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Post-Irradiation Examinations of High-Burnup PWR Fuel Rods—Initial Results

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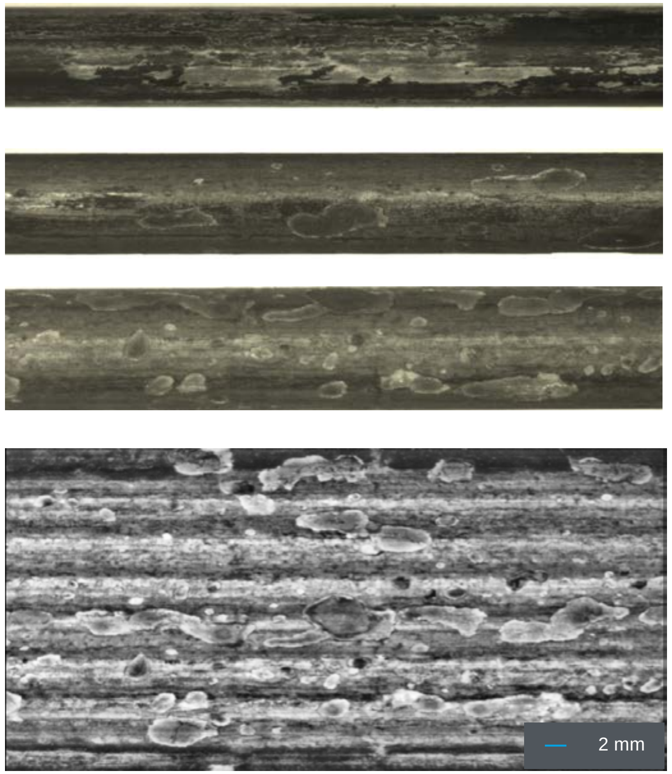
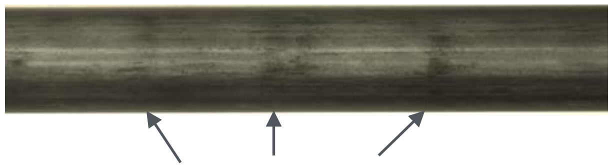
- Oxidation and CRUD levels varied among cladding alloys
- GTRF ranged from shallow to deep, but there were no observations of through-wall penetrations
- Pellet-to-pellet interfaces are often observable
- Pellet stack gaps were detected on nine rods ranging from 1 to 5 mm

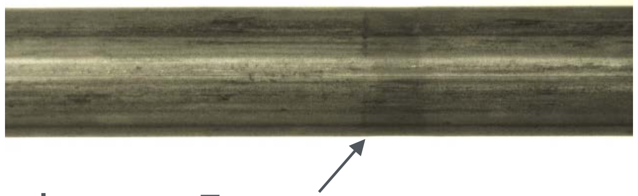
Examples of oxidized surfaces and CRUD deposits



Examples of GTRF marks



Pellet interfaces



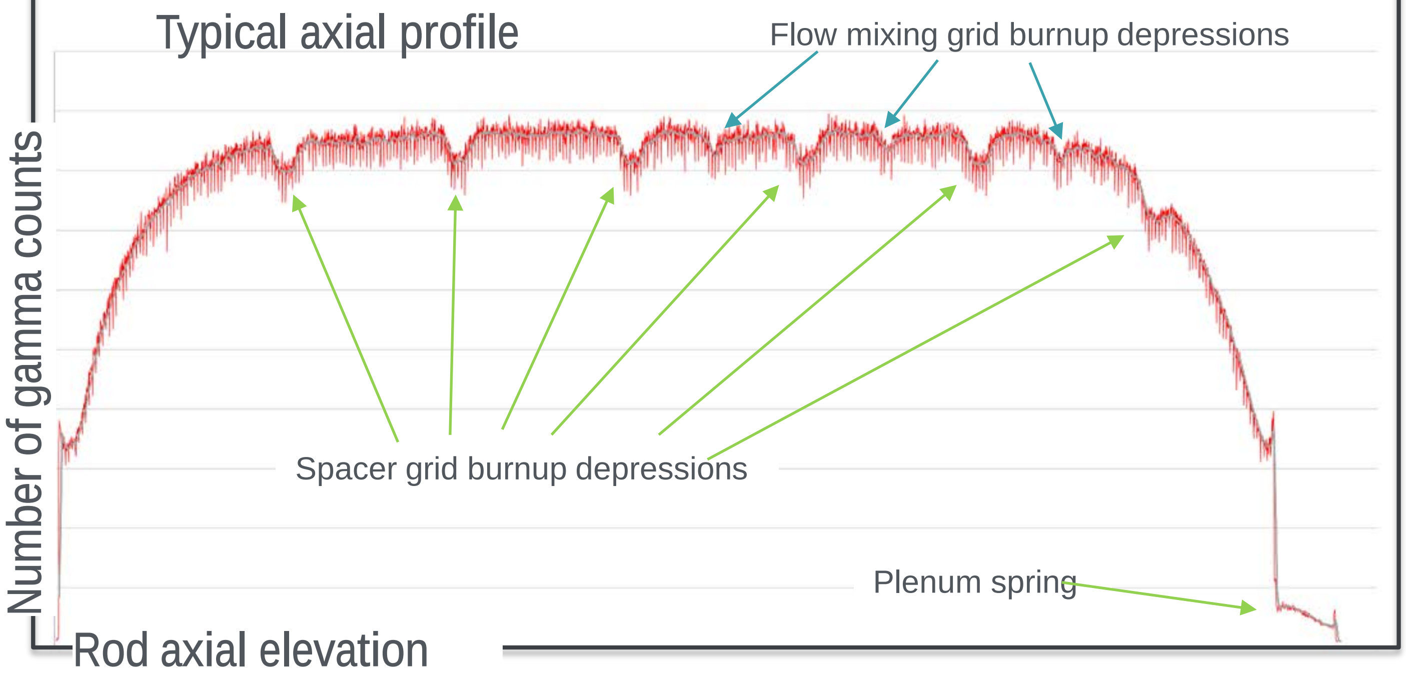
Visible pellet stack gap ~5 mm

Axial burnup profiles were as expected, with depressions in burnup at spacer grid locations and pellets clearly discernable

- Gamma scanning was used to
  - Measure relative gamma activity as a function of axial position
  - Note burnup depressions that indicate spacer grid elevations
  - Determine pellet stack height
  - Identify individual pellets and locate any gaps between pellets
  - Support identification of cutting locations for destructive test specimens

Rod cladding type & parent assembly*	Average pellet length (mm)	Average number of pellets in the rod	Average plenum length (mm)	Average fuel stack length (mm)	Average rod length (mm)
M5 / 30A	10.2	359	182	3,677	3,882
M5 / 5K7	10.1	363	181	3,679	3,884
ZIRLO / 6U3	9.9	372	179	3,679	3,890
ZIRLO / 3D8	10.1	367	175	3,685	3,891
ZIRLO / 3F9	9.9	374	177	3,682	3,891
LT Zirc-4 / 3A1	9.9	371	192	3,682	3,893
Zirc-4 / F35	13.7	270	175	3,695	3,888

*Pellet, plenum, stack length: ±1.5 mm; Rod length, ±0.5 mm



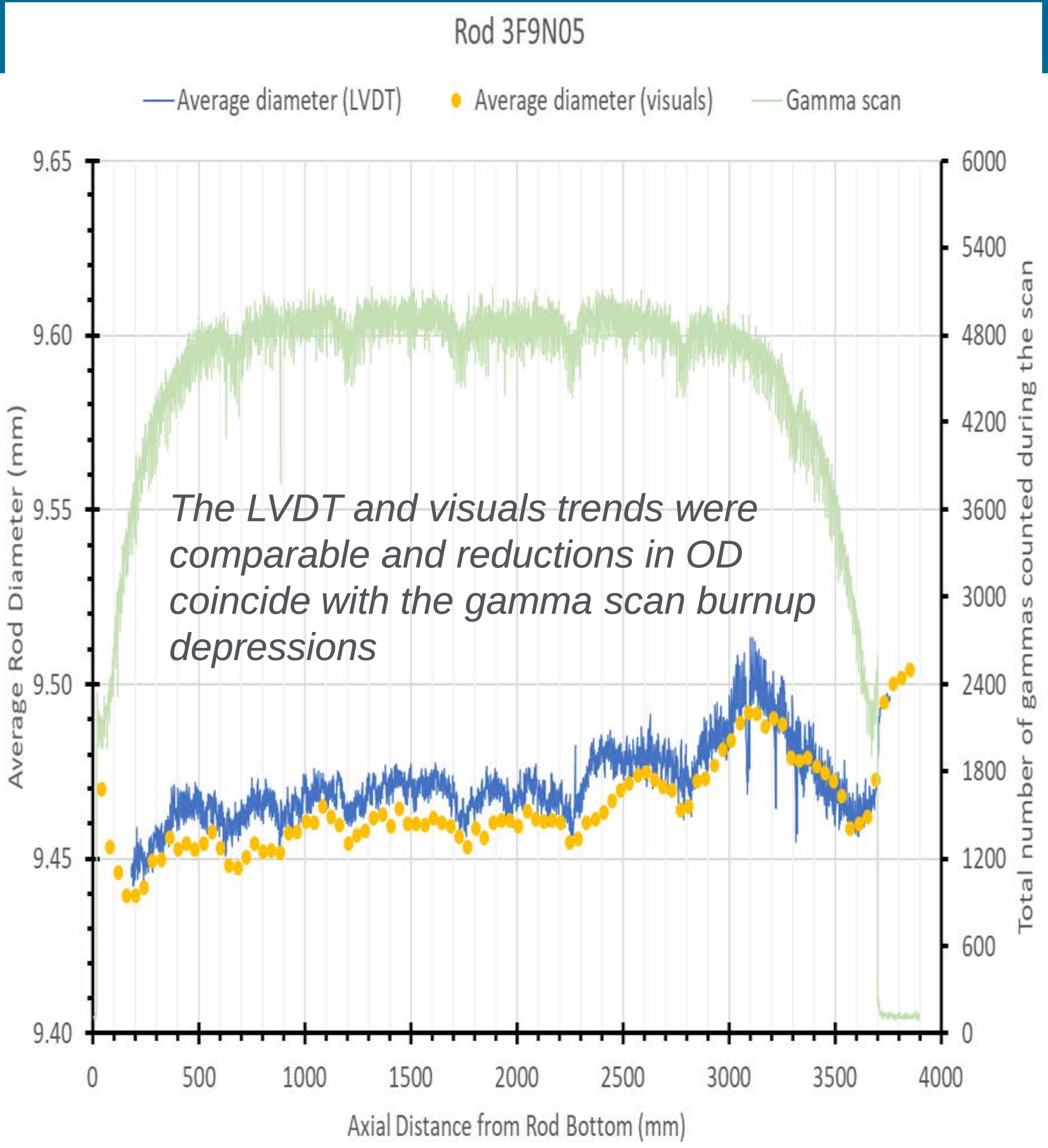
The rod's diameter follows the expected axial trend and is larger in HBU regions and smaller in lower-burnup regions

- The outer diameter of each sister rod was measured along its longitudinal axis in two ways
  1. A pair of linear variable differential transformers (LVDTs) was used to obtain orthogonal measurements
  2. ORNL developed an alternate diameter measurement technique utilizing the sister rod photographic database
     - A length-to-pixel ratio was determined by photographing a calibration rod

LVDT-measured outer rod diameter

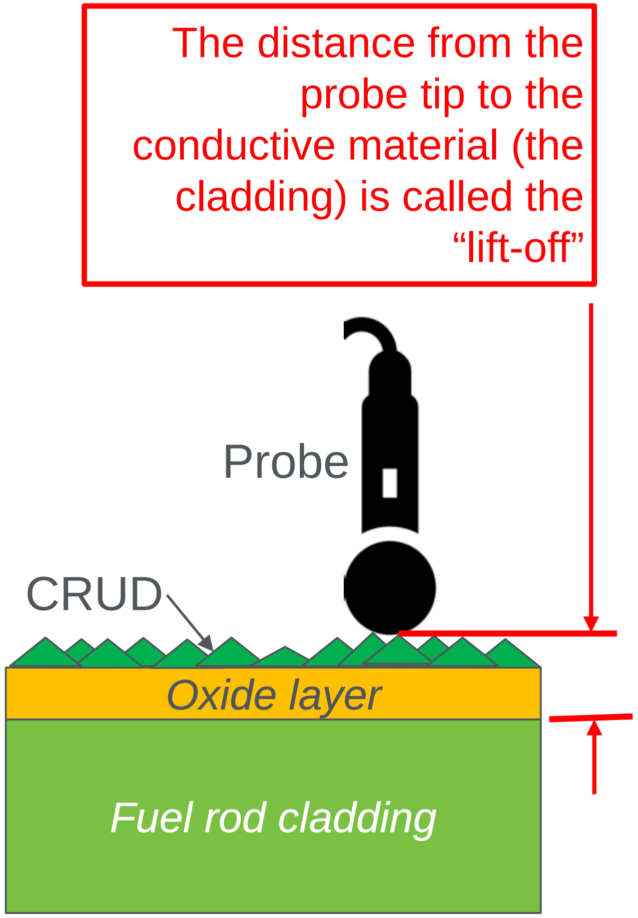
±0.02 mm

Cladding type / parent fuel assembly	Maximum measured OD (mm)	Average rod OD (mm)
M5 / 30A	9.51	9.45
M5 / 5K7	9.50	9.45
ZIRLO / 3D8	9.53	9.48
ZIRLO / 3F9	9.51	9.46
ZIRLO / 6U3	9.53	9.46
LT Zirc-4 / 3A1	9.61	9.48
Zirc-4 / F35	9.62	9.50



Eddy current scans were completed to measure lift-off and to look for cladding flaws

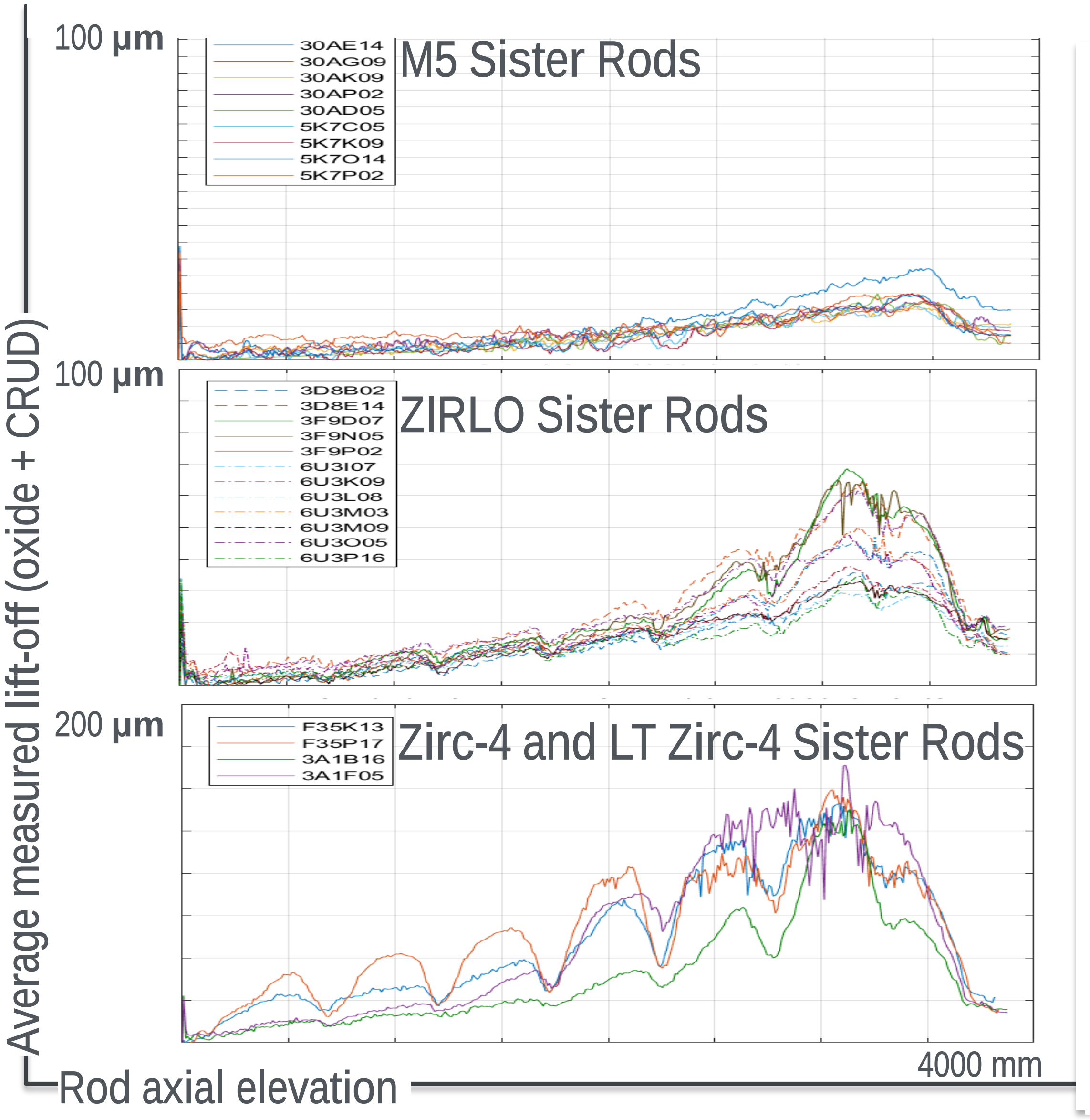
- Eddy current lift-off measurements use a contact probe to measure the distance from the probe tip to the electrically conductive surface (the fuel rod cladding)
- The measurement includes the thickness of any nonconductive surfaces between the probe tip and the cladding, including oxide, CRUD, and foreign material.
- Spalling oxide results in the indication of a thinner lift-off

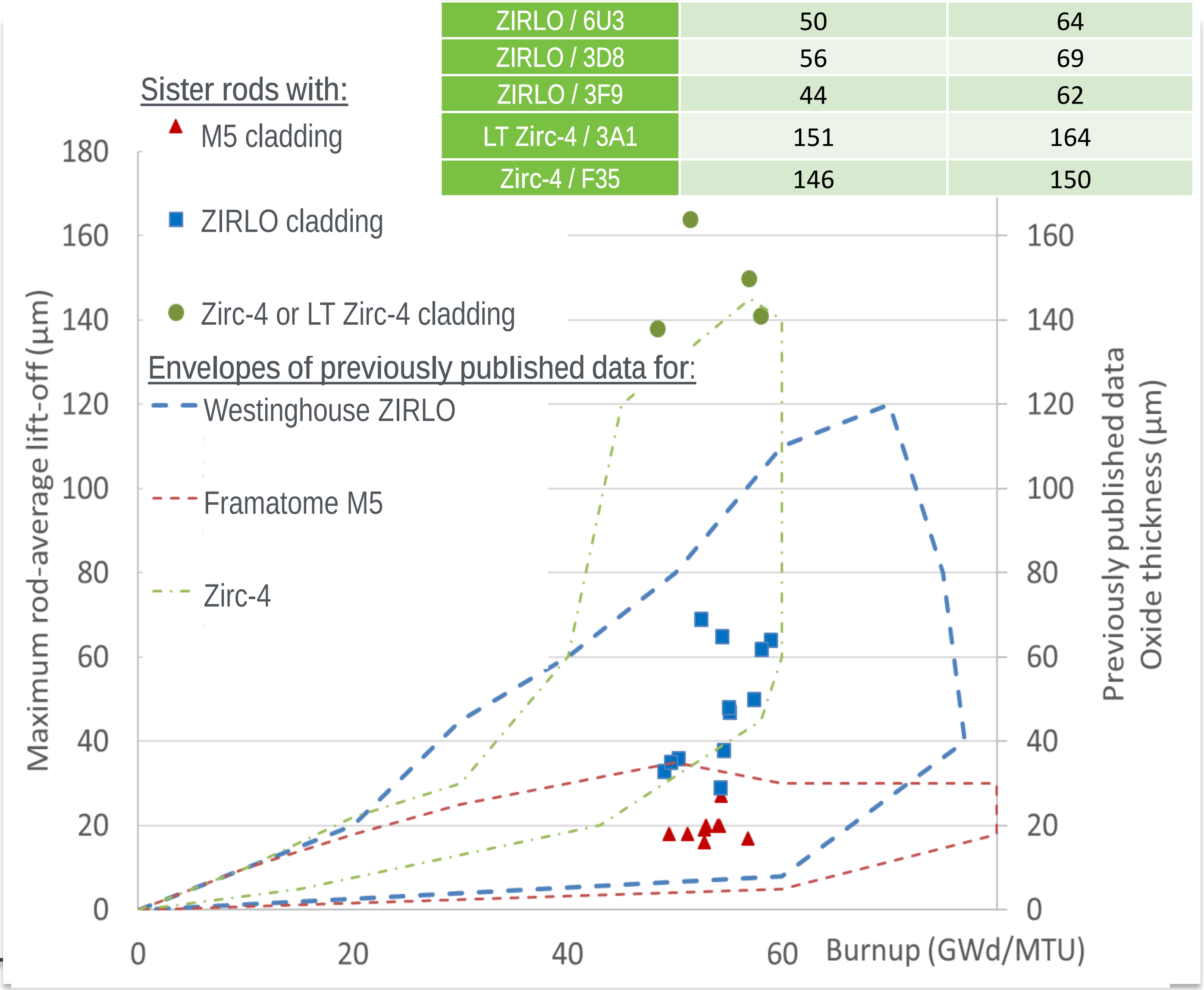


Lift-off measurement configuration

Average results were as expected, with the Zirc-4 and LT Zirc-4 clad rods having the highest lift-offs

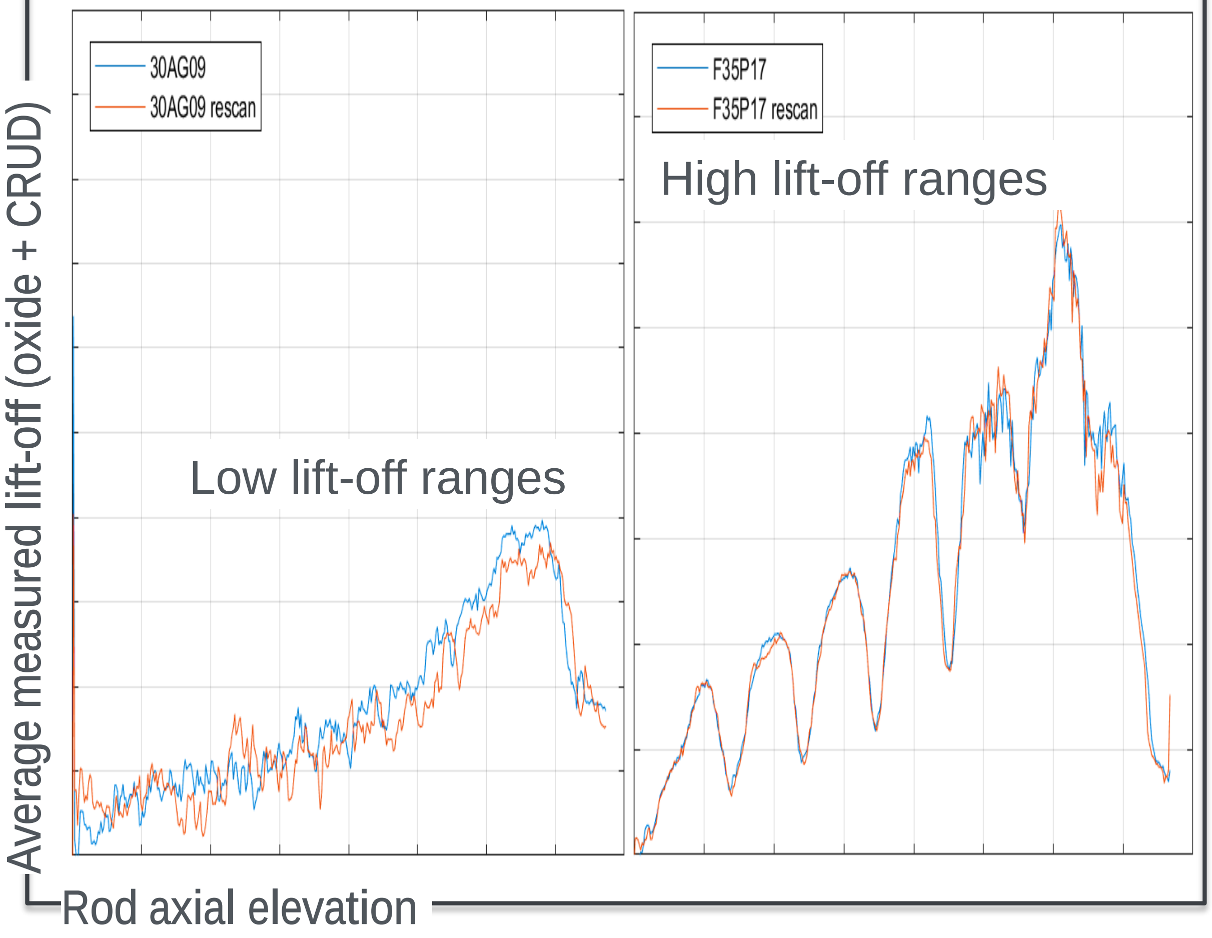
Rod cladding type & parent assembly	Average maximum rod-average measured lift-off, µm	Maximum rod average lift-off, µm
M5 / 30A	20	27
M5 / 5K7	19	20
ZIRLO / 6U3	50	64
ZIRLO / 3D8	56	69
ZIRLO / 3F9	44	62
LT Zirc-4 / 3A1	151	164
Zirc-4 / F35	146	150





The ORNL lift-off measurements were repeatable, but are higher than other independent measurements

- Some rods were scanned using ORNL's system more than once and on different days, demonstrating very good repeatability



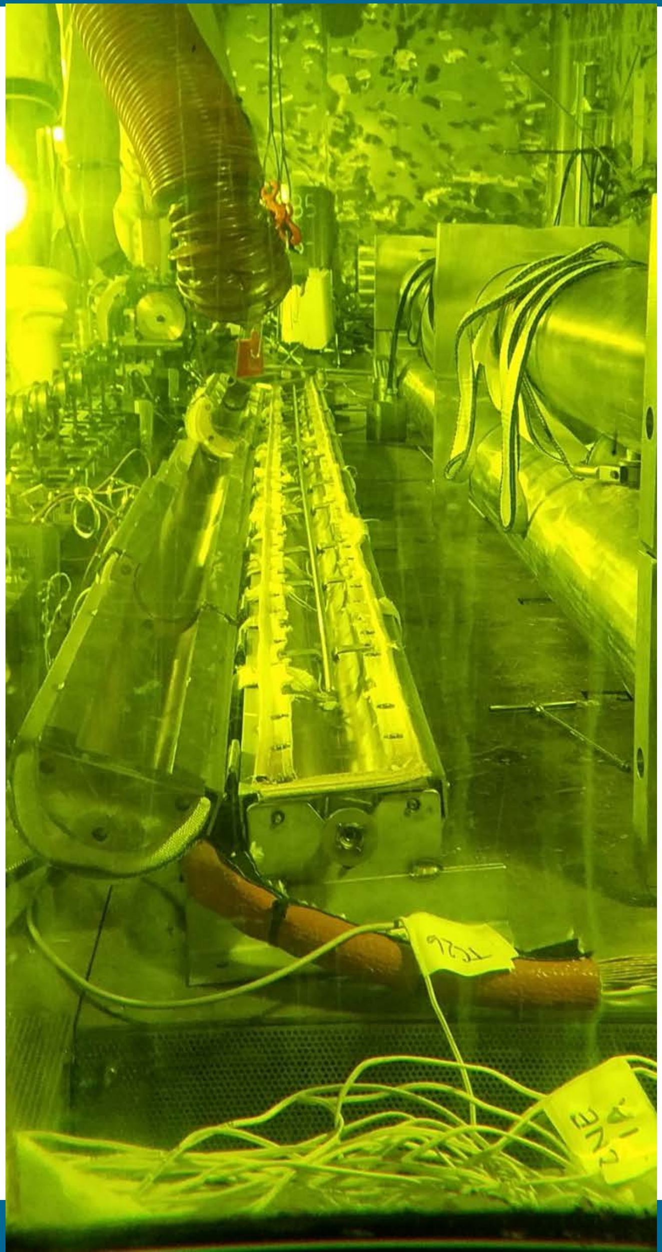
- EPRI performed a separate exam on the sister rods using a different set of eddy current coils (F-SECT) at discrete rod elevations
- Historical data available for two Zirc-4 F35 sister rods (circa 2002) indicates a lower average maximum lift-off, however, these two rods have a lot of spalling
- The metallography samples to be examined during the destructive examinations of the sister rods are expected to provide a definitive oxide thickness measurement for each sister rod

Cladding alloy	Alloy average lift-off, µm ORNL	EPRI F-SECT	Previous poolside [1]
M5	19	~17	n/a
ZIRLO	48	~45	n/a
LT Zirc-4	151	~105	n/a
Zirc-4	146	~130	113

1. Balfour, M. G., et al. *Corrosion of Zircaloy-Clad Fuel Rods in High-Temperature PWRs: Measurement of Waterside Corrosion in North Anna Unit 1, Interim Report, March 1992,* prepared by Westinghouse Electric Corporation for Electric Power Research Institute, TR-1004008, Tier 2 Research Project 2757-1, 1992.

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

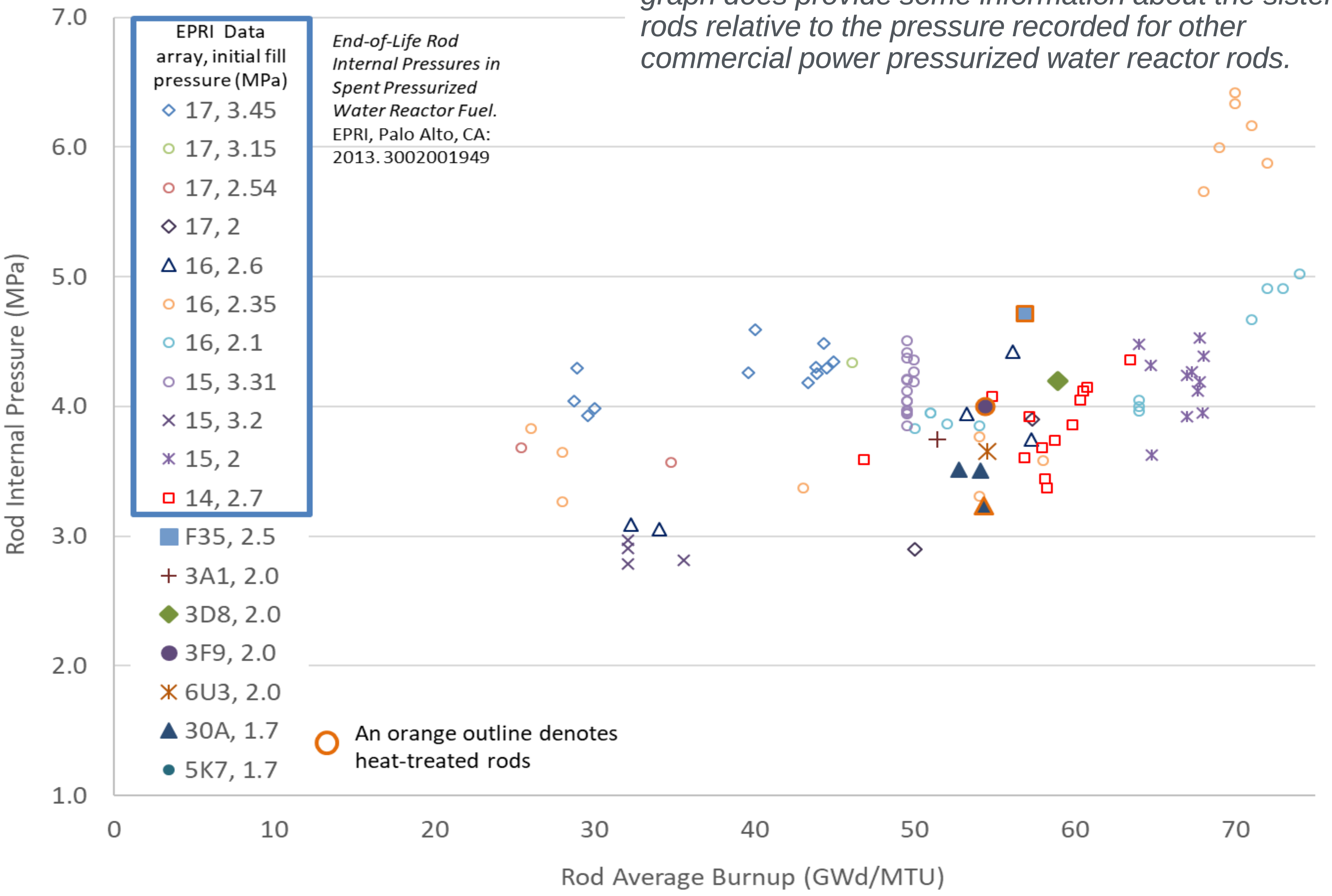
- The oven has seven zones using individual insulated heating blankets and is capable of multiple temperature profiles
- Each of the three selected sister rods was heat-treated using a flat axial profile at 400°C with a ≤ 5°C cooldown rate
- Each rod heat treatment included approximately 38 h heatup + 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



The rod internal pressures of eight sister rods have been measured and are between 3.2 and 4.7 MPa (464 to 682 psi) at 25°C

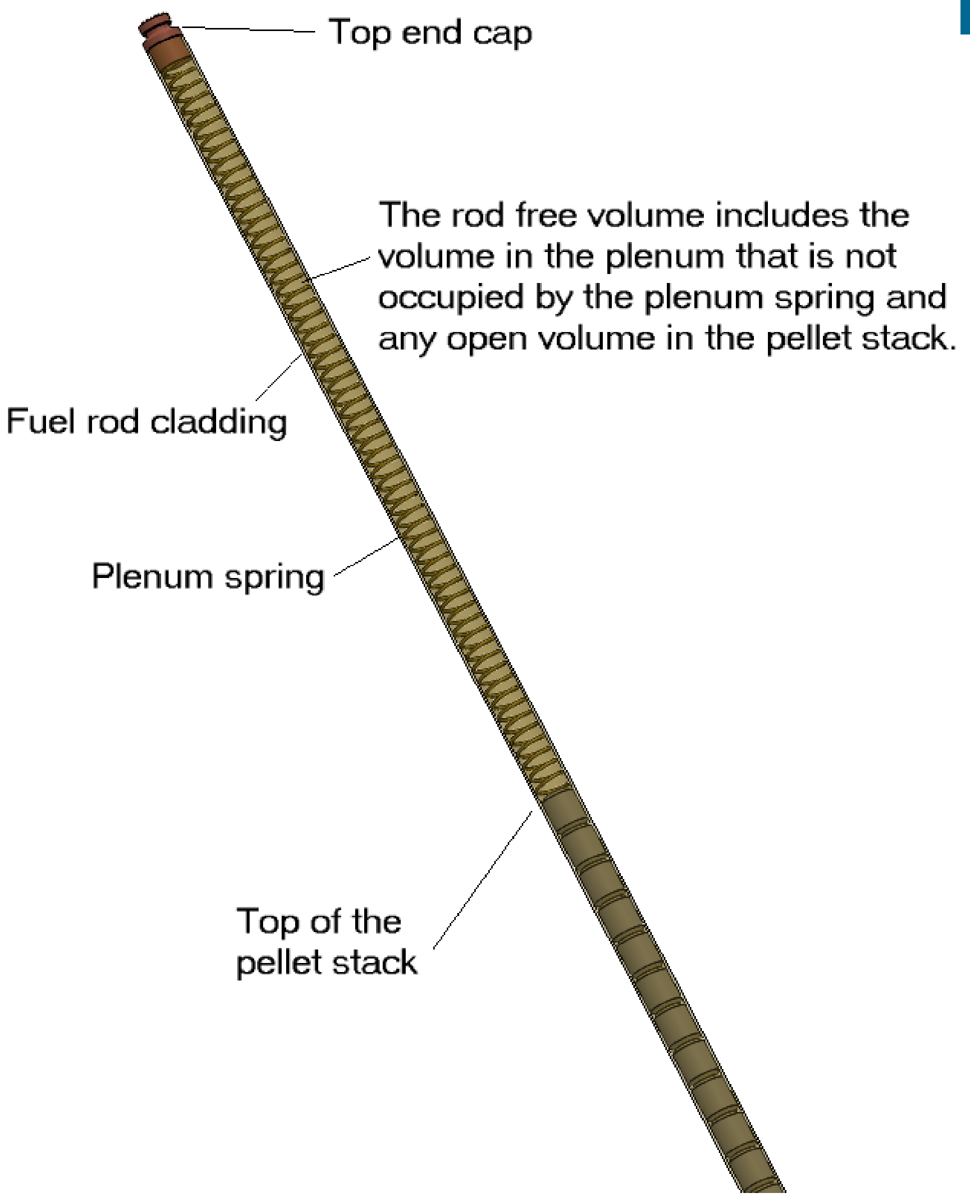
While the mechanical design of the sister rods is likely different from those presented in the EPRI report, the graph does provide some information about the sister rods relative to the pressure recorded for other commercial power pressurized water reactor rods.

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



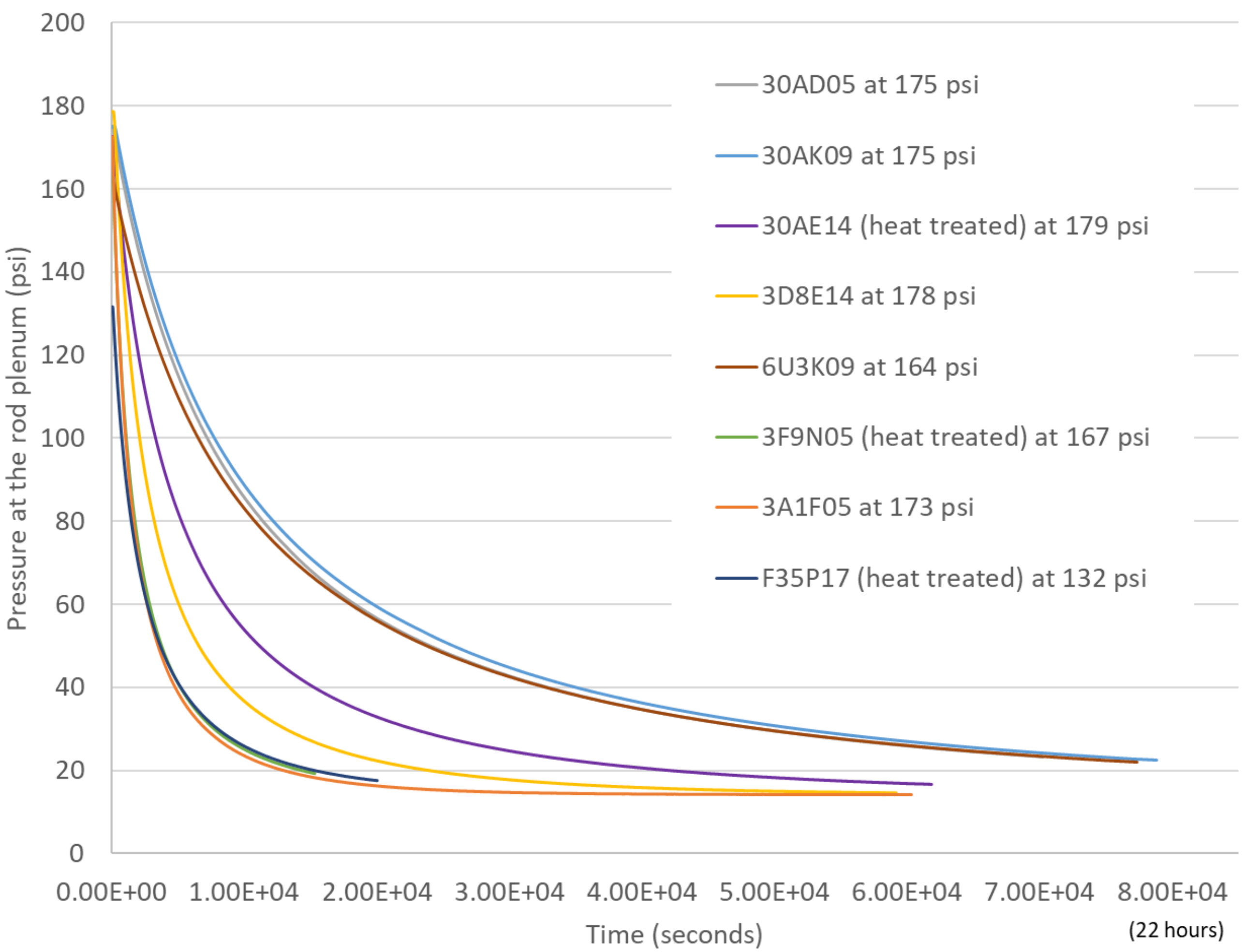
The internal free volumes of the eight sister rods measured to date are between 9.9 and 13.3 cc

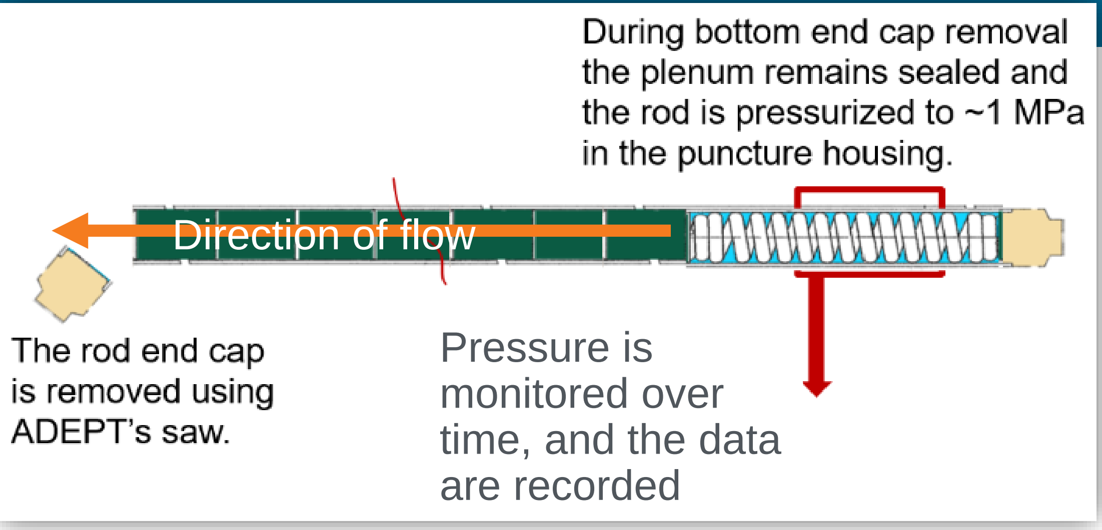
- Data include Zirc-4, LT Zirc-4, M5, and ZIRLO-clad rods
- All are on the low side of past available data collected by EPRI [1] which ranges from 11.1 to 39.5 cc
  - *Rod free volume at end of life is largely dependent on the initial free volume*
  - *The mechanical design of the sister rods is likely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



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

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

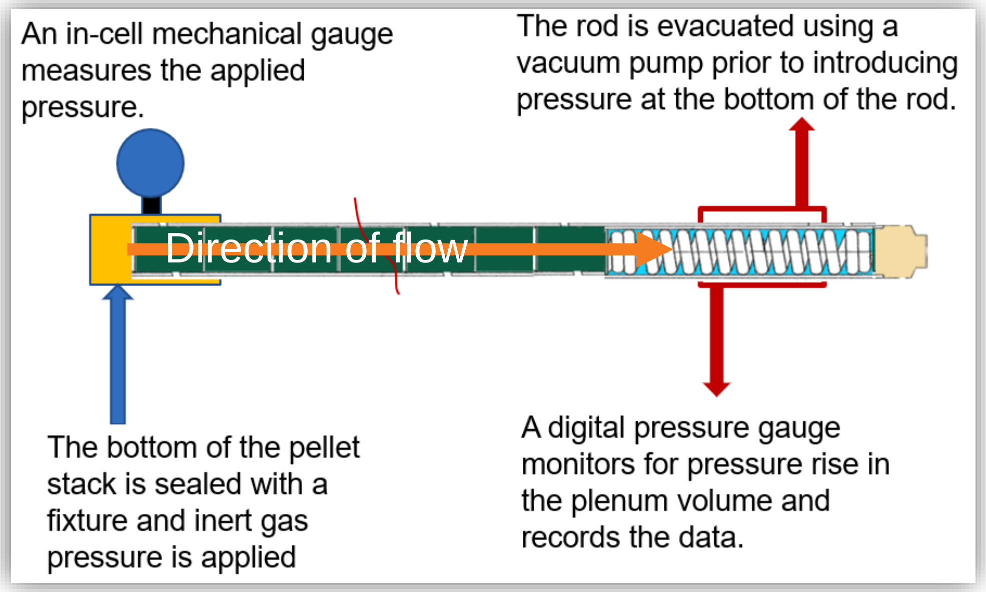




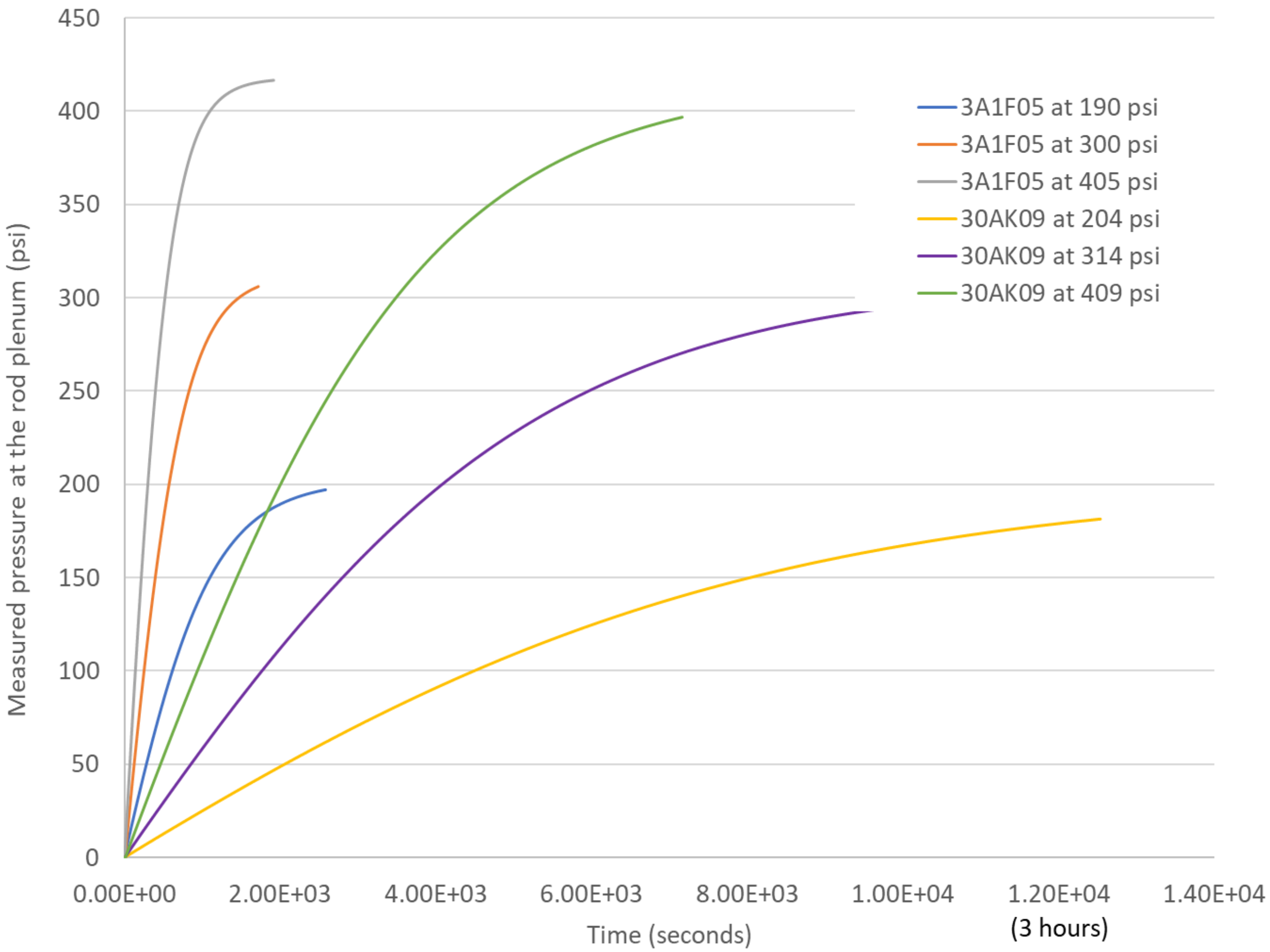
- The rod plenum was pressurized, and the end was cut off the rod
- The pressure in the plenum was monitored over time
- A decrease in plenum pressure indicated that gas can flow through the pellet stack
- Eight full-length rods tested; no obvious difference for heat-treated rods

All rods had good communication along the entire pellet stack at room temperature (RT)
This test simulates a rod with a large leak

Gas transmission tests that applied pressure in the opposite direction were also completed



- Two full-length rods were tested
- Pressure was applied at the bottom of the pellet stack
- The pressure was monitored at the rod plenum



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

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

Testing of the baseline and heat-treated rods will continue throughout 2019

- Supporting data to be obtained include
  - Metallography (ongoing)
  - Burnup (ongoing)
  - Fission gas composition (ongoing)
  - Total cladding hydrogen (planned start 1/2019)
  - Investigations of effects of GTRF marks and pellet stack gaps on mechanical response
  - Collection of aerosols released during rod fracture

Summary

- ORNL has successfully completed the nondestructive testing and the results are available in a detailed report at https://info.ornl.gov/sites/publications/Files/Pub109385.pdf
- Rod internal pressure, free volume, and gas transmission / decompression tests of 8 rods are complete
- Mechanical testing includes 3 baseline and 3 heat-treated fuel rods and is planned to begin in November 2018
- Detailed supporting data is being developed to characterize each rod

Annual ORNL status reports are issued in September

Test status is provided at EPRI Extended Storage Collaboration Program meetings twice yearly