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Update: High Burnup Fuel Test Results and Guidance

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NRC-Sponsored Testing NUREG/CR-7198, Rev. 1

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- ADAMS Accession No. ML17292B057
  - Results on flexural rigidity and fatigue life of high burnup fuel (zircaloy-4 cladding)
    - Prior-to and after cladding hydride reorientation
  - Evaluates the fuel rod as a composite system, including the presence of fuel inside the cladding and any pellet/cladding bonding effects
  - Incorporates Rev. 0 results: Phase I testing for non-reoriented cladding
  - New results: Phase 2 testing for reoriented cladding

Staff's Assessment of NUREG/CR-7198, Rev. 1

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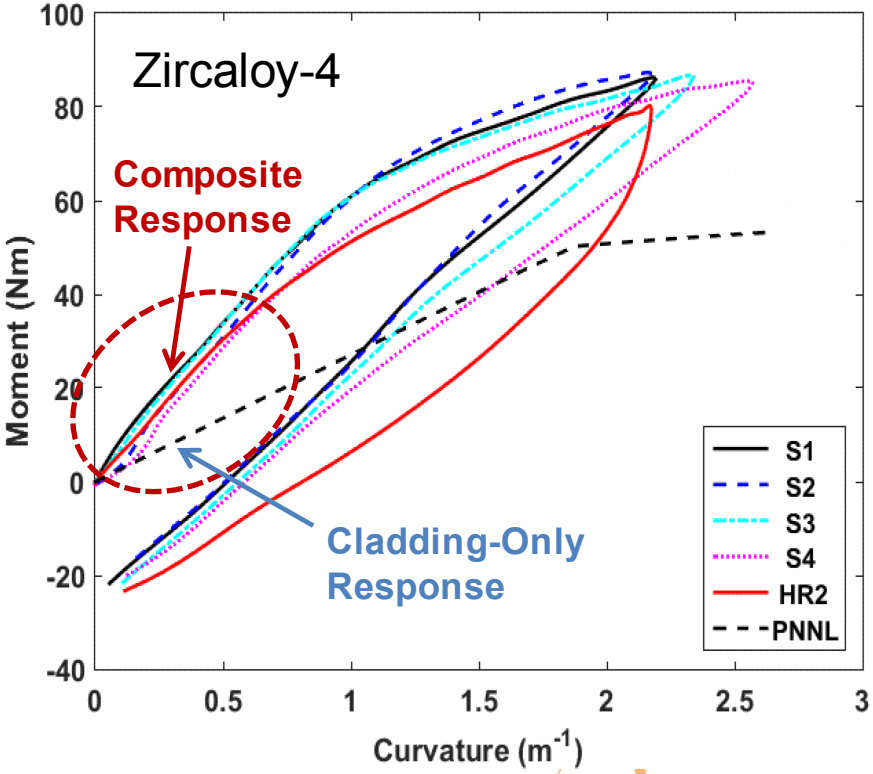
- At bending moments less than 35 Nm, the flexural rigidities of all non-reoriented rods (S1-S4) and the hydride-reoriented rod (HR2) are essentially the same.
- HAC 9-m (30-ft) side drop corresponds to bending moments < 35 Nm (< 100*g*)



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Staff's Conclusions per NUREG/CR-7198, Rev. 1

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- Zircaloy-4 results confirmed that hydride reorientation does not significantly decrease the fueled-rod flexural rigidity for expected loads during transfer operations, NCT or HAC
- Reoriented fueled rods showed markedly higher bending moment resistance compared to the cladding-only rod response
- Use of cladding-only mechanical properties is adequate for the evaluation of drop accident scenarios
  - Conclusion applicable to all modern cladding alloys

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Staff's NUREG

- Staff has developed example licensing and certification approaches based on the NUREG/CR-7198, Rev. 1 results
  - Staff ensuring consistency with new consolidated SRPs for dry storage and transportation
- Approaches vary depending on the condition of the fuel (undamaged vs. damaged) and length of time in dry storage
- Applicants may propose and demonstrate alternative approaches to be acceptable

Dry Storage (up to 20 years) Intact and Undamaged Fuel

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Normal, Off-Normal Conditions

↓

No changes from current Standard Review Plan

Accident Conditions

↓

Evaluate postulated drops using justified cladding mechanical property data (non-reoriented or reoriented cladding)

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Dry Storage (beyond 20 years) Intact and Undamaged Fuel

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Normal, Off-Normal, and Accident Conditions

1. Evaluate postulated drops using justified cladding mechanical property data (non-reoriented or reoriented);
2. Supplement the application with either of these licensing or certification approaches:

Surrogate demonstration program as confirmation of expected fuel configuration (NUREG-1927, Rev. 1)

Perform safety analyses assuming fuel rupture of design-bases fuel (e.g., 1% normal, 10% off-normal, 100% accident)

Transportation
Intact and Undamaged Fuel

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Directly-loaded or previously dry-stored (up to 20 years)

1. Evaluate NCT/HAC drops using justified cladding mechanical property data (non-reoriented or reoriented);
2. Evaluate NCT vibration per fueled-rod endurance limit

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Staff's NUREG NCT/HAC Drop Analyses

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- Method for calculating cladding tensile strains per rod dimensions and rod curvature from drop accident scenario
- Method for calculating rod curvature per applied bending moment and rod flexural rigidity
- Method for accounting for fuel pellet contribution to rod flexural rigidity
  - Fueled-rod/cladding-only FR ratio (per CIRFT static testing)
  - Approach is applied to zircaloy-4 per NUREG/CR-7198, Rev. 1 results and PNL-17700 non-reoriented properties
  - Approach can be replicated with other alloys

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Staff's NUREG NCT/HAC Drop Analyses

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- Method for calculating an applied bending moment on the rod per a drop accident *g*-load, and determining a safety margin per CIRFT static test data
  - Approach applied to a representative 15X15 PWR assembly with same rods tested by ORNL
  - Approach can be replicated with other assembly/rod designs
- Assessment of credibility of ductile-to-brittle transition as measured by ring compression testing of de-fueled rod specimens

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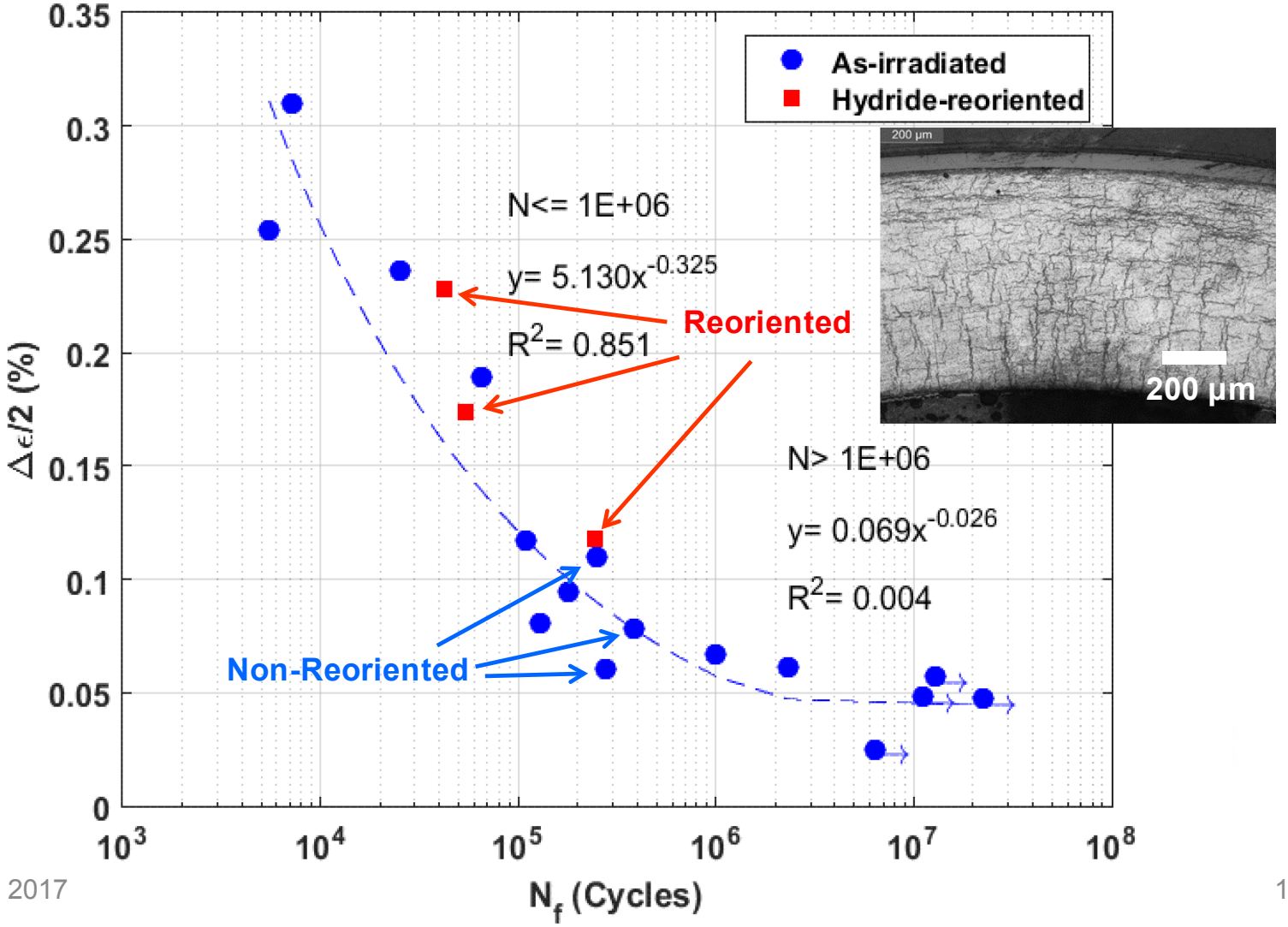
NUREG/CR-7198, Rev. 1
Fatigue Testing



Staff's NUREG NCT Vibration Evaluation

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- Hydride-reoriented (Phase 2) zircaloy-4 fuel rods failed at similar or higher equivalent strains than the non-reoriented (Phase 1) zircaloy-4 fuel rods
- Lower-bound fatigue S-N curve developed for zircaloy-4 per NUREG/CR-7198, Rev. 1 results
  - Equivalent strain amplitude (mean – 2σ) in lower-bound curve was reduced by a factor of 0.9 to account for limited test results
  - Approach can be replicated with dynamic test data (CIRFT) obtained for other cladding alloys

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Previously dry-stored (beyond 20 years)

1. Evaluate NCT/HAC drops using justified cladding mechanical properties (non-reoriented or reoriented);
2. Evaluate NCT vibration per fueled-rod endurance limit;
3. Supplement the application with either of these licensing or certification approaches:

Surrogate demonstration program as confirmation of expected fuel configuration (NUREG-1927, Rev. 1)

Perform safety analyses assuming fuel rupture of allowable fuel contents (e.g., 3% NCT, 100% HAC)

Dry Storage / Transportation Damaged Fuel

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All Conditions of Dry Storage/ Transport

1. Demonstrate structural performance of the can used for damaged fuel;
2. Perform safety analyses assuming fuel reconfiguration confined to the boundary of the can.

i.e., No changes from current Standard Review Plan

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Staff's NUREG General Conclusions

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- Zircaloy-4 results confirmed that hydride reorientation does not affect flexural rigidity nor fatigue endurance
  - Tensile stress field associated with the rod bending due to inertia is parallel to both radial and circumferential hydrides
- Staff expects similar fatigue performance for other alloys. However, supporting data should be provided in an application
- Approach for crediting flexural rigidity of the pellet in the drop analyses requires CIRFT static test data for other alloys
  - May not be needed if flexural rigidity of the cladding is sufficient to demonstrate safety (determined on case-by-case basis)
- DOE planning to acquire additional data (CIRFT dynamic/static, uniaxial tensile/pressure burst testing) under their Sister Rod Program

References

- NUREG-7198, Rev. 1, “Mechanical Fatigue Testing of High-Burnup Fuel for Transportation Applications”, J.-A Wang, H. Wang (2017).

Acronyms

- ADAMS: Agencywide Documents Access and Management System
- CIRFT: Cyclic Integrated Reversible-bending Fatigue Tester
- HAC: hypothetical accident conditions
- NCT: normal conditions of transport
- NRC: Nuclear Regulatory Commission
- ORNL: Oak Ridge National Laboratory
- PNL: Pacific Northwest National Laboratory
- Rev: Revision