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Post-Irradiation Examinations of High-Burnup Pressurized Water Reactor Fuel Rods

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Outline

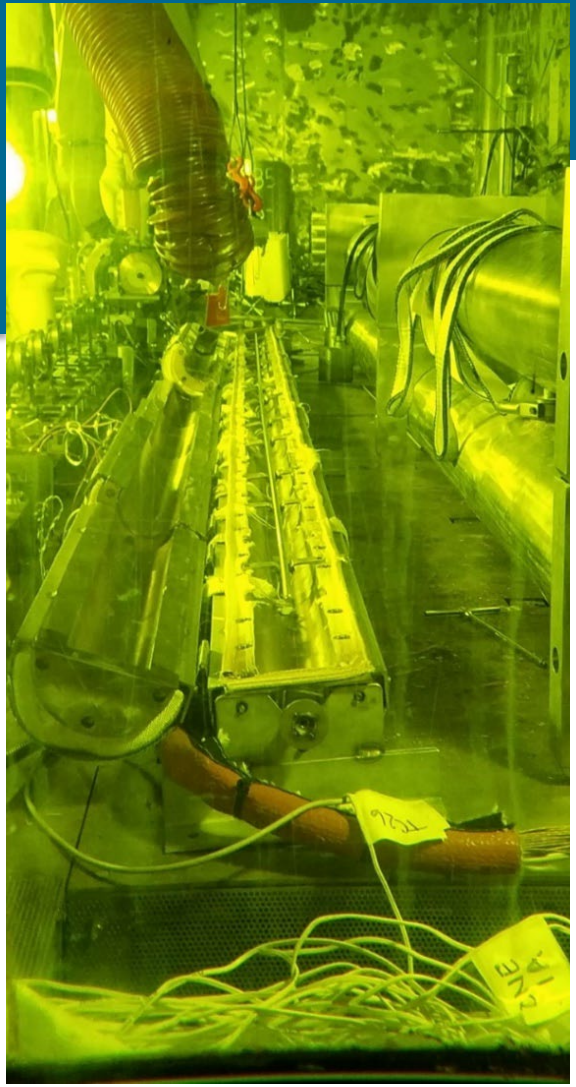
- Full-length rod heat treatments
- Rod internal pressure and free volume measurements
- Gas transmission and decompression tests
- Fission gas analysis results
- Metallographic results
- Plans for destructive examination

Phase 1 work will focus on characterization of 3 baseline rods and comparison with 3 heat-treated rods

- Three baseline rods—1 ZIRLO, 1 M5, and one low tin (LT) Zirc-4—are being examined
  - Optical microscopy will provide views of the pellet structure and cladding hydrides at selected rod elevations
  - Cladding total hydrogen and burnup will be determined at selected elevations
  - **Fueled** segment mechanical tests will be performed, including Cyclic Integrated Reversible-Bending Fatigue Tester (CIRFT), axial tension, 4-point bending, ring compression, microhardness, and burst tests
- Three corresponding sister rods have been heat treated to simulate dry storage vacuum drying and will be subjected to the same tests for comparison with the baseline rods

A specially designed heat treatment oven was used to simulate temperatures of dry storage vacuum drying on three sister rods: 1 M5, 1 ZIRLO, and 1 Zirc-4

- The oven has 7 zones using individual insulated heating blankets and is capable of multiple temperature profiles
- Each of the 3 selected sister rods was heat treated using a flat axial profile at 400 °C with a ≤5 °C/hr cooldown rate
- Each rod heat treatment included approximately 38 h heatup + 8 h at temperature + 100 h cooldown
- The metallographic and mechanical test results from the heat-treated rods will be compared with the data from baseline rods to determine if vacuum drying imposes any changes on the cladding



ORNL's 7-zone heat treatment oven located in the Irradiated Fuels Examination Laboratory can heat treat full length spent fuel rods.

Image provided by R.A. Montgomery; US Dept. of Energy, Oak Ridge National Laboratory

Rod internal pressure has been measured for 8 sister rods—3 baseline, 3 heat-treated, and 2 additional rods—and are between 3.2–4.7 MPa (464–682 psi) at 25 °C

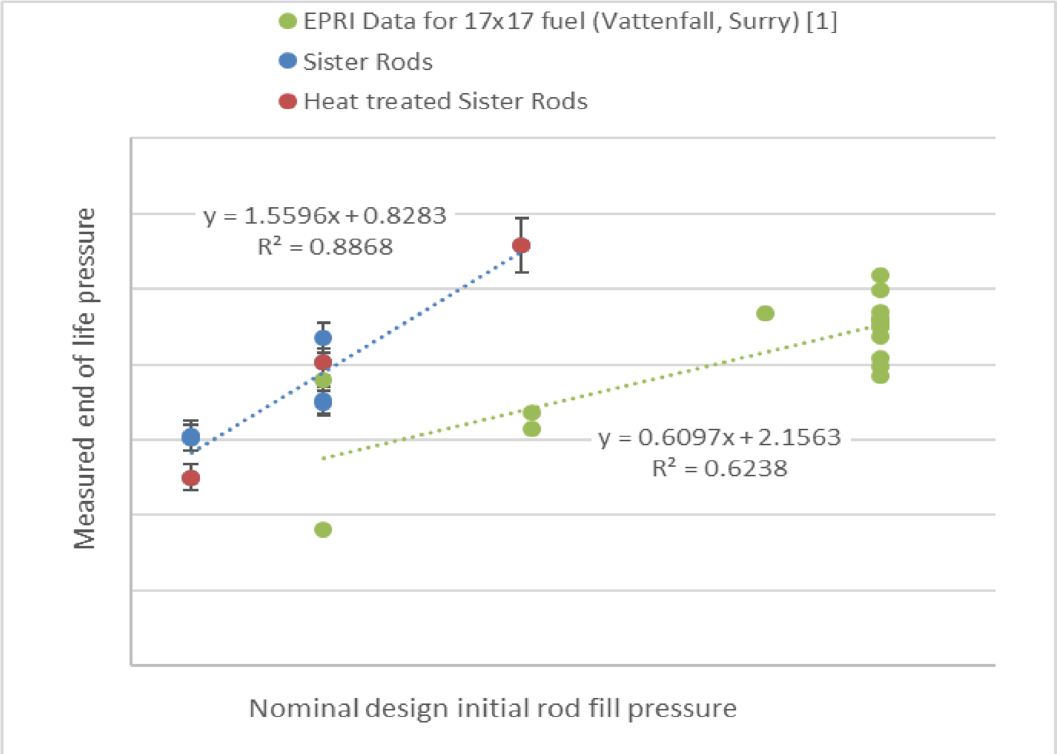


Image: R.A. Montgomery; US Dept. of Energy, Oak Ridge National Laboratory, including data from [1].

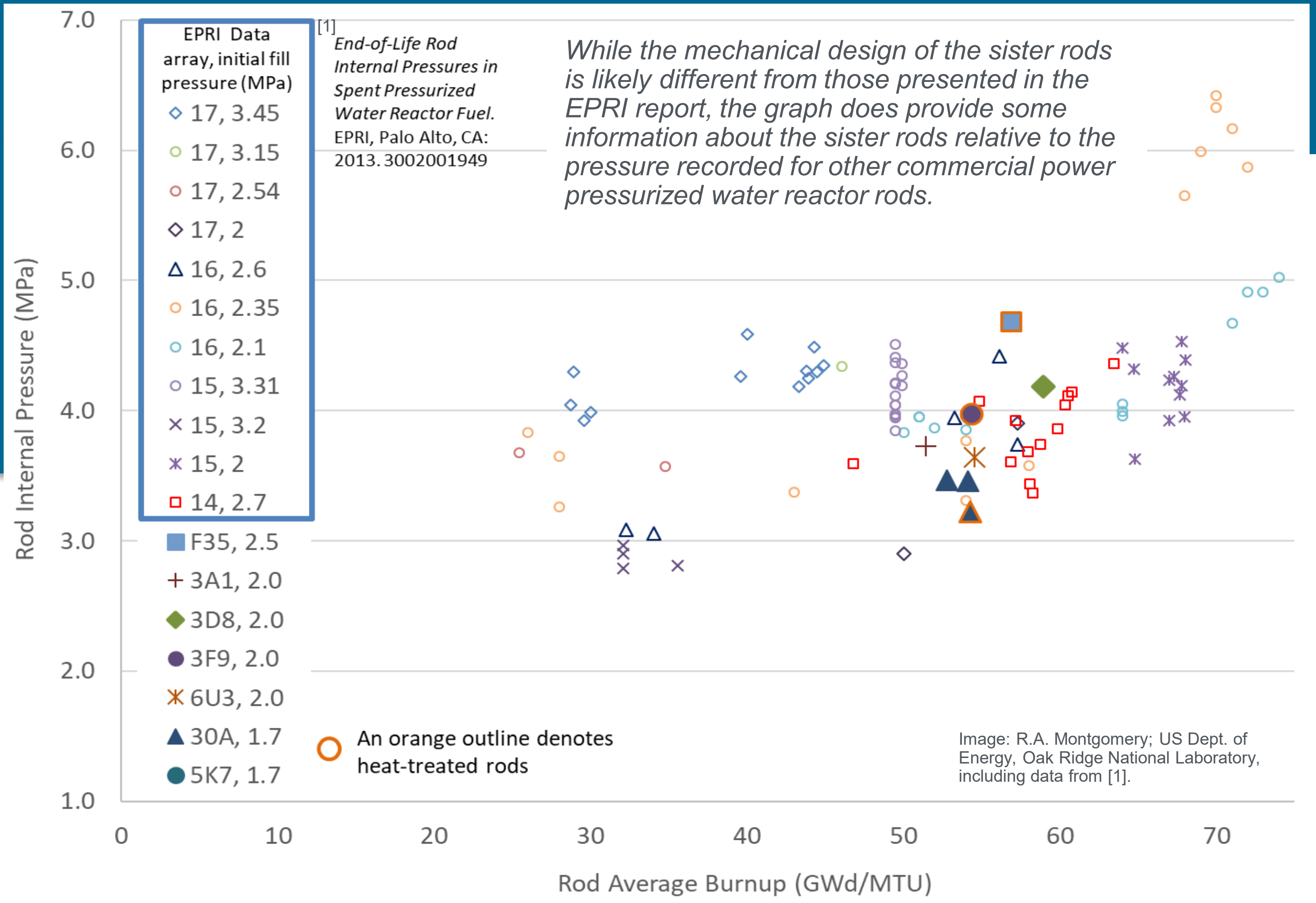


Image: R.A. Montgomery; US Dept. of Energy, Oak Ridge National Laboratory, including data from [1].

- Data include Zirc-4, LT Zirc-4, M5, and ZIRLO
- All are within the envelope of past data
- There is no apparent effect from the heat treatments

The internal free volumes of the 8 sister rods measured to date are between 9.9–13.3 cc

- Data include Zirc-4, LT Zirc-4, M5, and ZIRLO rods
- All are on the low side of past publicly available data collected by EPRI [1], which ranges from 11.1–39.5 cc
  - *Rod free volume at end of life is largely dependent on the initial free volume*
  - *The mechanical design of the sister rods is likely different from the older fuel rod designs within the EPRI database*
- There is no apparent effect due to heat treatments

[1] *End-of-Life Rod Internal Pressures in Spent Pressurized Water Reactor Fuel*, 3002001949, Electric Power Research Institute, Palo Alto, California, 2013.

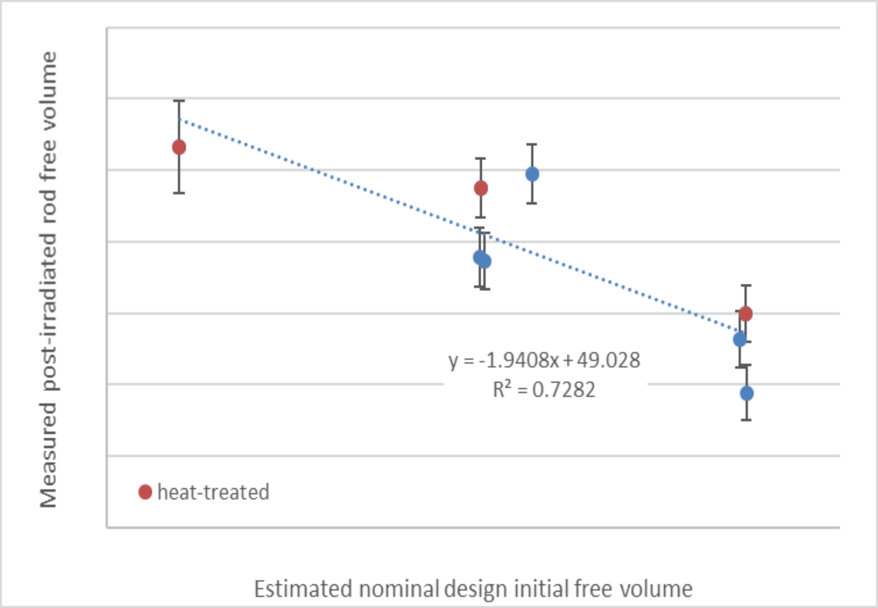


Image: R.A. Montgomery; US Dept. of Energy, Oak Ridge National Laboratory

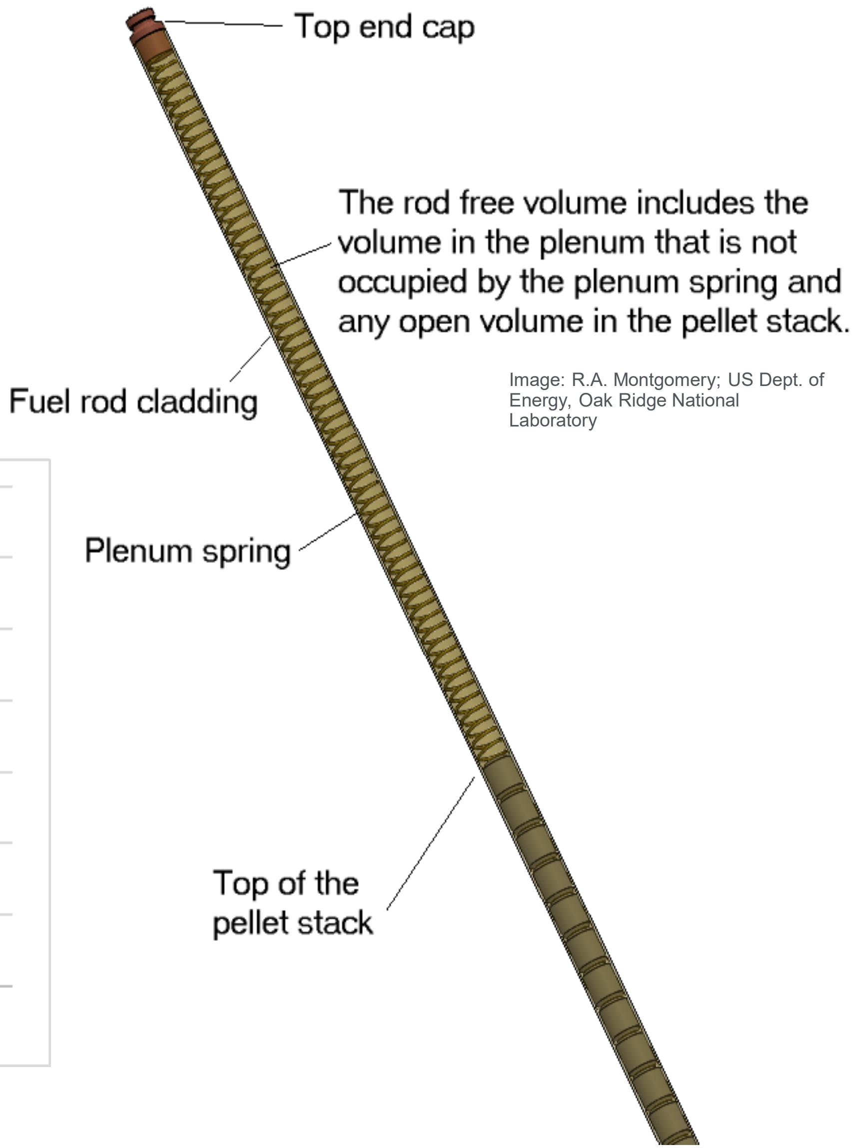


Image: R.A. Montgomery; US Dept. of Energy, Oak Ridge National Laboratory

Decompression tests were performed to determine if fission gases could flow freely through the full length of the fuel rod

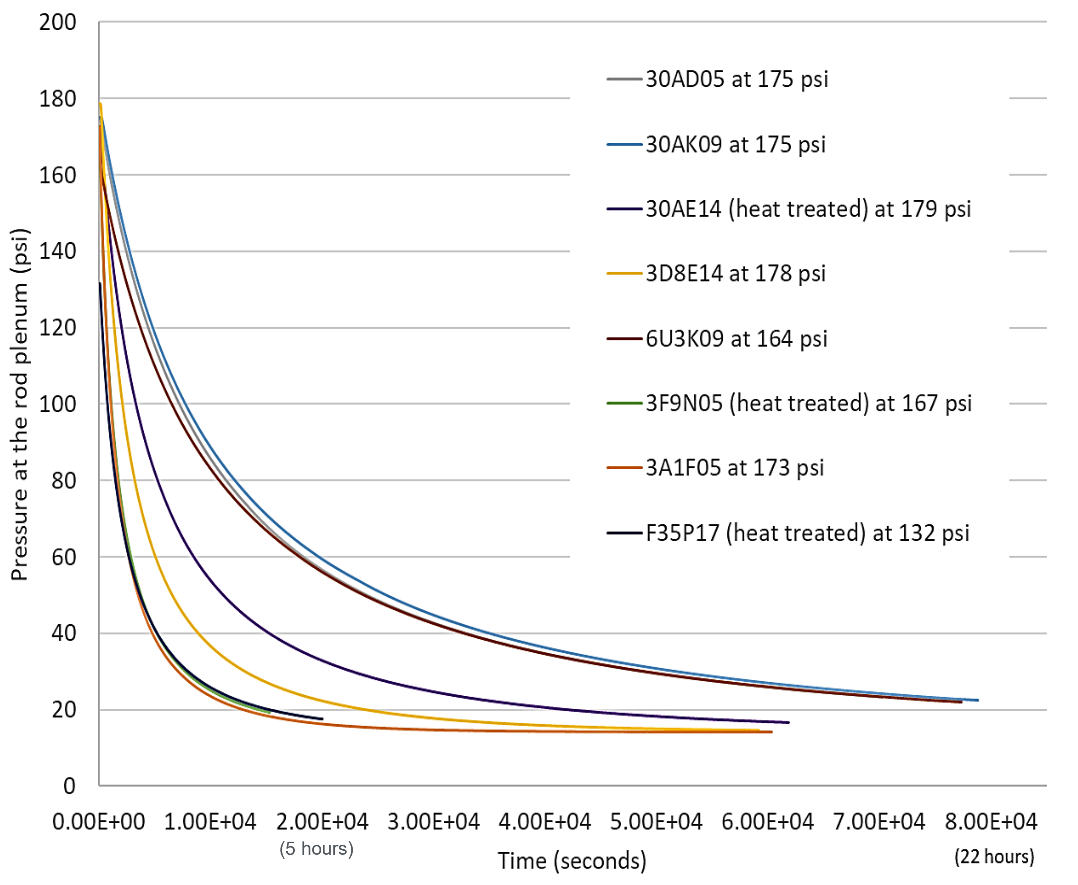


Image: R.A. Montgomery and R.N. Morris; US Dept. of Energy, Oak Ridge National Laboratory

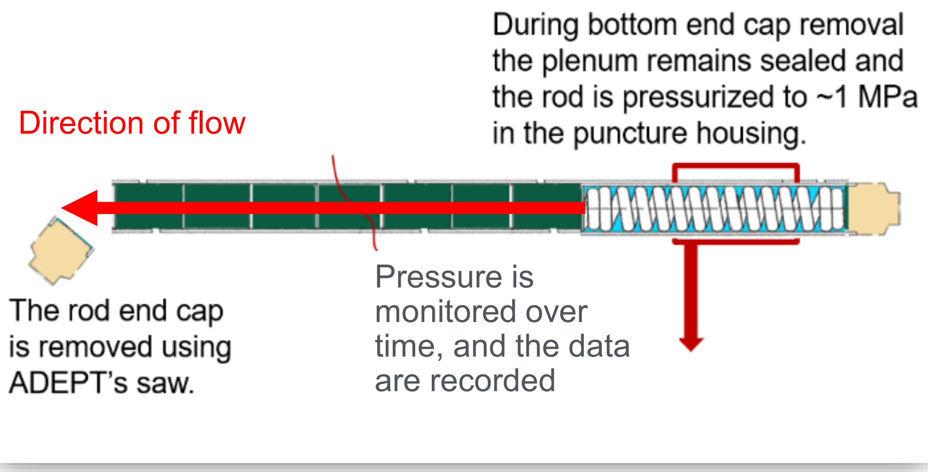


Image: R.A. Montgomery and R.N. Morris; US Dept. of Energy, Oak Ridge National Laboratory

- The rod plenum was pressurized with argon, and the bottom end cap was cut off the rod
- The pressure in the plenum was monitored over time, and a decrease in plenum pressure indicated that gas can flow through the stack
- Eight full-length rods were tested; no obvious difference was observed for heat-treated rods
- The applied starting pressure was about 1/3 of the typical end of life rod internal pressure; results indicate a higher starting pressure results in a shorter decompression time
- Since this test decompressed both the rod and apparatus volume, the time measured is likely ~3 times longer than the rod alone

All rods had good communication along the entire pellet stack at room temperature (RT).

This test simulates a rod with a large leak and provides rare data on the ability of fission gas to move through the pellet stack.

Gas transmission tests that applied and maintained pressure in the opposite direction were also performed

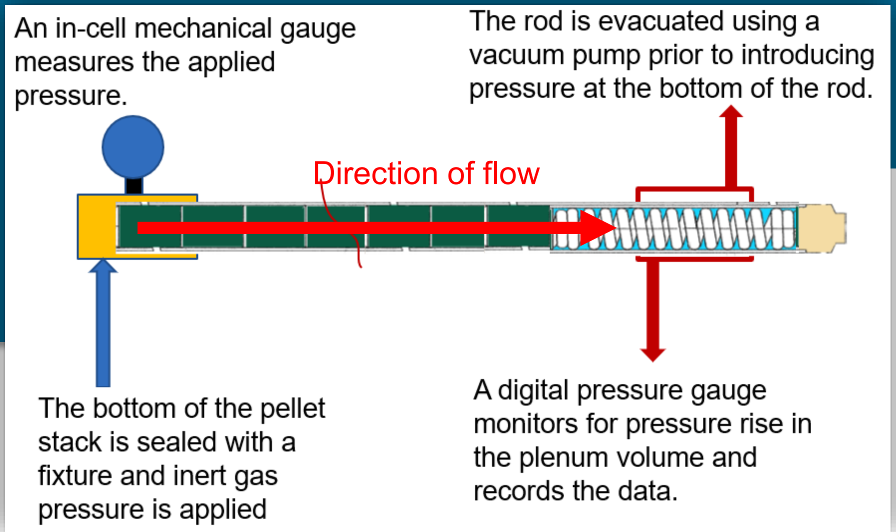


Image: R.A. Montgomery and R.N. Morris; US Dept. of Energy, Oak Ridge National Laboratory

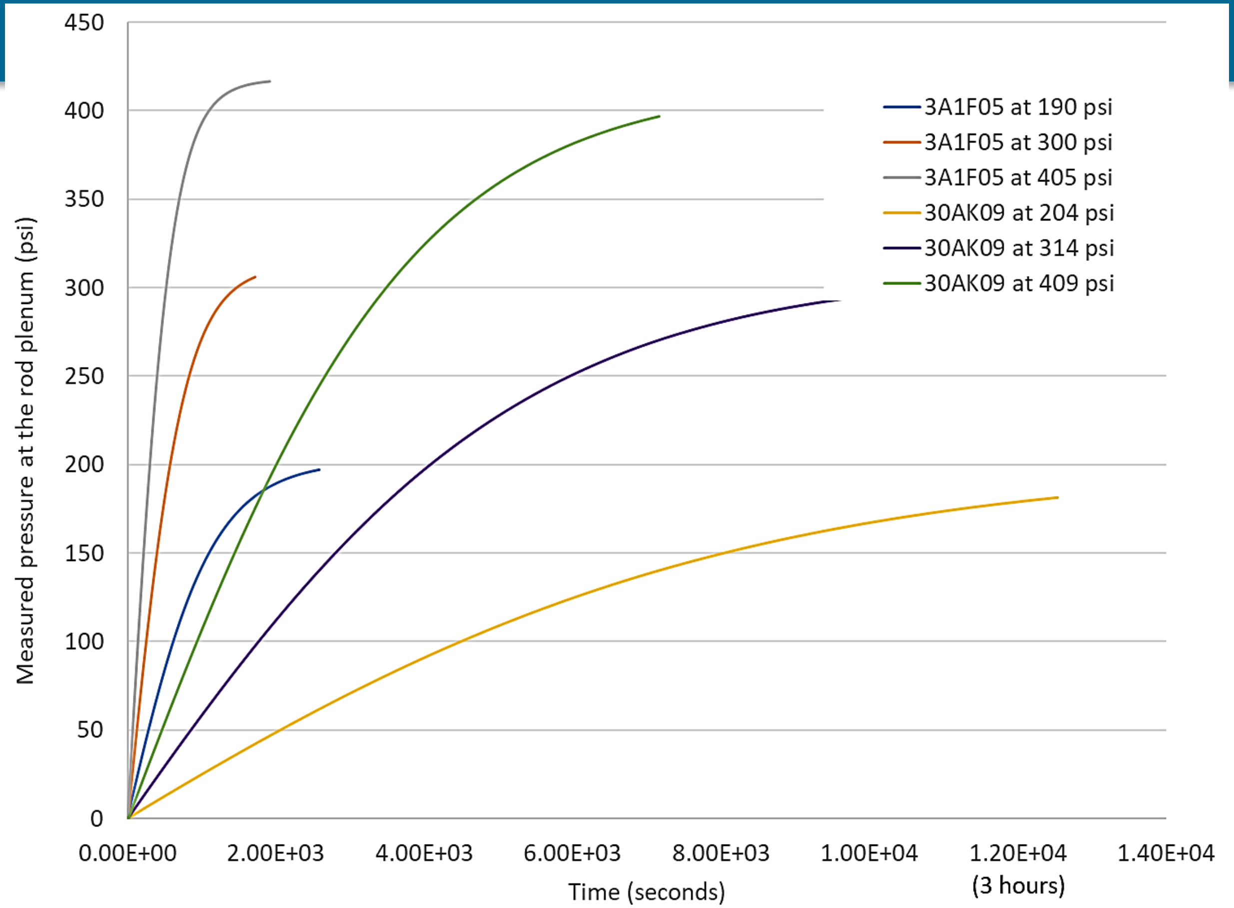


Image: R.A. Montgomery and R.N. Morris; US Dept. of Energy, Oak Ridge National Laboratory

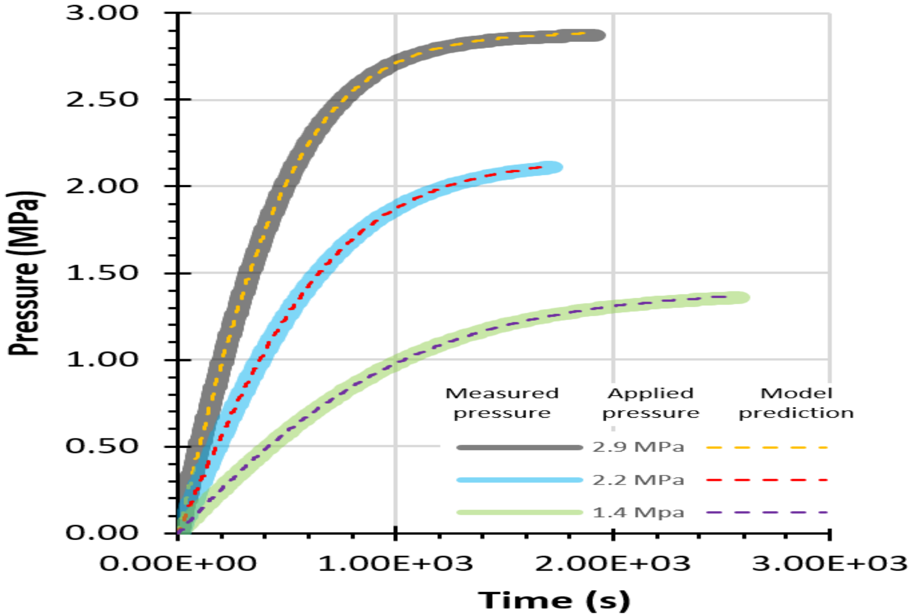
- Two full-length rods were tested; no heat treated rods were tested
- Pressure (argon) was applied at the bottom of the pellet stack
- The pressure was monitored at the rod plenum
- The applied starting pressure ranged from 35 to 80% of the measured end of life rod internal pressure; results indicate higher starting differential pressures result in a shorter time required to move through the stack

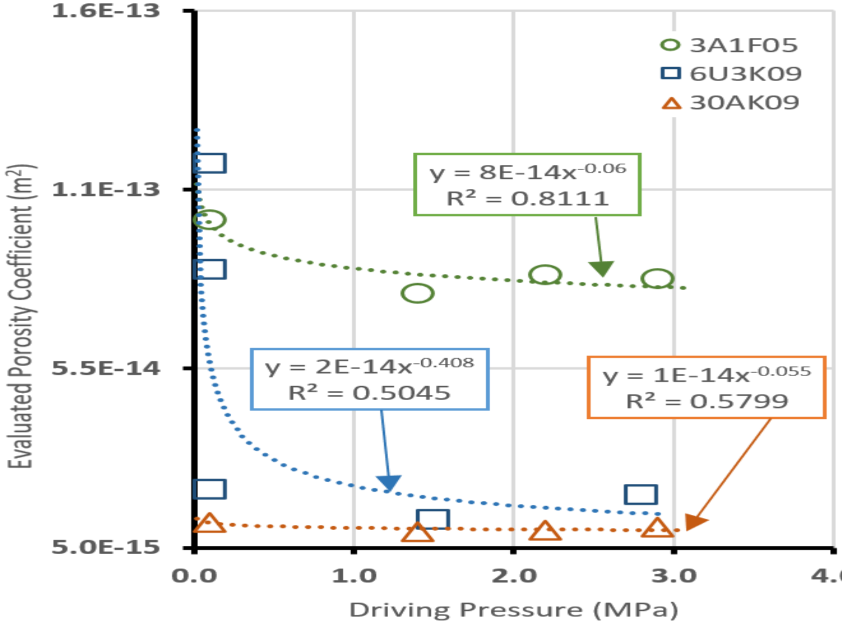
Both rods had good communication along the entire pellet stack at RT.

The test provides rare data on the ability of fission gases to move through the stack during transients.

Transmissibility through the pellet stack of a full length HBU rod is well correlated to a porosity factor and a time constant can be derived.

- Testing of the sister rods revealed that gas communication from one end of the pellet stack to the other is unobstructed, but slow, at RT.
- The flow regime appears to be somewhat similar to turbulent or choked flow conditions when a high pressure differential exists and approaches Darcy conditions at low pressure differentials.
- The time constants derived were on the order of minutes to hours depending on the starting pressure.
  - Gas equilibrium occurs over several hours, rather than in minutes or seconds.
  - How this changes as the rod is raised to higher temperature is not known, but some change in permeability due to thermal expansion effects is expected.
- The permeability of the pellet stack varied over less than an order of magnitude for this set of rods and may indicate some common feature about high burn-up fuel.
- Graphs of the data with burnup, lifetime maximum High Duty Core Index (HDCI), and operating lifetime average assembly middle of cycle predicted fuel temperature appear to indicate that the derived porosity coefficients are correlated to fuel temperature and maximum HDCI, but not to rod average burnup.



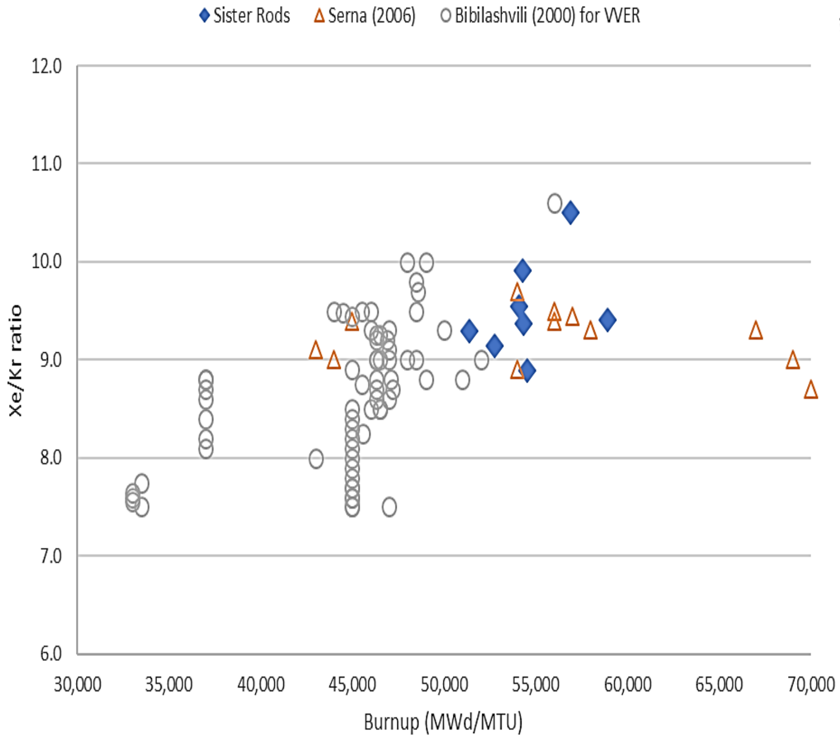


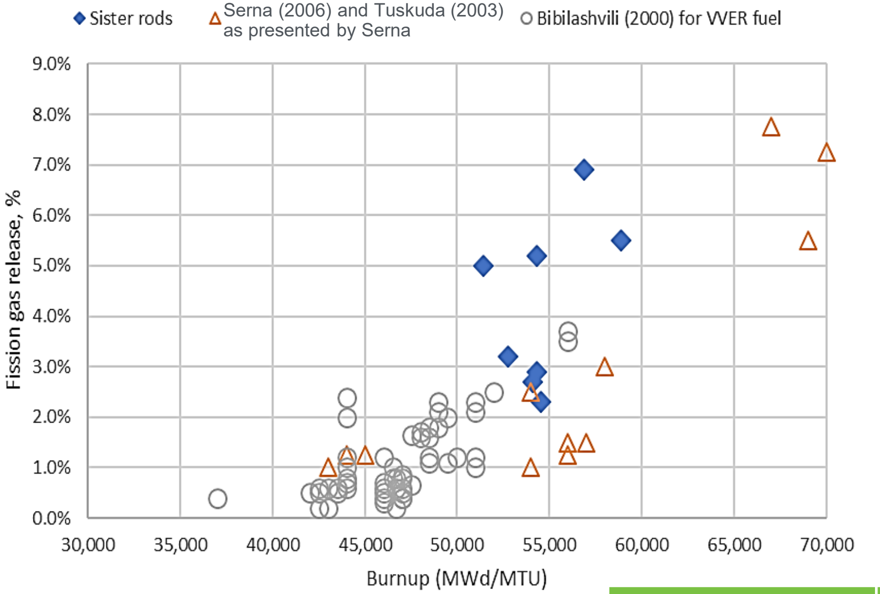
(Top) Rod 3A1F05 gas transmission tests at three different pressures. The time constants are 296, 389, and 639s, from highest to lowest pressure.

(Bottom) Variation of the evaluated porosity coefficient with the test driving pressure.

Images: R.A. Montgomery and R.N. Morris; US Dept. of Energy, Oak Ridge National Laboratory

Fission gas was sampled from the rod plenum and analysis results compare well with other available data



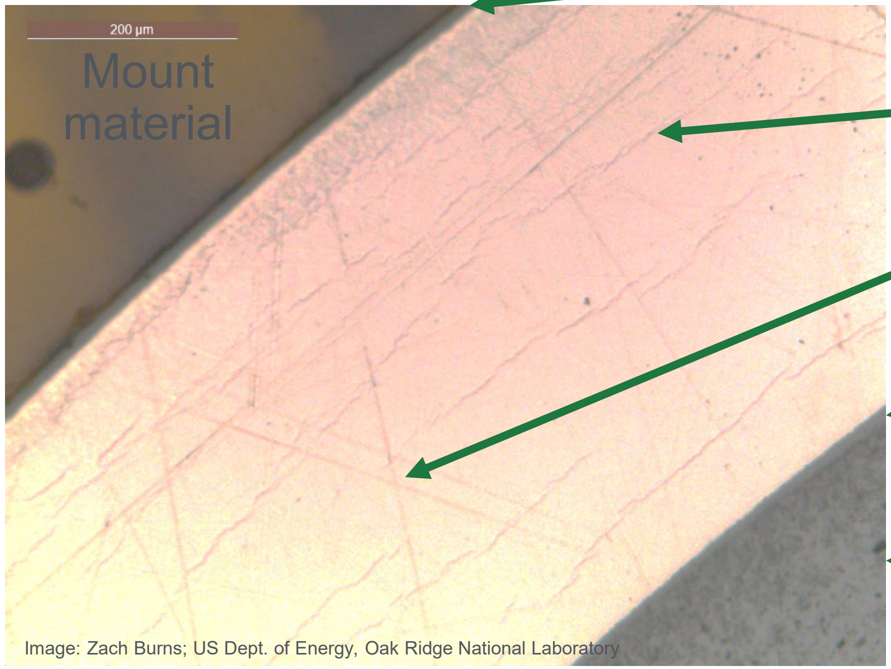


Images: R.A. Montgomery; US Dept. of Energy, Oak Ridge National Laboratory, with comparison data from [1] and [2].

1. Juan J.Serna et al. (2006) Experimental Observations on Fuel Pellet Performance at High Burnup, Journal of Nuclear Science and Technology, 43:9, 1045-1053.
2. Yu.K. Bibilashvili et al. (2000) Development of the Fission Gas Behaviour Model in the START-3 Code and its Experimental Support, Seminar Proceedings, Fission Gas Behaviour in Water Reactor Fuels, Cadarache, France.

Rod	Kr	Xe	He	Xe/Kr
6U3K09	1.1%	10.1%	88.8%	8.9
30AK09	1.7%	15.1%	83.0%	9.1
3D8E14	2.5%	23.1%	74.2%	9.4
3A1F05	2.1%	19.4%	78.9%	9.3
30AD05	1.5%	14.3%	84.1%	9.5
30AE14	1.6%	15.5%	83.3%	9.9
3F9N05	2.2%	20.7%	77.5%	9.4
F35P17	1.9%	20.4%	78.0%	10.5

Initial metallographic (MET) views of M5-clad sister rods 30AD05 (baseline) and 30AE14 (heat-treated) are being reviewed to determine if hydride reorientation resulted from the in-cell heat-treatment to 400˚C



As-Irradiated (3,240 mm elevation)

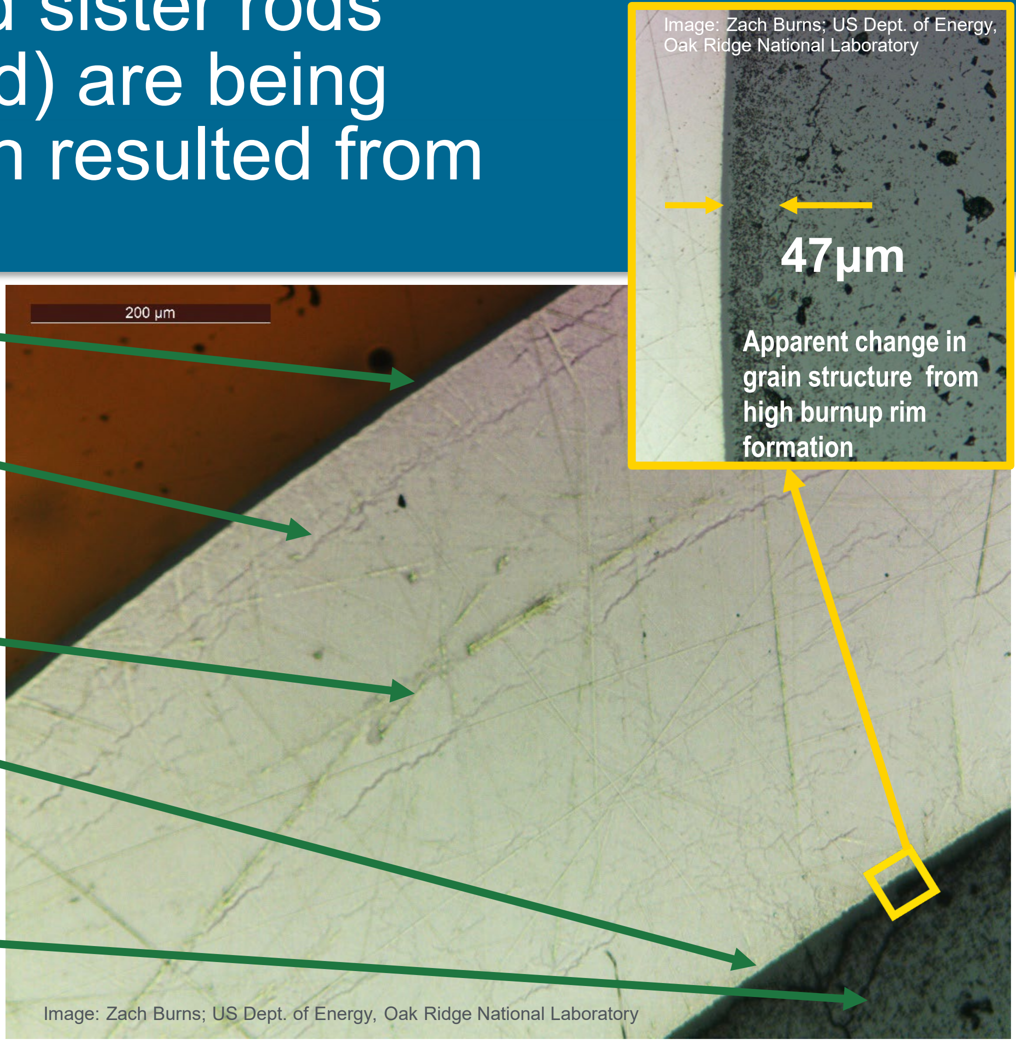
Waterside oxide layer

Circumferential Hydrides

Sample polishing artifacts

Pelletside oxide layer

pellet



Heat-treated (3,339 mm elevation)

These initial low-quality images are presented as a quick look at the data. Better quality images for the first six rods are expected to be available at the next ESCP meeting.

Total hydrogen analysis of selected rod elevations will begin in the spring.

Destructive mechanical testing will begin in 2018

- Initial mechanical testing program includes
  - 1 M5 baseline rod and
    1 M5 heat-treated rod
  - 1 ZIRLO baseline rod and
    1 ZIRLO heat-treated rod
  - 1 LT Zirc-4 baseline rod and
    1 Zirc-4 heat-treated rod

Planned ORNL Mechanical Tests	Planned Start
Cyclic reversible fatigue (CIRFT) at RT	11/2018
Fueled ring compression at RT	1/2019
Axial tension at RT and at 200 °C	2/2019
Four-point bending at RT and at 200 °C	4/2019
Microhardness at RT and at 200 °C	4/2019
Fueled burst tests (temperature TBD)	6/2019

Summary

- Rod characterization work is underway, including metallography, burnup determination, and cladding total hydrogen measurements
- Data on rod internal pressure, free volume, and fission gas analysis are consistent with other available data
- Gas transmission and decompression tests indicate that, at room temperature, the fission gas can travel (albeit relatively slowly) through the whole pellet stack
- Destructive mechanical testing is planned to begin in January 2019 and will focus on fueled rod segments
- Planned tests include CIRFT, axial tension, 4-point bend, fueled ring compression, microhardness, and burst tests on the 6 selected sister rods