Sister Rod Examinations at ORNL for the HBU Spent Fuel Data Project

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Examinations of the Sister Rods support technical gap closure and further the understanding of high burnup fuel characteristics

- **Commercial SNF operated at Dominion's North Anna reactor**
  - 17x17 PWR
  - "Sisters" to SNF that will be placed into long term dry storage in the Research Project Cask (RPC)
- **25 HBU rods from 7 different SNF assemblies**
  - 9 M5™ rods
  - 12 Zirlo rods
  - 2 low tin Zirc-4 rods
  - 2 Zirc-4 rods
- **Primary exam objectives**
  - Establish a baseline for comparison with the RPC rods
  - Collect information to address identified technical gaps
  - Provide empirical data to support modeling and simulation

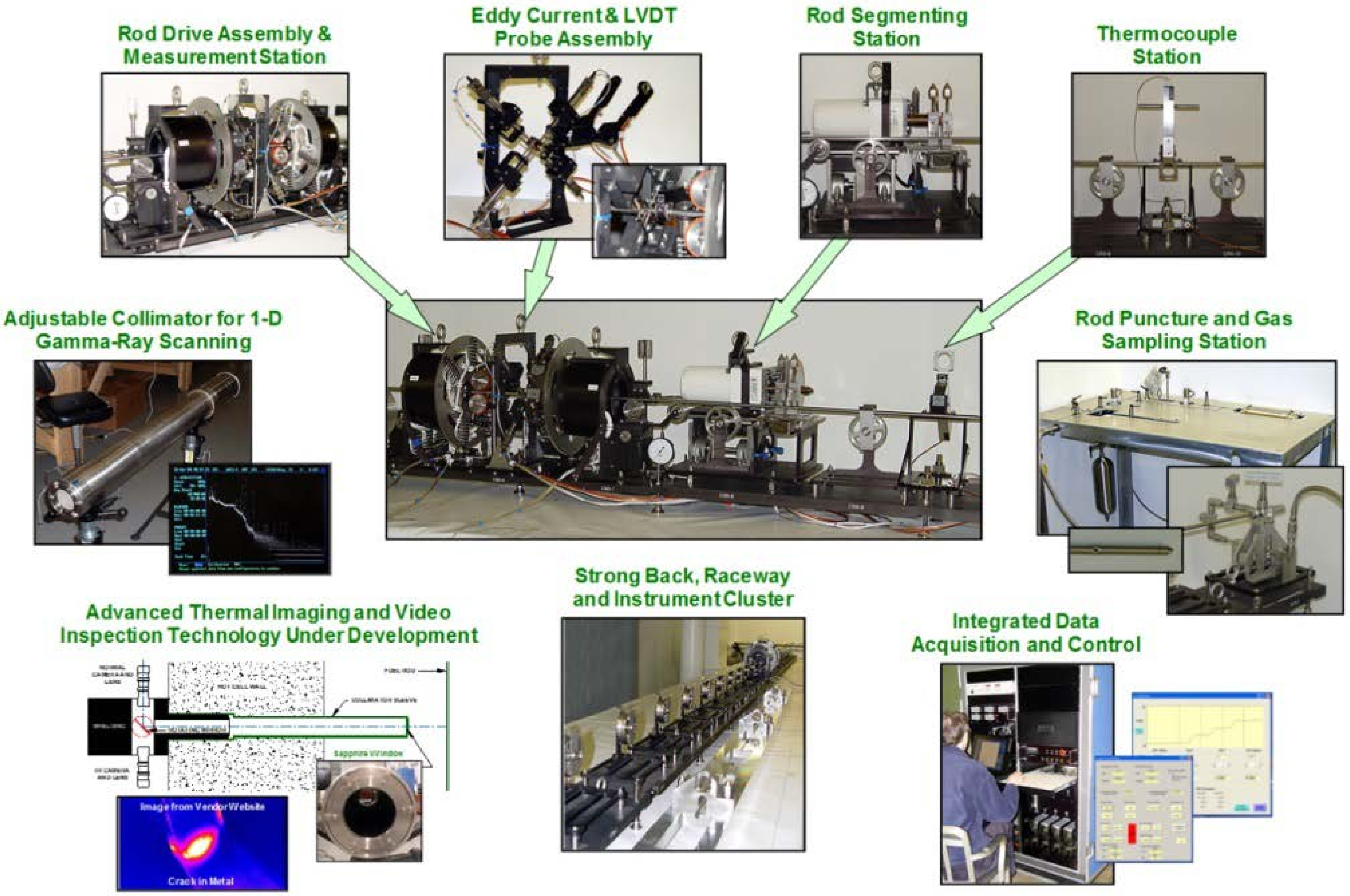
The Sister Rods were received at ORNL in January 2016 and testing is underway

- **Non-destructive examinations began in October 2016**
  - 1D gamma scanning underway
  - Remaining examinations include
    - Profilometry
    - Rod length
    - Eddy current
    - Surface temperature
    - Visuals
- **Destructive examinations expected to begin in FY17**

SISTER ROD NON-DESTRUCTIVE EXAMINATION STATUS

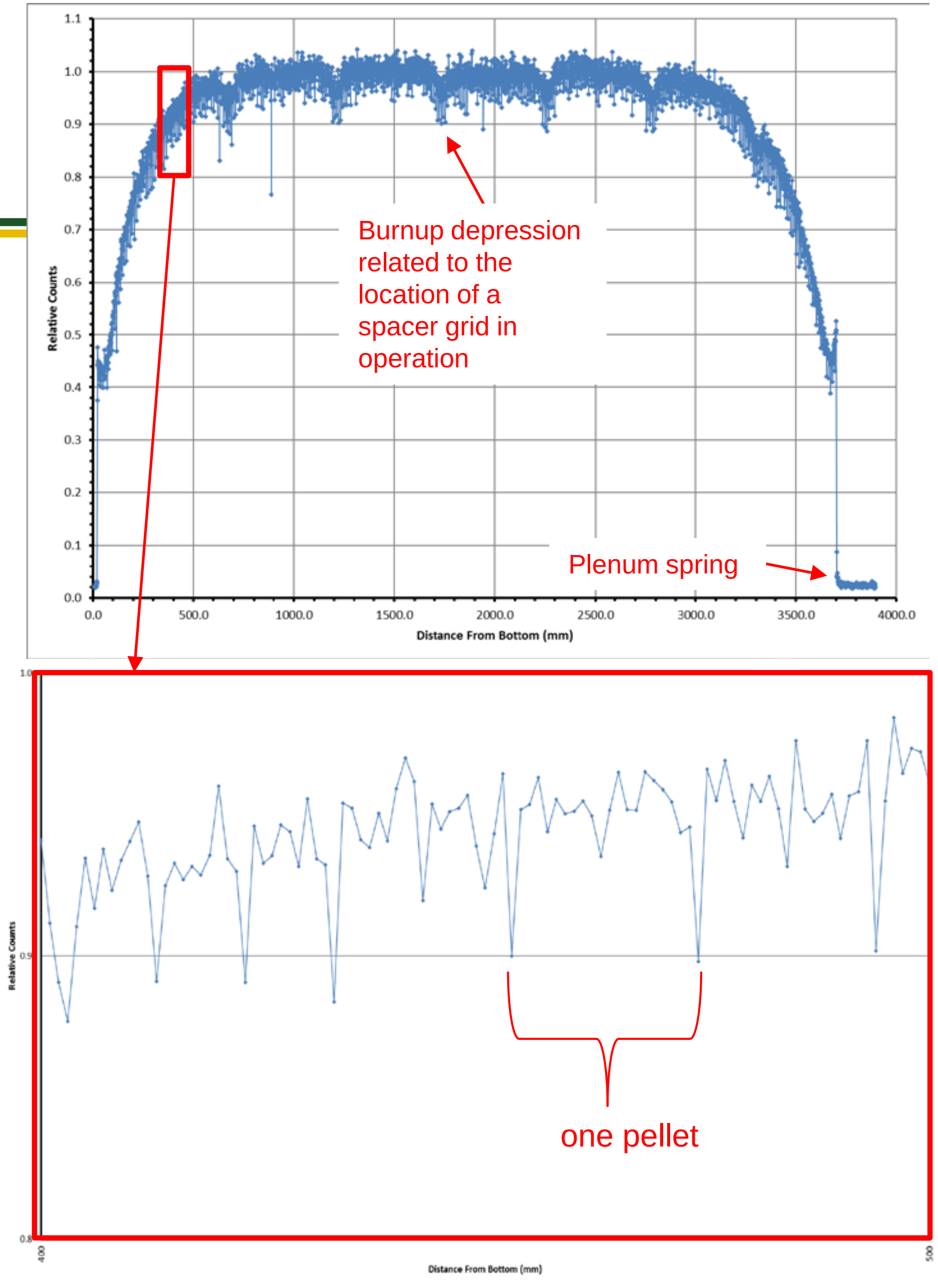
All 25 Sister Rods are currently being non-destructively examined using the ORNL Advanced Diagnostics and Evaluation Platform (ADEPT)

- Status:
  - Gamma scans
    - Approx. 40% completed
  - Fuel rod overall length
    - Approx. 40% completed
  - Eddy current
    - *Not started*
  - Profilometry
    - *Not started*
  - Rod surface temperature
    - *Not started*
  - Visual inspection
    - *Not started*



Gamma Scanning is progressing on schedule

- One rod is measured at a time
- Goal is to define the overall axial burnup profile of the rod and look for any significant pellet gaps
- Measurements are taken at discrete points along the axis of the rod at ~1 mm intervals
- A NaI detector is used counting at 400 to 800 keV
- The detector is not calibrated to a standard and all measurements are therefore relative
- The pellets are the source of the gammas and each pellet is observable
- Grid depressions are visible
- The plenum spring is visible but the rod end caps are not
- The end cap lengths are inferred by the travel length and the measured overall rod length

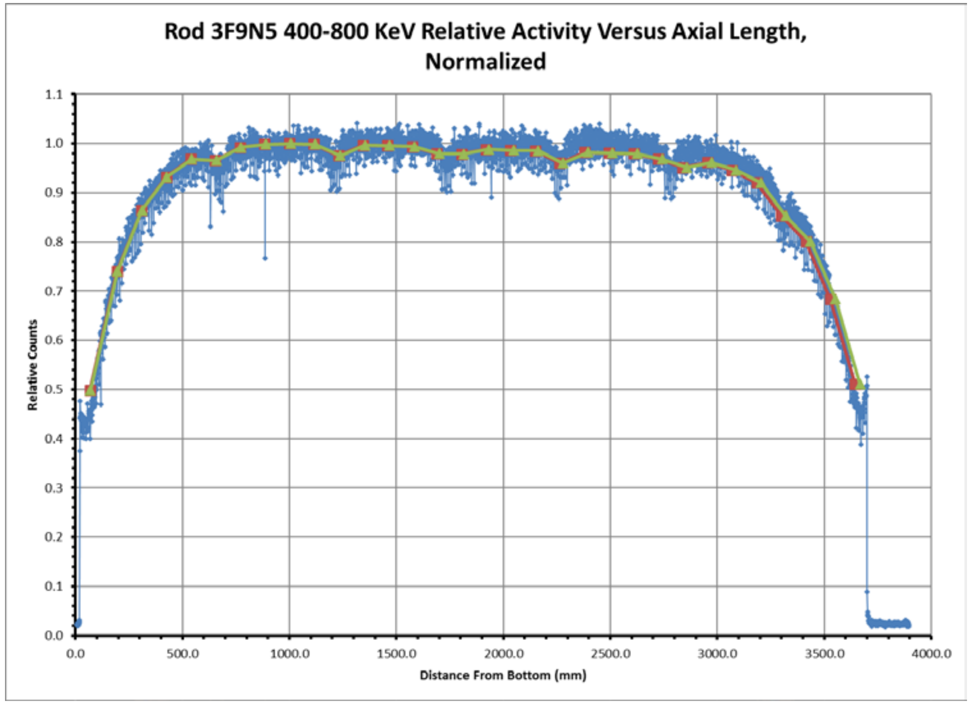


Burnup depression related to the location of a spacer grid in operation

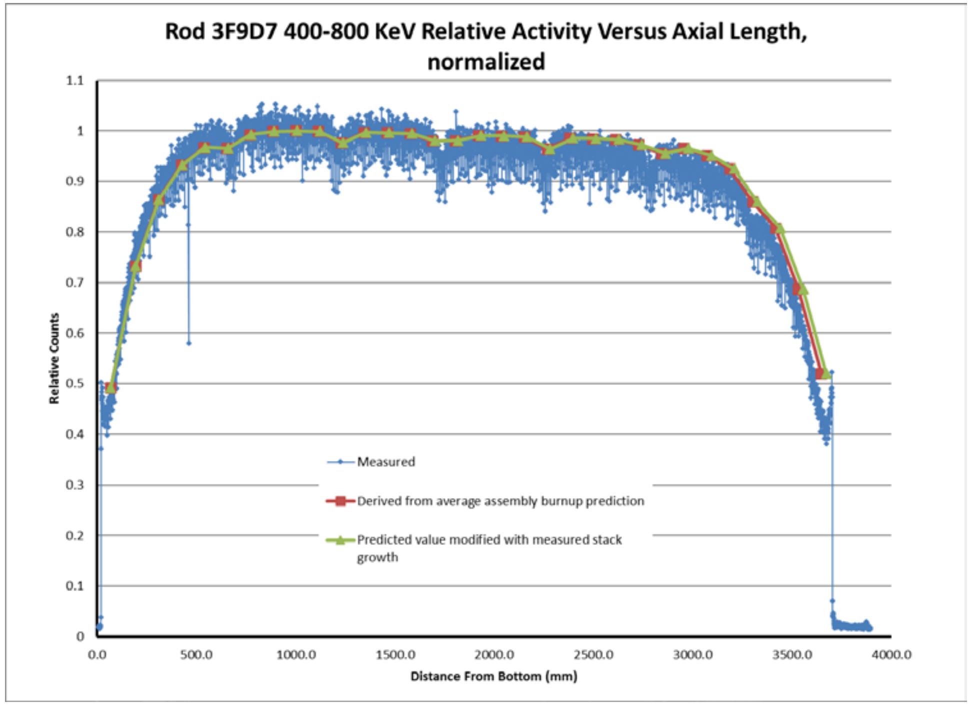
Plenum spring

one pellet

Gamma Scanning results

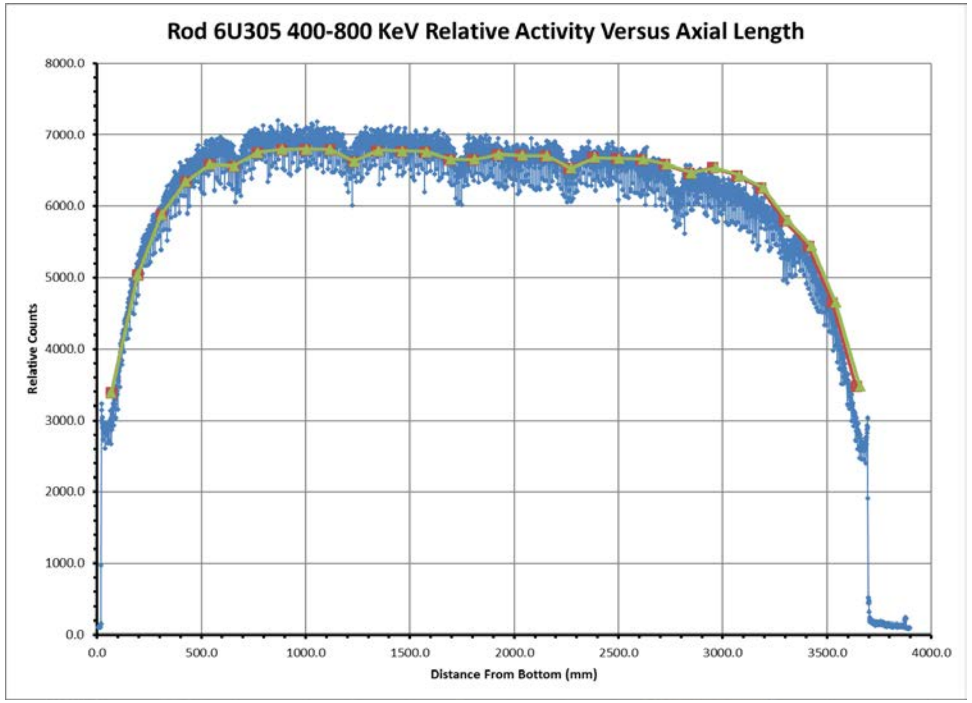


Assembly type: NAIF/P+Z
Cladding type: Zirlo
Stack growth: 0.640%
Rod growth: 0.402%
Anomalous indications: possible stack gap @800 mm



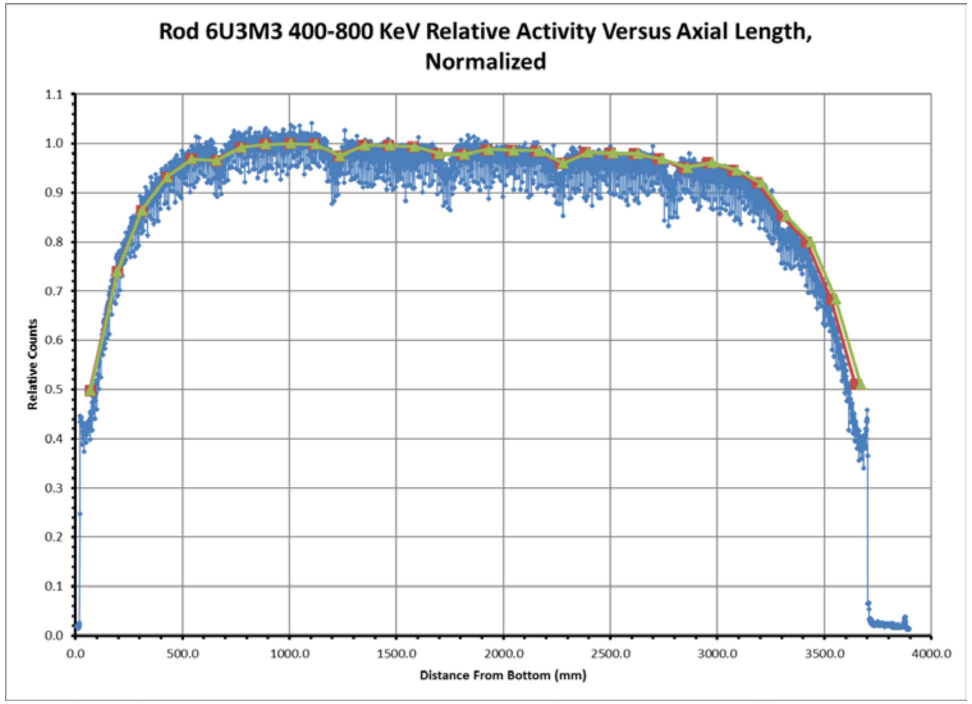
Assembly type: NAIF/P+Z
Cladding type: Zirlo
Stack growth: 0.722%
Rod growth: 0.351%
Anomalous indications: possible gap @462 mm

Gamma Scanning results



Rod 6U305 400-800 KeV Relative Activity Versus Axial Length

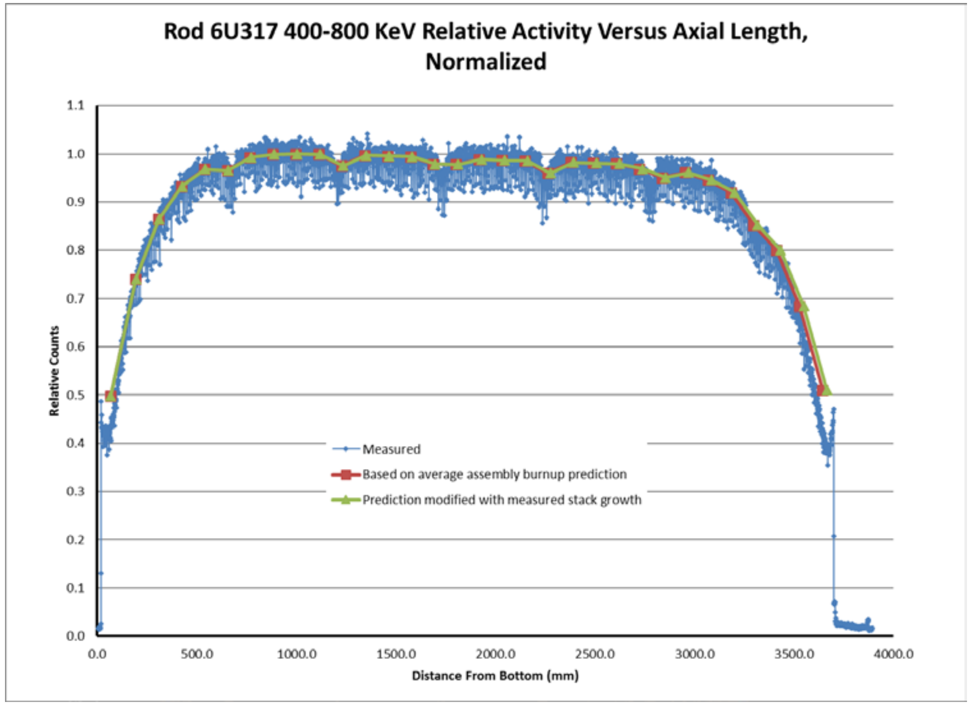
Assembly type: NAIF/P+Z
Cladding type: Zirlo
Stack growth: 0.503%
Rod growth: 0.362%
Anomalous indications: none



Rod 6U3M3 400-800 KeV Relative Activity Versus Axial Length, Normalized

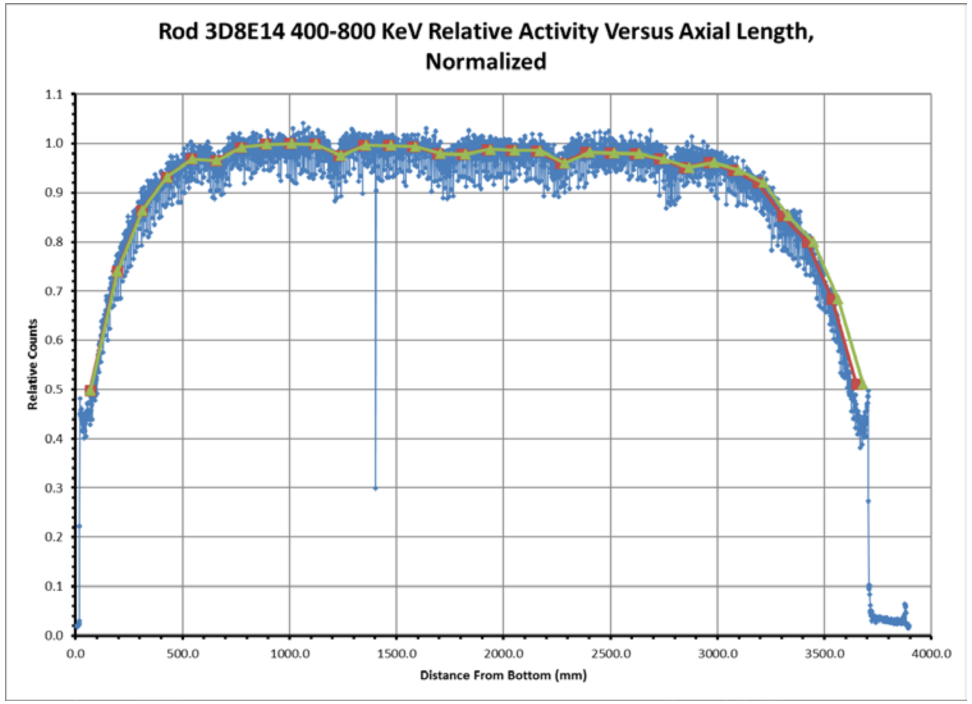
Assembly type: NAIF/P+Z
Cladding type: Zirlo
Stack growth: 0.667%
Rod growth: 0.405%
Anomalous indications: none

Gamma Scanning results

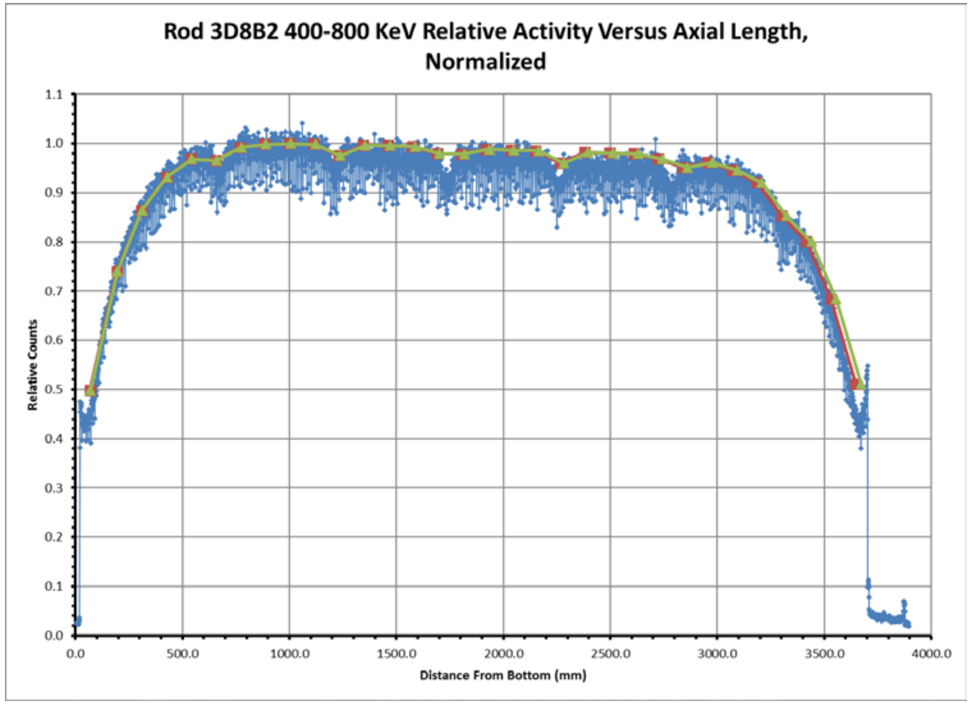


Assembly type: NAIF/P+Z
Cladding type: Zirlo
Stack growth: 0.612%
Rod growth: 0.309%
Anomalous indications: none

Gamma Scanning results

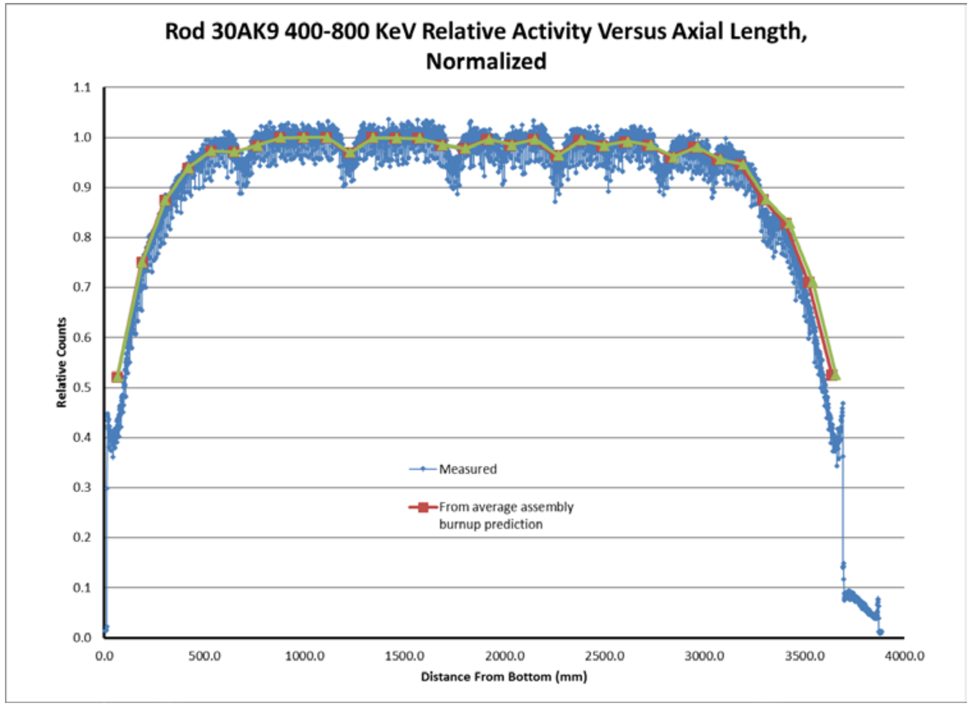


Assembly type: NAIF/P+Z
Cladding type: Zirlo
Stack growth: 0.804%
Rod growth: 0.448%
Anomalous indications: possible stack gap ~1400 mm

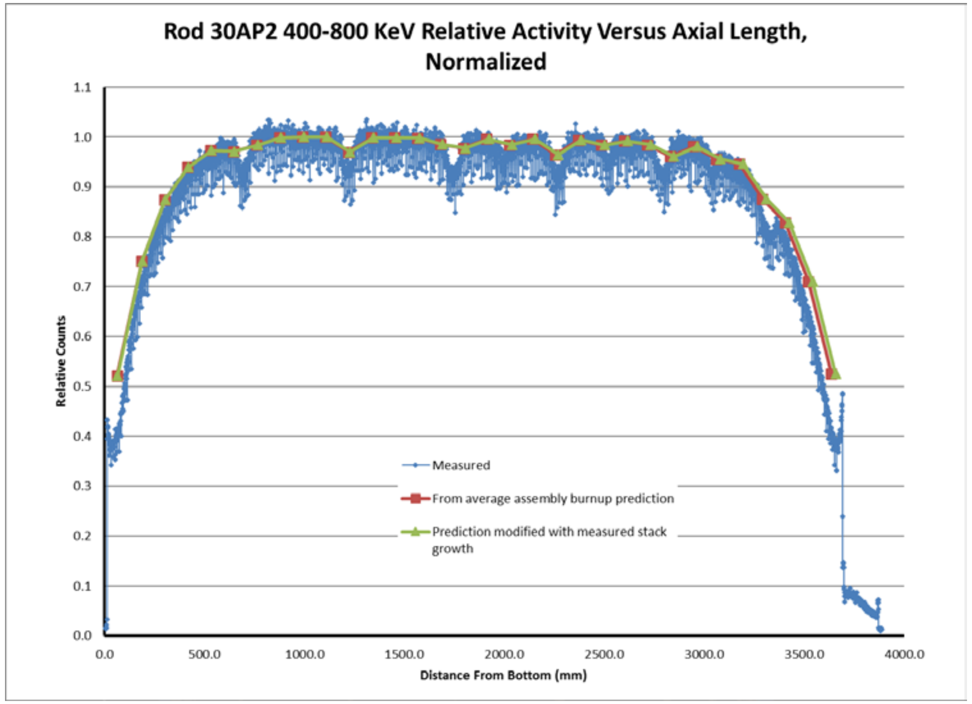


Assembly type: NAIF/P+Z
Cladding type: Zirlo
Stack growth: 0.694%
Rod growth: 0.340%
Anomalous indications: none

Gamma Scanning results

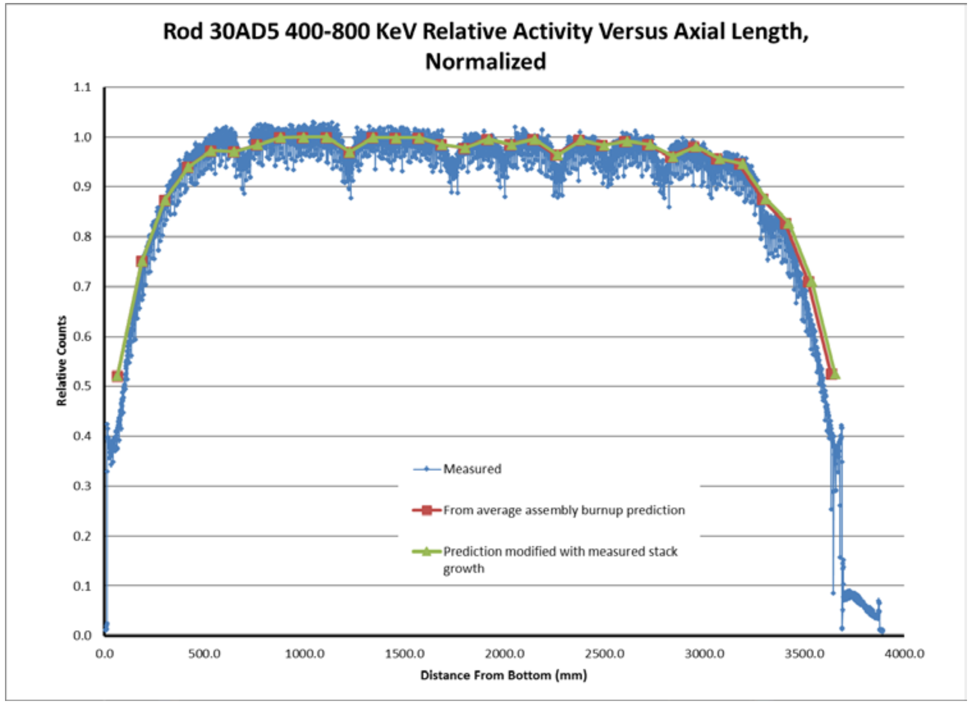


Assembly type: AMBW
Cladding type: M5
Stack growth: 0.585%
Rod growth: 0.415%
Anomalous indications: none



Assembly type: AMBW
Cladding type: M5
Stack growth: 0.585%
Rod growth: 0.422%
Anomalous indications: none

Gamma Scanning results



Assembly type: AMBW
Cladding type: M5
Stack growth: 0.530%
Rod growth: 0.540%
Anomalous indications: higher rod growth than stack growth

SISTER ROD DESTRUCTIVE EXAMINATION PLAN OBJECTIVES

Planned Destructive Examinations include a comprehensive suite of tests aimed at addressing the identified gaps to extended dry storage and transport

- Baseline the condition of the sister rods before storage
  - At least one of each cladding alloy in the cask (for this purpose Zirc-4 ≈ low tin Zirc-4)
- Identify and measure any performance / material property changes to SNF rods resulting from vacuum drying/cooldown
  - Selected rods having high rod internal pressure and high hydrogen/precipitated hydrides
    - Based on prediction of RIP and typical indicators of hydrogen content
  - Plan to test one of each cladding alloy (for this purpose Zircaloy-4 ≈ low tin Zircaloy-4)
  - Heat treat full length rods prior to puncture to preserve the as-discharged RIP/cladding stress state, although some specimens will necessarily be heat treated after puncture/segmentation.
  - Target temperatures up to 400^{o}C
- Measure mechanical properties typically used as input to models and simulations

BASELINING OBJECTIVES, TESTS, AND ROD SELECTION

The baselining objective is to compare the sister rod characteristics with the cask rod characteristics (those important to dry storage and transport)

- Relative burnup distribution
- Rod length
- Stack height and diameter
- Cladding ID/OD/oxide thickness
- Total hydrogen content
- Amount of precipitated hydrides and orientation
- Clad microstructure
- Clad incipient flaws
- Pellet structure, thickness of high burnup rim, friability of the pellet/HBU rim
- Existence/efficiency/strength of pellet-cladding chemical bond
- Rod internal pressure
- Composite rod properties (fatigue lifetime, impact toughness, transverse load bearing, bending/torsion strength)
- Cladding strength properties (yield, ultimate, elongation, Young’s Modulus, strain hardening modulus, impact toughness)

The baselining objective is to compare the sister rod characteristics with the cask rod characteristics (those important to dry storage and transport)

- Relative burnup distribution
- Rod length
- Stack height and diameter *partial
- Cladding ID/OD/oxide thickness *partial
- Total hydrogen content
- Amount of precipitated hydrides and orientation
- Clad microstructure
- Clad incipient flaws *partial
- Pellet structure, thickness of high burnup rim, friability of the pellet/HBU rim
- Existence/efficiency/strength of pellet-cladding chemical bond
- Rod internal pressure
- Composite rod properties (fatigue lifetime, impact toughness, transverse load bearing, bending/torsion strength)
- Cladding strength properties (yield, ultimate, elongation, Young’s Modulus, strain hardening modulus, impact toughness)

Obtained during non-destructive examinations

The baselining objective is to compare the sister rod characteristics with the cask rod characteristics (those important to dry storage and transport)

- Relative burnup distribution
- Rod length
- Stack height and diameter
- Cladding ID/OD/oxide thickness
- Total hydrogen content
- Amount of precipitated hydrides and orientation
- Clad microstructure
- Clad incipient flaws *partial
- Pellet structure, thickness of high burnup rim, *partial friability of the pellet/HBU rim
- Existence/efficiency/strength of pellet-cladding chemical bond *partial
- Rod internal pressure
- Composite rod properties (fatigue lifetime, impact toughness, transverse load bearing, bending/torsion strength)
- Cladding strength properties (yield, ultimate, elongation, Young's Modulus, strain hardening modulus, impact toughness)

Obtained through destructive optical examinations and chemical assay

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- Relative burnup distribution
- Rod length
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- Cladding ID/OD/oxide thickness
- Total hydrogen content
- Amount of precipitated hydrides and orientation
- Clad microstructure
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- Pellet structure, thickness of high burnup rim, friability of the pellet/HBU rim
- Existence/efficiency/strength of pellet-cladding chemical bond
- Rod internal pressure
- Composite rod properties (fatigue lifetime, impact toughness, transverse load bearing, bending/torsion strength)
- Cladding strength properties (yield, ultimate, elongation, Young’s Modulus, strain hardening modulus, impact toughness)

Obtained through destructive examination mechanical tests

Destructive baselining tests will measure the composite rod (fuel/clad) properties

- Baselining tests will be performed on fueled segments
  - *Used, for example, in simulations where the fuel rods are modeled as representative beams during transport*
  - Rod internal pressure
  - Bending strength
  - Torsion strength
  - Transverse load bearing
  - Impact toughness
  - Fatigue lifetime
  - Pellet-cladding bond efficiency/strength and pellet friability

Destructive baselining tests will measure the composite rod (fuel/clad) properties

- Baselining tests will be performed on fueled segments
  - *Used, for example, in simulations where the fuel rods are modeled as representative beams during transport*
  - **Rod internal pressure – gas puncture**
  - Bending strength
  - Torsion strength
  - Transverse load bearing
  - Impact toughness
  - Fatigue lifetime
  - Pellet-cladding bond strength and pellet friability

It is preferable to puncture all 25 sister rods at ORNL to provide consistent equipment and instrumentation.

Rod internal pressure measurements are key information and must be consistent to derive any value.

Destructive baselining tests will measure the composite rod (fuel/clad) properties

- Baselining tests will be performed on fueled segments
  - *Used, for example, in simulations where the fuel rods are modeled as representative beams during transport*
  - Rod internal pressure
  - **Bending strength – 4-point bending (4PB)**
  - Torsion strength
  - Transverse load bearing
  - Impact toughness
  - Fatigue lifetime
  - Pellet-cladding bond strength and pellet friability

Also, an indication of brittle or ductile fracture modes

This is a simple standard test that is easily repeated using standard fixtures

Destructive baselining tests will measure the composite rod (fuel/clad) properties

- Baselining tests will be performed on fueled segments
  - *Used, for example, in simulations where the fuel rods are modeled as representative beams during transport*
  - Rod internal pressure
  - Bending strength
  - **Torsion strength – spiral notch torsion (SNTT)**
  - Transverse load bearing
  - Impact toughness
  - Fatigue lifetime
  - Pellet-cladding bond strength and pellet friability

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- Baselining tests will be performed on fueled segments
  - *Used, for example, in simulations where the fuel rods are modeled as representative beams during transport*
  - Rod internal pressure
  - Bending strength
  - Torsion strength
  - **Transverse load bearing – ring compression (RCT)**
  - Impact toughness
  - Fatigue lifetime
  - Pellet-cladding bond strength and pellet friability

Destructive baselining tests will measure the composite rod (fuel/clad) properties

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  - *Used, for example, in simulations where the fuel rods are modeled as representative beams during transport*
  - Rod internal pressure
  - Bending strength
  - Torsion strength
  - Transverse load bearing
  - **Impact toughness – spiral notch torsion (SNTT)**
  - Fatigue lifetime
  - Pellet-cladding bond strength and pellet friability

Destructive baselining tests will measure the composite rod (fuel/clad) properties

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  - *Used, for example, in simulations where the fuel rods are modeled as representative beams during transport*
  - Rod internal pressure
  - Bending strength
  - Torsion strength
  - Transverse load bearing
  - Impact toughness
  - **Fatigue lifetime – cyclic integral reversible fatigue (CIRFT)**
  - Pellet-cladding bond strength and pellet friability

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- Baselining tests will be performed on fueled segments
  - *Used, for example, in simulations where the fuel rods are modeled as representative beams during transport*
  - Rod internal pressure
  - Bending strength
  - Torsion strength
  - Transverse load bearing
  - Impact toughness
  - Fatigue lifetime
  - **Pellet-cladding bond strength and pellet friability – microhardness, measured particulate release**

Selected dynamic tests will include post-test particle size distribution measurements

- These measurements will help to quantify material releaseability, aerosolized and respirable fractions
  - Candidate tests are CIRFT and SNTT
  - Measurement methods to be established

Destructive baselining tests will also be performed on defueled cladding segments

- Data from defueled cladding segments will provide:
  - *Material properties used, for example, in evaluating/predicting the ability of the cladding to survive combined stresses without fracture*
  - Tensile properties
  - Hoop strain
  - Transverse load bearing considering hydride content / orientation

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- Data from defueled cladding segments will provide:
  - *Material properties used, for example, in evaluating/predicting the ability of the cladding to survive combined stresses without fracture*
  - **Tensile properties (yield, ultimate, elongation, Young’s Modulus, strain hardening modulus) – uniaxial tension and microhardness**
  - Hoop strain
  - Transverse load bearing considering hydride content / orientation

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- Data from defueled cladding segments will provide:
  - *Material properties used, for example, in evaluating/predicting the ability of the cladding to survive combined stresses without fracture*
  - Tensile properties
  - **Hoop strain – expanding cone-wedge**
  - Transverse load bearing considering hydride content / orientation

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- Data from defueled cladding segments will provide:
  - *Material properties used, for example, in evaluating/predicting the ability of the cladding to survive combined stresses without fracture*
  - Tensile properties
  - Hoop strain
  - **Transverse load bearing considering hydride content / orientation – ring compression**

Also, an indication of brittle or ductile fracture modes with temperature

Baselining Sister Rod Selections

Clad material	Donor assembly identifier	Sister rod lattice location	Assembly average BU	Key characteristics	Cask-stored sister	
					Assembly Identifier	Cask rod lattice location
Zirlo	6U3	I07	52,758	This rod is the sister to 3 different fuel assemblies in the central, middle, and outer regions of the basket. Operated adjacent to a guide tube.	3U4 3U9 3U6	I07 I11 I11
Zirlo	3D8	E14	54,952	This pair of rods provide a range of HBU exposure from the same operating conditions and lot of materials. Rod E14 has approximate highest burnup in the assembly and is expected to have the highest sister rod burnup, while rod B02 has approximately the lowest burnup in the assembly.	5D9 5D5	N13 M4
Zirlo	3D8	B02			5D9 5D5	B16 P16
M5	5K7	O14	53,335	Approximately average assembly burnup; the rod was operated in a GT diagonal location. 5K7 was operated hot-hot-cold and also had the highest pellet enrichment of the assembly batches represented. The assembly design included mid-span mixing grids which should have lowered the rod operating temperature in the hot spans somewhat..	5K6 3K7 5K1	C4
M5	30A	D05	52,020	D05 & E14 represent in-reactor rod operation next to guide tubes with (E-14) and without (D-5) burnable poisons. Because the poisons influence power output during irradiation the rods are expected to have different characteristics. Their last cycle was uprated in the last quarter and this was the highest power density cycle for the sister rods. Highest pellet enrichment. Of the sister rods, predicted to have the highest decay heat. Design included mid-span mixing grids.	57A	E14
M5	30A	E14			57A	D05
Low tin Zr-4	3A1	B16	50,012	Rod having lowest burnup in assembly; close to assembly periphery. Operated in a typical cell. GTRF marks observed.	OA4	B16

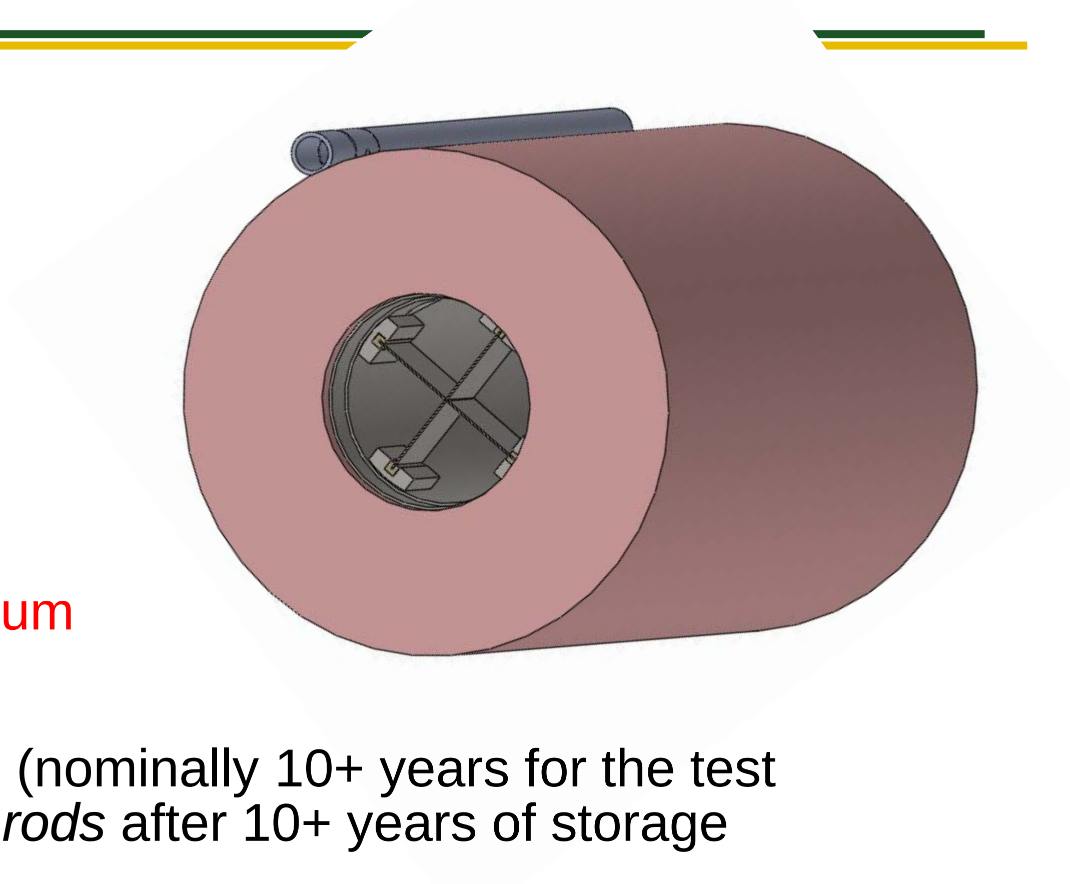
Backup Rods for Baselining

Clad material	Donor assembly identifier	Sister rod lattice location	Assembly average BU	Key characteristics	Cask-stored sister	
					Assembly Identifier	Cask rod lattice location
Zirlo	3F9	D07	52,280	Rod having approximate average assembly burnup	4F1 3F6 6F2	D07 D07 D07
M5	30A	K09	52,020	Sister rod to assembly rod in assembly 57A lance position with close proximity to the peak (hottest) rod position (I07) in the cask	57A	I07
Low tin Zr-4	3A1	F05	50,012	Rod having highest burnup in assembly; reasonably close to center of assembly	OA4	F05

Puncture these rods but hold for possible follow up testing

MEASURE ANY PERFORMANCE CHANGES TO SNF RODS RESULTING FROM VACUUM DRYING/COOLDOWN

Lab-simulated cask drying conditions will be applied to selected full-length intact sister rods to understand the implications of the operation on SNF rod integrity



- Time/Temperatures of interest include:

T0: As received condition of the rods in the hot cells corresponding to the HBU post-reactor operation and pre-dry storage fuel rods.
Data to be obtained from the Baseline Sister Rods.

T1: the condition of the rods at the time after they have been loaded into the storage canister, have been dried, and the canister has been backfilled with helium
Not available from the RPC rods

T10: the condition of the rods after long term dry storage (nominally 10+ years for the test program) *The plan is to get this data from the RPC rods* after 10+ years of storage

Lab-simulated thermal conditions can close the gaps in understanding vulnerabilities caused by fuel drying

Lab-simulated cask drying conditions will be applied to selected full-length intact sister rods to understand the implications of the operation on rod integrity

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Not available from the RPC rods

T10: the condition of the rods after long term dry storage no
Plan to get this data from the RPC rods after 10+ years

Terminology:

FHT = full length rod heat treatment prior to puncture

SEG = a segment of a rod that has been pressurized and heat treated followed by slow cooling

SEG-REWET = a segment of a rod that has been pressurized and heat treated followed by a quench

Lab-simulated thermal conditions can close the gaps in understanding vulnerabilities caused by fuel drying

Mechanical testing will be the same as that used for baselining to provide a direct comparison

- Rod internal pressure – puncture after the heat treatment to preserve the as-discharged RIP/cladding stress state
- Bending strength
- Torsion strength
- Transverse load bearing
- Impact toughness
- Fatigue lifetime
- Pellet-cladding bond strength and pellet friability
- Tensile properties
- Hoop strain
- Transverse load bearing considering hydride content / orientation

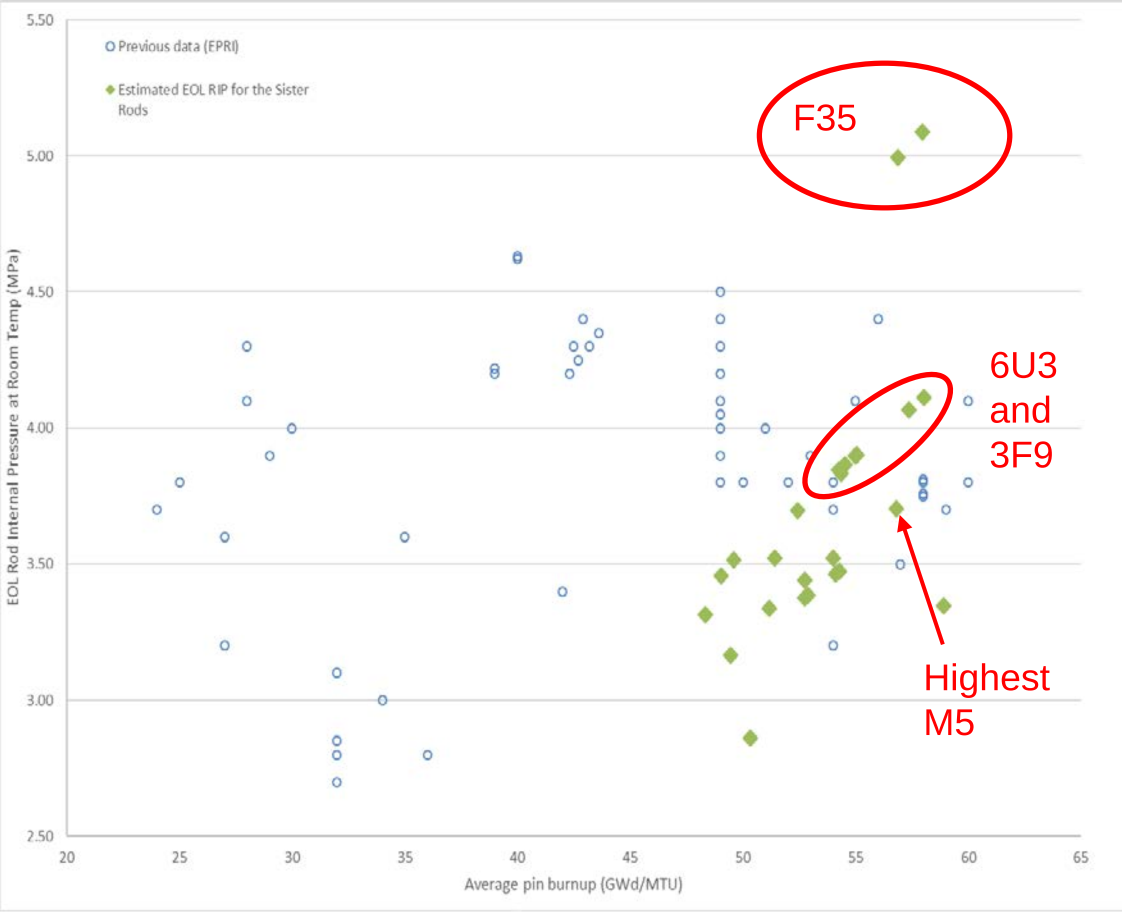
There is also an opportunity to test the waterside cladding surface emissivity using specimens from other testing

Selection of rods / segments for ORNL heat treatments is based on estimated cladding hydrogen content and rod internal pressure

- For full rod heat treatments (FHT)
  - Desire high rod internal pressure <u>and</u> high hydrogen/precipitated hydrides
    - RIP based on simulations / hand calculations
    - Hydrogen content based on rod EFPD/fuel temperature/burnup
  - Prefer one of each cladding alloy
- For heat treated rod segments (SEG and SEG-REWET)
  - Desire high hydrogen content
  - RIP will be applied

Selection of full length Heat Treatment specimens

- **Selection Criteria**
  - High rod internal pressure
  - High hydrogen content
  - M5 and Zirlo must be included



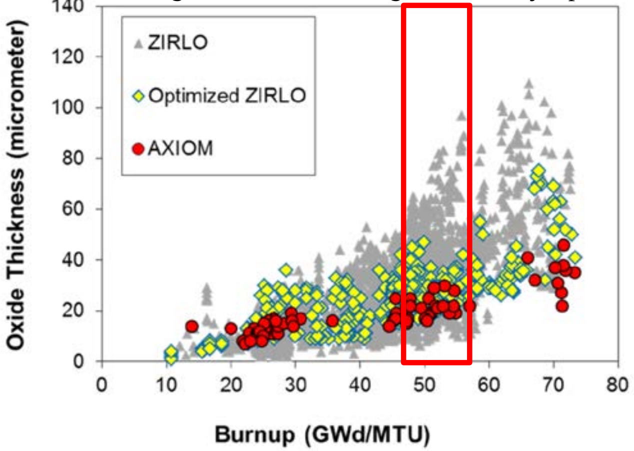
F35

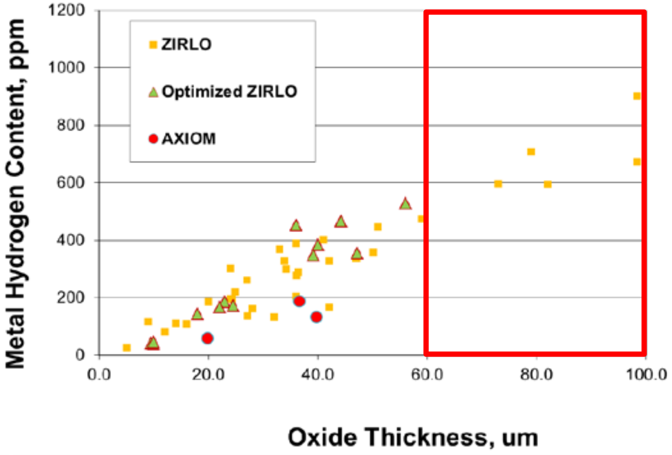
6U3 and 3F9

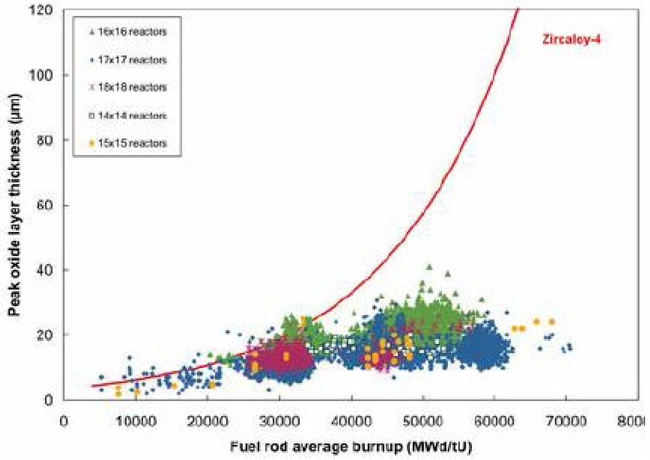
Highest M5

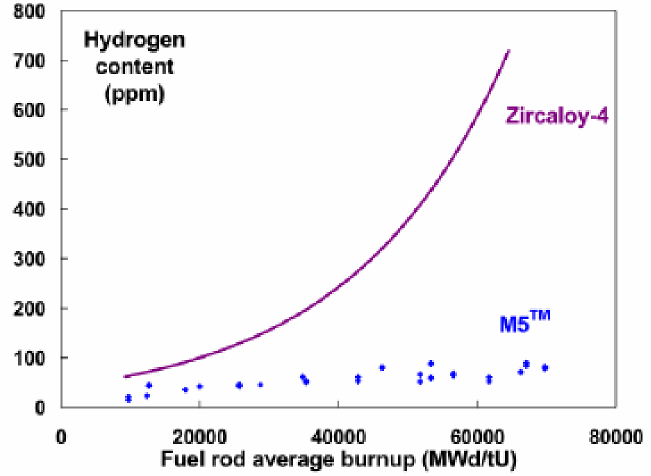
Highest burnup ≠ highest EOL RIP

Guirong Pan et al, Advantages Gained by Optimized Zirlo and Axiom PWR Cladding Materials, TopFuel 2016.









J.-P. Mardon et al., “Influence of Composition and Fabrication Process on Out-of-pile and In-pile properties of M5 Alloy”, ASTM 12th Int. Symp. on Zirconium in the Nuclear Industry, Toronto/Or, USA, June 1998.

Selection method for full length rod heat treatment

Predicted RIP	Expected hydrogen content
F35 P17 (Zirc-4)	Most of the HBU Zirlo are considered comparable at 200 to 600 ppm (large uncertainty in the available data) The highest BU rod is 3D8 E14 (200 to 600ppm) Baseline rod
6U3M09 (Zirlo)	F35 P17 (estimated BU)
6U3 K09 (Zirlo)	LT Zirc-4 expected to be around 400 ppm
3F9 N05 (Zirlo)	All M5 expected to be <100ppm
….all Zirlo except 3D8	
M5: 5K7 and 30A rods are all comparable @ ~3.5 MPa 30A G09 is available	

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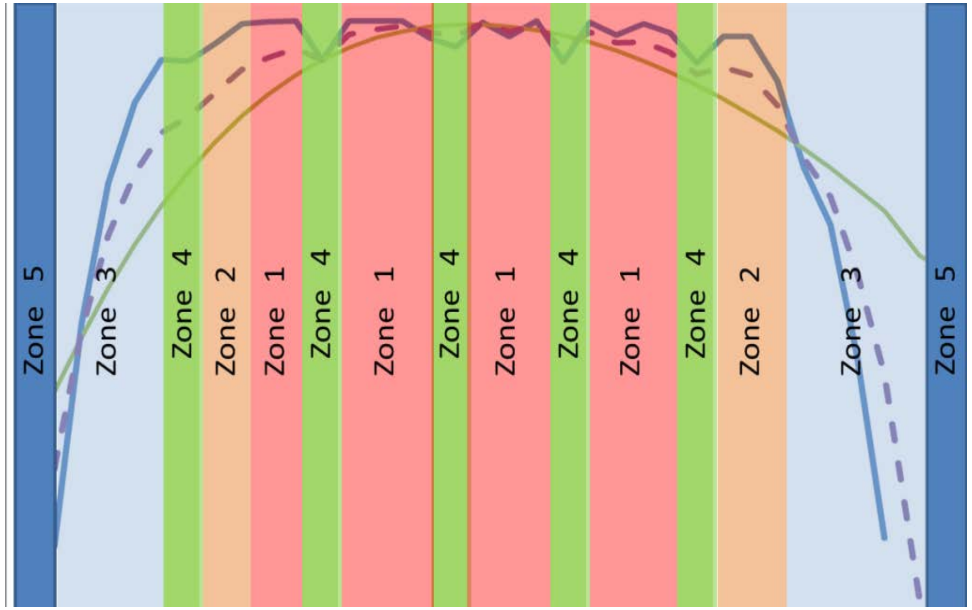
Heat Treatment backup rods: If more data is prescribed by the results from the initial three rods. No puncture until initial HT rods are tested.

SPECIFIC SPECIMEN SELECTION FROM EACH SISTER ROD

Specific specimen selection approach is based on fuel performance experience

- **Minimalistic number of samples to guide future test decisions**
  - Initial selections represent a minimum number of tests
  - If the results are inconclusive, conflicting, or warrant additional information, reserved material will be used for additional testing
- **Samples from several "zones"**
  - Zone 1, highest duty
  - Zone 2, just off the highest duty
  - Zone 3, in the stack but lower duty
  - Zone 4, under grid
  - Zone 5, outside the fuel stack
- **Where possible, provide corresponding locations for comparison among rods**

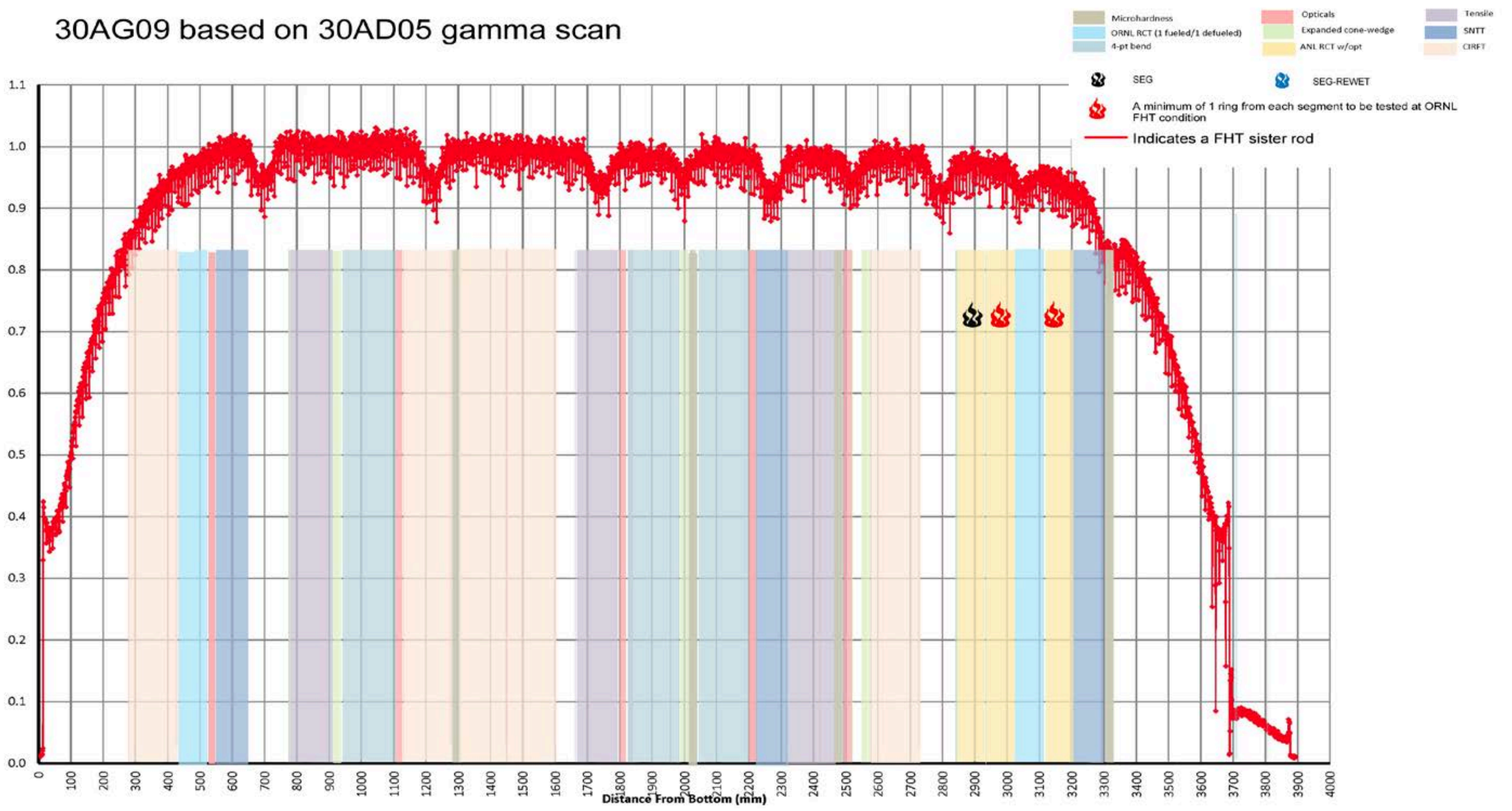


Final specimen selection will be guided by the NDE results

- **Visuals provide locations of grid-to-rod fretting (GTRF) wear, oxide spallation, CRUD**
  - Must be considered as they can affect some test results
  - Some tests will specifically measure the impact of GTRF and grid burnup depressions under grids
- **Gamma scanning provides a basis for selecting specimens that will be consist throughout its length**
  - Avoid burnup gradients unless they are specifically being tested
  - Allows for better comparisons from rod-to-rod
- **Eddy current should identify gross flaws / cladding cracks and can provide an indication of oxide thickness variation along the axial length of the rod to supplement the spot measurements using METs / destructive methods**
- **ORNL’s test plan will be revised to provide more exact specimen descriptions when the NDE is complete**

An example of DE specimen selections

- Gamma scanning and other NDE results are used to guide sample cutting
- Where direct comparison of samples is desired (e.g., between baseline and FHT or SEG) corresponding or adjacent elevations will be used, as possible



Typical number of test specimens – Baseline Rods

- SNTT – 3 per rod
- CIRFT – up to 5 (3 dynamic, 1 static, 1 cumulative) per rod
- 4-point bend - 3 per rod
- Axial tension – 3 per rod
- RCT - 2@ORNL, remainder@ANL
  - 6 on Zirlo rods
  - 4 on M5 rods
  - 3 on Zirc-4 rods
- ECW – 3 per rod
- Microhardness – 4 per rod

No tests currently specified on
Baseline Backup rods
except for gas puncture

- METs – up to 8 per rod
- Total hydrogen – up to 8 per rod
- No "typical" specimens allocated: SEM, TEM, emissivity
  - A limited number of specimens are specified for particular comparisons; additional tests to be added as necessary based on the results of the DE
- 3 segments selected from 1 baseline rod for SEG heat treatments to confirm that segment heat treatments can duplicate full rod methods
- 6 segments from 2 baseline rods for SEG-REWET (quench) to examine any effects related to pool re-immersion
- Dynamic testing to incorporate a characterization of the released particles for application to releasable fraction/respirable fraction

Typical number of test specimens – FHT Rods

- SNTT – 3 per rod
- CIRFT – up to 5 (3 dynamic, 1 static, 1 cumulative) per rod
- 4-point bend - 3 per rod
- Axial tension – 3 per rod
- **RCT - 2@ORNL, remainder@ANL**
  - **5 on Zirlo rods**
  - **6 on M5 rods**
  - **4 on Zirc-4 rods**
- ECW – 3 per rod
- Microhardness – 4 per rod
- METs – up to 8 per rod
- Total hydrogen – up to 8 per rod
- No “typical” specimens allocated: SEM, TEM, emissivity
  - A limited number of specimens are specified for particular comparisons; additional to be added as necessary based on the results of the DE
- Dynamic testing to incorporate a characterization of the released particles for application to releasable fraction/respirable fraction

At least one FHT specimen from each alloy will be RCTed by ANL. If the results are as expected, the remainder may be pressurized / heat-treated to other conditions by ANL.

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Initial Test Matrix (slide 1 of 2)

NOTES:

[a] Samples taken from locations spaced axially along the rod in Zones 1, 2, and 3, with one sample from Zone 4.

[b] Samples taken from Zone 1

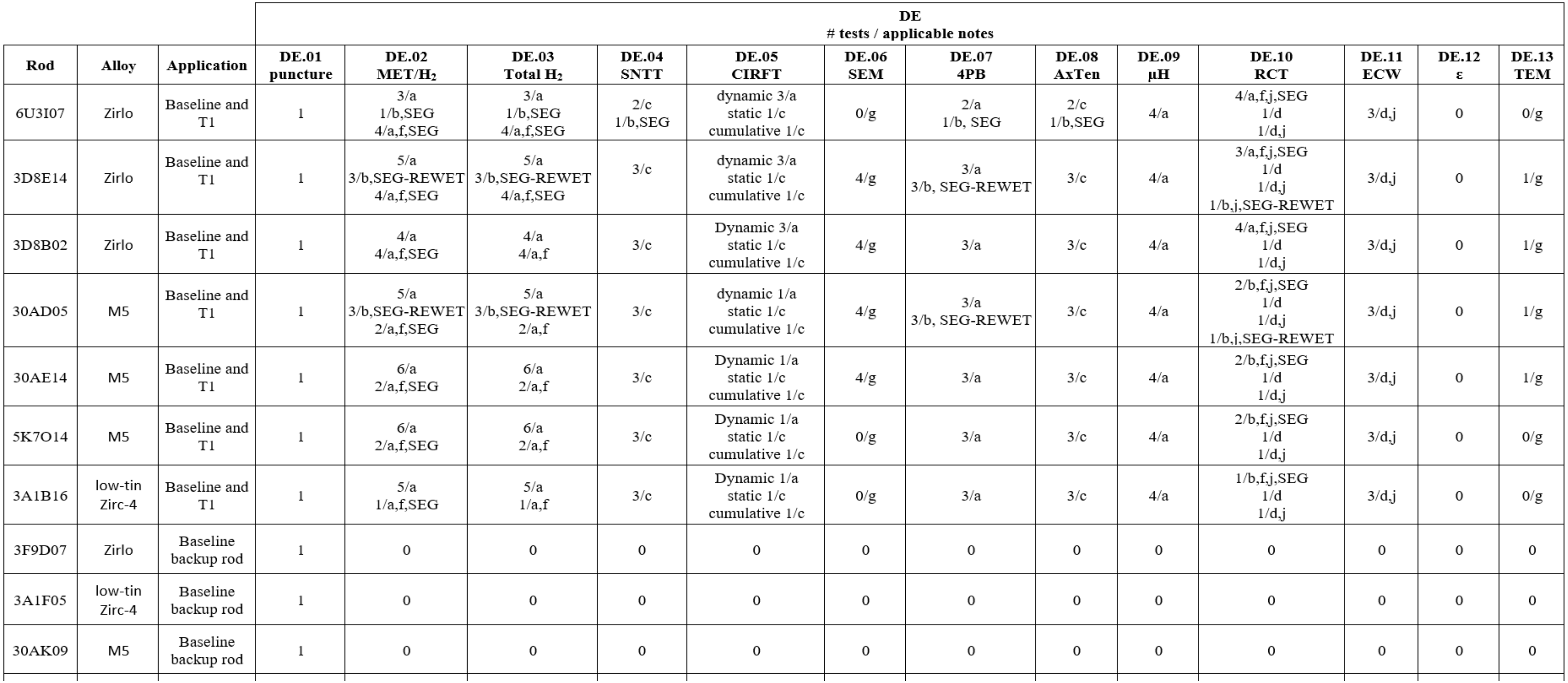
[c] Samples taken from Zone 1 and Zone 2, as possible.

[d] Samples taken from Zone 1, 2 and 3.

[f] ANL DE; 4 samples are derived from each segment allocated plus pre- and post-test opticals.

[g] as required based on the results of other DE.

[j] defueled specimen.



			DE # tests / applicable notes												
Rod	**Alloy**	**Application**	**DE.01 puncture**	**DE.02 MET/H_2**	**DE.03 Total H_2**	**DE.04 SNTT**	**DE.05 CIRFT**	**DE.06 SEM**	**DE.07 4PB**	**DE.08 AxTen**	**DE.09 µH**	**DE.10 RCT**	**DE.11 ECW**	**DE.12 ε**	**DE.13 TEM**
6U3I07	Zirlo	Baseline and T1	1	3/a 1/b,SEG 4/a,f,SEG	3/a 1/b,SEG 4/a,f,SEG	2/c 1/b,SEG	dynamic 3/a static 1/c cumulative 1/c	0/g	2/a 1/b, SEG	2/c 1/b,SEG	4/a	4/a,f,j,SEG 1/d 1/d,j	3/d,j	0	0/g
3D8E14	Zirlo	Baseline and T1	1	5/a 3/b,SEG-REWET 4/a,f,SEG	5/a 3/b,SEG-REWET 4/a,f,SEG	3/c	dynamic 3/a static 1/c cumulative 1/c	4/g	3/a 3/b, SEG-REWET	3/c	4/a	3/a,f,j,SEG 1/d 1/d,j 1/b,j,SEG-REWET	3/d,j	0	1/g
3D8B02	Zirlo	Baseline and T1	1	4/a 4/a,f,SEG	4/a 4/a,f	3/c	Dynamic 3/a static 1/c cumulative 1/c	4/g	3/a	3/c	4/a	4/a,f,j,SEG 1/d 1/d,j	3/d,j	0	1/g
30AD05	M5	Baseline and T1	1	5/a 3/b,SEG-REWET 2/a,f,SEG	5/a 3/b,SEG-REWET 2/a,f	3/c	dynamic 1/a static 1/c cumulative 1/c	4/g	3/a 3/b, SEG-REWET	3/c	4/a	2/b,f,j,SEG 1/d 1/d,j 1/b,j,SEG-REWET	3/d,j	0	1/g
30AE14	M5	Baseline and T1	1	6/a 2/a,f,SEG	6/a 2/a,f	3/c	Dynamic 1/a static 1/c cumulative 1/c	4/g	3/a	3/c	4/a	2/b,f,j,SEG 1/d 1/d,j	3/d,j	0	1/g
5K7O14	M5	Baseline and T1	1	6/a 2/a,f,SEG	6/a 2/a,f	3/c	Dynamic 1/a static 1/c cumulative 1/c	0/g	3/a	3/c	4/a	2/b,f,j,SEG 1/d 1/d,j	3/d,j	0	0/g
3A1B16	low-tin Zirc-4	Baseline and T1	1	5/a 1/a,f,SEG	5/a 1/a,f	3/c	Dynamic 1/a static 1/c cumulative 1/c	0/g	3/a	3/c	4/a	1/b,f,j,SEG 1/d 1/d,j	3/d,j	0	0/g
3F9D07	Zirlo	Baseline backup rod	1	0	0	0	0	0	0	0	0	0	0	0	0
3A1F05	low-tin Zirc-4	Baseline backup rod	1	0	0	0	0	0	0	0	0	0	0	0	0
30AK09	M5	Baseline backup rod	1	0	0	0	0	0	0	0	0	0	0	0	0

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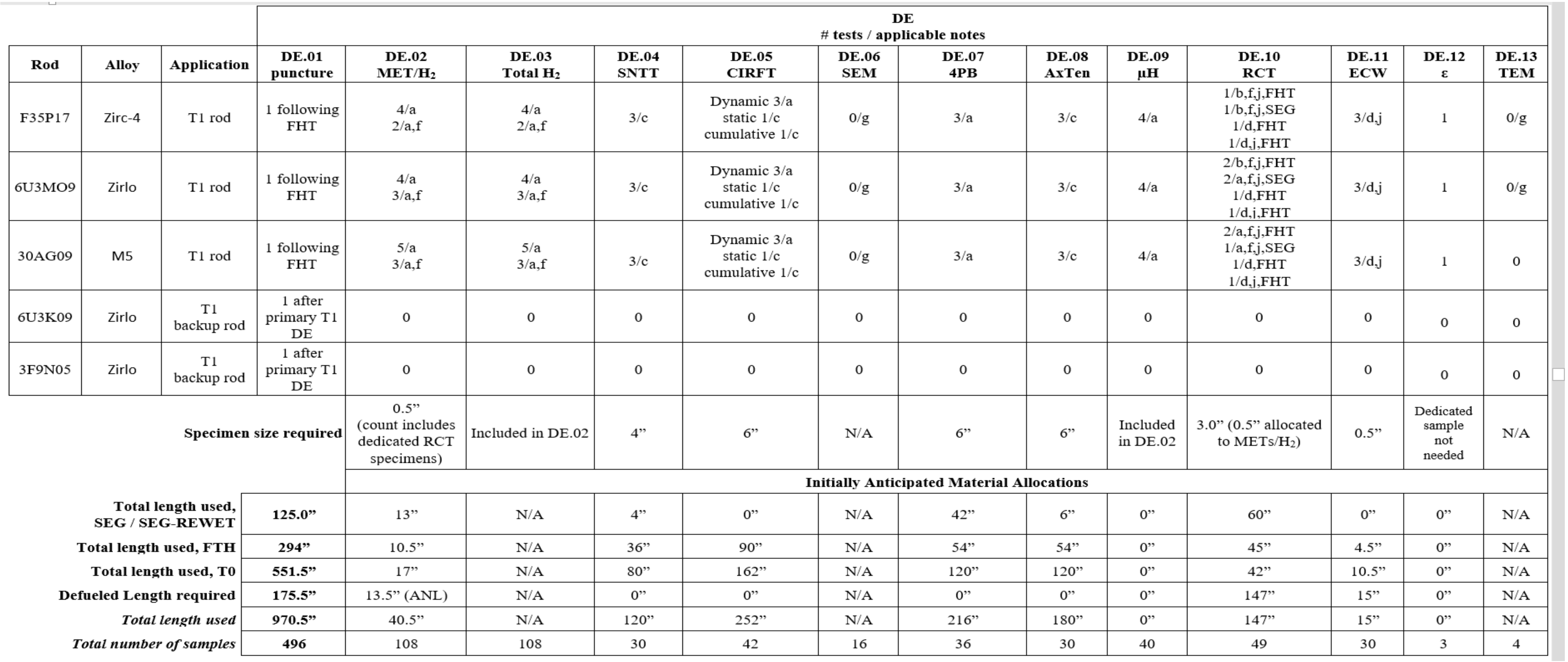
Initial Test Matrix (slide 2 of 2)

NOTES:

[a] Samples taken from locations spaced axially along the rod in Zones 1, 2, and 3, with one sample from Zone 4.
[b] Samples taken from Zone 1
[c] Samples taken from Zone 1 and Zone 2, as possible.
[d] Samples taken from Zone 1, 2 and 3.
[f] ANL DE; 4 samples are derived from each segment allocated plus pre- and post-test opticals.
[g] as required based on the results of other DE.
[j] defueled specimen.



			DE **# tests / applicable notes**												
Rod	**Alloy**	**Application**	**DE.01 puncture**	**DE.02 MET/H_2**	**DE.03 Total H_2**	**DE.04 SNTT**	**DE.05 CIRFT**	**DE.06 SEM**	**DE.07 4PB**	**DE.08 AxTen**	**DE.09 μH**	**DE.10 RCT**	**DE.11 ECW**	**DE.12 ε**	**DE.13 TEM**
F35P17	Zirc-4	T1 rod	1 following FHT	4/a 2/a,f	4/a 2/a,f	3/c	Dynamic 3/a static 1/c cumulative 1/c	0/g	3/a	3/c	4/a	1/b,f,j,FHT 1/b,f,j,SEG 1/d,FHT 1/d,j,FHT	3/d,j	1	0/g
6U3MO9	Zirlo	T1 rod	1 following FHT	4/a 3/a,f	4/a 3/a,f	3/c	Dynamic 3/a static 1/c cumulative 1/c	0/g	3/a	3/c	4/a	2/b,f,j,FHT 2/a,f,j,SEG 1/d,FHT 1/d,j,FHT	3/d,j	1	0/g
30AG09	M5	T1 rod	1 following FHT	5/a 3/a,f	5/a 3/a,f	3/c	Dynamic 3/a static 1/c cumulative 1/c	0/g	3/a	3/c	4/a	2/a,f,j,FHT 1/a,f,j,SEG 1/d,FHT 1/d,j,FHT	3/d,j	1	0
6U3K09	Zirlo	T1 backup rod	1 after primary T1 DE	0	0	0	0	0	0	0	0	0	0	0	0
3F9N05	Zirlo	T1 backup rod	1 after primary T1 DE	0	0	0	0	0	0	0	0	0	0	0	0
Specimen size required				0.5” (count includes dedicated RCT specimens)	Included in DE.02	4”	6”	N/A	6”	6”	Included in DE.02	3.0” (0.5” allocated to METs/H_2)	0.5”	Dedicated sample not needed	N/A
				Initially Anticipated Material Allocations											
Total length used, SEG / SEG-REWET			**125.0”**	13”	N/A	4”	0”	N/A	42”	6”	0”	60”	0”	0”	N/A
Total length used, FTH			**294”**	10.5”	N/A	36”	90”	N/A	54”	54”	0”	45”	4.5”	0”	N/A
Total length used, T0			**551.5”**	17”	N/A	80”	162”	N/A	120”	120”	0”	42”	10.5”	0”	N/A
Defueled Length required			**175.5”**	13.5” (ANL)	N/A	0”	0”	N/A	0”	0”	0”	147”	15”	0”	N/A
Total length used			**970.5”**	40.5”	N/A	120”	252”	N/A	216”	180”	0”	147”	15”	0”	N/A
Total number of samples			**496**	108	108	30	42	16	36	30	40	49	30	3	4

Summary

- **All NDE expected to be finished by the end of FY17**
  - The gamma scans / length measurements are ongoing and about 40% complete
- **7 Sister Rods have been selected for initial baselining**
  - 3 M5; 3 Zirlo; 1 low tin Zirc-4
  - 3 Sister Rods are reserved as backup rods for baselining
- **3 Sister Rods have been selected for full length heat treatment to simulate the vacuum drying process**
  - 1 Zirlo (expected to have highest hydrogen concentration and some of the highest RIP)
  - 1 Zirc-4 (expected to also have high hydrogen concentration and predicted highest RIP)
  - 1 M5 (expected to have both low RIP and hydrogen concentration but tested for completeness)
  - 2 Zirlo backup rods will be reserved, unpunctured, to provide for any additional work needed to follow up on the results of the initial 3 heat-treated Sister Rods
- **Mechanical testing of baseline and heat treated rods will be consistent for direct comparison**
- **Mechanical testing will provide data to support beam-type predictive simulations, cladding integrity modeling, releaseable material fractions**
- **Tentative specimen selections are available; more detailed specimen cutting plans will be based on the NDE when it is complete**

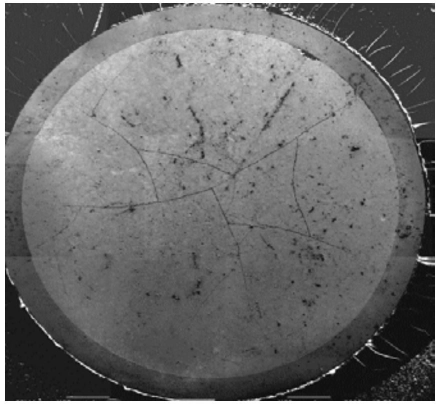
BACKUP SLIDES

ASTM versus non-ASTM R&D Tests

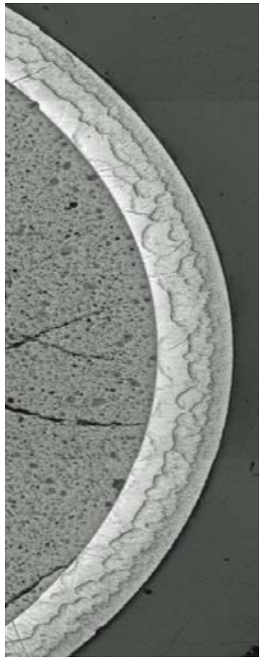
- **ASTM-approved test procedures**
  - Established by committee consensus as an appropriate method for deriving a property of interest
  - Generally has been used enough to have established test uncertainties and equipment related variances
  - Specifies sample preparation, test set up, equipment to be used
  - Advantageous since all of the “bugs” have been eliminated and should be laboratory agnostic
- **Where available, ASTM test procedures are specified**
- **Because radioactive materials applications have a small user group and application area, typically ASTM-approved test procedures have not been established**
- **Many of the sister rod tests specified were developed to evaluate the performance of radioactive materials (e.g. SNF) where there aren’t ASTM-approved procedures due to limited applicability and experience**

Optical and hydrogen content examinations will be performed on selected samples from locations near the mechanical test specimens

- Metallographic examinations will provide:
  - Hydride structure
  - Oxide thickness
  - Grain size analysis
  - Fuel radial profile
  - Clad hydride relative density
  - Hydride rim thickness/orientation
- Total hydrogen content of cladding will be measured using hot vacuum extraction



An example of the level of detail possible using low magnification SEM imaging

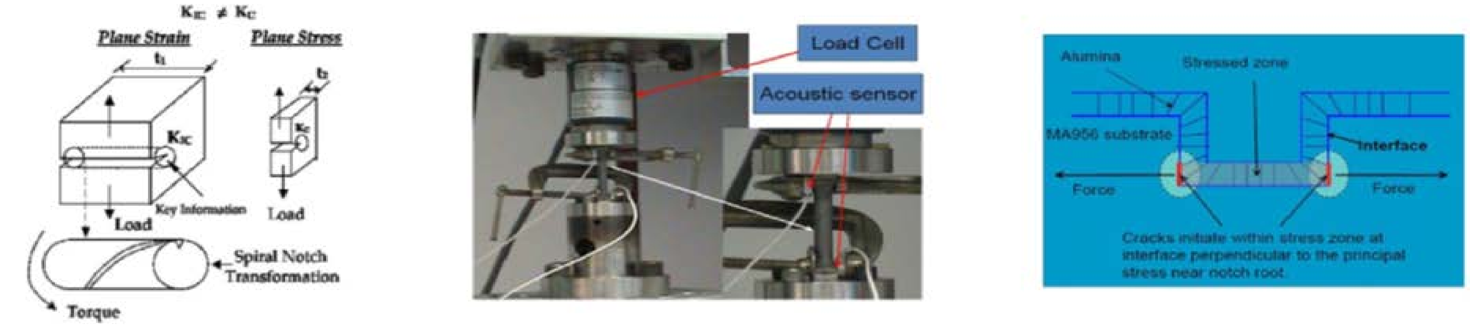


An example of optical (MET) hydride morphology

Spiral Notch Torsion Testing (SNTT) will measure the fracture toughness of the composite pellet/clad system

- Predicts fuel performance during dynamic conditions
- Provides:
  - Fracture toughness,
  - Interface bonding efficiency
  - Torsional rigidity
  - Shear resistance/ modulus
  - Young's modulus
  - Ductile-to-brittle transition temperature (DBTT)

a) schematic of the theory b) SNTT fracture test setup c) halves of tested A302B specimens

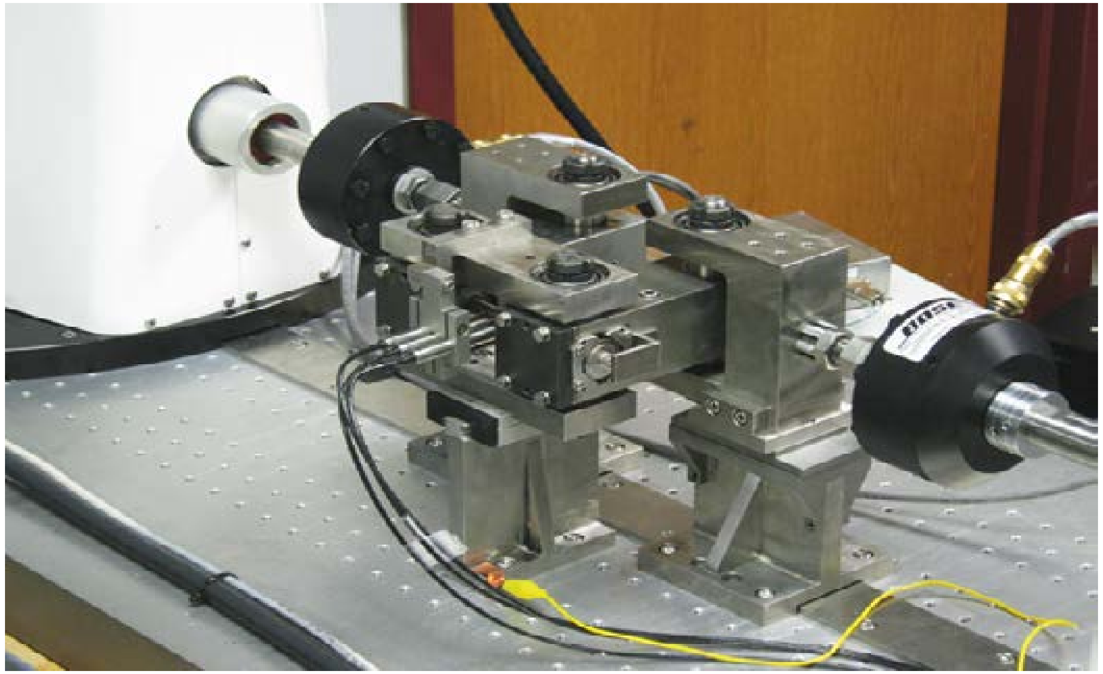


d) CT and SNTT specimens e) SNTT coating test setup f) U-grooved spiral coating test

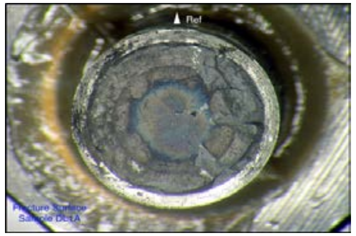
SNTT theory and test equipment

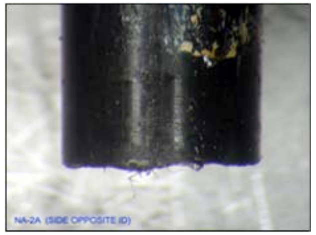
Cyclic integrated reversible-bending fatigue tester (CIRFT) will provide cumulative effects information on the fueled system during transport

- Minimum of 3 tests per rod:
  - Fatigue life (dynamic)
  - Mechanical properties (static)
  - Shock / impact effect on fatigue life (dynamic)
- Provides:
  - Load/cycle curve (S-N curve)
  - Fatigue strength
  - Flexural strength
  - Young's modulus
  - Ultimate tensile strength
- Also, for this test, any fuel aerosols that are released on rupture will be collected and quantified



The cyclic integrated reversible-bending fatigue tester (CIRFT)

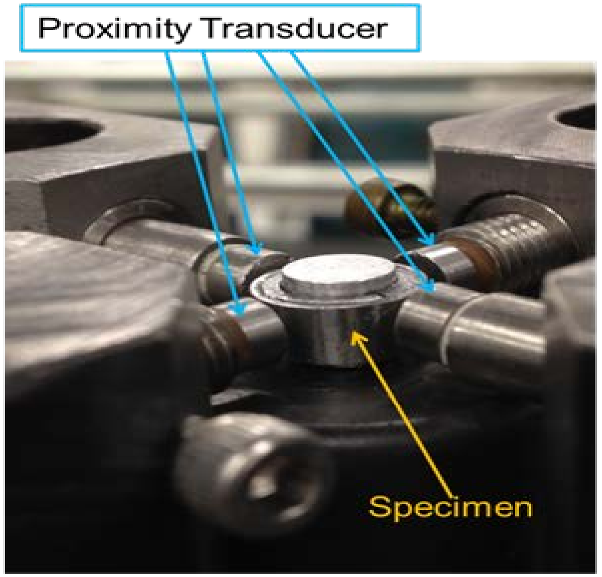




Expanded plug-wedge test provides transverse (hoop) tensile properties on clad materials

- Test methodology:
  - Utilizes four hardened steel wedges with an aluminum plug; when loaded, the plug will provide a radial expansion force to the clad ring.
  - Load-radial displacement data is converted into hoop stress-strain curves.
  - Test can be conducted at temperatures of interest
- Provides transverse (hoop) tensile properties:
  - Yield stress
  - Clad material hardening behavior
  - Ultimate tensile strength
  - Young's modulus
- Results also support DBTT analyses


MTS electro-magnetic load frame

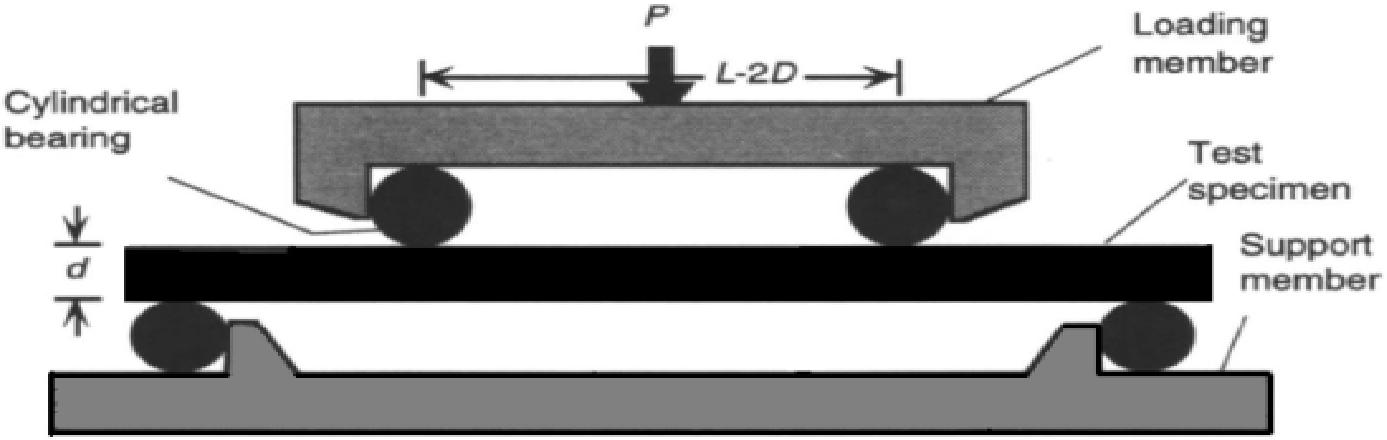


Four Proximity Transducer


(Left) Side view, (Right) Top view of the tested specimen

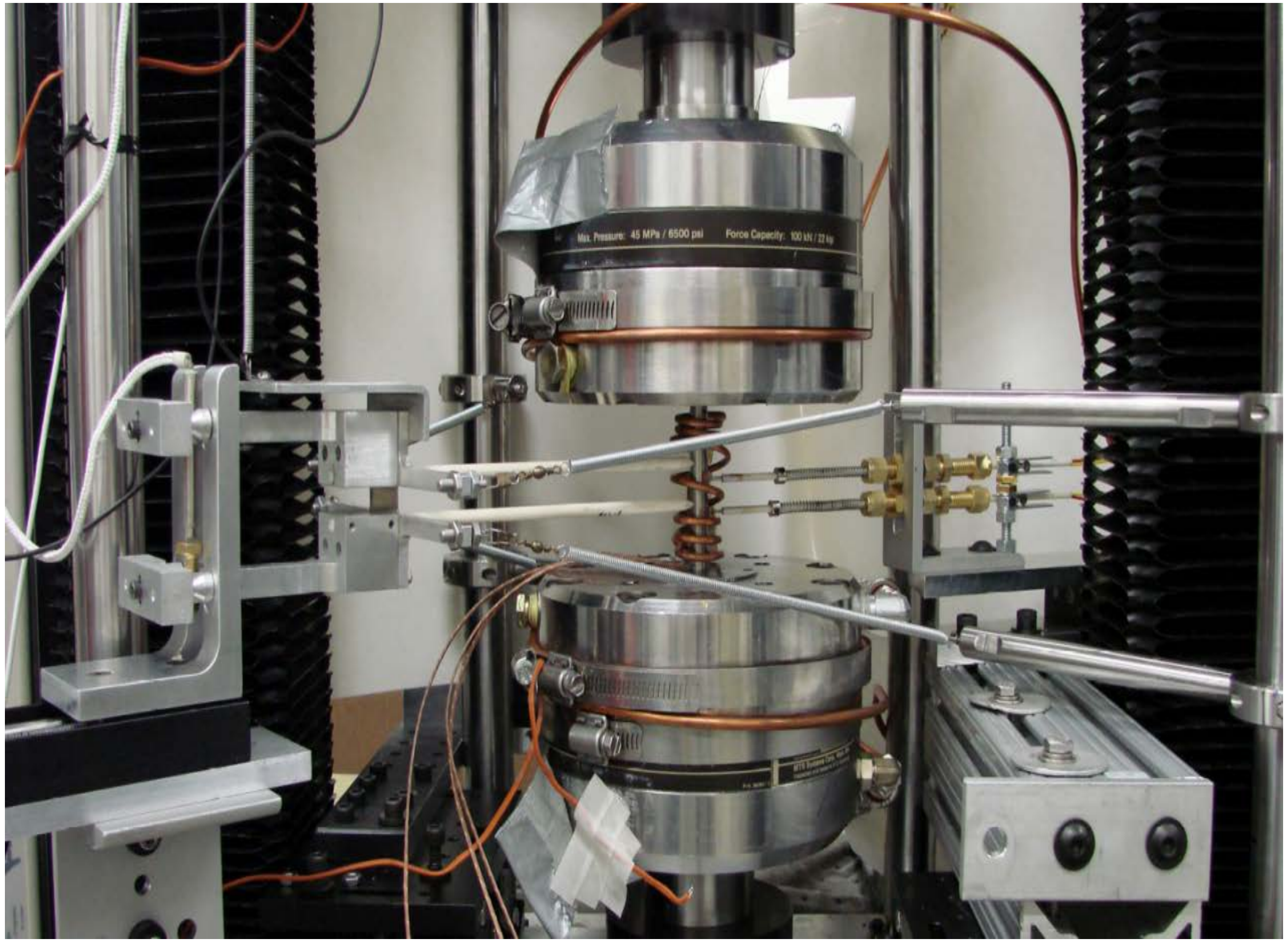
4-point bending tests provide an established, well understood test protocol to back up the static CIRFT testing

- This testing can be conducted at locations that may not have CIRFT equipment
  - 4 PB does not provide reversible bending fatigue testing
- Bending is measured with and without fuel to obtain static material properties
- Validates and provides a comparison of static CIRFT methods and data
  - Allows for direct data comparison with existing measurements



Tube Tensile Testing (axial direction) provides the material properties of cladding (defueled)

- Information collected from these tests include:
    - Yield strength
    - Ultimate tensile strength
    - Uniform elongation
    - Total elongation
    - Young's Modulus
    - Poisson's ratio
    - Strain hardening
- Testing can be done at various temperatures



Tensile testing fixture (as configured for elevated temperature tests)

Ring Compression Testing (RCT) simulates a "pinch" type load at grid-spacer springs and potential rod contact on other fuel or the cask basket walls

- A database will be generated for fueled samples to compare to defueled tests being conducted at ANL, providing the following data:
  - Ductile/Brittle transition temperature (defueled testing)
  - Stress/strain in radial compression
  - Yield strength in radial compression
  - Young's modulus in radial compression
- Simulating drying conditions will allow evaluation of hydride reorientation affects

(b) Photograph of Instron 8511 with ring sample

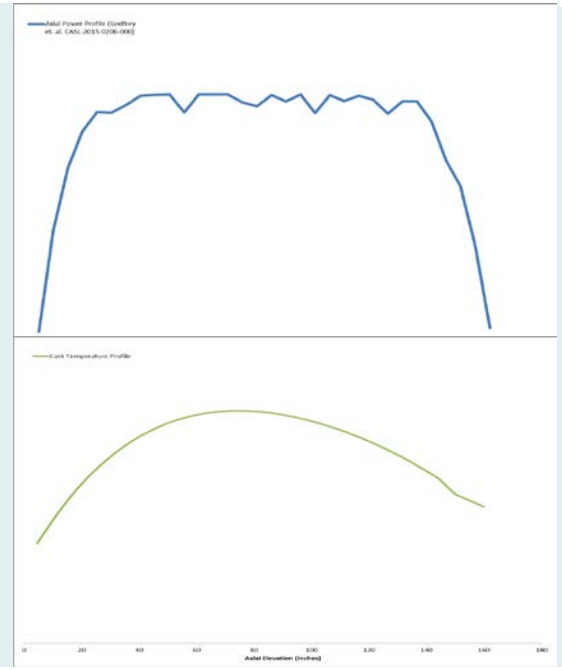
From a broad perspective, all sister rods are similar to each other; however, it is important to recognize that they are in fact all unique

- Similarities
  - 17x17 PWR
  - 0.496” Fuel rod pitch
  - 144” Active fuel length
  - No axial zoning, no IFBA
  - 0.374” / 0.329” Cladding
  - Pellet OD 0.3225”
  - Several manufactured in the same assembly production batch
  - Operated using the same fuel management strategy at a single reactor site with all rods out (except 2 zirc-4 rods from F-35)
  - EFPD ~ 500
  - average rod burnup ~53 GWd/mtU
  - In-reactor assembly temperatures (except for the Zirc-4 and low tin Zirc-4 which were about 80F hotter on average)

- Differences
  - Initial rod enrichments (~22% variation)
  - cladding materials (4 varieties)
  - Initial fill pressure (~50% variation)
  - Plenum length/ free gas volume (~15% variation)
  - Plenum spring volume (~10% variation)
  - Pellet chamfer/dish geometry (~2% variation)
  - Two different units at North Anna and some rods operated in both units
  - First cycle burnable poison assemblies (6P to 21P)
  - Rod-average burnup (17% variation)
  - Cooling time (6 to 28yrs)
  - Rod-average decay heat (~73% variation)
  - 1 assembly was operated in a control rod location with rods partially inserted during its last cycle (F35 – 2 zirc-4 rods)

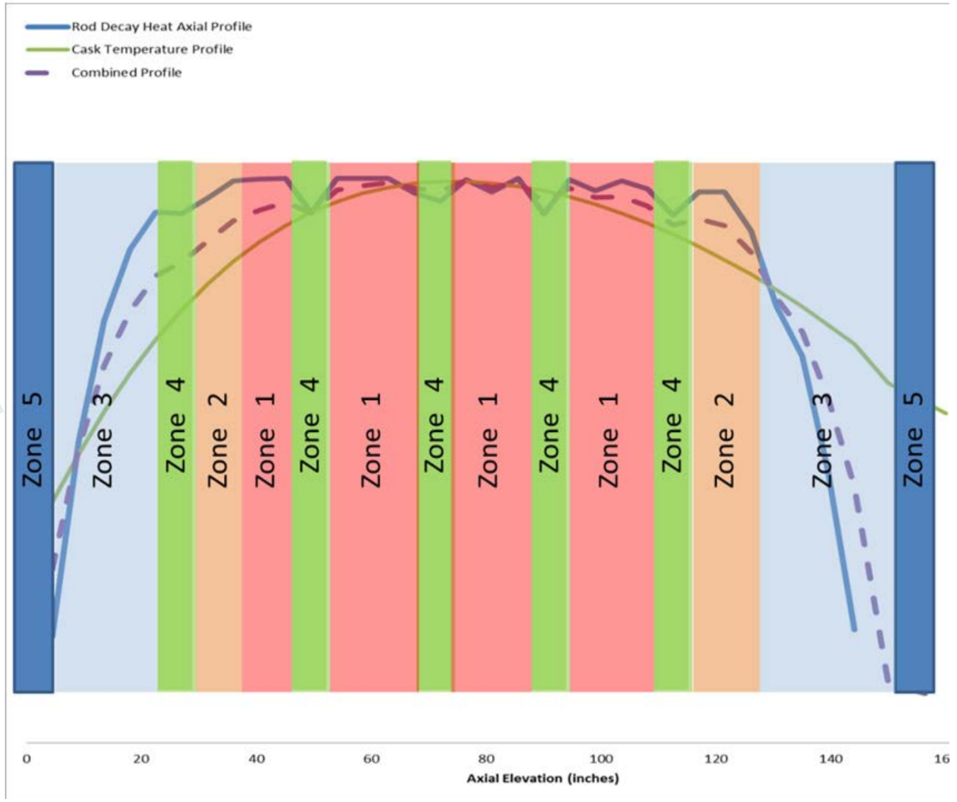
**Variation based on maximum difference from the average of all sister rods.*

The axial decay heat profile of the rod and the temperature variations in the RPC must be understood and accommodated in the DE



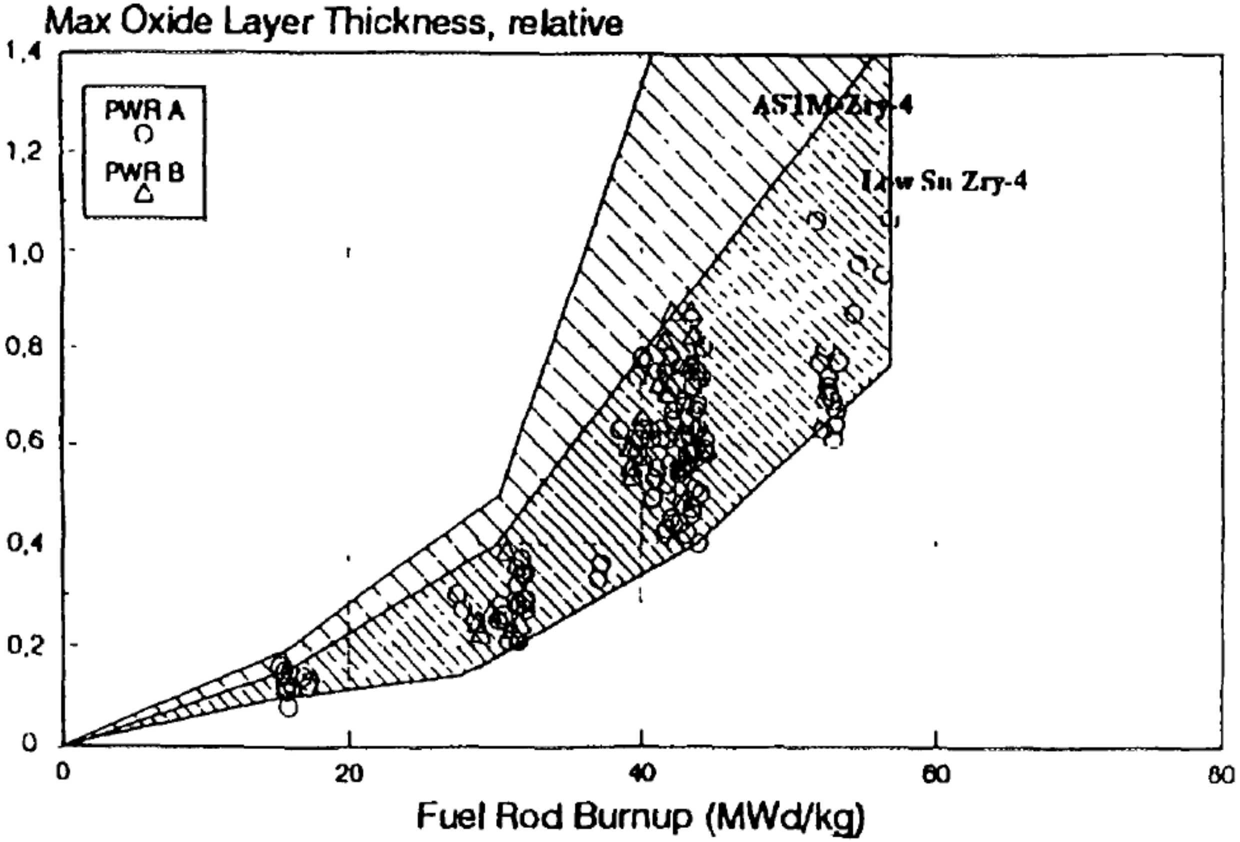
- **In reactor, the fuel burns unevenly; that is, the fission rate varies depending upon the axial elevation**
  - Neutron flux, rod power and fuel temperatures vary axially
  - Decay heat generally follows burnup
  - Effects of spacer grids are evident

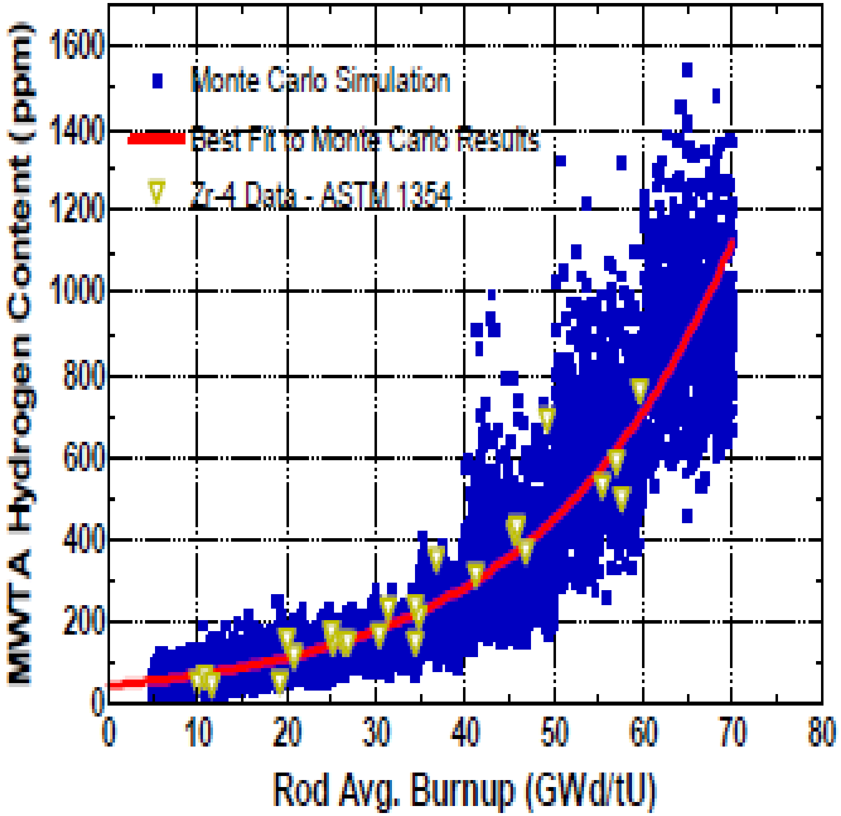
- **Axial temperature variations are also expected to occur within the RPC, with the hotter areas located in the central elevations of the RPC**
  - To be simulated on selected sister rods; more about this later



Zone 1: high-burnup, hottest, fueled elevations
Zone 2: high-burnup, fueled elevations
Zone 3: variable lower burnup, fueled elevations
Zone 4: under-grid fueled elevations
Zone 5: unfueled elevations

A comparison of the oxidation and hydrogen pickup rates for low tin Zircaloy-4 and Zircaloy-4 indicate similar performance expectations for hydride precipitation density





Total Hydrogen Content in Low-Tin Zircaloy-4 as a Function of Burnup (EPRI 2007)