Update on High Burnup Fuel Hydride Reorientation

Ricardo Torres, Ph.D., Materials Engineer
Division of Spent Fuel Management
Office of Nuclear Material Safety and Safeguards

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Background

- Safety Review Objectives – Spent Fuel Assemblies
  - Subcriticality – *unsustainable fission reaction*
  - Confinement / Containment – *no material release*
  - Radiation shielding – *on-site worker, public dose limits*
  - Thermal performance - *controlled fuel temperature*
  - Structural performance – *maintain analyzed configuration, assure retrievability*

Background

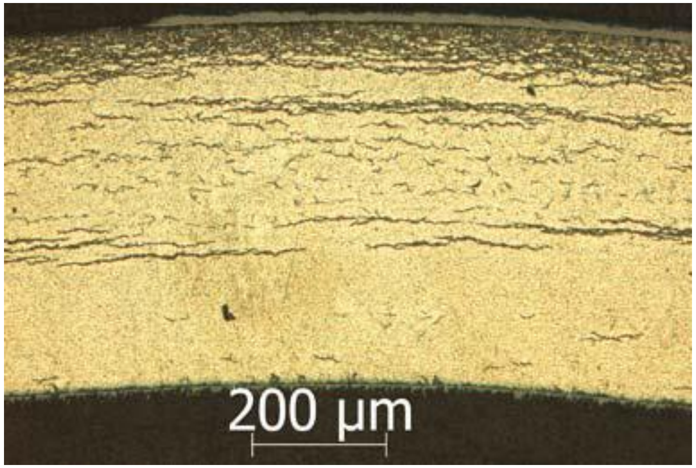
- Standard Review Guidance – Spent Fuel Assemblies
  - Dry Storage
    - NUREG-1567 (2000) – SRP Specific Licenses (ISFSIs)
    - NUREG-1536, R1 (2010) – SRP Dry Storage Systems (CoCs)
    - ISG-2, Rev 2 – Retrievability (2016)
  - Transportation
    - NUREG-1617 (2000) - SRP
  - Common Guidance
    - ISG-1, Rev. 2 (2007) – SNF Classification
    - ISG-11, Rev. 3 (2003) – Cladding Considerations

Background

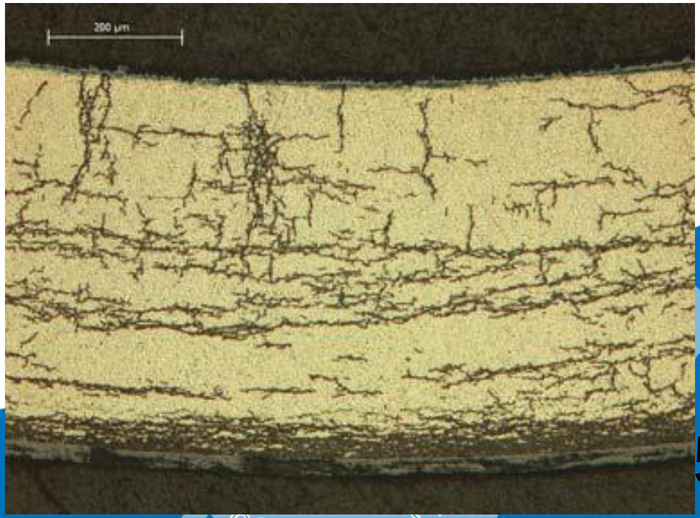
- ISG-11, Rev. 3 (2003)
  - Defines staff-acceptable maximum cladding temperature for high burnup fuel [400 °C (752 °F)]
    - Normal conditions of storage and transport, short-term loading operations
  - Cited references provide experimental evidence that, at this temperature:
    - Sufficient creep strain capacity - failures not expected
    - Hydride reorientation would be minimized

Hydride Reorientation

- What is it?
  - Hydrogen in the cladding dissolves during short-term loading operations
  - As the fuel cools down, it re-precipitates in a different orientation
- Why is it an issue?
  - Variation of mechanical properties over time
  - Concern for reduced ductility



ZIRLO™: 68 GWd/MTU
530±70 wppm H

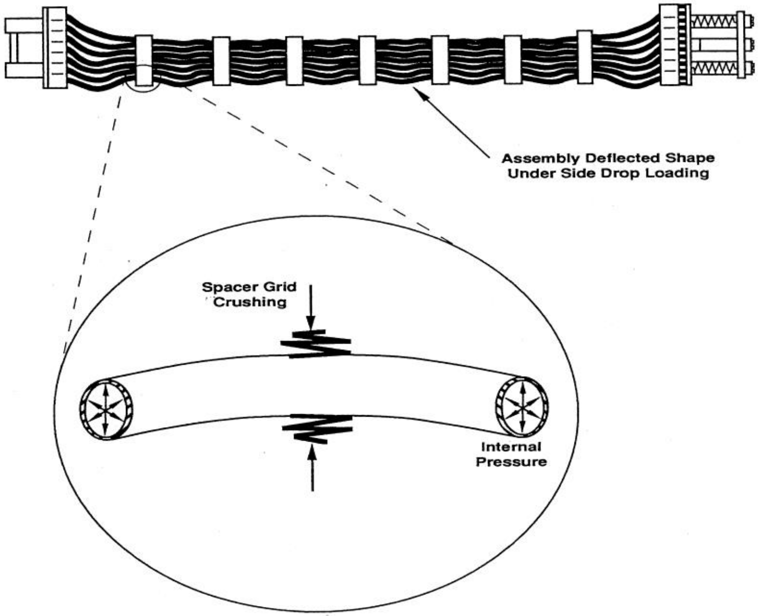


Regulations Impacted

- Storage
  - 72.122(h)(1) – protect cladding against gross rupture
  - 72.122(l) – ready retrieval of spent fuel
  - 72.124(a) – system maintained subcritical
  - 72.128(a) – adequate safety normal/accident conditions
- Transportation
  - 71.33(b)(3) – fuel geometry known prior to transport
  - 71.55(d)(2) – geometry not substantially altered (NCT)
  - 71.89 – package opening instructions

Consequences

- Fuel reconfiguration not expected due to bending loads (NCT, all storage conditions)
  - Tensile stress field associated with the rod bending due to inertia is parallel to both radial and circumferential hydrides
- Expected to only potentially compromise cladding integrity during pinch-type loads (30-ft side drop – transportation)
- NRC and DOE continued to sponsor confirmatory research



Draft RIS

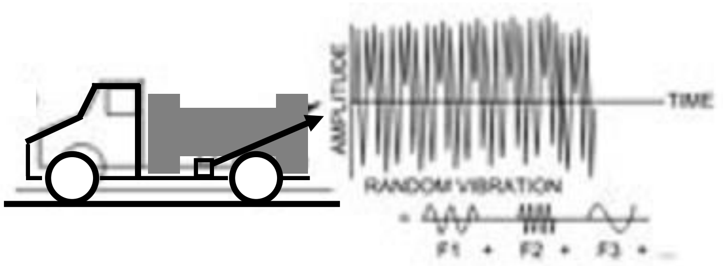
- Provided high level information on staff-accepted approaches for addressing concerns of radial hydride reorientation
  - Defense-in-depth reconfiguration analyses
  - Cladding remains above justified “ductile-to-brittle-transition” temperature
  - Material properties accounting for radial hydrides
- Draft issued for public comment – March 5, 2015
- Received 35 comments in 6 letters

Since the Draft RIS…

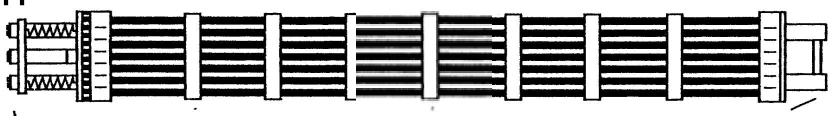
- NUREG-1927, Rev. 1 issued
  - Addresses CoC and specific license renewals including HBU fuel
    - HBU Fuel Monitoring and Assessment Program (Appendix B)
    - Reliance on defense-in-depth reconfiguration analyses not addressed (revision to approved design bases)
- Draft MAPS Report completed
  - Provides technical bases on aging effects due to HR (renewals)
- Additional research completed
  - Ring compression testing of defueled specimens (DOE – ANL)
  - Bending fatigue testing (NRC, DOE – ORNL)

Bending / Fatigue Testing

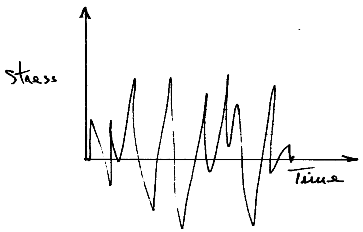
A transportation cask will experience some level of oscillation due to normal conditions of transport.



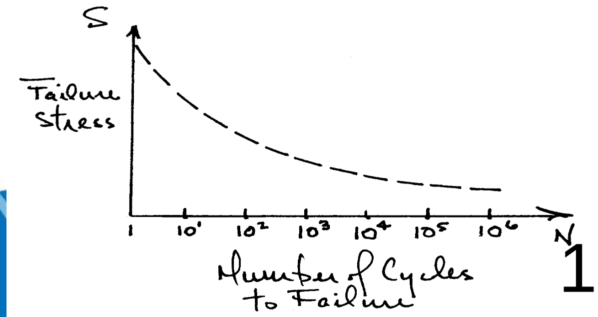
That oscillation will be transmitted in some way to the contents of the cask, the fuel elements.



The oscillation transmitted to the fuel elements will result in local stresses



Large number of cycles during transport may result in cladding failures, even if the maximum stresses are far below the yield stress of the material.

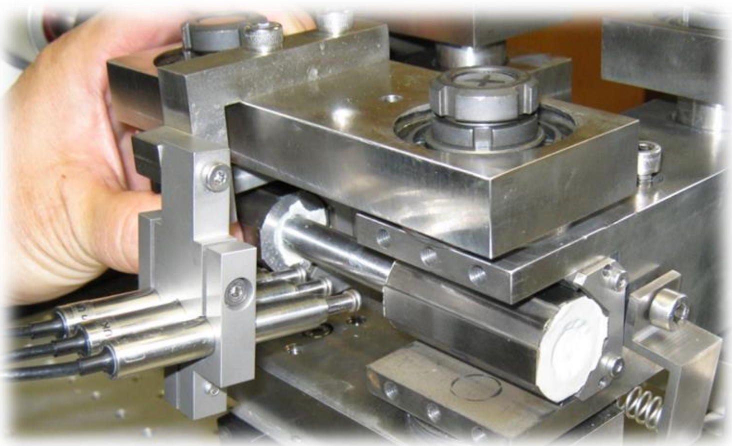


Bending / Fatigue Testing

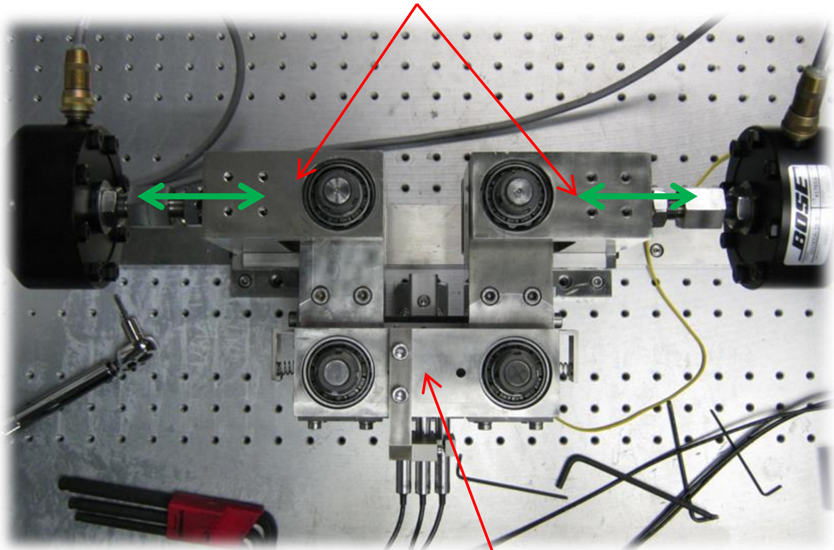
- Purpose: Confirm expected behavior during bending (vibration) loads
- Objectives:
  - Determine if the presence of fuel pellet increases the flexural rigidity (bending stiffness) of the fuel rod (storage/transportation)
  - Determine if the presence of fuel pellet increases the failure strain of the cladding (storage/transportation)
  - Determine the number of cycles to failure for high burnup fuel rods at a range of elastic strain levels (transportation)

Instrumentation (CIRFT)

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment



Push-pull force applied to U-Frame results in bending moment on the test segment



Location of test segment

NMSS
Division of Spent Fuel Management

Materials Tested

- PWR SNF with Zircaloy-4 cladding (NRC-sponsored)
  – Burnup range: 63.8 to 66.8 GWd/MTU
- NRC Phase 1 test (non-reoriented HBU samples)
  – 4 static bend tests + 16 vibration fatigue tests at a wide range of bending moment amplitudes
- NRC Phase 2 test (reoriented HBU samples)
  – 1 static bend test + 3 vibration fatigue tests at a range of bending moment amplitudes
- Additional DOE-sponsored testing on other alloys

Reorientation Procedure

U.S.NRC
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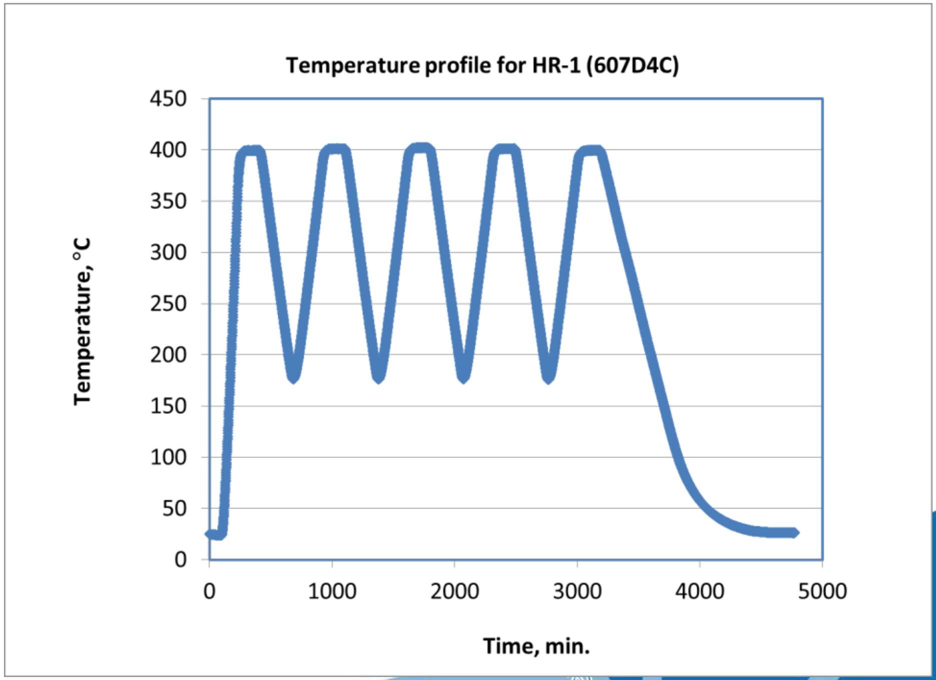
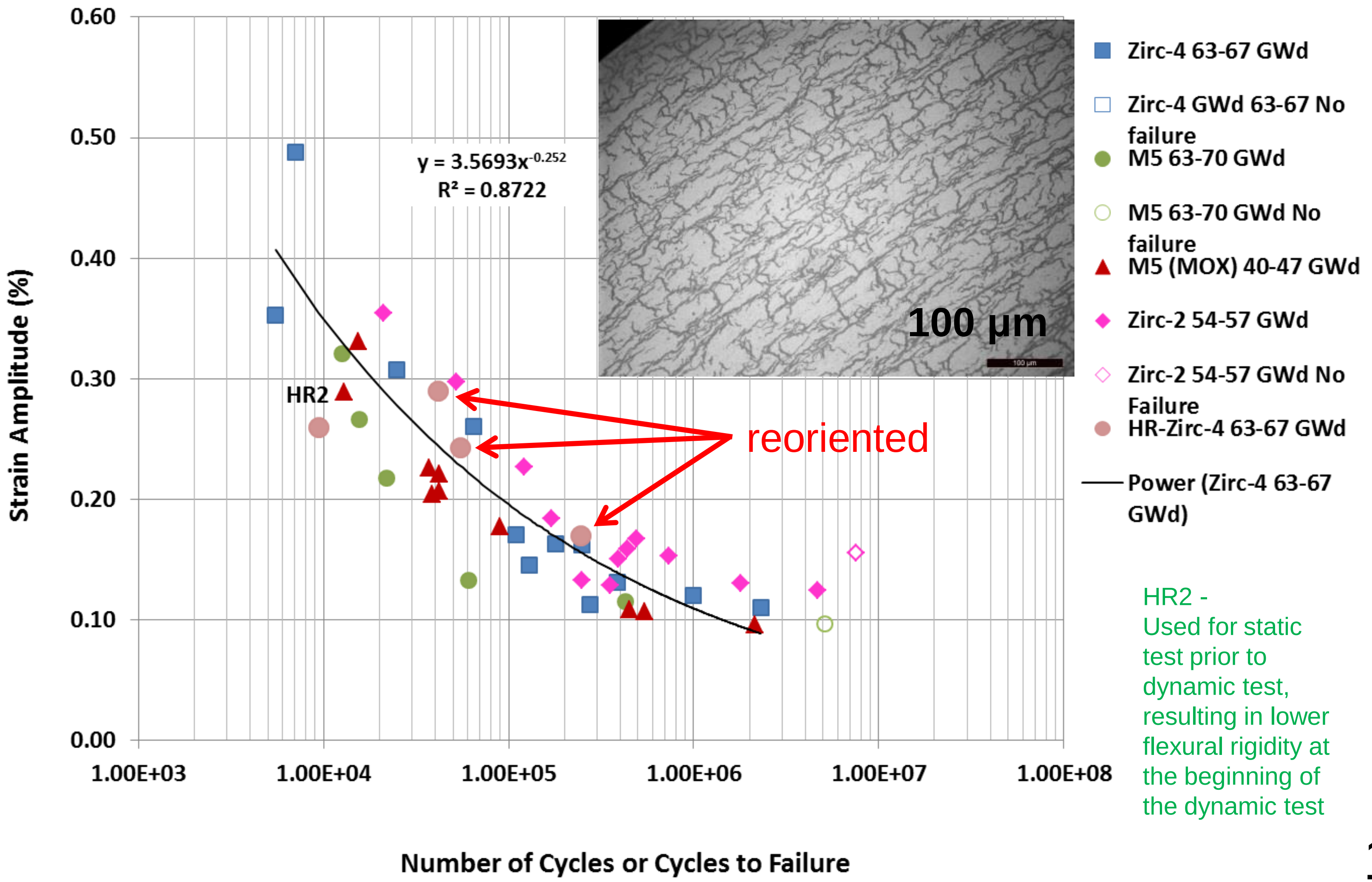
- Rod internal pressure, peak cladding temperature and number of thermal transients reasonably bound those achieved during drying operations
- Yields highest reorientation and therefore provide mechanical properties in the most limiting condition

Reorientation Procedure
Hoop Stress - 140 MPa; RIP – 3200 psi
5 cycles; 400°C for 3 hours per cycle
Cooling rate: 0.5-1°C/min

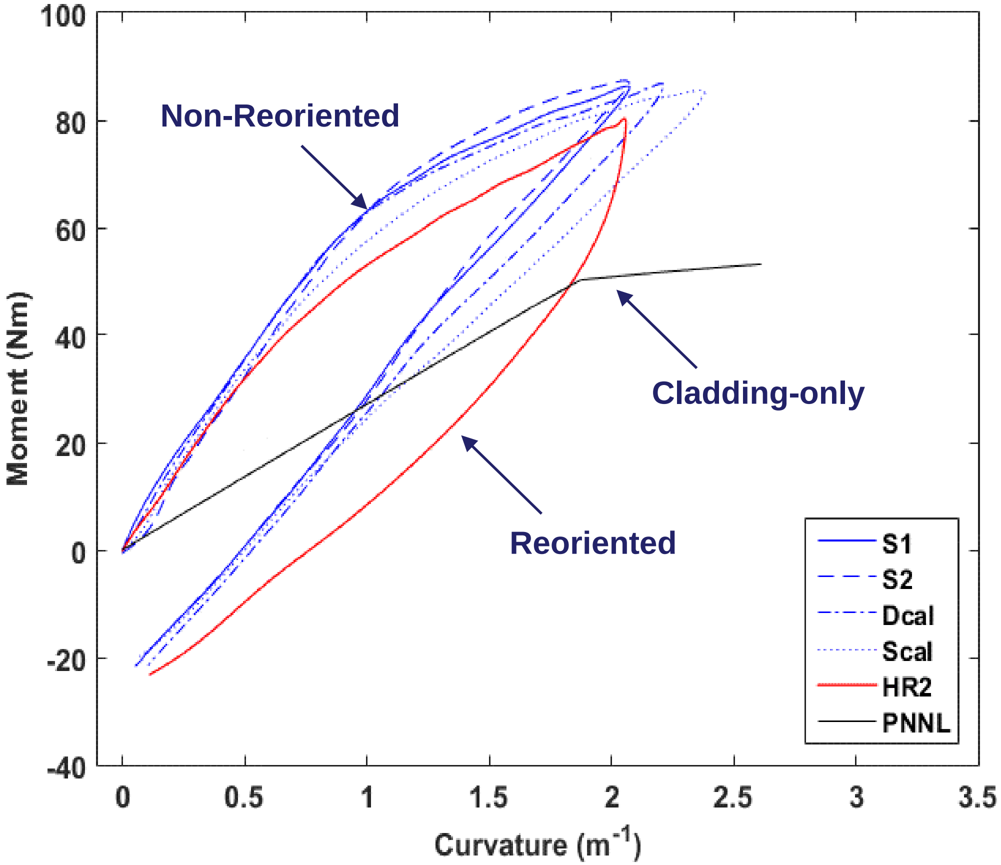


CIRFT Dynamic Testing



HR2 - Used for static test prior to dynamic test, resulting in lower flexural rigidity at the beginning of the dynamic test

CIRFT Static Testing



HR2 characteristics:

- Same flexural rigidity at applied bending moments below 40 N·m
- Decreased flexural rigidity at higher loads
- Reoriented response is still markedly above the cladding-only calculated response
  - Based on data from material with only circumferential hydrides

Phase II Conclusions

- As expected, fuel pellet increased the bending stiffness of the cladding
  – High CIRFT bending displacements were insufficient to rupture reoriented cladding
- High confidence that highly-reoriented HBU fuel can withstand substantial vibration loading without failure
  – Use of cladding-only mechanical properties in approved design-bases analyses is adequate and conservative

Implications to Guidance

- Results have prompted the staff to reevaluate technical position on “embrittlement” of HBU fuel cladding
- Staff working on technical bases to demonstrate maximum circumferential bending strains due to inertial loads during a 30-ft drop expected to remain within the elastic regime
  - Pinch-type loads insufficient to compromise cladding integrity
  - No longer need to demonstrate material remains above “ductile-to-brittle-transition temperature”

Implications to Guidance

- Staff revising approaches proposed in Draft RIS
- Preliminary new approaches:
  - Transportation
    - Use of lower-bound endurance limit from CIRFT dynamic testing, *or* reliance on defense-in-depth consequence analyses (NCT)
    - Use of circumferential-only cladding mechanical properties (HAC)
      - Potential allowance to account for increased rod flexural rigidity due to presence of fuel pellet
  - Storage
    - Use of cladding-only (circumferential-only) mechanical properties continues to be acceptable
    - Use of confirmatory HBU fuel surrogate program (NUREG-1927, Rev. 1) (storage periods > 20 yrs)

Current Efforts

- ORNL finalizing update to NUREG-7198
  - Incorporate Phase II results for reoriented cladding
- Staff drafting supplement to Standard Review Plans
  - Replace draft RIS
- Issue draft for public comment – Summer 2017

Acronyms

- ANL: Argonne National Laboratory
- CIRFT: Cyclic Integrated Reversible-bending Fatigue Testing
- CoC: Certificate of Compliance
- DOE: Department of Energy
- HAC: Hypothetical Accident Conditions
- HBU: High Burnup Fuel
- ISFSI: Independent Spent Fuel Storage Installation
- ISG: Interim Staff Guidance
- NCT: Normal Conditions of Transport
- NRC: Nuclear Regulatory Commission
- ORNL: Oak Ridge National Laboratory
- RHR: Hydride Reorientation
- SNF: Spent Nuclear Fuel
- ZIRLO™: Proprietary Westinghouse cladding alloy