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U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Spent Fuel and Waste Science and Technology (SFWST)

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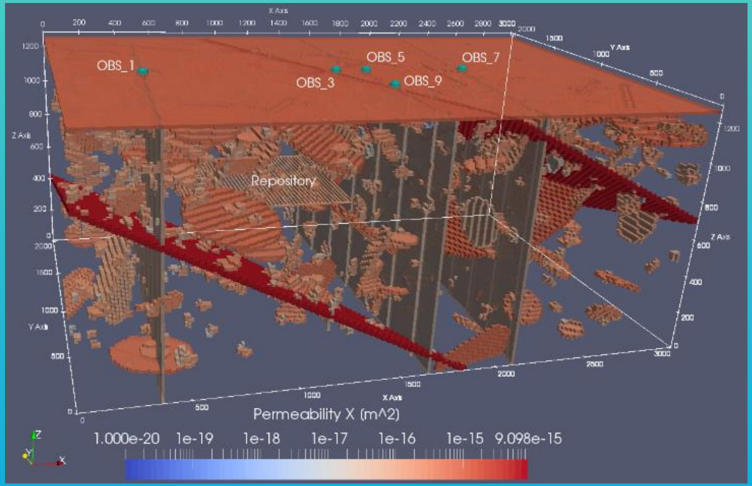

Sibling Pin Test Campaign Phase I Summary and Draft Phase II Test Plan Overview

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Sandia National Laboratories

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NWTRB Public Meeting

Idaho Falls, Idaho

August 30, 2023

Acknowledgements

- Argonne National Laboratory (ANL), Oak Ridge National Laboratory (ORNL), and Pacific Northwest National Laboratory (PNNL)

- The US Department of Energy (DOE) Office of Nuclear Energy sponsor, Ned Larson, and the Spent Fuel and Waste Science and Technology storage and transportation program

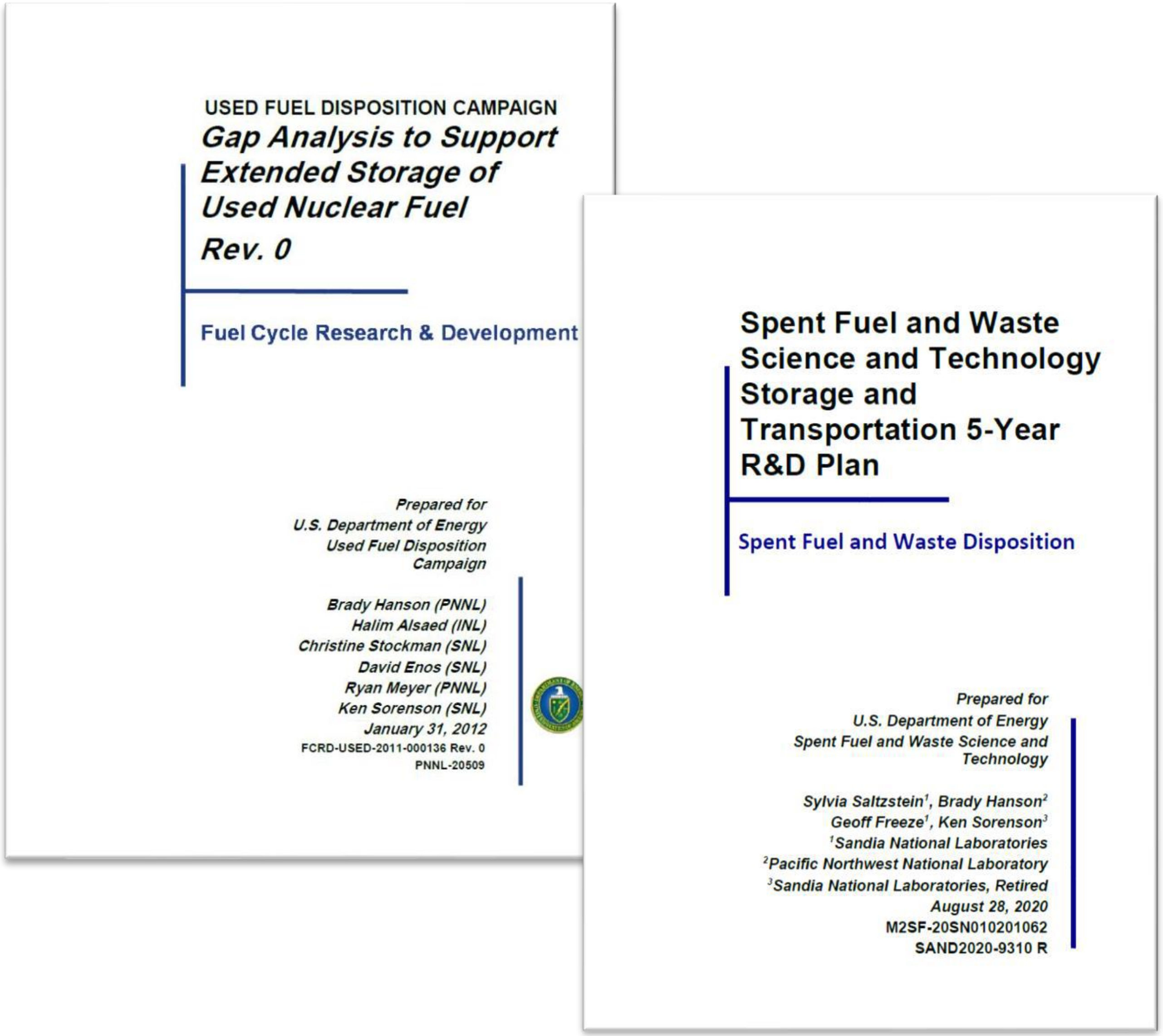
- The Electric Power Research Institute (EPRI), Westinghouse, Framatome, and Dominion Energy

- The US Nuclear Regulatory Commission (NRC)

Gap Analyses

After the suspension of the Yucca Mountain Project, the DOE needed to determine what the potential concerns were if commercial fuel remained stored at the nation's nuclear power reactors for decades or centuries, instead of going into a deep geologic repository.

- The DOE funded the national labs to determine what R&D was needed to develop the technical basis for the extended storage and subsequent transportation of spent nuclear fuel.
- A Gap Analysis was completed in 2012 with updates through 2019.
- A 5-year Research & Development (R&D) plan was completed in 2020.



USED FUEL DISPOSITION CAMPAIGN

Gap Analysis to Support Extended Storage of Used Nuclear Fuel

Rev. 0

Fuel Cycle Research & Development

Prepared for
U.S. Department of Energy
Used Fuel Disposition Campaign

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January 31, 2012
FCRD-USED-2011-000136 Rev. 0
PNNL-20509

Spent Fuel and Waste Science and Technology Storage and Transportation 5-Year R&D Plan

Spent Fuel and Waste Disposition

Prepared for
U.S. Department of Energy
Spent Fuel and Waste Science and Technology

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August 28, 2020
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SAND2020-9310 R

Storage and Transportation R&D Plan

Gaps

Gap	Near term	Mid term	Long term	
Demo/Sibling Pin Testing	• Collect baseline data to gain insight into fuel and cladding degradation mechanisms and their effect on safety	• Complete testing/data reports to finalize work of H_2 effects on cladding • Assess effects of gross rupture		• Prepare facility and move canister
Thermal Profiles	• Complete Round Robins • Conduct small & large scale testing • Perform Uncertainty Analyses	• Continue testing/analyses on canistered and bare fuel systems in horizontal and vertical orientations, leaking canisters, plugged vents, and time to boil.	• Complete cumulative assessments of specific designs	• Close Gap
Stress Profiles	• Design, Fabricate, and Test 8-Axle Railcar • Complete 30cm drop test analysis • Determine pinch loads and seismic loads	• Assess canister drop scenarios • Assess cumulative effects of SSC systems under storage design and operational conditions.	• Conduct large scale tests to validate model results of canister performance under design and operational condition.	
Welded Canister	• Continue corrosion initiation and crack growth rate tests • Continue brine stability testing and collect additional dust samples • Refine, improve, and validate deposition models	• Obtain residual stress measurements on different canisters • Perform small scale and larger-scale (e.g., SNL dry cask simulator) testing to provide data for deposition modeling	• Conduct a full-scale canister deposition demonstration at various heat loads to provide data on deposition and brine stability • Examine multiple repair and mitigation techniques to extend the lifetime of a canister	
Drying	• Design and perform lab-scale tests with well-defined conditions to improve sampling and analysis techniques • Collect and analyze in-service gas samples	• Design and perform larger-scale tests using heater assemblies to quantify residual water as a function of drying parameters	• Design and perform a full-scale test using heater assemblies • Perform a consequence analysis	• Close Gap
Monitoring	• R&D to interrogate cask internals without cask penetrations.	• Test on a demo canister		• Close Gap
ATF/BWR/ IFBA Testing	• Work with NE-4 to define ATF testing program	• Identify fuels to test and facilities to use for testing • Prepare test plans		• Conduct testing

High Burnup (HBU) Spent Fuel Data Project (or “Demo Project”)

- A **high priority activity** identified in the initial 2012 gap assessment.
- A DOE & EPRI collaboration focused on understanding the performance of high burnup fuel (>45 GWd/MTU) in “typical” dry storage conditions.
- An instrumented TN-32B dry storage cask (or “Demo Cask”) was loaded with 32 HBU Pressurized Water Reactor (PWR) fuel assemblies in 2017 and placed in dry storage for ~10 years. Later it will be re-opened and the fuel inspected.
- Demo Cask is stored on the North Anna Nuclear Power Plant (NPP) Independent Spent Fuel Storage Installation (ISFSI).
- Temperatures were monitored and recorded during the drying process and continue to be monitored while the cask is in dry storage.

Loaded TN-32B for the High Burnup Demo at North Anna NPP. The solar panel is powering the 63 thermocouples inside the canister. Photo Credit: North Anna NPP

Sibling Pin (or "Sister Rod") Test Campaign

- The Sibling Pin test campaign is a DOE-funded research activity that is part of the High Burnup Spent Fuel Data Project.
- Focused on generating characterization, material property, and performance data for HBU fuel rods.
- Destructive examinations and non-destructive examinations (NDEs) are performed at ORNL, PNNL, and ANL of 25 HBU fuel rods.
- 25 HBU fuel rods selected with characteristics and histories that closely match those used in the Demo Cask.

Cladding Type	# Rods	Pin Burnup (GWd/MTU)
M5®	9	49-57
ZIRLO®	12	49-59
Zr-4	2	58
Low-SN Zr-4	2	48-51

Original Sibling Pin Test Campaign Objectives

- Generate baseline (t0) comparison data corresponding to the condition of the rods being loaded into a dry storage cask (i.e., post irradiation and pool storage, but before dry storage).
- Generate post-drying (t0') comparison data corresponding to the condition of the rods after they have undergone drying, helium backfill, and placement on the storage pad.
- Generate data for other cask designs and conditions.
  - Consider conditions modeled for other Dry Cask Storage Systems with different thermal profiles, histories, and fuel rod properties.
  - Support the surge in renewals of storage licenses expected when sibling pin test campaign started.

High-Burnup Spent Fuel Rod Phase 1 Test Plan Visualization

7-5-18

We start with 25 rods. Both labs will perform similar tests, but ORNL will test fueled rods and PNNL will test defueled rods. ANL will perform RCT and RHT on rod segments.

PNNL — Heat Treatment of Segments or Whole Rods to 400°C — ORNL

- 3 Rods: 1 M5®, 1 Zirlo®, 1 Zirc-4
- Cool at ≤5°C/hr to 100°C

PNNL — No Heat Treatment (as irradiated) — ORNL[1]

- 2-3 Rods: M5®, Zirlo®, Low-Tin Zirc-4

6 rods are heat treated and 4 are not; all rods undergo the same series of initial tests at room temperature.

PNNL — Initial Tests at Room Temperature — ORNL

- Rod Internal Pressure
- Gas Communication
- Optical Microscopy
- Hydrogen Content
- ASTM Micro-hardness
- RCT & RHT Test Samples *(Send to ANL)*
  - RCT Tests @ 20°C to 200°C
  - RHT @ 400°C PCT

Rod segments are then tested at room temperature and 200°C[2].

PNNL to Test Defueled Rods

PNNL — Test at 200°C[3] — ORNL

- ASTM Axial Tensile
- ASTM Burst
- ASTM 4-point Bend
- Fueled RCT @ ORNL

ORNL to Test Fueled Rods

PNNL — Room Temperature — ORNL

- ASTM Axial Tensile
- ASTM Burst
- ASTM 4-point Bend
- Fueled RCT @ ORNL
- CIRFT @ ORNL
- Particle Release @ ORNL

1) *ORNL may use multiple M5® or Zirlo® rods as well as Low-Tin Zirc-4 rod segments for testing.*
2) *Tests will be conducted on samples from multiple axial regions of each fuel rod.*
3) *Not all tests may be able to be performed at 200°C.*

- Deviations from this test plan will be based on continuous learning and approved before execution.
- As test results are obtained, our community reviews the data, and DOE determines a path forward.

Sibling Pin Phase I Status

- Initial NDE of the 25 Sibling Pin fuel rods was completed by ORNL in 2018.
- The heat treatment was intentionally designed to increase the potential for radial hydride formation while limiting peak cladding temperature (PCT) to the NRC-recommended value (400 ^{o}C) at as-discharged rod internal pressures.
- Time at peak temperature was restricted to 8 hours to limit annealing of irradiation damage.
- Phase I testing is on-going, but largely complete.

High-Burnup Spent Fuel Rod Phase 1 Test Plan Visualization

7-5-18

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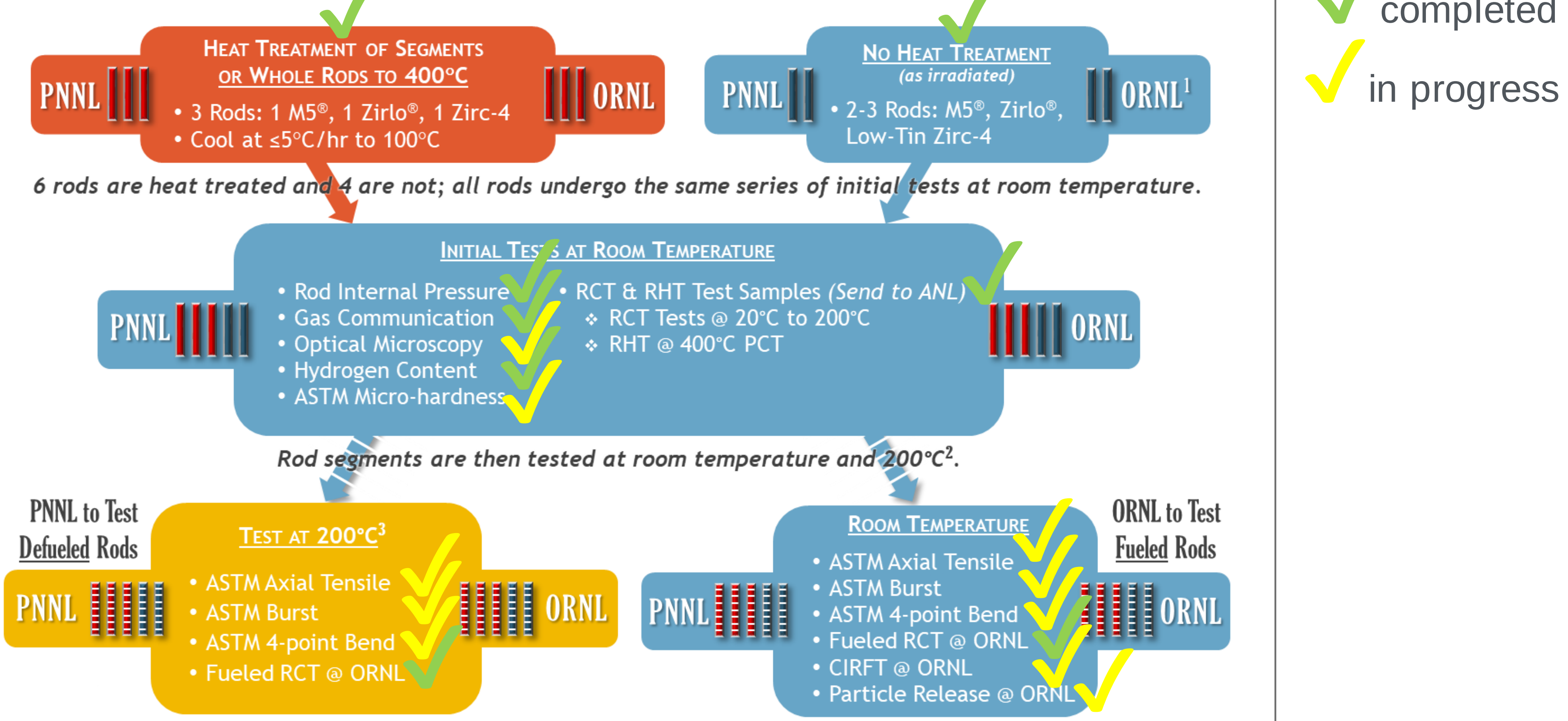

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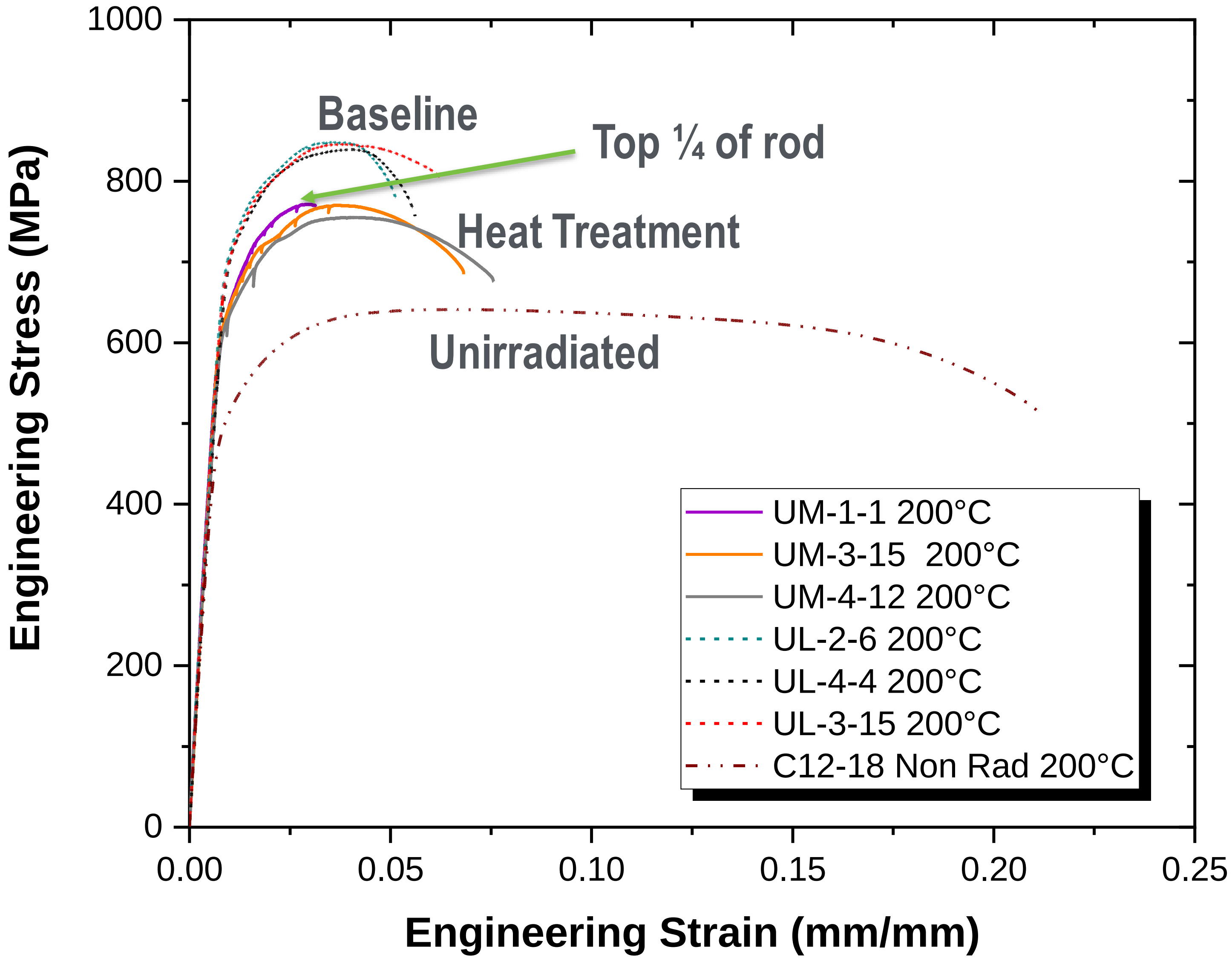
Phase I High Level Select Lessons-Learned

- Heat treatment of fuel rods at 400 ºC for 8 h can affect fuel rod performance.
  - Generally yield strength, ultimate strength, and Young's modulus decrease while ductility increases. It is alloy dependent.
  - Heat treatment resulted in minor radial hydride reorientation and appeared not to degrade performance

- End-of-life (EOL) rod internal pressures (RIP) were lower than used in initial ring compression testing, indicating hoop stresses may be too low to cause damaging radial hydrides.

- Cladding metal fatigue cycles observed in the Multi Modal Transportation Test (MMTT) are well within the region where fatigue damage should not accumulate for commercial rods.

Tensile Stress-Strain Effect of 8 hr Heat Treatment @ 400˚C (ZIRLO® @ 200˚C) t0 vs t0' (Slide Courtesy of Brady Hanson, PNNL – Example)



	Young's Modulus (GPa)	Yield Stress (eng) (MPa)	Ultimate Tensile Stress (eng) (MPa)	Uniform Elongation (%)
Baseline	89±8	703±14	844±11	3.8±0.5
Heat treatment	89±1	629±18	762±22	3.9±0.6
% change	0	11	10	0

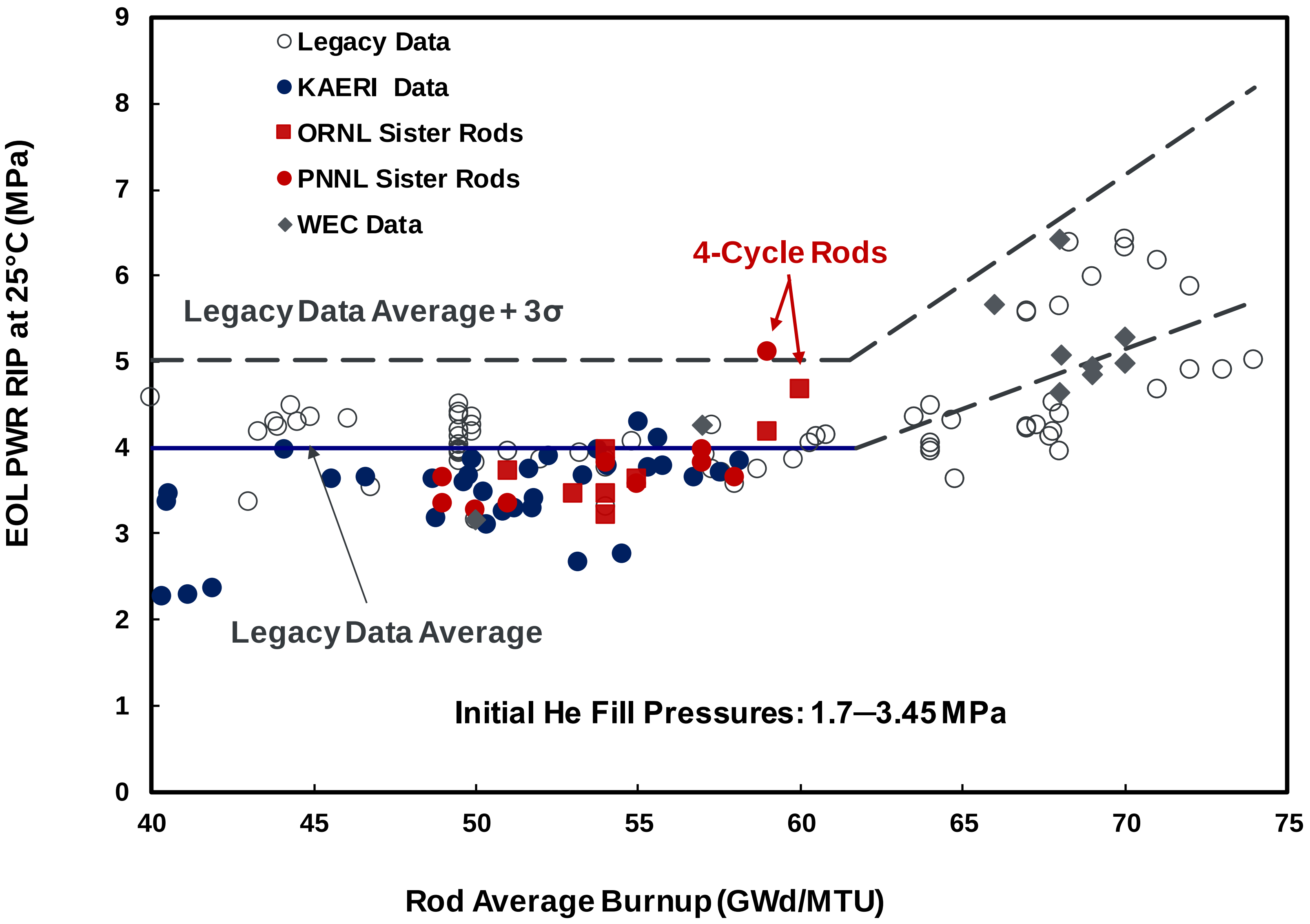
Neglecting samples from top ¼ of rod
Decrease from baseline
Increase from baseline

Solid lines (UM) underwent Heat treatment prior to testing (t0')

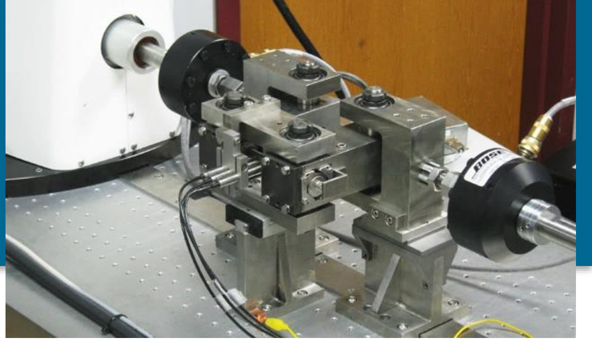
Dashed lines (UL) are baseline (t0)

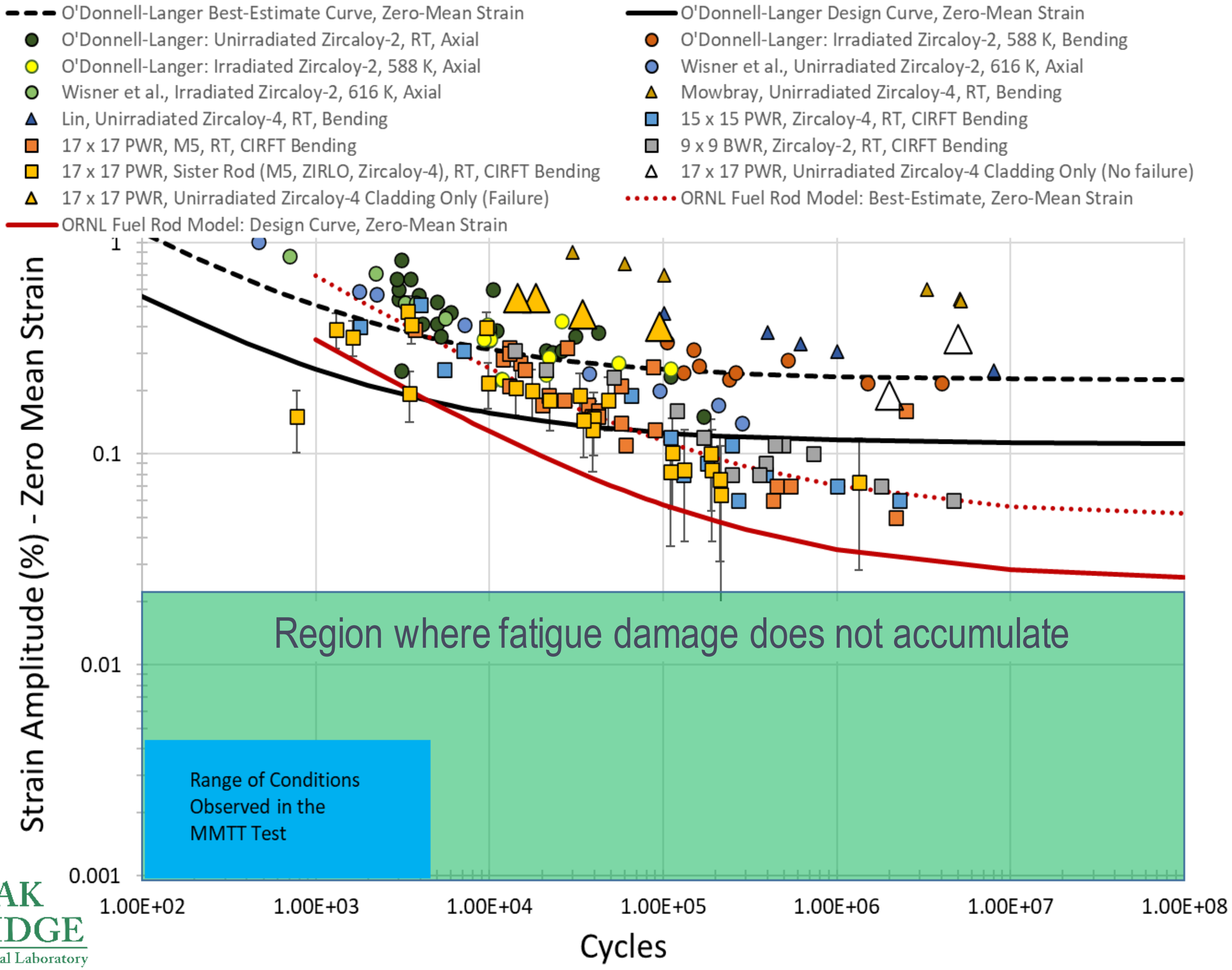
PWR (Non-Integral Fuel Burnable Absorber) EOL-RIP Data @ 25^{o}C

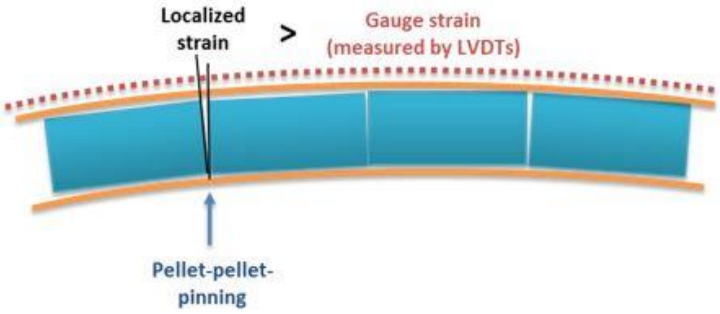
(Slide Courtesy of Mike Billone, ANL)



The range of conditions observed in the MMTT shipping test are well within the region where fatigue damage should not accumulate (Slide courtesy of Rose Montgomery, ORNL)







Multimodal Transportation Test (MMTT)

- Three surrogate PWR assemblies with rods instrumented with strain gages were shipped from Spain to Pueblo, Colorado in an ENSA ENUN 32P cask
- In Pueblo, Colorado, the cask experienced extreme shipping conditions at the Transportation Technology Center, Inc.
- The range of conditions represents the most severe strain amplitudes observed in the MMTT

The focus of future testing will be on defining the high cycle endurance limit of pressurized segments, considering transportation temperatures

(Source: Montgomery et al., "*Sister Rod Destructive Examinations (FY22) Appendix F-2: Evaluation of Fuel Rod Fatigue During Spent Fuel Transportation*", 2022. ORNL/SPR-2022/2736

Oak Ridge National Laboratory

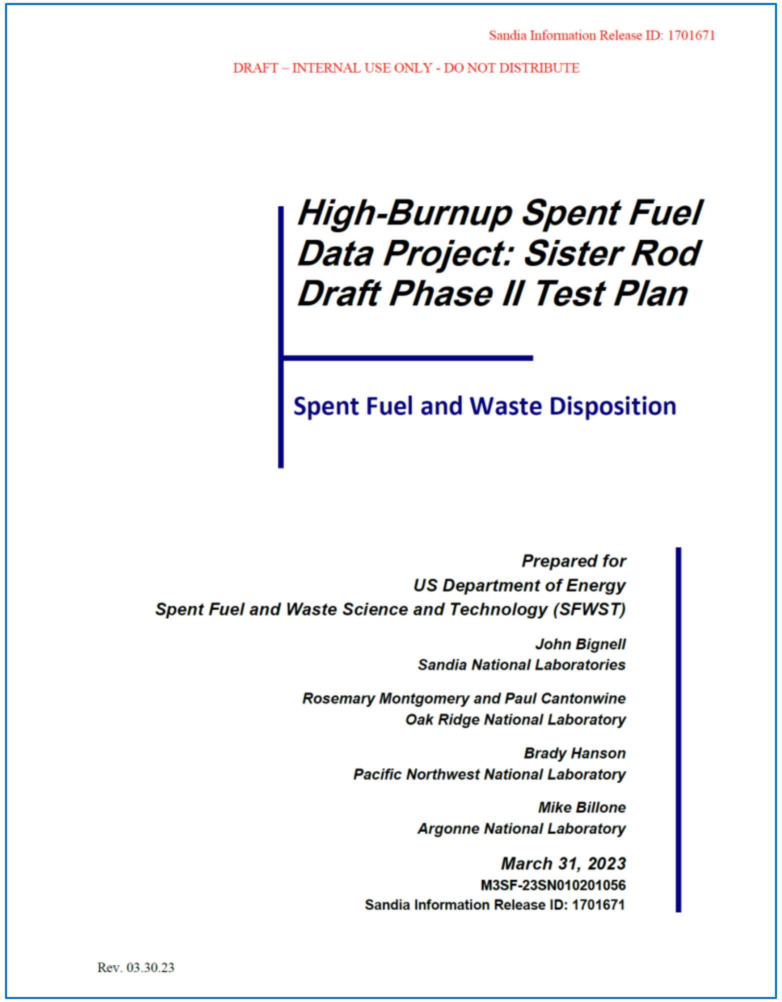
Phase I High Level Select Lessons-Learned (cont.)

- Fueled ring compression tests (RCTs) indicate a large transverse load bearing capability, independent of hydride reorientation.
- Outer diameter oxide layer thickness, total hydrogen content, and hydride density and length generally increase moving from the bottom of the rod towards the top.
- Fission gas appears to move more easily through the heat-treated rods.

Sibling Pin (Sister Rod) Draft and Final Phase II Test Plan

- A Draft Phase II Test Plan was recently completed which describes the Phase II test priorities and the reasoning behind their prioritization, as well as outlines a high-level plan for Phase II testing.

- A final (non-draft) version of the test plan will be published later this year, with updates based on additional feedback from internal and external stakeholders.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High-Burnup Spent Fuel Data Project: Sister Rod Draft Phase II Test Plan

Spent Fuel and Waste Disposition

Prepared for
US Department of Energy
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Draft Phase II Test Priorities and Prioritization Approach

- Priorities for Phase II Testing Are Based On:
  - Previously Identified Gaps and Their Importance.
  - Lessons-Learned from Work Completed To-Date.
  - An Assessment of Phase I Accomplishments Against Original Objectives of the Sibling Pin Test Campaign and the High Burnup Demonstration Project.

- Additionally, input from external stakeholders has been solicited and considered in the prioritization.
  - EPRI Extended Storage Collaboration Program (ESCP) Survey.
  - Technical Exchange with Nuclear Regulatory Commission (NRC).

Reassessment of Gaps for Phase II

- A 2017 assessment of cladding and fuel specific gaps produced the following prioritization.
  - HIGH Priority: Hydride Reorientation and Radial Hydride Induced Embrittlement
  - MEDIUM Priority: Delayed Hydride Cracking
  - LOW Priority: Creep, Radiation Damage Annealing, Oxidation.
- The high prioritization of the hydride reorientation and radial hydride induced embrittlement gap motivated the design of the heat treatment for Phase I testing.
- Data obtained from the Phase I testing have resulted in a reassessment of the importance of these gaps, most notably the gaps related to:
  - hydride reorientation and radial hydride induced embrittlement,
  - radiation damage annealing, and
  - creep.

Radiation Damage Annealing and Creep Gaps

- Previously, the radiation damage annealing and creep gaps were given a low priority. Results from Phase I testing indicate they should have higher priorities.
- Comparison of cladding yield and ultimate strengths derived from Phase I tension and bending tests of baseline and heat treated cladding and fuel rod samples showed larger than anticipated reductions in those values as a result of the heat treatment.
- Because the NRC accepts the use of a yield failure criterion for demonstration of cladding performance for licensing purposes of storage and transportation casks, reduced yield strengths may have significant implications for licensing of current and future systems.
- While annealing usually is accompanied by increases in ductility that can reduce the risk of cladding failure, the reduced material strengths can facilitate creep.
- An increased emphasis on quantifying the effects of annealing, including its effects on creep, is appropriate in Phase II testing.

Hydride Reorientation and Radial Hydride Embrittlement Gap

- Previously, the hydride reorientation and radial hydride embrittlement gap was given a high priority. Results from Phase I testing indicate it should have a lower priority.

- Rod internal pressures measured during Phase I testing indicate that significant cladding degradation due to radial hydride precipitation during cooling from a heat treatment temperature of 400 ^{o}C (the NRC recommended PCT limit) is unlikely.

- Defueled ring compression tests (RCTs) completed as part of Phase I support this, and fueled RCTs completed as part of Phase I demonstrate that the fuel pellets constrain deformation of the cladding under pinch loading conditions, increasing the load necessary to cause cladding failure.

- A reduced emphasis on quantifying hydride reorientation and radial hydride induced embrittlement is appropriate in Phase II testing.

Status of Project Objectives After Phase I Testing

ID	Status	HBU Fuel Data Project and Sibling Pin Objective
1	Incomplete	Provide data to DOE that is needed to make informed decisions on waste management issues.
2	Complete	Establish baseline (t0) characteristics and properties of the fuel rods going into the Demo Cask.
3	Incomplete	Generate data (t0') that enables the prediction of the effects of drying on mechanical properties and fuel rod performance for the fuel rods in the demo cask, as well as for fuel rods in other current and future systems.
4	Incomplete	Provide data to support licensing and re-licensing of new and existing dry storage and transportation casks.

- Objective 2 is considered complete.
  - Phase I testing has gathered a significant amount of t0 data.

- Objectives 1, 3, and 4 are considered incomplete.
  - The Phase I heat treatment is insufficient to address the range of temperatures and exposure durations anticipated for current and future systems → Data covering a wider range of temperatures/durations are needed.
  - Creep was not addressed in Phase I → Creep data to support near term licensing and re-licensing of new and existing systems are needed.

External Stakeholder Input: EPRI ESCP

- A survey was distributed to attendees of EPRI's ESCP 2023 Winter Meeting soliciting feedback on preliminary plans for Phase II testing.
  - 15 people responded: 5 industry, 2 consulting engineers, and 8 research/national lab.

- Responses to the survey indicate:
  - A desire for testing at peak cladding temperatures (PCTs) above the current NRC guidance limit of 400 ^{o}C, including to address off-normal conditions and to support industry initiatives.
  - A desire for testing at PCTs at and below the current NRC guidance limit of 400 ^{o}C, to address PCTs representative of current and future systems designed to satisfy the current guidance limit where thermal conservatisms have been removed.
  - A desire for data to support tollgate assessments under NRC-approved Aging Management Plans (AMPs).

External Stakeholder Input: NRC

- In January 2023, members of the DOE Sibling Pin program participated in a technical exchange with the NRC, to discuss technical results relevant to Phase II test planning.

- Observations from members of the Sibling Pin team following the technical exchange*.
  - Preference for expanding the data set for temperatures at or below the current NRC recommended limit (400 ^{o}C) was expressed, with some interest in investigating temperatures above 400 ^{o}C.
  - An interest in obtaining creep data in the near term, particularly for M5® cladding, was expressed.
  - Interest in fatigue and static bend testing on aggressively conditioned (for reoriented hydrides) rods, like those described in NUREG-2224, to provide bounding data was expressed.
  - Interest in further investigating the effects of thermal cycling on cladding ductility was expressed.

** In no way should these observations be interpreted as guidance from, or an official stance of, the NRC, and in no way were these observations taken as direction from the NRC on what tests or test conditions should or should not be performed as part of the test campaign.*

Draft Phase II Test Priorities

- **Annealing**: Obtain data to characterize the effects of annealing on HBU cladding material properties and fuel rod performance for temperatures and exposure times anticipated for current and future systems.

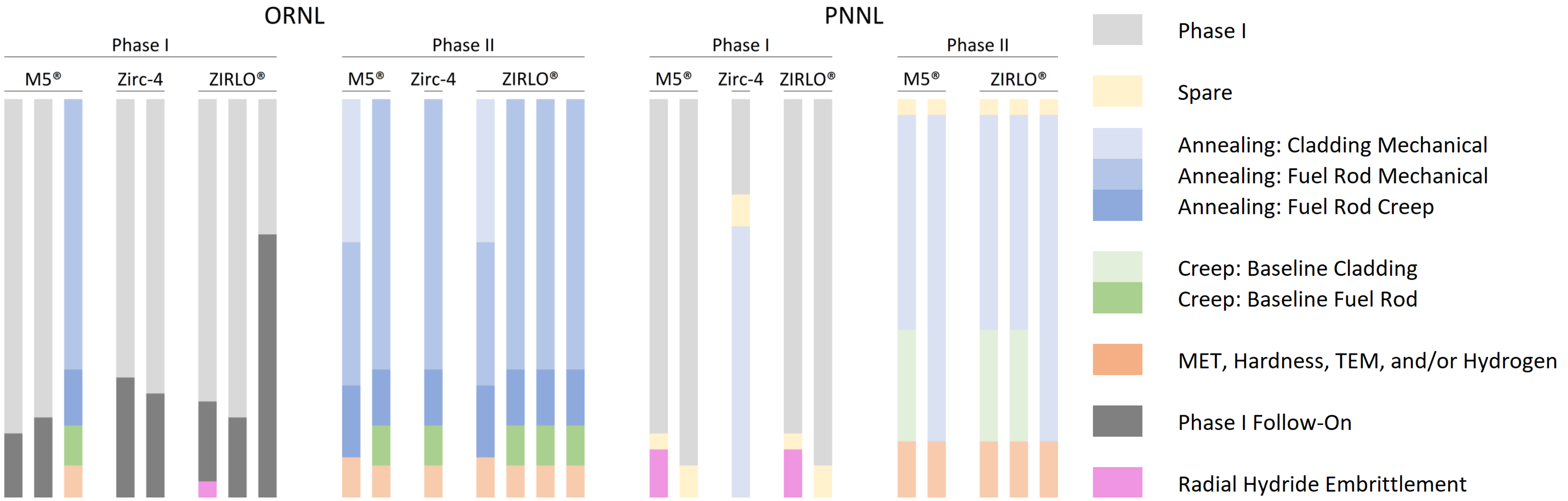
- **Creep**: Obtain data to characterize the creep behavior of baseline HBU cladding material and fuel rods for temperatures and internal pressures representative of, and/or bounding of, those anticipated for current and future systems.

- **Annealing & Creep**: Obtain data to characterize the creep behavior of annealed HBU cladding material and fuel rods for creep temperatures and internal pressures representative of, and/or bounding of, those anticipated for current and future systems.

- **Hydride Reorientation and Radial Hydride Induced Embrittlement**
  - Obtain data to characterize the low temperature ductility of high hydrogen content M5® and ZIRLO® cladding materials following their exposure to a bounding radial hydride treatment (RHT).
  - Obtain data to characterize the low temperature ductility of high hydrogen content M5® and ZIRLO® cladding materials following their exposure to thermal cycling.
  - Obtain data to characterize the fatigue and bend performance of aggressively conditioned M5® and ZIRLO® fuel rods.

Draft Phase II Test Visualization

- Shading in the figure indicates the approximate percentage of each Sibling Pin fuel rod assigned to each Draft Phase II priority.
- In general, characterization methods in Phase II will mimic those employed in Phase I testing.



Questions