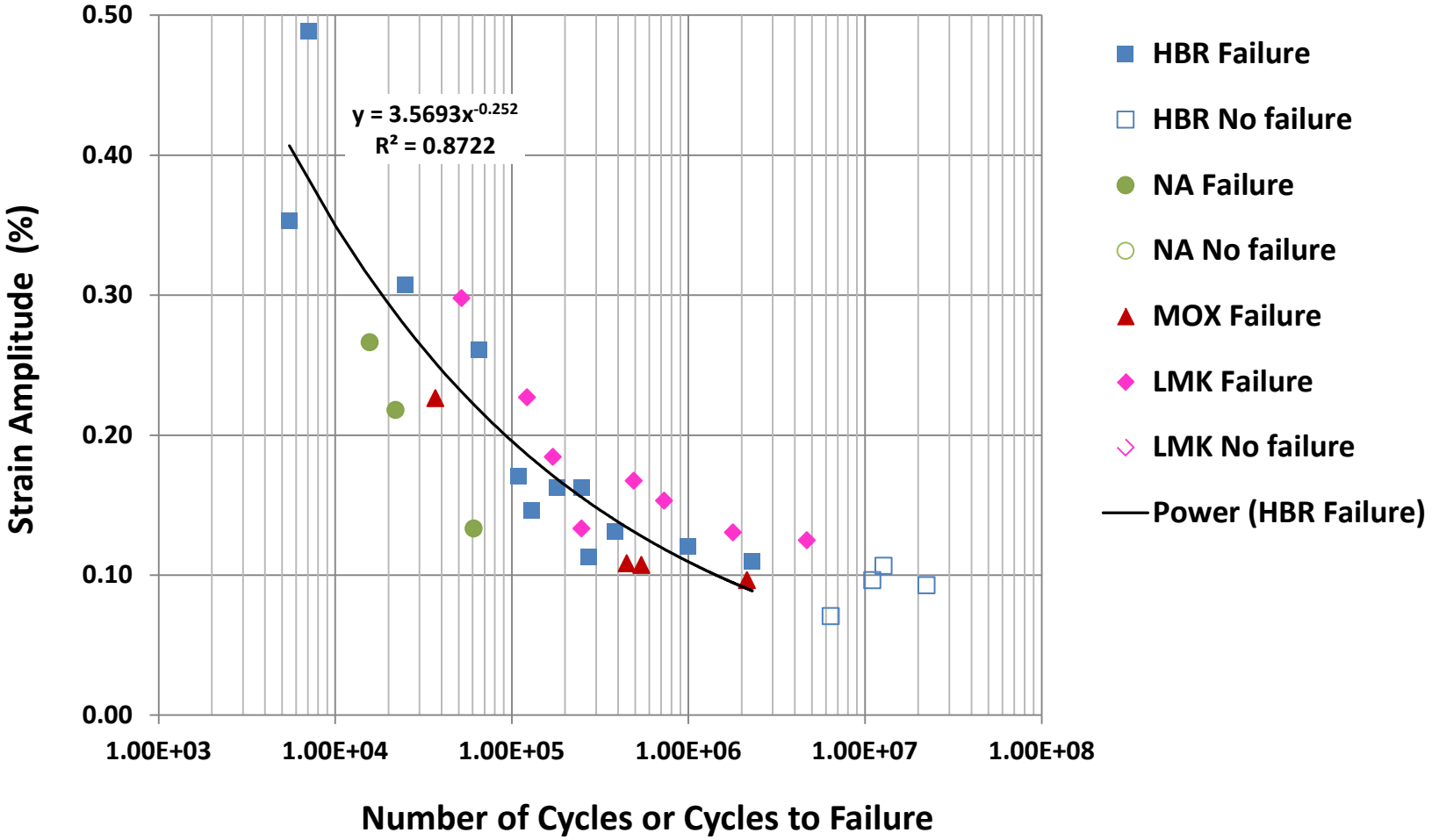
Overall CIRFT Fatigue Test Results



HBU [GWD/MTU]

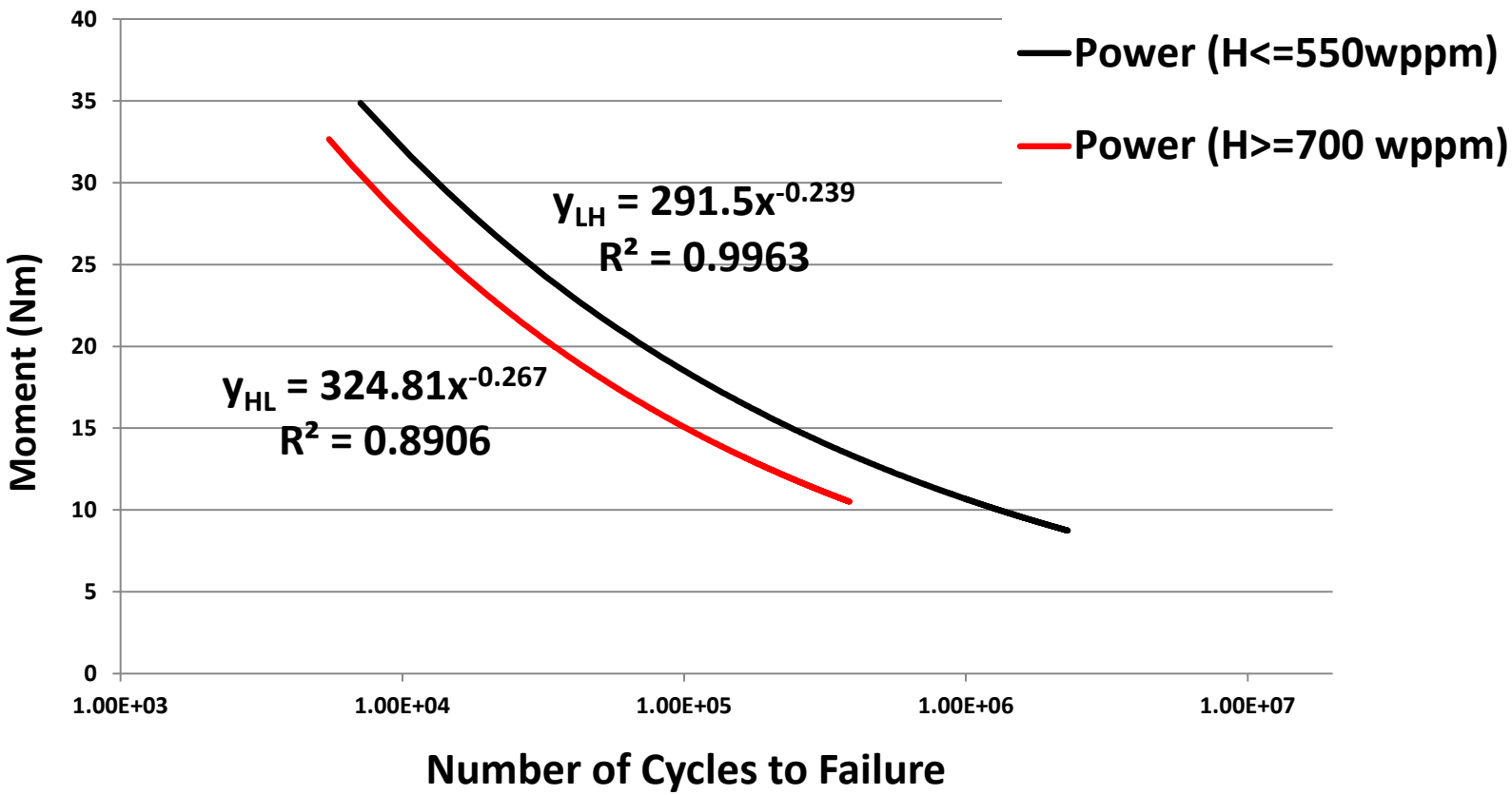
HBR: 64-67
MOX: 40-49
NA: 60-63
BWR,-LMK: 54-57

Strain vs. Failure Frequency

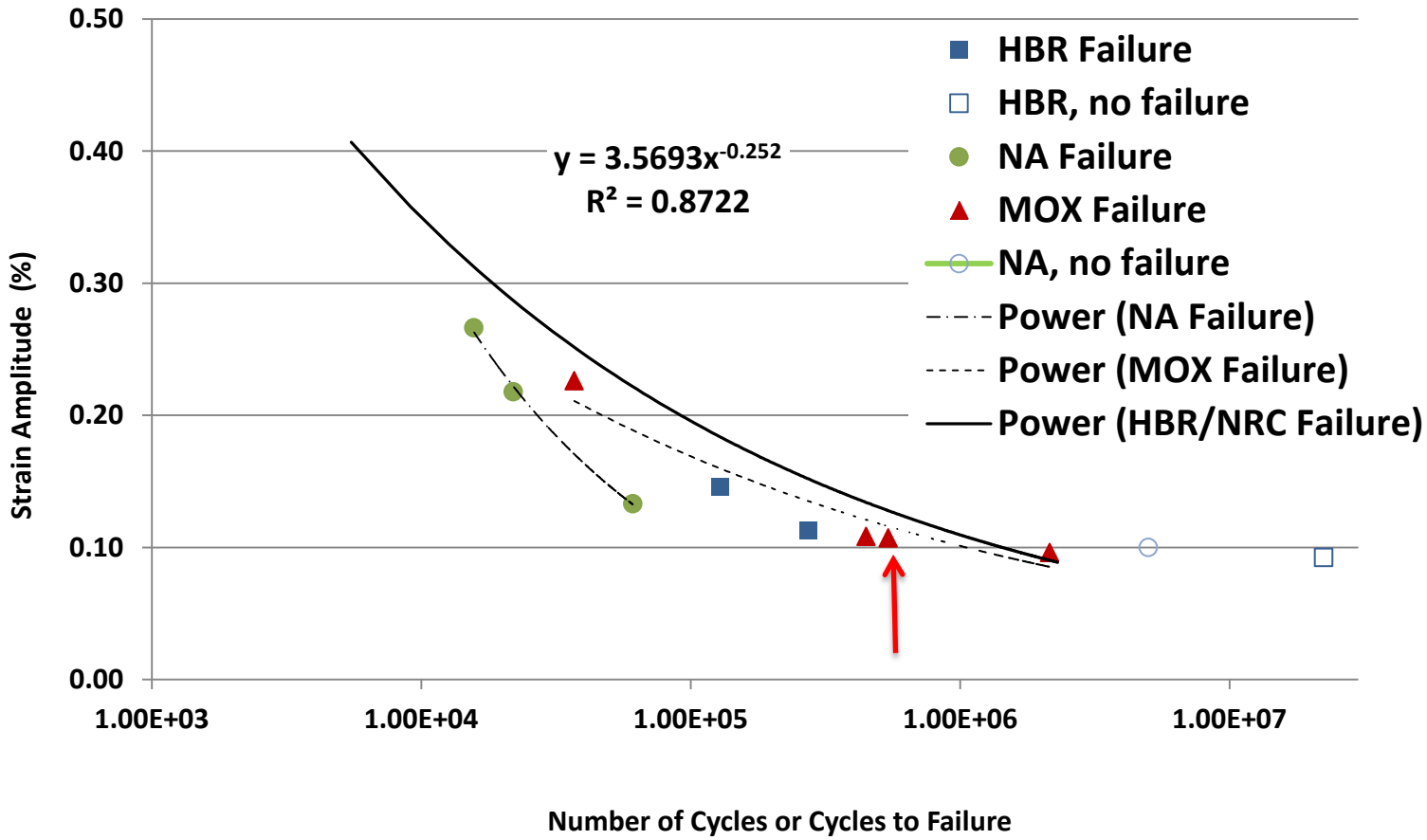


HBR SNF S-N data indicates a hydrogen content dependency

Hydrogen was estimated from oxide thickness, detailed hydrogen measurement is needed to further quantitative hydrogen dependent failure mechanism

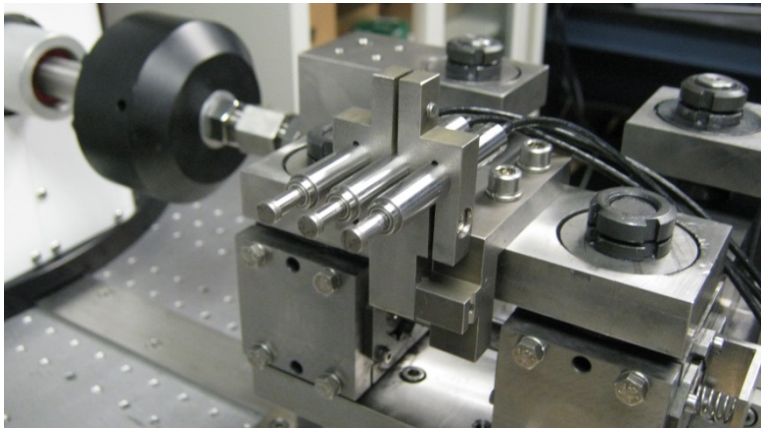


Limited testing on different cladding materials indicates different damage mechanisms need to be understood



The data point with red arrows represents test data where the sample experienced a two foot drop (twice), while both MOX rods experienced the same dynamic loading of 5N·m.

Modeling (FEA) provides insights into the CIRFT testing results



- **Finite element analysis 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*
- **Currently investigating the effects of hydride reorientation on the fatigue life of high burnup fuel.**

Early "conclusions" and observations from this testing show:

- **The fuel provides strength (flexural rigidity) to the fuel/clad system**
- **When the fuel is fatigued to failure, the 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 fuel did not fail after more than10M cycles*

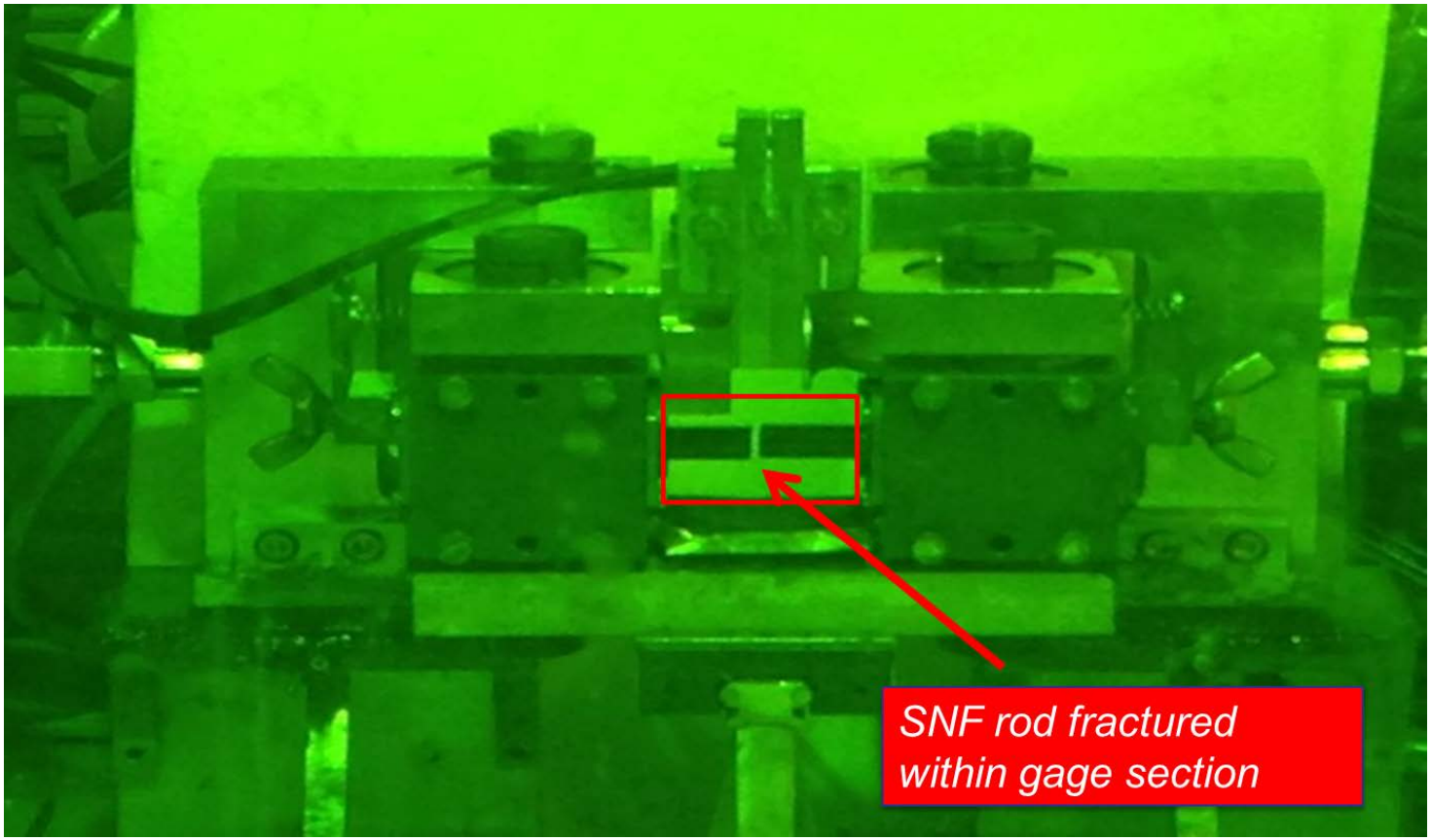
FY16 Work will focus on detailed analysis of experimental data, testing of additional material and testing for higher intensity "jolts"

- *Analyze ORNL SNF test data from FY 15 experiments*
  - *Evaluate the hydride reorientation and other CIRFT test results using FEA*
  - *PIE of hydride reorientation experiments*
- *Continue current tests on two remaining clad types*
- *Test lower burnup segments.*
- *Test at high temperatures (100-200C)*
- *See if there are NDE ways to identify areas of PCI and PPI.*
- *"Jolt" testing – testing of fuel/clad system to understand the effects of low occurrence (000's of cycles) but higher impact NCT loads*

Is there a transition where the fuel/clad and pellet/pellet bonding is insufficient to provide "composite" stiffness

Backup Slides

CIRFT system testing in hot cell shows tested sample failed at middle of the gage section



CIFRT test data provides new insights into SNF rod dynamic response and integrity

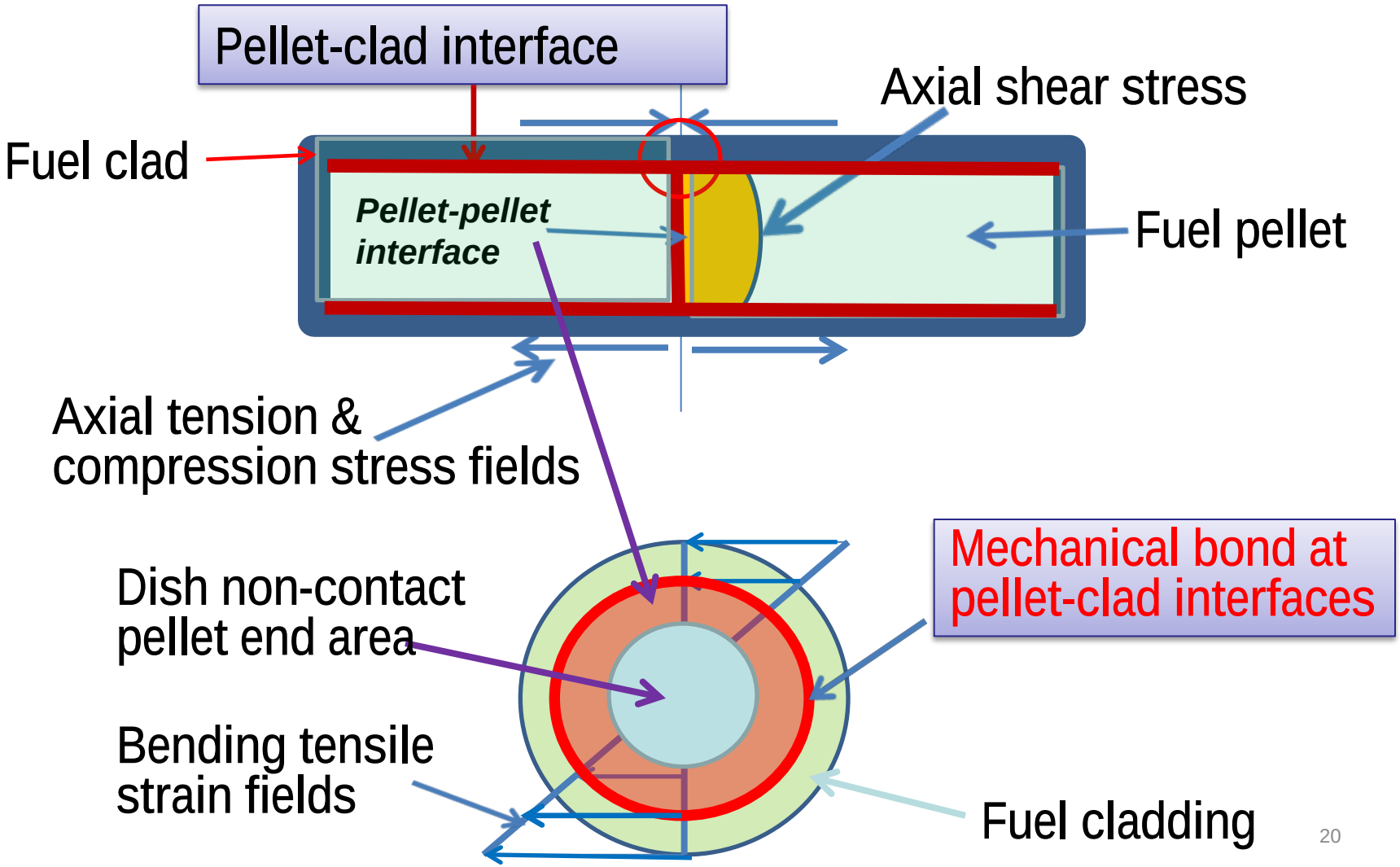
- Pellet-clad-interaction; P-C bonding efficiency
- Hydrogen concentration does affect UNF system strength
- UNF system has significant stress concentrations and residual stress distributions
- Fuel rod generally fails at the pellet-pellet interface
- At low loads, (below clad threshold/fracture toughness) the UNF system can withstand millions of vibration cycles
- Transient shocks of NCT induced accumulated damage can significantly reduce SNF fatigue lifetime.

CIFRT test data provide new insights into SNF dynamic behavior

The CIRFT approach successfully demonstrates controllable fatigue fracture on HBU SNF in a normal vibration mode; this enables us to examine the underlying mechanisms in SNF system dynamic performance

- SNF system interface bonding efficiency
- Fuel structural support to the SNF system
- Significant variation in stress and curvature during SNF fatigue cycles due to pellet segments and clad interaction
- Clad hydride system microstructure dynamic evolution
- SNF system S-N limit related to the clad fracture threshold
- SNF failure initiated at pellet-pellet-clad interface region and appears to be spontaneous failure

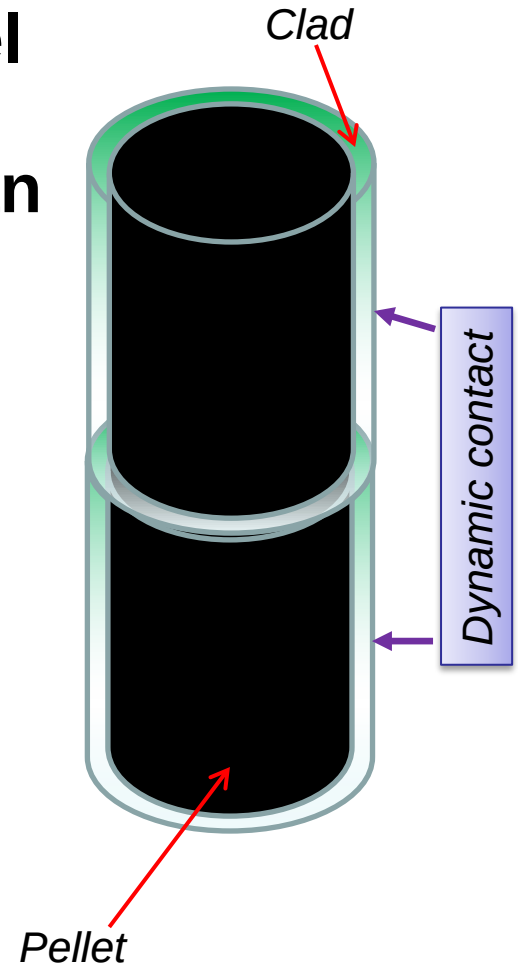
Fuel pellets provide structural support to HBU SNF during NCT



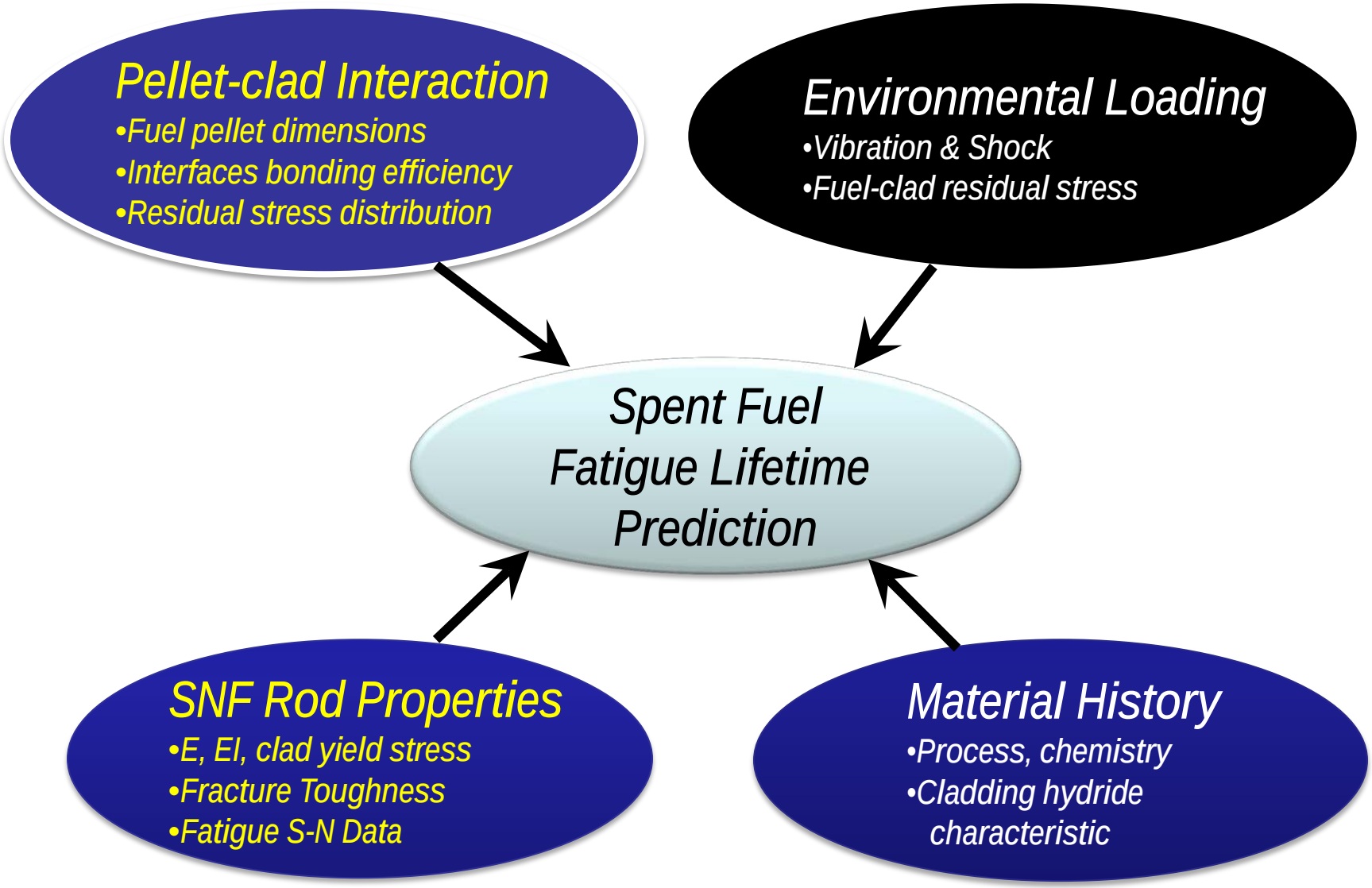
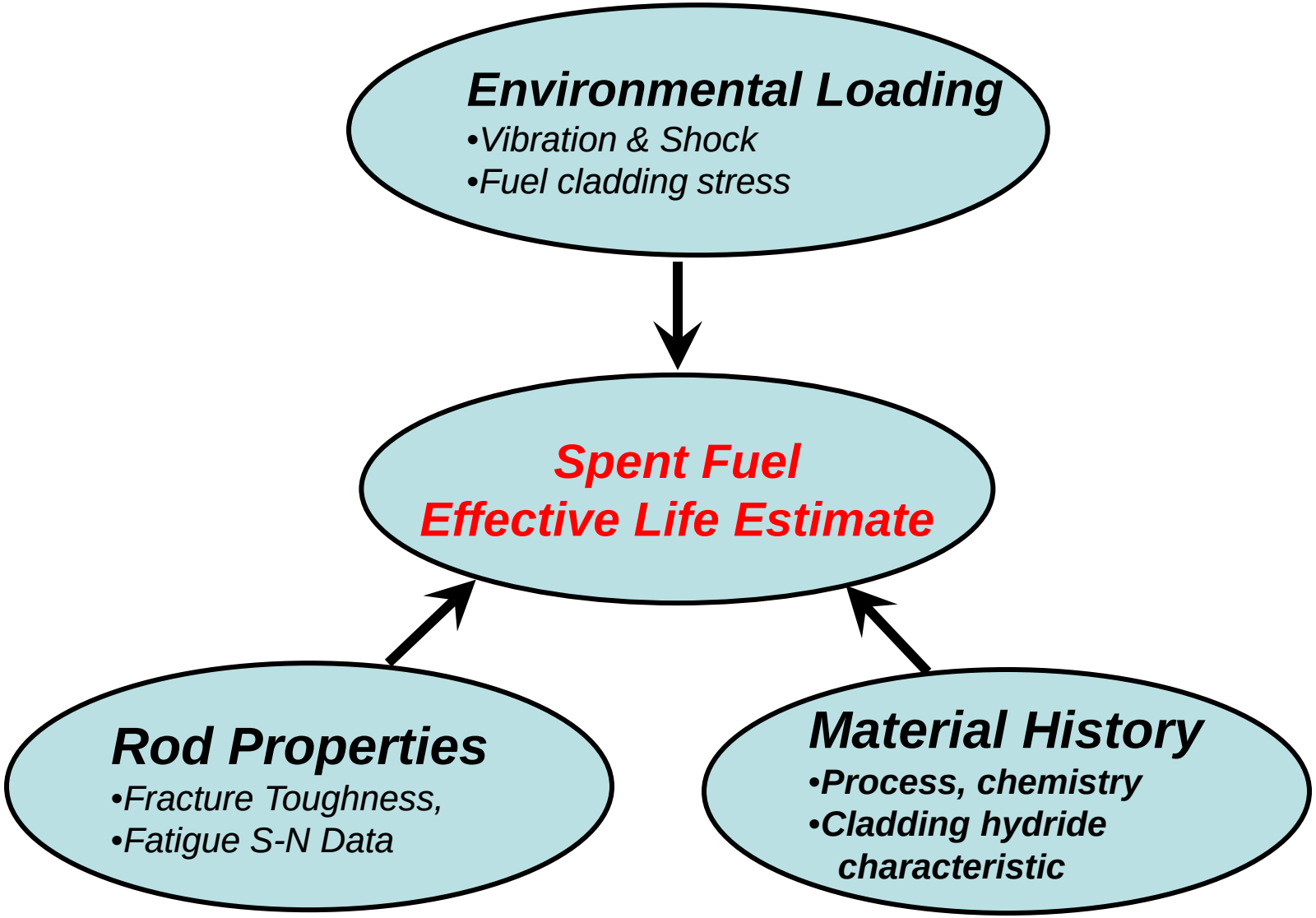
HBU fuel provided support to clad structure will increase overall SNF system fracture toughness

- **Fuel-clad interface bond enables fuel to carry bending flexural load**
- **Pellet with sufficient bond to clad can also carry high shear resistance for SNF system.**
- **Fuel internal support to clad reduce clad local buckling potential**

Static CIRFT testing shows significant oxide spallation



Key components in SNF vibration reliability & effective lifetime prediction



UNF Fatigue Test System Developed and Fatigue Strength Measured – What Next?