Spent Fuel Research Activities – Research Efforts Affecting Spent Fuel Storage and Transportation

Mechanical Testing of High Burnup Fuel for Transportation Applications

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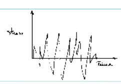
Background

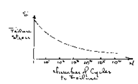
A transportation cask will experience some level of oscillation due to normal conditions of transport.

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



The fuel cladding has the potential for fatigue failure if a large number of cycles are seen during transport, even if the maximum stresses seen by the cladding are far below the yield stress of the material. High burnup material in particular may be highly brittle. In addition, it is not clear how the ceramic fuel will effect the potential for cladding failure.



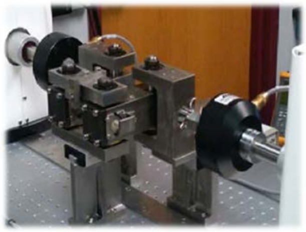
Current regulation state: "Evaluation of each package design under normal conditions of transport must include a determination of the effect on that design of the conditions and tests specified in this section" 10 CFR 71.71(c)(5) specifies the condition: "*Vibration.* Vibration normally incident to transport."

Research Questions

- How does the presence of fuel impact the flexural rigidity (bending stiffness) of the fuel rod?
- How does the presence of fuel impact the failure strain of the cladding?
- How many cycles to failure for high burnup fuel (HBF) rods at a range of elastic strain levels.
- Will radial hydrides impact the bending stiffness or fatigue life of high burnup fuel (HBF) rods?

Testing Equipment

An innovative bending fatigue testing system was developed to measure the static and dynamic response of high burn-up SNF rods. The device is referred to as the Cyclic Integrated Reversible-bending Fatigue Tester (CIRFT)

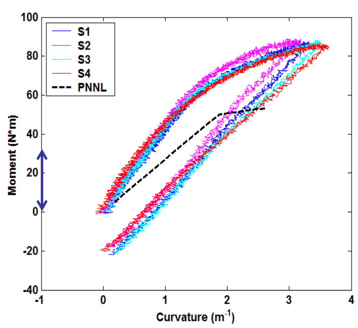


Irradiated Material Tested

- PWR Spent Nuclear Fuel (SNF) with Zircaloy-4 Cladding
- Burnup ranged from 63.8 to 66.8 GWd/MTU
- Phase 1 test (non-reoriented HBF samples) program
  - Static bend tests have been completed on 4 samples
  - Vibration fatigue tests have been completed on 16 samples, at a wide range of bending moment amplitudes
- Phase 2 test (reoriented HBF samples) program
  - Static bend tests will be performed on 1 sample
  - Vibration fatigue tests will be performed on 3 samples*, at a range of bending moment amplitudes

*note, the number of tests is contingent on success of each reorientation procedure.

Phase I Results - Static



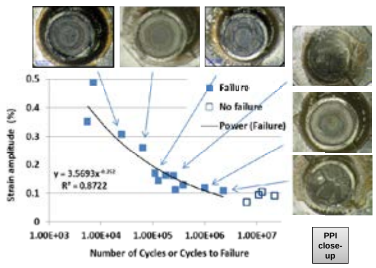
Significance:

The static CIRFT test results indicate a significant increase in flexural rigidity of a fueled high burnup fuel rod compared to that of the defueled high burnup rod specimen.

Each static test segment experienced 1–2% plastic strain without failure, demonstrating ductile performance of high burnup fuel.

Results also revealed that fuel pellet-pellet interfaces play a large role in fracture properties.

Phase I Results - Dynamic



Significance:

The dynamic CIRFT test results indicate the strain amplitude required for fatigue failure of high burnup fuel, at millions of vibration cycles, is higher than the strain amplitude expected during transportation.

However, the results are cladding pedigree specific and the fuel behavior results must also be evaluated in combination with details of cask design and expected transportation loading conditions.

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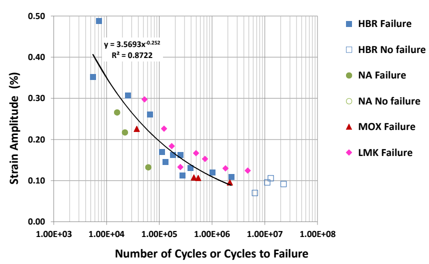
Ongoing Testing on CIRFT



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Ongoing Testing on CIRFT

- Fatigue tests will be conducted on HBU fuel segments that have been subjected to radial hydride reorientation.
- Test segments will be sectioned from the same irradiated rod as previous NRC tests.
- Impact of radial hydrides on the fatigue life of high burnup fuel rods will be evaluated based on comparison of the fatigue life of rods with circumferential hydrides to rods with radial hydrides.
- Equipment build up and procedure development for hydride reorientation for high burnup fuel are complete.
- Phase II testing is expected to be completed this Spring.

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Documentation

- The results of Phase I testing have been published in NUREG/CR-7198, "Mechanical Fatigue Testing of High-Burnup Fuel for Transportation Applications."
- Phase II testing will be reported in a future publication

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Research Questions Answered

- How does the presence of fuel impact the flexural rigidity (bending stiffness) of the fuel rod?
  - Fuel increases the flexural rigidity of the fuel rod. The extent that fuel and cladding work together as a composite to provide bending strength can be quantified.
- How does the presence of fuel impact the failure strain of the cladding?
  - Each static test segment experienced 1–2% plastic strain without failure, demonstrating ductile performance of fueled high burnup fuel.
- How many cycles to failure for high burnup fuel (HBF) rods at a range of elastic strain levels.
  - A cycles-to-failure curve was defined. The strain amplitude required for fatigue failure of high burnup fuel, at millions of vibration cycles, is higher than the strain amplitude expected during transportation
- Will radial hydrides impact the bending stiffness or fatigue life of high burnup fuel (HBF) rods?
  - Fuel rods with radial hydrides are expected to behave similarly. Results are expected later this Spring.

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Conclusions

- A unique testing device was developed to measure bending stiffness and fatigue behavior of high burnup spent fuel rods as a fuel/cladding system.
- **5 static tests:** 4 completed on as-irradiated HBU fuel, 1 to be completed on a HBU fuel rod subjected to hydride reorientation
  - Static results to date demonstrate that the presence of fuel increases the bending stiffness relative to calculations using cladding properties alone.
- **19 dynamic tests:** 16 completed on as-irradiated HBU fuel, 3 to be completed on a HBU fuel rod subjected to hydride reorientation
  - Dynamic results to date demonstrate that high burnup fuel can experience a large number of cyclic loads without failure. An effective fatigue limit can be interpreted from the available data.
- Comparison of as-irradiated and reoriented results will address whether radial hydrides impact the bending stiffness or fatigue life of high burnup fuel rods.

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Backup

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Publications

- J.-A. J. Wang, H. Wang, Y. Yan, R. Howard, and B. Bevard, “High Burn-up Spent Fuel Vibration Integrity Study Progress Letter Report (Out-of-Cell Fatigue Testing Development–Task 2.1),” ORNL/TM-2010/288, Oak Ridge National Laboratory, Oak Ridge, TN, January 2011.
- J.-A. J. Wang, H. Wang, T. Tan, H. Jiang, T. Cox, and Y. Yan, “Progress Letter Report on U Frame Test Setup and Bending Fatigue Test for Vibration Integrity Study (Out-of-Cell Fatigue Testing Development–Task 2.2),” ORNL/TM-2011/531, Oak Ridge National Laboratory, Oak Ridge, TN, January 2012.
- J.-A. J. Wang, H. Wang, T. Cox, and Y. Yan, “Progress Letter Report on U-Frame Test Setup and Bending Fatigue Test for Vibration Integrity Study (Out-of-Cell Fatigue Testing Development–Task 2.3),” ORNL/TM-2012/417, Oak Ridge National Laboratory, Oak Ridge, TN, August 2012.
- J.-A. J. Wang, H. Wang, and Ting Tan, “An Innovative Dynamic Reversal Bending Fatigue Testing System for Evaluating Spent Nuclear Fuel Rod Vibration Integrity or Other Materials Fatigue Aging Performance,” ORNL Invention Disclosure 201102593, DOE S 124,149, April 8, 2011, Patent in review, 13/396,413, February 14, 2012.
- H. Wang, J.-A. J. Wang, T. Tan, H. Jiang, T. S. Cox, R. L. Howard, B. B. Bevard, and M. E. Flanagan, “Development of U-frame Bending System for Studying the Vibration Integrity of Spent Nuclear Fuel,” *Journal of Nuclear Materials* 440, 201–213 (2013).
- J.-A. J. Wang, H. Wang, B. B. Bevard, R. L. Howard, and M. E. Flanagan, “SNF Test System for Bending Stiffness and Vibration Integrity,” *International High-Level Radioactive Waste Management Conference*, Albuquerque, NM, April 28–May 2, 2013.
- J.-A. J. Wang, H. Wang, T. Cox, and C. Baldwin, “Progress Letter Report on Bending Fatigue Test System Development for Spent Nuclear Fuel Vibration Integrity Study (Out-of-Cell Fatigue Testing Development–Task 2.4),” ORNL/TM-2013/225, Oak Ridge National Laboratory, Oak Ridge, TN, July 2013.
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- J.-A. J. Wang and H. Wang, “Progress Letter Report on Reversal Bending Fatigue Testing of Zry-4 Surrogate Rod (Out-of-Cell Fatigue Testing Development–Task 2.4),” ORNL/TM-2013/297, Oak Ridge National Laboratory, Oak Ridge, TN, August 2013.
- J.-A. J. Wang and H. Wang, 2014 Semi-Annual Progress Letter Report on Used Nuclear Fuel Integrity Study in Transportation Environments, ORNL/TM-2014/63, April 2014
- J-A Wang, H. Jiang, and H. Wang, “Using Surrogate Rods to Investigate the Impact of Interface Bonding Efficiency on Spent Nuclear Fuel Vibration Integrity,” ORNL/TM-2014/257, July 2014.
- J-A Wang, H. Jiang, and H. Wang, “The Impact of Interface Bonding Efficiency on High Burn-up Spent Nuclear Fuel Vibration Integrity,” ORNL/TM-2014/288, August 2014.

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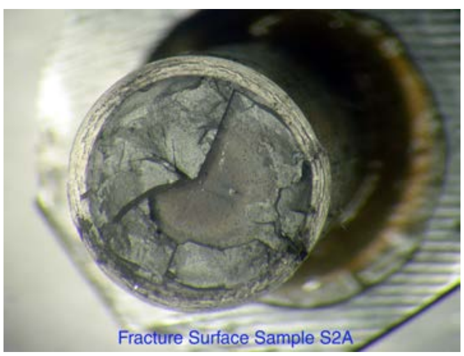
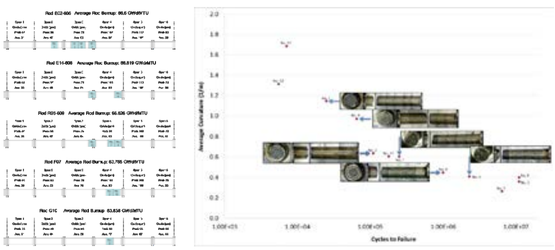


Fracture Surface Sample S2A



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Background