High-Burnup Spent Fuel Data Project: Sister Rod Final Phase II Test Plan

Spent Fuel and Waste Disposition

Prepared for
US Department of Energy
Spent Fuel and Waste Science and Technology (SFWST)

John Bignell
Sandia National Laboratories

Rosemary Montgomery and Paul Cantonwine
Oak Ridge National Laboratory

Brady Hanson and Ricardo Torres
Pacific Northwest National Laboratory

Mike Billone
Argonne National Laboratory

September 15, 2023
M3SF-23SN010201057
SAND2023-09981R

Prepared by: John L. Bignell
Sandia National Laboratories
Albuquerque, New Mexico 87185

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

APPENDIX E

NFCSC DOCUMENT COVER SHEET[1]

Name/Title of Deliverable/Milestone/Revision No.: High-Burnup Spent Fuel Data Project: Sister Rod Final Phase II Test Plan, M3SF-23SN010201057

Work Package Title and Number: SF-23SN01020105 - Fuel Integrity Support - SNL

Work Package WBS Number: 1.08.01.02.01

Responsible Work Package Manager: John Bignell John Bignell 09/15/2023
(Name/Signature)

Date Submitted: 09/15/2023

Quality Rigor Level for Deliverable/Milestone[2]	☐ QRL-1 ☐ Nuclear Data	☐ QRL-2	☒ QRL-3	☐ QRL-4 Lab. QA Program[3]

This deliverable was prepared in accordance with QA program which meets the requirements of: Sandia National Laboratories
(Participant/National Laboratory Name)

☒ DOE Order 414.1 ☐ NQA-1 ☐ Other

This deliverable was subjected to:

☒ Technical Review ☐ Peer Review

Technical Review (TR)	**Peer Review (PR)**
Review Documentation Provided	**Review Documentation Provided**
☐ Signed TR Report or,	☐ Signed PR Report or,
☐ Signed TR Concurrence Sheet or,	☐ Signed PR Concurrence Sheet or,
☒ Signature of TR Reviewer(s) below.	☐ Signature of PR Reviewer(s) below.

Name and Signature of Reviewers:

Name: Ken Sorenson Signature: KB Sorenson 09/15/2023

Name: Signature:

Name: Signature:

NOTE 1: *Appendix E should be filled out and submitted with the deliverable. Or, if the PICS:NE system permits, completely enter all applicable information in the PICS:NE Deliverable Form. The requirement is to ensure that all applicable information is entered either in the PICS:NE system or by using the NFCSC Document Cover Sheet.*

- *In some cases, there may be a milestone where an item is being fabricated, maintenance is being performed on a facility, or a document is being issued through a formal document control process where it specifically calls out a formal review of the document. In these cases, documentation (e.g., inspection report, maintenance request, work planning package documentation or the documented review of the issued document through the document control process) of the completion of the activity, along with the Document Cover Sheet, is sufficient to demonstrate achieving the milestone.*

NOTE 2: *If QRL 1, 2, or 3 is not assigned, then the QRL 4 box must be checked, and the work is understood to be performed using laboratory QA requirements. This includes any deliverable developed in conformance with the respective National Laboratory / Participant, DOE or NNSA-approved QA Program.*

NOTE 3: *If the lab has an NQA-1 program and the work to be conducted requires an NQA-1 program, then the QRL-1 box must be checked in the work Package and on the Appendix E cover sheet and the work must be performed in accordance with the Lab's NQA-1 program. The QRL-4 box should not be checked.*

This page is intentionally left blank.

SUMMARY

The Sibling Pin test campaign is a Department of Energy (DOE) research activity within the Spent Fuel and Waste Science and Technology (SFWST) program that is tasked with characterization of high burnup (HBU) fuel in support of the High Burnup Spent Fuel Data Project. Of the 25 fuel rods in the Sibling Pin inventory, approximately 9 rod lengths have been consumed during the first phase (Phase I) of the test campaign leaving approximately 16 rod lengths for the second phase (Phase II) of testing. This plan outlines the Phase II testing and the motivations for performing these tests.

Priorities for Phase II testing are based on previously identified knowledge gaps, lessons-learned from Phase I work, the original objectives of the High Burnup Spent Fuel Data Project and the Sibling Pin test campaign, and input from external stakeholders. The priorities for Phase II testing are to obtain data to characterize the effects of annealing on cladding mechanical properties and fuel rod performance, to quantify the creep behavior of cladding materials and fuel rods and the effects of creep deformations on the performance of cladding and fuel rods, and to gather data to support the final closure of the hydride reorientation and radial hydride induced embrittlement gap for HBU fuel rods.

Phase II testing activities are planned to be completed at PNNL, ORNL, and ANL. It is important to understand both the composite behavior of fuel rods (cladding with fuel) and the stand-alone behavior of cladding to achieve the objectives of the Sibling Pin test campaign. In an approach similar to that employed for Phase I, Phase II testing conducted at ORNL will focus primarily on the characterization of fuel rods (cladding with fuel) and testing at PNNL and ANL on the characterization of defueled cladding. Each laboratory will develop detailed plans for the specific subset of Phase II tests to be performed at their facilities, based on the objectives and tests described here.

ORNL’s Phase II fuel rod inventory consists of approximately 10.1 rod lengths of material. Approximately 0.6 rod lengths are planned to be utilized to investigate annealing of defueled cladding over annealing temperatures ranging from 300 °C to 450 °C and annealing times ranging from 4 to 6000 hours. Axial tension tests using subsized tension test coupons are planned for this investigation. Approximately 5.8 rod lengths are planned to be utilized to investigate the effects of annealing on the mechanical and creep characteristics and performance of fuel rods. Specific levels of annealing relevant to current and future storage and transportation systems are planned to be targeted. Mechanical characterization will include 4-point bend (4PB), cyclic integrated reversible-bending fatigue tester (CIRFT), axial tension, and bounding and accelerated creep tests. An additional 0.5 rod lengths are planned to be used to investigate the creep behavior of baseline fuel rods using bounding and accelerated creep tests. The balance of Phase II rod material is planned to be used for metallography, hydrogen content, microhardness, and optional transmission electron microscopy (TEM) measurements. Segments from the approximately 2.1 rod lengths of material assigned to Phase I testing, but not consumed during that testing, are planned to be utilized to address open Phase I questions (e.g., what is the effect of internal pressurization on the fatigue performance of fuel rods) and to investigate the fatigue and bend performance of aggressively conditioned M5® and ZIRLO® fuel rods.

PNNL’s Phase II fuel rod inventory consists of approximately 6.2 rod lengths of material. Approximately 4.1 rod lengths are planned to be utilized to investigate annealing of defueled cladding over annealing temperatures ranging from 300 °C to 450 °C and annealing times initially ranging from 1 to 12 weeks (165 to 2100 hours). Full scale (i.e., 6-inch long defueled specimens to match Phase I testing, with exception of the one F35K13 Zirc-4 rod which will use 5.5-inch long defueled specimens) cladding tension tests are planned for this characterization. Approximately 1.0 rod length is planned to be used to investigate creep and the effects of creep on the performance of defueled cladding. Creep characterizations are planned to be based on pre- and post-annealing profilometry of tension test specimens that undergo the same annealing treatment as the other specimens in the study but are pressurized to higher internal pressures to encourage creep during annealing. Tension testing of the creep specimens is planned to be performed following annealing to characterize the tensile characteristics of the specimens that have undergone creep

deformations. The balance of Phase II rod material is planned to be used for metallography, hydrogen content, and microhardness measurements.

ANL's Phase II inventory consists of defueled cladding or spare fuel rod segments originally apportioned for Phase I testing. Approximately 7 of those segments are planned to be used to complete ring compression tests (RCTs) to investigate the effects of a bounding radial hydride treatment (RHT) and temperature cycling on the low temperature ductility of M5® and ZIRLO® cladding materials.

ACKNOWLEDGEMENTS

The authors would like to acknowledge and thank the many people who contributed to this report, named or otherwise - we apologize if we have failed to indicate your contributions here. We would like to thank our United States (U.S.) Department of Energy Office of Nuclear Energy sponsor Ned Larson, and the Spent Fuel and Waste Science and Technology National Technical Director, Dave Sassani, without whom none of this would be possible. We would also like to thank Sylvia Saltzstein and Scott Sanborn at Sandia National Laboratories for their support of the Sibling Pin work. We would also like to thank the individuals at the U.S. Nuclear Regulatory Committee (NRC) and at the Electric Power Research Institute (EPRI) for reviewing the draft version of this test plan and providing helpful and insightful comments. Finally, we would like to thank Ken Sorenson for his review of the draft and final versions of this test plan.

This page is intentionally left blank.

CONTENTS

SUMMARY iii

ACKNOWLEDGEMENTS v

REVISION HISTORY xiii

ABREVIATIONS/ACRONYMS/UNITS xv

1. INTRODUCTION 1

2. BACKGROUND 1

3. PHASE II TEST PRIORITIES 3
    3.1 Gap Reassessment Based on Phase I Testing 3
    3.2 Objective Status After Phase I Testing 4
    3.3 External Stakeholder Input 5
    3.4 Phase II Test Priorities 6

4. PHASE II TEST PLAN 7
    4.1 ORNL Phase II Tests 8
        4.1.1 Rod Internal Pressure, Void Volume, Gas Communication 9
        4.1.2 Annealing, Annealing and Creep, and Creep 9
        4.1.3 Phase I Follow-On Testing 10
    4.2 PNNL Phase II Tests 11
        4.2.1 Rod Internal Pressure, Void Volume, Gas Communication 11
        4.2.2 Annealing and Creep 11
        4.2.3 Creep 12
    4.3 ANL Phase II Tests 12
    4.4 Phase II Test Summary 13

5. REFERENCES 15

This page is intentionally left blank.

LIST OF FIGURES

Figure 1: Sibling Pin Phase II Testing Visualization. 14

This page is intentionally left blank.

LIST OF TABLES

Table 1: Inventory of Sibling Pin Fuel Rods [5]..8
Table 2: ORNL’s Available Fuel Rod Inventory for Sibling Pin Phase II Testing. 9
Table 3: PNNL’s Available Fuel Rod Inventory for Sibling Pin Phase II Testing......................................11
Table 4: ANL’s Available Sample Inventory for Sibling Pin Phase II Testing..13

This page is intentional left blank.

REVISION HISTORY

Date	Description of Changes
9/15/2023	Initial Release.

This page is intentionally left blank.

ABREVIATIONS/ACRONYMS/UNITS

°C	Degrees Celsius
4PB	Four Point Bend
AMP	Aging Management Program
ANL	Argonne National Laboratory
CIRFT	Cyclic Integrated Reversible-Bending Fatigue Tester
DCSS	Dry Cask Storage System
DE	Destructive Examination
DOE	Department of Energy
EOL	End-of-Life
EPRI	Electric Power Research Institute
ESCP	Extended Storage Collaboration Program
GWd/MTU	Gigawatt Days Per Metric Ton of Uranium
h	Hour
HBU	High Burn Up
ID	Identifier
IFBA	Integral Fuel Burnable Absorber
IR	Information Release
ISFSI	Independent Spent Fuel Storage Installation
NDE	Non-Destructive Examination
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
PCT	Peak Cladding Temperature
PNNL	Pacific Northwest National Laboratory
PWR	Pressurized Water Reactor
R&D	Research and Development
RCT	Ring Compression Test
t0	Time Zero (Post Irradiation and Pool Storage, But Before Dry Storage)

t0’	Time Zero Prime (Post Drying, Helium Backfill, and Placement on Storage Pad)
RHT	Radial Hydride Treatment
RIP	Rod Internal Pressure
SFWST	Spent Fuel and Waste Science and Technology
SNF	Spent Nuclear Fuel
TBD	To Be Determined
TN-32B	Transnuclear, Inc. Dry Storage Cask
wppm	Weight Parts-Per-Million

SPENT FUEL AND WASTE DISPOSITION SIBLING PIN PHASE II TEST PLAN

1. INTRODUCTION

The Sibling Pin test campaign, as part of the High Burnup Spent Fuel Data Project, is a Department of Energy (DOE) research activity within the Spent Fuel and Waste Science and Technology (SFWST) program that is tasked with characterization of high burnup (HBU, ≥45 GWd/MTU) fuel rods representative of those placed in the High Burnup Spent Fuel Data Project demonstration cask (the "demo cask" or "Research Project Cask"). Data from the demo cask will be utilized to understand degradation mechanisms of HBU fuel rods and assemblies in typical dry storage conditions and provide evidence to further support the technical basis for the extended dry storage of HBU fuel. The Sibling Pin test campaign was created to generate characterization and mechanical property data for HBU fuel rods that support the goals of the High Burnup Spent Fuel Data Project through nondestructive and destructive examination of pressurized water reactor (PWR) HBU fuel rods with characteristics comparable to those in the demo cask. Of the 25 fuel rods in the Sibling Pin inventory, approximately 9 rod lengths have been consumed during the first phase (Phase I) of the test campaign leaving approximately 16 rod lengths for the second phase of testing (Phase II). This plan outlines the Phase II testing.

2. BACKGROUND

Following the suspension of licensing activities for the Yucca Mountain Project in 2010, DOE increased funding for research activities to generate data needed to make informed decisions on waste management issues and to strengthen the technical basis for the extended storage and subsequent transportation of spent nuclear fuel (SNF). A gap assessment completed in 2012 [1,7] guided the development of initial research and development (R&D) plans. Subsequent updates to the gap assessment and rankings [2,3,8] informed updates to the initial plan. The High Burnup Spent Fuel Data Project [4], also called the "High Burnup Demonstration Project", or "Demo Project" is identified as a high priority activity in the initial 2012 gap assessment.

The High Burnup Spent Fuel Data Project is a collaborative DOE and Electric Power Research Institute (EPRI) research activity focused on understanding the performance of high burnup fuel (>45 GWd/MTU) in "typical" dry storage conditions. The project consists of loading an instrumented TN-32B dry storage cask (the "demo cask" or "Research Project Cask") with 32 high burnup PWR fuel assemblies from the North Anna Nuclear Power Plant (NPP) spent fuel pool and placing that cask in dry storage. Approximately 10 years after loading, the cask is planned to be reopened and the fuel inside inspected. As stated in the High Burnup Spent Fuel Data Project test plan [4], the main objectives of the project are to:

- provide confirmatory data (i.e., data that can be used to determine whether small-scale, accelerated testing can be used to assess the state of HBU fuel in actual systems) for model validation and potential improvement,
- provide input to future SNF dry storage cask designs,
- support license renewals and new licenses for Independent Spent Fuel Storage Installations (ISFSIs), and
- support transportation licensing for high burnup SNF.

The High Burnup Spent Fuel Data Project test plan also specifically points out that data derived from the project could help address questions the Nuclear Regulatory Commission (NRC) has surrounding HBU fuel storage and transportation specifically by providing data:

- to form part of the basis for the development of aging management programs (AMPs),
- to support high burnup license renewal applications, and
- to bolster confidence in the ability of cladding to maintain its integrity during the transport of SNF.

In 2017, the demo cask was loaded, dried following standard procedures, and placed in dry storage at the North Anna NPP ISFSI. Cask temperatures were monitored and recorded throughout the drying process and continue to be monitored while the cask is in dry storage.

The Sibling Pin test campaign [5] is a DOE-funded research activity that is part of the High Burnup Spent Fuel Data Project. The activity is focused on generating characterization, material property, and performance data for HBU fuel rods to support the objectives of the High Burnup Spent Fuel Data Project. These data are derived through the non-destructive and destructive examination (NDE and DE, respectively) of 25 HBU fuel rods with characteristics and histories that closely match those used in the demo cask [5]. Because these fuel rods, or pins, are like those in the demo cask, they are referred to as “sisters” or “siblings” of the demo cask fuel rods, and the test campaign as the “Sister Rod” or “Sibling Pin” test campaign. The specific objectives of the Sibling Pin test campaign, as described in the test plan [5], are to:

- generate baseline (time zero or t0) comparison data,
    - Determine the characteristics, material properties, and fuel rod performance of the as-received rods to provide a baseline corresponding to the condition of the SNF being loaded into the Research Project Cask (i.e., post irradiation and pool storage, but before dry storage).
- generate post-drying (time zero prime or t0’) comparison data, and
    - Determine the characteristics, material properties, and fuel rod performance of the rods after they have undergone drying, helium backfill, and placement on the storage pad.
- generate data for other cask designs and conditions.
    - The sister rods will be tested against the conditions measured in the Research Project Cask as well as against conditions modeled for other Dry Cask Storage Systems (DCSSs) that have different thermal profiles and histories.
    - Similarly segments of sister rods will be tested under a range of hoop stresses and temperatures to account for other fuel and cask designs.
    - The bulk of the testing will be done to determine the t0’ data under a variety of conditions to support the surge in renewals of storage licenses expected over the next five years.

Sibling Pin testing is being performed at Oak Ridge National Laboratory (ORNL), Pacific Northwest National Laboratory (PNNL), and Argonne National Laboratory (ANL). Initial NDE of the 25 Sibling Pin fuel rods was completed in 2018 [9]. Phase I DE testing is on-going but largely complete [10, 11, 12, 13, 14, 15, 16, 17, 18]. As outlined in the Phase I test plan overview [6], testing in Phase I has focused on generating t0 baseline and t0’ post-drying comparison test data. Only one thermal treatment to simulate a drying scenario, 400 °C peak cladding temperature (PCT) for 8 hours, with 10 °C/h heat-up and ≤4 °C/h cool-down rates, was investigated to generate t0’ data. The thermal treatment was intentionally designed to increase the potential for radial hydride formation while limiting PCT to the NRC-recommended value (400 °C [19, 20]) at as-discharged rod internal pressures. Time at peak temperature was restricted to 8 hours to limit annealing of irradiation damage. The intent of the investigations was to generate data to determine if radial hydride-induced embrittlement is an issue for HBU fuel under reasonably representative conditions.

Sibling Pin test activities have been motivated by fuel and cladding specific gaps identified as high and medium priority in the initial gap assessment completed in 2012 [1,7] and periodic updates to the gap assessment and rankings that have been completed since then [2,3,8]. In 2012 hydride reorientation and radial hydride embrittlement, delayed hydride cracking, creep, radiation damage annealing, and oxidation were all identified as high or medium priority cladding gaps. All fuel specific gaps were categorized as low importance.

In 2017 a reassessment of the gaps reduced the importance of creep, radiation damage annealing, and oxidation from medium to low, leaving hydride reorientation and radial hydride induced embrittlement as the only high importance fuel or cladding specific gap. For this reason, Phase I testing focused on collecting data to address that gap. The importance of creep and radiation damage annealing were reduced from medium to low, due in part to temperature measurements obtained from the demo cask. During the loading, drying, and initial two-week storage of the demo cask, the maximum PCT measured was 237 °C during drying and 231°C during the thermal soak following He backfill, significantly below the ~350 °C predicted value in the original licensing calculations [21], suggesting that actual PCTs in dry cask storage systems loaded to date are likely lower than originally thought. Thermal creep for these lower realistic PCTs is expected to be minimal supporting a reduction in importance from medium to low. Also, data on creep were expected to be obtained from the demo cask fuel rods upon its reopening, negating the need to obtain creep data as part of Sibling Pin testing. Radiation damage annealing was also reduced in importance from medium to low as annealing at the lower realistic PCTs was anticipated to be minimal. Separately, oxidation was reduced in importance from medium to low because the oxidative process requires the presence of air and/or sufficient water, and the likelihood of having either was thought to be low.

3. PHASE II TEST PRIORITIES

Priorities for Phase II testing are based on the previously identified gaps and their importance, lessons-learned from work completed to-date, and an assessment of Phase I accomplishments against the original objectives of the High Burnup Spent Fuel Data Project and Sibling Pin test campaign. Additionally, input from external stakeholders has been solicited and considered in the prioritization.

3.1 Gap Reassessment Based on Phase I Testing

The 2017 reassessment of the cladding and fuel specific gaps identified hydride reorientation and radial hydride induced embrittlement as a high importance gap, delayed hydride cracking as a medium importance gap, and creep, radiation damage annealing, and oxidation as low importance. Additionally, all fuel specific gaps were identified as low importance. Data obtained from Phase I testing have resulted in a reassessment of the importance of several of these gaps, specifically the hydride reorientation and radial hydride induced embrittlement and radiation damage annealing gaps.

Rod internal pressures measured during Phase I testing [11] indicate that significant cladding degradation due to radial hydride precipitation during cooling from a peak drying or storage temperature of 400 °C (which is the NRC recommended PCT limit) is unlikely. The measured internal pressures which range from 3.2 to 5.1 MPa at 25 °C and approximately correlate with cladding hoop stress ranging from 66 (M5®) to 71 (ZIRLO®) to 94 (Zirc-4) MPa at 400 °C, are below the hoop stress thought necessary to cause significant radial hydride formation that would degrade cladding ductility. In fact, defueled RCTs completed as part of Phase I [17,18] have demonstrated that baseline and heat treated (400 °C for 8 h) M5® and ZIRLO® claddings remain ductile at temperatures as low as 20 °C, and that Zirc-4 cladding remains ductile at temperatures as low as 20 °C for material in the baseline condition and as low as 120 °C for material in the heat-treated condition. In addition, it was observed that the fuel pellets constrain deformation of the cladding under fueled RCTs [11], such that plastic deformation of the cladding under pinch loading conditions are not expected. For these reasons, the hydride reorientation and radial hydride induced embrittlement gap is no longer considered high importance. However, the heat treatment employed in Phase I utilized rod internal pressures (RIPs) that matched the end-of-life (EOL) RIPs measured in the Phase I Sibling Pin fuel rods. For the M5®, ZIRLO® claddings, the EOL RIPs ranged from 3.2 to 4.2 MPa. A reasonable bounding pressure for HBU M5® and ZIRLO® fuel rods is 5.0 MPa. For Integral Fuel Burnable Absorber (IFBA) ZIRLO®-clad fuel rods with B-10, RIP values as high as 5.5 MPa have been measured within the average-burnup licensing limit. It remains to be demonstrated that for bounding RIPs cladding ductility remains high at low temperatures. The hydride reorientation and radial hydride induced embrittlement gap importance is therefore thought to be medium, and limited Phase II testing is planned to address the remaining open items associated with this gap.

Comparison of cladding yield and ultimate strengths derived from Phase I tension and bending tests of baseline and heat treated (400 °C for 8 h) cladding and fuel rod samples showed larger than anticipated reductions in those values as a result of the heat treatment [16]. This effect is thought to be attributable to the annealing of radiation damage, although other mechanism such as cold work annealing may also play a role. While reductions in the yield and ultimate strengths are associated with annealing, they are usually associated with increases in ductility. Increased ductility can mean a reduced risk of cladding failure, but the reduced material strengths can facilitate creep. Also, 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. For these reasons, the importance of the radiation damage annealing gap is thought to be high, and significant Phase II testing is planned to address this gap.

3.2 Objective Status After Phase I Testing

The objectives of the High Burnup Spent Fuel Data Project and Sibling Pin test campaign can be condensed down to the following four primary objectives.

1. Provide data to DOE that is needed to make informed decisions on waste management issues.
2. Establish baseline (t0) characteristics and properties of the fuel rods going into the demo cask.
3. 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 storage and transportation systems.
4. Provide data to support licensing and re-licensing of new and existing dry storage and transportation casks.

Only the second objective, establish baseline (t0) characteristics and properties, may be considered complete. While Phase I testing did consider a drying scenario (400 °C for 8 h), data derived from it are insufficient to address the range of temperatures and exposure durations required to consider the first, third, and fourth objectives complete. Current licensing limits allow PCTs as high as 400 °C under normal conditions, and PCTs as high as 570 °C for off-normal conditions. While current systems are expected to have PCTs significantly below these limits, as demonstrated by temperature measurements taken during the loading, drying, and initial storage of the demo cask, other current and future casks may have PCTs that approach or exceed them. For these reasons, a significant amount of Phase II testing is planned to investigate the effects of a range of annealing temperatures and exposure durations on cladding material properties and fuel rod performance.

Phase I testing has not addressed creep. Creep data are needed to adequately address objective four. Previous Sibling Pin planning assumed that creep behavior would be obtained from measurements made on the fuel rods in the demo cask, upon its re-opening. Timelines surrounding near term licensing and re-licensing data needs, and the current anticipated schedule associated with the re-opening of the demo cask, make it necessary for data on creep to be collected in the near term by the Sibling Pin test campaign. Additionally, the relatively low PCTs in the demo cask will limit any annealing and creep that might occur in those fuel rods, likely making it difficult or impossible to glean meaningful creep information from those fuel rods for systems with rods at higher temperatures. This need, in conjunction with the unanticipated magnitude of the annealing effect observed in the Phase I testing and uncertainty surrounding the effects of annealing on creep behavior, is the reason a significant amount of testing is planned for Phase II to investigate creep and the effects of a range of annealing temperatures and exposure durations on the creep behavior of defueled cladding and fuel rods.

3.3 External Stakeholder Input

A survey was distributed to attendees of EPRI's Extended Storage Collaboration Program (ESCP) Winter Meeting held November 7-10, 2022, in Charlotte, North Carolina soliciting their feedback on preliminary plans for Phase II testing. A total of 15 people responded, including 5 industry representatives, 2 consulting engineers, and 8 from research institutions or national laboratories. Responses from individuals that are part of the Sibling Pin project are excluded here.

Responses to the survey indicate a desire within the respondent community for testing at temperatures above the current NRC guidance limit of 400 °C, with data up to 450 °C to support industry initiative being of particular interest. Similarly, there is support for collecting data (i.e., creep data) to support tollgate assessments under NRC-approved aging management programs as well as to collect data addressing off-normal conditions. When asked what the most important HBU spent fuel data that could be obtained, 29% of respondents indicated data for PCTs above the current NRC guidance limit of 400 °C to support industry initiatives, and 23% indicated data to support tollgate assessments under NRC-approved aging management programs (note 23% also indicated additional data on baseline rod properties). When asked what peak cladding temperatures or other conditions should be investigated in Phase II of the Sibling Pin test campaign, 40% said 450 °C, and 24% said multiple thermal cycles (>10 cycles) at a higher allowable temperature swing (>65 °C). When asked what should be given priority for the remaining Phase II fuel rods given that the maximum measured demo cask PCT was only 237 °C, obtaining more data for temperatures currently applicable to licensing and license renewals (<400 °C) or obtaining data at higher temperatures, 71% indicated higher temperature data should be the priority. Finally, when asked how important they felt obtaining data under temperatures expected during off-normal events, 67% of the respondents indicated it was somewhat or extremely important to do so. For these reasons a significant amount of Phase II testing is planned to investigate the effects of a range of annealing temperatures and exposure durations on cladding material properties and baseline fuel rod performance at temperatures up to 450 °C, and some testing is planned to investigate the creep behavior of cladding and fuel rods to support tollgate assessments under NRC-approved aging management programs.

Responses to the survey also indicate that future storage and transportation systems will likely have PCTs that more closely match the current 400 °C PCT NRC guidance limit. When asked what changes they were considering in light of recent industry initiatives and published information on package temperatures, 32% indicated they were revising codes and analyses to produce more accurate dry storage temperature predictions, 28% indicated they were moving to higher enrichments, burnups, and/or duty in the next 10 years, and 24% indicated storing shorter-cooled spent nuclear fuel. Each of these actions could result in actual PCTs higher than those measured in the demo cask and closer to the current 400 °C guidance limit. For this reason a significant amount of Phase II testing is planned to investigate the effects of a range of annealing temperatures and exposure durations on cladding material properties and fuel rod performance spanning from lower temperatures approaching those measured in the demo cask to temperatures at the current NRC guidance 400 °C PCT recommended limit.

In January 2023, members of the DOE Sibling Pin program participated in a technical exchange with the NRC. The technical exchange provided an opportunity for the Sibling Pin team to discuss technical results with NRC staff members relevant to Phase II test planning and to get a general understanding of their perspective. Summarized below are observations from members of the Sibling Pin team collected following the technical exchange. 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.

Topics discussed during the technical exchange were focused mainly on what fuel rod temperatures were most relevant for further exploration and the importance of obtaining creep data in the near term (before the demo cask is reopened). The team felt a preference was expressed for further expanding the data set for temperatures at or below the current NRC recommended limit (400 °C), due to the low PCTs measured in the demo cask and the current lack of data spanning the range between the demo cask temperatures and the current 400 °C PCT NRC recommended limit. Some interest was expressed in investigating temperatures above 400 °C to address off-normal scenarios (current NRC recommended limit of 570 °C); however, given the low probability of current systems actually experiencing PCTs approaching the much higher off-normal limit, an extrapolation approach based on testing at modestly elevated temperatures (e.g., 450 °C), with limited targeted confirmatory testing at higher off-normal temperatures, might be an acceptable approach to employ. Interest was also expressed in obtaining creep data in the near term, particularly for M5® cladding. While there was a clear preference for creep testing to be performed at realistic temperatures and pressures, it was widely acknowledged that accelerated testing at elevated temperatures and/or pressures would likely be required to obtain meaningful creep data in a reasonable time, and that care would have to be exercised in the design of the creep test parameters to ensure the data obtained are applicable to realistic scenarios. Additionally, understanding synergistic effects between annealing and creep behavior was discussed and thought to be important. Phase II creep and annealing tests plan to investigate temperatures ranging from 300 °C to 450 °C. Creep testing will likely utilize accelerated testing methods, but also investigate more realistic conditions bounding of those anticipated in the field. These plans align well with the priorities of the NRC as interpreted by the Sibling Pin team.

Two additional observations of note the team had following the technical exchange are that interest was expressed in additional fatigue and static bend testing on aggressively conditioned (for reoriented hydrides) rods, like those described in NUREG-2224, to provide bounding data on the effects of hydride reorientation and radial hydride induced embrittlement on fatigue performance and the contribution of the pellet to the composite rod's flexural rigidity. Also, interest was expressed in further investigating the effects of thermal cycling on cladding ductility. Current NRC guidance limits thermal cycling to less than 10 cycles with a temperature swing of less than 65 °C. However, to account for reflooding, one temperature cycle >65°C is allowed (NUREG-2224). Planned Phase II testing includes fatigue and static bend testing of aggressively conditioned fuel rod segments and ring compression testing (RCT) of cladding subjected to bounding thermal cycling, both of which align well with the expressed interest in having such data.

3.4 Phase II Test Priorities

It is important to understand both the composite behavior of fuel rods (cladding with fuel) and the stand-alone behavior of cladding to achieve the objectives of the Sibling Pin test campaign. In an approach similar to that employed for Phase I, Phase II testing completed at ORNL will focus primarily on the characterization of fuel rods (cladding with fuel) and testing at PNNL and ANL on the characterization of defueled cladding. Priorities for this Phase II testing are listed below.

- **Annealing:** Obtain data to characterize and model the effects of exposure time at temperature on HBU cladding material properties and fuel rod performance for temperatures and exposure times that span those anticipated during drying, storage, and transportation of HBU fuel rods. Priority is on annealing conditions that are consistent with systems designed to meet the current 400 °C NRC recommended limit.
- **Creep:** Obtain data to characterize the creep behavior of baseline HBU cladding material and baseline fuel rods for temperatures and internal pressures anticipated during drying, storage, and transportation of HBU fuel rods. Note, if accelerated testing is employed, the design of the test shall ensure that the data obtained are meaningful and applicable to realistic scenarios.

- **Annealing & Creep:** Obtain data to characterize the effects of annealing on the creep behavior of HBU cladding material and fuel rods for annealing temperatures and exposure times, and for creep temperatures and internal pressures anticipated during drying, storage, and transportation of HBU fuel rods. Note that the temperatures, exposure times, and/or internal pressures employed to achieve annealing in test samples for this investigation will differ from those utilized during the creep portion of the testing. This mimics a scenario where annealing occurs during the higher temperatures experienced at early storage and creep predominantly occurs at lower temperatures during long term storage. Also, if accelerated creep testing is employed, the design of the test shall ensure that the data obtained are meaningful and applicable to realistic scenarios.
- **Hydride Reorientation and Radial Hydride Induced Embrittlement**
    - **[Ductility]**: Obtain data for high hydrogen content M5® and ZIRLO® cladding materials to determine their low temperature ductility following exposure to a radial hydride treatment (RHT) with rod internal pressure that is a reasonable upper bound for pressures anticipated to be encountered during drying, storage, and transportation of HBU fuel rods, and an exposure time at temperature that is limited to minimize irradiation damage annealing.
    - **[Thermal Cycling]**: Obtain data for high hydrogen content M5® and ZIRLO® cladding materials to determine their low temperature ductility following their exposure to a radial hydride treatment (RHT) involving the cycling of temperature for a rod internal pressure that is a reasonable upper bound for pressures anticipated to be encountered during drying, storage, and transportation of HBU fuel rods, and an exposure time at temperature that is limited to minimize irradiation damage annealing.
    - **[Fatigue, Bending]**: Obtain data to determine the effects of radial hydrides on the fatigue and bend performance of M5® and ZIRLO® fuel rods that have been aggressively conditioned to generate bounding radial hydride distributions within the cladding.

4. PHASE II TEST PLAN

The Phase II testing activities described in this plan will be completed at PNNL, ORNL, and ANL. In an approach similar to that employed for Phase I, Phase II testing completed at ORNL will focus primarily on the characterization of fuel rods (cladding with fuel) and testing at PNNL and ANL on the characterization of defueled cladding. The Phase II testing activities outlined in this plan are based on preliminary proposals developed and approved by each laboratory for testing to be completed at their facilities. Based on the objectives and high-level test plan outlined here, each laboratory will develop a detailed plan for the specific subset of Phase II tests to be performed at their facilities. Note that details given in this plan pertaining to the number, size, processing, or usage of test samples are only estimates based on the current plan and are included to convey some of the detail considered in the development of the plan. These details should not be interpreted as specific requirements levied on each laboratory. As was the case for tests planned and performed as part of Phase I, planned Phase II tests might be modified or abandoned, or alternate tests added, as new information is acquired, our understanding of the technical issues change, or we gain additional feedback on priorities from stakeholders. Any changes to approved test plans will have to be reviewed and accepted by program management before implementation.

Table 1 lists the complete inventory of Sibling Pin fuel rods, including the approximate percentage of those rods available for Phase II testing. Thirteen of the 25 rods in the inventory were originally assigned to Phase I, but not all of those rods were fully consumed in Phase I, including 1 M5® [30AK09] that went entirely unused, 1 Zirc-4 [F35K13] with only 20% utilization, and 1 ZIRLO® [6U3K09] with only 35% utilization. The available balance of the Phase I rods will be used, where appropriate, in Phase II testing.

Table 1: Inventory of Sibling Pin Fuel Rods [5].

Rod ID	Cladding Material	Cycles	Rod Avg. Burnup (GWd/MTU)	Laboratory	Test Phase	Approximate Available for Phase II
3A1F05	LT Zirc-4	2	51	ORNL	I	25%
F35P17	Zirc-4	4	60	ORNL	I	30%
F35K13	Zirc-4	4	58	PNNL	I	75%
30AD05	M5®	3	54	ORNL	I	15%
30AE14	M5®	3	54	ORNL	I	20%
30AK09	M5®	3	54	ORNL	I	100%
5K7K09	M5®	3	54	PNNL	I	5%
5K7P02	M5®	3	51	PNNL	I	5%
3D8E14	ZIRLO®	3	59	ORNL	I	20%
3F9N05	ZIRLO®	3	54	ORNL	I	20%
6U3K09	ZIRLO®	3	55	ORNL	I	65%
6U3L08	ZIRLO®	3	55	PNNL	I	5%
6U3M03	ZIRLO®	3	57	PNNL	I	5%
3A1B16	LT Zirc-4	2	48	ORNL	II	100%
30AG09	M5®	3	53	ORNL	II	100%
5K7O14	M5®	3	53	ORNL	II	100%
30AP02	M5®	3	49	PNNL	II	100%
5K7C05	M5®	3	57	PNNL	II	100%
3D8B02	ZIRLO®	3	50	ORNL	II	100%
3F9D07	ZIRLO®	3	52	ORNL	II	100%
6U3I07	ZIRLO®	3	54	ORNL	II	100%
6U3M09	ZIRLO®	3	55	ORNL	II	100%
3F9P02	ZIRLO®	3	49	PNNL	II	100%
6U3O05	ZIRLO®	3	58	PNNL	II	100%
6U3P16	ZIRLO®	3	50	PNNL	II	100%

4.1 ORNL Phase II Tests

ORNL's Phase II fuel rod inventory is listed in Table 2. Of the 10.1 rod lengths available, approximately 0.6 rod lengths are planned to be utilized to investigate annealing of defueled cladding, 5.0 rod lengths to investigate the effects of annealing on the mechanical characteristics and performance of fuel rods (cladding with fuel), 0.8 rod lengths to investigate the effects of annealing on the creep behavior of fuel rods, 0.5 rod lengths to investigate the creep behavior of baseline fuel rods, and 0.7 rod lengths for metallography, microhardness, or hydrogen content characterizations. The balance of rod lengths (~2.1), comprised of portions of rods not consumed during Phase I testing, are planned to be utilized to address open Phase I questions or to investigate the fatigue and static bend performance of aggressively conditioned M5® and ZIRLO® fuel rods.

Table 2: ORNL's Available Fuel Rod Inventory for Sibling Pin Phase II Testing.

Cladding Material	Total Available Rod Lengths	Number of Full-Length Rods
LT Zirc-4	1.3	1
Zirc-4	0.3	0
M5®	3.4	3
ZIRLO®	5.1	4

4.1.1 Rod Internal Pressure, Void Volume, Gas Communication

ORNL will complete rod internal pressure and void volume measurements for all untested rods in their inventory. Gas communication will be measured on each rod at room temperature, with particulates from the downstream flows collected. A maximum pressure of 5 MPa will be used to complete the testing.

4.1.2 Annealing, Annealing and Creep, and Creep

Annealing is planned to be investigated by ORNL in a stepped approach. The initial step will develop annealing relationships for M5® and ZIRLO® cladding, as well as investigate the effects of annealing on the behavior of those fuel rods for a few scenarios. The follow-on step will investigate the effects of annealing scenarios-of-interest on fuel rod performance, using the annealing relationships developed in the initial step to design the annealing heat treatments.

For the initial step, the plan is to use 1 M5® fuel rod and 1 ZIRLO® fuel rod. Each of these rods could provide up to 54 to 60 - 25 mm long and 12 - 152 mm long samples. Each 25 mm long sample provides material for a defueled mini-tension test coupon (approximately 17.5 mm in length and similar in design to the coupon shown in [22]) and material for pre- and post-annealing heat treatment metallography, hardness, and optional transmission electron microscopy (TEM) measurements. Approximately 54 of the 25 mm long samples are planned to be used to investigate 18 heat treatments (time at temperature) for material drawn from three fuel rod elevations (e.g., "lower", "middle", "upper" or some other logical scheme), which represent different irradiation temperatures. Preceding heat treatment, approximately 2 to 5 mm of each sample will be removed for pre-annealing metallography, hardness measurements, and optional TEM measurements. The remaining portions of each sample will then be subjected to a heat treatment, in groups of three, at a temperature ranging from 300 °C to 450 °C for a period ranging from 4 to 6000 hours. Following heat treatment, an additional 2 to 5 mm of each sample will be removed for post-annealing metallography, hardness measurements, and optional TEM measurements. The remaining material from each sample will be used to manufacture a mini-tension test specimen which will be pulled uniaxially at room temperature to acquire annealed cladding tensile properties. The broken specimens from those tests will be used to measure total hydrogen in the sample. It is planned to use the balance of the 25 mm long samples to obtain baseline cladding properties. For four heat treatments per rod, 3 - 152 mm long samples will undergo heat treatment along with the 25 mm long samples. The plan is to use the 3 - 152 mm long samples to complete post-anneal fueled 4-point bend (4PB), fueled cyclic integrated reversible-bending fatigue tester (CIRFT), and fueled creep tests. The 4PB and CIRFT tests are planned to be performed at room temperature and to be either unpressurized or pressurized. Creep tests will be accelerated. The 12 - 152 mm long samples from each rod allow for those tests to be performed for 2 anneal levels, at two elevations. Data from the tests will be used to develop annealing relationships for M5® and ZIRLO® cladding, and to investigate the effects of annealing on the bending, fatigue, and creep behavior of the annealed fuel rods.

In the follow-on step, the plan is to use the remaining full length rods (2 M5®, 3 ZIRLO®, and 1 LT Zirc-4) to investigate the effects of annealing on fuel rod performance and creep for annealing scenarios of interest, as well as investigate the creep behavior of baseline fuel rods. Each rod can supply enough material to investigate 3 heat treatments (time at temperature) as well as provide samples for the investigation of creep in baseline fuel rods. It is planned that approximately 20 - 152 mm long and 21 - 12.7 mm long samples will be obtained from each rod. Two of the 152 mm long samples from each rod are planned to be used for baseline creep testing (possibly one accelerated test and one bounding of prototypical PCTs and RIPs test), and 2 to 3 of the 12.7 mm long samples for metallography, hardness, hydrogen, and optional TEM measurements of the baseline fuel rod. The remaining samples from each rod will come from portions of the rod that will undergo one of three heat treatments. Heat treatment parameters will be selected to achieve annealing levels of interest (e.g., 25% or 50%) based on the annealing relationships determined during the initial step of the annealing investigation. Rods or rod segments will be pressurized to their EOL RIPs before heat treatment. From each heat treatment approximately 6 - 152 mm long samples and 6 - 12.7 mm long samples will be derived, with the 152 mm long samples planned to be used to complete two fueled 4PB tests, two fueled CIRFT tests, one fueled axial tension test, and one fueled creep test, and the 12.7 mm long samples for metallography, hardness, hydrogen, and optional TEM measurements. For a select set of 4PB and/or CIRFT tests, released aerosols are planned to be collected and analyzed.

4.1.3 Phase I Follow-On Testing

The balance of rod lengths (~2.1) not utilized in the annealing and creep investigations, which are comprised of portions of rods not consumed during Phase I testing, are planned to be utilized to address the fatigue and bend performance of aggressively conditioned M5® and ZIRLO® fuel rods and open Phase I questions.

To investigate the fatigue performance and stiffness of aggressively conditioned M5® and ZIRLO® clad fuel rods, 1 to 3 samples each of M5® and ZIRLO® clad fuel rods are planned to be subjected to CIRFT testing and 1 to 3 samples each of M5® and ZIRLO® clad fuel rods are planned to be subjected to 4PB testing. Samples will either be 152 mm or 102 mm in length and will undergo aggressive RHT conditioning to generate radial hydrides before testing. During testing, samples may be either unpressurized or pressurized and tested at room temperature. Results from the testing will be used to quantify the fatigue and bend performance of aggressively conditioned M5® and ZIRLO® clad fuel rods.

To investigate the effects of internal pressure on fuel rod fatigue, bending, and uniaxial tensile performance, limited numbers of fueled CIRFT, fueled 4PB, and fueled uniaxial tension tests are planned to be performed. CIRFT tests will be performed at room temperature and pressurized to bounding EOL RIPs. 4PB and uniaxial tension test specimens will be pressurized to bounding EOL RIPs and the test completed at either room temperature or 200 °C. Data from these tests will be compared against data from analogous unpressurized tests to quantify the effect of internal pressure on fuel rod performance.

Fatigue characteristics of portions of the fuel rods in their lower end, where gamma scan gradients are large, are planned to be characterized using fueled CIRFT tests. One to 3 samples for fuel rods with each type of cladding will be subjected to CIRFT testing. Samples will be either 152 mm or 102 mm in length. During testing, samples may be unpressurized or pressurized and tested at room temperature. Results from the testing will be used to quantify the fatigue performance of fuel rods over their lower ends.

4.2 PNNL Phase II Tests

PNNL's Phase II fuel rod inventory is listed in Table 3. Of the 6.2 rod lengths available, approximately 4.1 rod lengths are planned to be utilized to investigate annealing of defueled cladding, 1.0 rod length to investigate creep in defueled cladding, and 0.8 rod lengths for metallography, microhardness, or hydrogen content characterizations of defueled cladding.

Table 3: PNNL's Available Fuel Rod Inventory for Sibling Pin Phase II Testing.

Cladding Material	Total Available Rod Lengths	Number of Full-Length Rods
LT Zirc-4	0.0	0
Zirc-4	0.8	0
M5®	2.2	2
ZIRLO®	3.2	3

4.2.1 Rod Internal Pressure, Void Volume, Gas Communication

PNNL completed rod internal pressure and void volume measurements for all ten rods in their inventory prior to Phase I testing. All ten rods were cut into 4 segments of approximately equal length with the M5® and ZIRLO® segments shown in Table 3 being stored in inerted storage tubes. Gas communication will be measured on each segment of each rod at room temperature, with particulates from the downstream flows collected. A maximum pressure of 5 MPa will be used to complete the testing.

4.2.2 Annealing and Creep

Annealing is planned to be investigated by PNNL in a stepped approach. The plan is that 13 of the untested 152.4 mm long cladding only samples already cut from the Phase I Zirc-4 F35K13 rod will be subjected to heat treatments at temperatures ranging from of 300 °C to 450 °C for periods ranging from 170 to 2100 hours. A total of 12 time-temperature combinations (two samples will be treated at 450 °C for ~350 hours) are planned to be investigated. The samples will be unpressurized during heat treatment to keep annealing effects separate from potential hydride reorientation effects since the hoop stress for this rod would exceed 90 MPa at higher temperatures and because the samples would be too short after cutting off the heat effected zone from welding on end plugs. Following the heat treatment, a 6.4 mm long portion of the sample will be cut from each end for metallography and microhardness measurements. The remaining 139.6 mm of sample will be used to perform a uniaxial tension test at room temperature to acquire tensile properties for the annealed cladding. An additional 4 of the untested 152.4 mm long cladding only samples will be tested without undergoing annealing to establish baseline tensile properties for the cladding for direct comparison with the annealed sample results. Data from the tests will be used to develop annealing relationships for Zirc-4 cladding. Unirradiated (e.g., as-fabricated) cladding of each alloy will be tested at 450 °C, 400 °C, 350 °C and 300 °C for periods ranging from 170 to 2100 hours to examine the kinetics of annealing of cold work and other potential effects of the heat treatment. Microhardness tests will be performed before and after annealing as well as uniaxial tension testing at room temperature and 200 °C for comparison with the Sibling Pin samples to be tested during Phase II.

Following the Zirc-4 and unirradiated rod tests, the plan is for one M5® rod (5K7C05) and one ZIRLO® rod (6U3P16) to be cut into approximately 17 - 190.5 mm long samples for investigation of annealing. Approximately 21 - 12.7 mm long samples, bracketing each longer sample, will also be cut from each rod for metallography, microhardness, and hydrogen content measurements. Each 190.5 mm long sample will be capped and welded shut, pressurized to the rod's EOL RIP, and then subjected to a heat treatment at a temperature of either 300 °C, 350 °C, or 400 °C for a period of 170 to 2100 or more hours. Following the heat treatment, the welded end caps and adjacent heat effected material (12.7 mm) will be cut from each end of the sample, and an additional 6.4 mm long sample cut from each end for metallography and microhardness measurements. The remaining ~152.4 mm of the sample will be used to perform a uniaxial tension test at an elevated temperature (e.g., 200 °C to allow for direct comparison with Phase I test results) to acquire tensile properties for the annealed cladding. Data from the tests will be used to develop annealing relationships for M5® and ZIRLO® cladding.

Approximately 52% of the remaining M5® rod (30AP02) and two ZIRLO® rods (3F9P02 and 6U3P16) from PNNL's inventory are planned to be used to further investigate annealing, filling in any gaps identified during the initial testing. Cutting of the rods into samples and testing will be identical in nature to that described above, with only the heat treatment parameters (time and temperature) varying, based on the results from the first two rods. Approximately 11 of the 17 - 190.5 mm long samples per rod (~65%) are planned for the annealing study. All tensile experiments will be performed according to ASTM standards for full-length axial tension tube tests.

4.2.3 Creep

Approximately 32% of the one M5® rod and two ZIRLO® rods used in the annealing study are planned to be used to investigate creep. This corresponds to 35% of the approximately 17 – 190.5 mm long samples per rod (i.e., 6 of the 17 samples per rod). Samples will be taken 2 each from the lower, middle, and upper axial areas of each rod. Creep test samples will be identical to those used for the initial M5® and ZIRLO® annealing tests, except they will be pressurized to higher pressures before heat treatment to accelerate creep. The pressurized samples will be heat treated at a temperature between 300 °C and 400 °C for periods of at least 170 to 2100 or more hours, although much longer times are anticipated at the lower temperatures. Times will be determined based on results from testing of unirradiated cladding samples. Profilometry of the sample taken before and after pressurization and heat treatment will be compared to quantify changes in geometry resulting from the heat treatment. The sample will be sectioned as mentioned previously, specifically the welded end caps and adjacent heat effected material will be cut from each end of the sample, and an additional 6.4 mm long portion of the sample cut from each end for metallography and microhardness measurements. The remaining 152.4 mm of sample will be used to perform a uniaxial tension test at an elevated temperature (e.g., 200 °C) to acquire tensile properties for the cladding subjected to accelerated creep. Data from the tests will be used to develop creep estimates for M5® and ZIRLO® cladding and to quantify the combined effects of annealing and creep on its tensile properties.

4.3 ANL Phase II Tests

ANL's Phase II inventory, listed in Table 4, consists of defueled cladding segments originally apportioned to ANL for Phase I testing. To complete the testing described below, one or two additional segments of baseline M5® cladding with hydrogen content > 100 weight-parts-per-million (wppm) may be required, as only two of the remaining M5® segments satisfy that criterion. Two baseline segments (one for each material) are planned to be used to investigate hydride reorientation and radial hydride embrittlement in M5® and ZIRLO® cladding materials subject to a bounding RHT, 1 additional baseline segment to investigate the sensitivity of hydride reorientation and radial hydride embrittlement to RHT temperature in ZIRLO® cladding materials, and 4 baseline segments (two for each material) to investigate hydride reorientation and radial hydride embrittlement in M5® and ZIRLO® cladding materials due to thermal cycling.

Table 4: ANL's Available Sample Inventory for Sibling Pin Phase II Testing.

Cladding Material	Number of 90 - 152 mm Long Samples		
	Total	Baseline	Phase I Heat Treated (400 °C for 8 h)
LT Zirc-4	1	1	0
Zirc-4	3	2	1
M5®	6	5	1
ZIRLO®	6	5	1

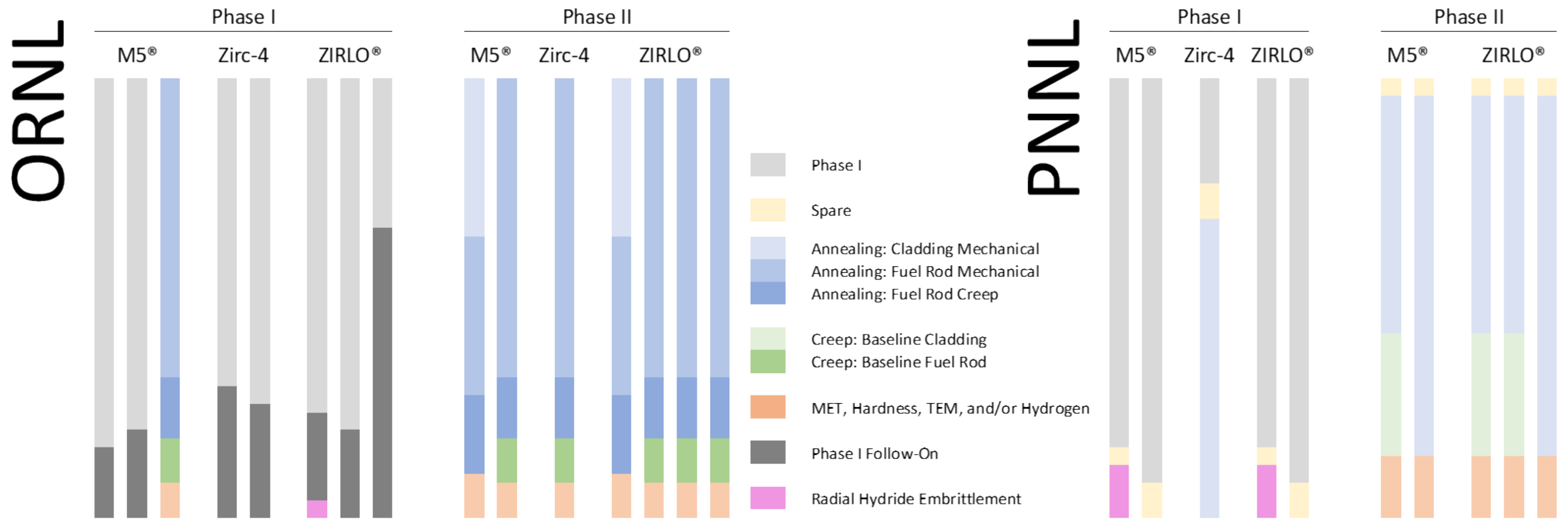
To investigate the effects of hydride reorientation and radial hydride embrittlement for M5® and ZIRLO® cladding materials for a bounding RHT, one baseline M5® segment with hydrogen content of >100 wppm and one baseline ZIRLO® segment will be pressurized to 5 MPa RIP at room temperature (this pressure is bounding of the measured M5® and ZIRLO® RIPs) and subjected to a RHT at the PCT for 1 hour then cooled at a rate of 5 °C/h. The 1-hour hold time at the PCT is selected to limit radiation damage annealing that might occur. The PCT for M5® will be based on the measured hydrogen content and the dissolution temperature for that hydrogen content. The ZIRLO® segment with the highest hydrogen content available will be subjected to a PCT of 400 °C for one hour followed by cooling at 5 °C/h. Following the RHT for M5® and ZIRLO® segments, the segments will be further sectioned, and RCTs performed at a range of temperatures spanning from 20 °C to 200 °C. Hydrogen-content measurements and metallographic examinations of the pre- and post-RHT will be conducted. The data obtained will be used to determine the low temperature ductility of the cladding.

To investigate a previous observation for ZIRLO® in which the ductility for cladding subjected to a 350 °C RHT was lower than for cladding subjected to a 400 °C RHT, one ZIRLO® segment in the baseline condition will be pressurized to 5.5 MPa (bound for non-IFBA and IFBA fuel rods) at room temperature and subjected to a RHT with peak temperature of 350 °C for 1 hour then cooled at a rate of 5 °C/h. As was the case with the previous segments, RCTs, metallography, and hydrogen measurements will be completed, and the ductility of the 350 °C RHT specimen will be evaluated.

To investigate the effects of thermal cycling on hydride reorientation and radial hydride embrittlement of M5® and ZIRLO® cladding materials, two baseline ZIRLO® and two baseline M5® segments will be pressurized to 5 MPa RIP at room temperature and subjected to a RHT consisting of a heat up to either 350 °C (M5® cladding only), 400 °C (M5® and ZIRLO® claddings), or 450 °C (ZIRLO® cladding only) and temperature cycling from the peak temperature down 100 °C and back for 1 to 3 cycles. During cycling the cooling rate will be 5 °C/h. M5® segments with hydrogen contents > 100 wppm and ZIRLO® segments with the highest available hydrogen content will be used for the tests. Identical testing and characterization (i.e., RCT, metallography, hydrogen content) as described above will be performed for each segment and low temperature ductility will be determined.

4.4 Phase II Test Summary

Figure 1 provides a visual summary of the planned Phase II testing.



ANNEALING

- Cladding Mechanical, Fuel Rod Mechanical, and Fuel Rod Creep [M5®, ZIRLO®]
  - 300 °C to 450 °C for 4 to 6000 Hours, Unpressurized
  - MET, Hardness, TEM (Pre- and Post- Anneal), and Hydrogen
  - Defueled Subsized Tension (Per Rod: 18 Time-Temp. Combos. @ 3 Rod Elevations)
  - Fueled 4PB, CIRFT, Accelerated Creep (Per Rod: 2 Anneal Levels, 2 Rod Elevations)
- Fuel Rod Mechanical and Fuel Rod Creep [M5®, ZIRLO®, LT Zirc-4]
  - Annealing Scenarios of Interest, Pressurized to EOL RIP
  - MET, Hardness, TEM (Pre- and Post- Anneal), and Hydrogen
  - 2 x 4PB, 2 x CIRFT, 1 x Axial, 1 x Accelerated Creep - All Fueled (Per Rod: 3 Time-Temp. Combos)
  - Selective Released Aerosol Collection and Analysis

CREEP

- Baseline Fuel Rod [M5®, ZIRLO®, LT Zirc-4]
  - MET, Hardness, TEM, and Hydrogen
  - Per Rod: 1 x Accelerated Creep, 1 x Bounding Creep

PHASE I FOLLOW-ON

- Aggressively Conditioned Fuel Rod [M5®, ZIRLO®]
  - Per Clad Material: 1-3 x CIRFT, 1-3 x 4PB (Both Fueled)
- Internal Pressure [M5®, ZIRLO®, Zirc-4]
  - Per Clad Material: Limited # of CIRFT, 4PB, Tension (All Fueled)
- Fatigue Performance, Low Rod Elevations [M5®, ZIRLO®, Zirc-4]
  - Per Clad Material: 1-3 CIRFT (Fueled)

ANNEALING

- Cladding Mechanical [M5®, ZIRLO®, Zirc-4]
  - Zirc-4: 300 °C to 450 °C for 170 to 2100 Hours, Unpressurized
  - M5® & ZIRLO®: 300 °C to 400 °C for 170 to 2100 or More Hours, Pressurized to EOL RIP
  - MET, Hardness (Pre- and Post- Anneal), and Hydrogen
  - Defueled Cladding ASTM Tension (Per Rod: 17 Samples)
  - Unirradiated Defueled Cladding Tests Also Performed for Comparison

CREEP

- Baseline Cladding [M5®, ZIRLO®]
  - Same Heat Treatments as Annealing Study, Elevated Pressure to Accelerate Creep
  - MET, Hardness, and Hydrogen
  - Accelerated Creep & Post-Creep ASTM Tension (Per Rod: 6 Samples)

ANL

HYDRIDE REORIENTATION AND RADIAL HYDRIDE EMBRITTLEMENT

- Bounding Temperature and RIP [M5®, ZIRLO®]
  - 1 Segment Each of M5® & ZIRLO®: 400 °C for 1 Hour, Cooled @ 5 °C/Hour, Bounding RIP (5 MPa @ RT)
  - 1 Segment ZIRLO®: 350 °C for 1 Hour, Cooled @ 5 °C/Hour, Bounding (for non-IFBA and IFBA fuel rods) RIP (5.5 MPa @ RT)
  - RCT @ Temps. Between 20 and 200 °C with MET, and Hydrogen
- Temperature Cycling [M5®, ZIRLO®]
  - 2 Segment M5®: 350 °C, 400 °C, 1 to 3 -/+ 100 °C Temp. Cycles, Cooled @ 5 °C/Hour, Bounding RIP (5 MPa @ RT)
  - 2 Segment ZIRLO®: 400 °C, 450 °C, 1 to 3 -/+ 100 °C Temp. Cycles, Cooled @ 5 °C/Hour, Bounding RIP (5 MPa @ RT)
  - RCT @ Temps. Between 20 and 200 °C with MET, and Hydrogen

Figure 1: Sibling Pin Phase II Testing Visualization.

5. REFERENCES

1. Hanson, Brady, Alsaed, Halim, Stockman, Christine, Enos, David, Meyer, Ryan, & Sorenson, Ken. (2012). *Gap Analysis to Support Extended Storage of Used Nuclear Fuel Rev. 0*. FCRD-USED-2011-000136 Rev. 0 (PNNL-20509). United States. https://www.osti.gov/servlets/purl/1133836
2. Teague, Melissa C., Saltzstein, Sylvia J., Hanson, Brady, Sorenson, Ken B., & Freeze, Geoffrey A. (2019). *Gap Analysis to Guide DOE R&D in Supporting Extended Storage and Transportation of Spent Nuclear Fuel: An FY2019 Assessment (Final Report)*. SAND2019-15479 R. https://doi.org/10.2172/1592862
3. Saltzstein, Sylvia, Hanson, Brady, Freeze, Geoff, & Sorenson, Ken. (2020). *Spent Fuel and Waste Science and Technology Storage and Transportation 5-Year R&D Plan*. M2SF-20SN010201062 (SAND2020-9310 R). U.S. Department of Energy.
4. Electric Power Research Institute (EPRI) (2014). *High Burnup Dry Storage Research and Development Project: Final Test Plan*. Electric Power Research Institute. Washington, District of Columbia. https://www.energy.gov/ne/articles/high-burnup-dry-storage-cask-research-and-development-project-final-test-plan
5. Hanson, Brady D., Marschman, Steven C., Billone, Michael C., Scaglione, John, Sorenson, Ken B., & Saltzstein, Sylvia J. (2016). *High Burnup Spent Fuel Data Project: Sister Rod Test Plan Overview*. FCRD-UFD-2016-000063 (PNNL-25374). U.S. Department of Energy. https://www.energy.gov/ne/articles/high-burnup-spent-fuel-data-project-sister-rod-test-plan-overview
6. Saltzstein, Sylvia J., Billone, Mike, Hanson, Brady, & Scaglione, John (2018). *Visualization of the High-Burnup Spent Fuel Rod Phase 1 Test Plan: Technical Memo*. SAND2018-8042 O. Sandia National Laboratories. https://doi.org/10.2172/1974059
7. Hanson, Brady (2012). *Review of Used Nuclear Fuel Storage and Transportation Gap Analyses*. FCRD-USED-2012-000215 (PNNL-21596). U.S. Department of Energy. https://www.energy.gov/ne/articles/review-used-nuclear-fuel-storage-and-transportation-technical-gap-analyses
8. Hanson, Brady D., & Alsaed, HamlinA. (2019). *Gap Analysis to Support Extended Storage and Transportation of Spent Nuclear Fuel: Five-Year Delta*. SFWD-SFWST-2017-000005, Rev. 1 (PNNL-28711). U.S. Department of Energy.
9. Montgomery, Rose, Bevard, Bruce B., Morris, Robert N., Goddard Jr., James S., Smith, Susan K., Hu, Jianwei, Beale, John, & Yoon, Byungsik. (2018). *Sister Rod Nondestructive Examination Final Report*. M2SF-17OR010201021 (ORNL/SPR-2018/801). https://doi.org/10.2172/1465039
10. Montgomery, Rose, & Bevard, Bruce (2023). *Sister Rod Destructive Examinations (FY22)*. M2SF-23OR010201024 (ORNL/SPR-2022/2678). https://doi.org/10.2172/1976043
11. Montgomery, Rose, & Bevard, Bruce B. (2022). *Sister Rod Destructive Examinations (FY2021)*. M2SF-22OR010201042 (ORNL/SPR-2021/2303). https://doi.org/10.2172/1864435
12. Shimskey, R. W., Edwards, M. K., Geeting, J., Allred, J. R., Cooley, S. K., Daniel, R. C., & Cox, R. M., (2019). *Initial Results of Destructive Examination of Ten Sister Rods at PNNL*. PNNL-28548. Pacific Northwest National Laboratory, Richland, Washington.
13. Shimskey, R. W., Allred, J. R., Daniel, R. C., Edwards, M. K., Geeting, J., MacFarlan, P. J., Richmond, L. I., Scott, T. S., & Hanson, B.D. (2019). *PNNL Phase 1 Update on Sibling Pin Destructive Examination Results*. PNNL-29179. Pacific Northwest National Laboratory, Richland, Washington.

14. Shimskey, R. W., Allred, J. R., Asmussen, S. E., Cooley, S. K., Daniel, R. C., Edwards, M. K., Geeting, J., Huber, Z. F., MacFarlan, P. J., Richmond, L. I., Westesen, A. M., Westman, B. E, & Hanson, B. D. (2021). *PNNL FY 2020 Sibling Pin Testing Results*. PNNL-31036. Pacific Northwest National Laboratory, Richland, Washington.

15. Shimskey, Rick W., Allred, Jarrod R., Asmussen, Susan E., Cooley, Scott K., Daniel, Richard C., Dinh, Liem H., Edwards, Matthew K., Geeting, John GH, Goulet, AJ P., Huber, Zachary F., Klymyshyn, Nicholas A., Lonergan, Jason M., MacFarlan, Paul J., Nickerson, Ethan K., Richmond, Lauren I., Roosendaal, Timothy J., Torres Pagan, Ricardo D., Westesen, Amy M., Westman, Bjorn E., & Hanson, Brady D. (2022). *PNNL FY2021 Sibling Pin Testing Results*. M2SF-21PN010201057 & M2SF-22PN010201062 (PNNL-32783). https://doi.org/10.2172/1865621

16. Shimskey, R. W., Allred, J. R., Asmussen, S. E., Cooley, S. K., Daniel, R. C., Edwards, M. K., Geeting, J., Goulet, A. P., Holbrook, C. H., MacFarlan, P. J., Nickerson, E. K., Richmond, L. I., Roosendaal, T. J., Westesen, A. M., Westman, B. E., & Hanson, B. D. (2023). *PNNL FY2022 Sibling Pin Testing Results*. M2SF-23PN010201041 (PNNL-33781). https://doi.org/10.2172/1985813

17. Billone, M. C., Burtseva, T. A., Chen, Y., & Han, Z. (2020). *Ductility of M5® and ZIRLO® Sibling Pin Cladding*. M2SF-20AN010201012 (ANL-20/47). Argonne National Laboratory. https://www.osti.gov/servlets/purl/1973847

18. Billone, M. C., Burtseva, T. A., Chen, Y., and Han, Z. (2023). *Ductility of Zircaloy-4 Sibling Pin Cladding*. M2SF-23AN010201012 (ANL-22/69). Argonne National Laboratory https://www.osti.gov/servlets/purl/1721622

19. Office of Nuclear Material Safety and Safeguards (2020). *Standard Review Plan for Spent Fuel Dry Storage Systems and Facilities - Final Report*. NUREG-2215. U.S. Nuclear Regulatory Commission, Washington, District of Columbia, U.S.A.

20. Borowski, J., Call, M., Dunn, D., Rigato, A., Smith, J., Solis, J., Tapp, J., & White, B. (2020). *Standard Review Plan for Transportation Packages for Spent Fuel and Radioactive Material: Final Report*. NUREG-2216. Office of Nuclear Materials Safety and Safeguards, U.S. Nuclear Regulatory Commission, Washington, District of Columbia, U.S.A.

21. Electric Power Research Institute (EPRI) (2019). *High Burnup Dry Storage Research Project Cask Loading and Initial Results*. Technical Report 3002015076. Electric Power Research Institute. Palo Alto, California.

22. Gussev, M. N., Garrison, B., Massey, C., Le Coq, A., Linton, K., Terrani, K. A. (2023). A Correlation-Based Approach for Evaluating Mechanical Properties of Nuclear Fuel Cladding Tubes. *Journal of Nuclear Materials*, Volume 574 (2023) 154192. https://doi.org/10.1016/j.jnucmat.2022.154192