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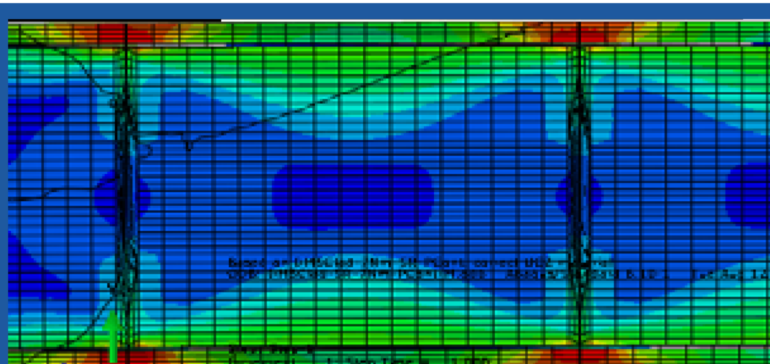

SPENT FUEL & WASTE SCIENCE & TECHNOLOGY

High Burn-Up Demo Sister Rod Testing Program

Presented: REG CON 2017

White Flint, MD

October 31, 2017

Sylvia J. Saltzstein

Sandia National Laboratories

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1 What is the High Burn-Up Demo Sister Rod Testing Program?

Obtaining Data on High Burnup Cladding After 10 Years of Dry Storage

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- **DOE/EPRI High Burnup Confirmatory Data Project Goal:**
  To provide confirmatory data for models, future SNF dry storage cask design, to support license renewals and new licenses for ISFSIs

- **Steps**
  1) Loading a commercially licensed TN-32B storage cask with high burn-up fuel in a utility storage pool *(planned for October 31, 2017)*
     - *Loading well characterized fuel of 4 common cladding alloys*
     - *Instrumenting cask outfitted with thermocouples*
     - *Gas samples taken before going to pad and periodically during storage*
  2) Drying using industry standard practices
  3) Storing at utility dry cask storage site – 10 years
  4) Transporting to lab to open
  5) Testing rods to understand mechanical properties

Prairie Island Dry Storage

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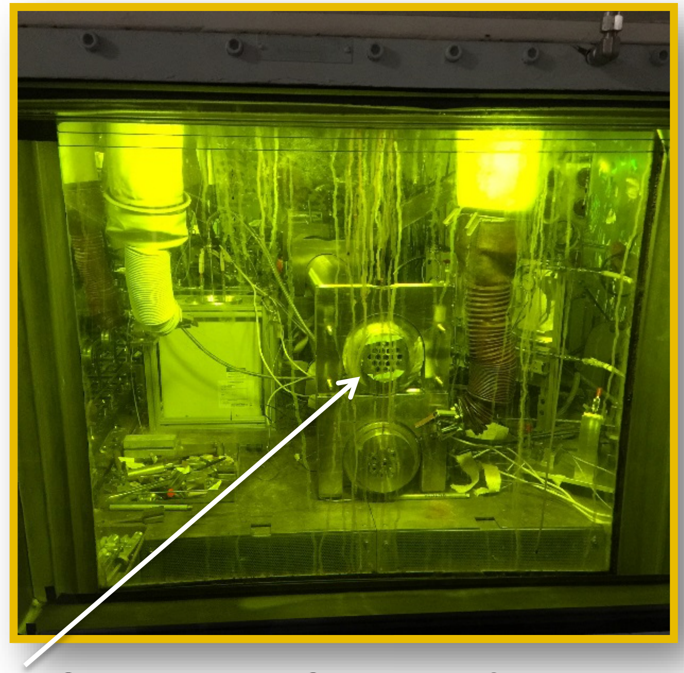
High Burnup Confirmatory Data Project – Obtaining *Baseline* Data

- **25 fuel rods with similar histories to those in the cask will be tested to document pre-storage properties.**
- **“Sister Rod” Acquisition & Testing**
  - Areva and Westinghouse rods pulled in June and January 2015 from different assemblies
    - *9 AREVA M5® rods*
    - *12 Westinghouse Zirlo® rods*
    - *4 Westinghouse Zircaloy-4*
      - 2 Low-tin
      - 2 Standard
  - All 25 sister rods currently at Oak Ridge National Laboratory undergoing nondestructive analysis
  - Non-destructive tests began in FY17; destructive tests planned to begin in FY18
    - *14.5 rods at ORNL*
    - *10 rod equivalents at PNNL*
    - *0.5 rod equivalents at ANL*



25 Sister Rods in ORNL Hot Cell

Photo: Saltzstein, SNL

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2 PREP FOR LOADING AND STORAGE

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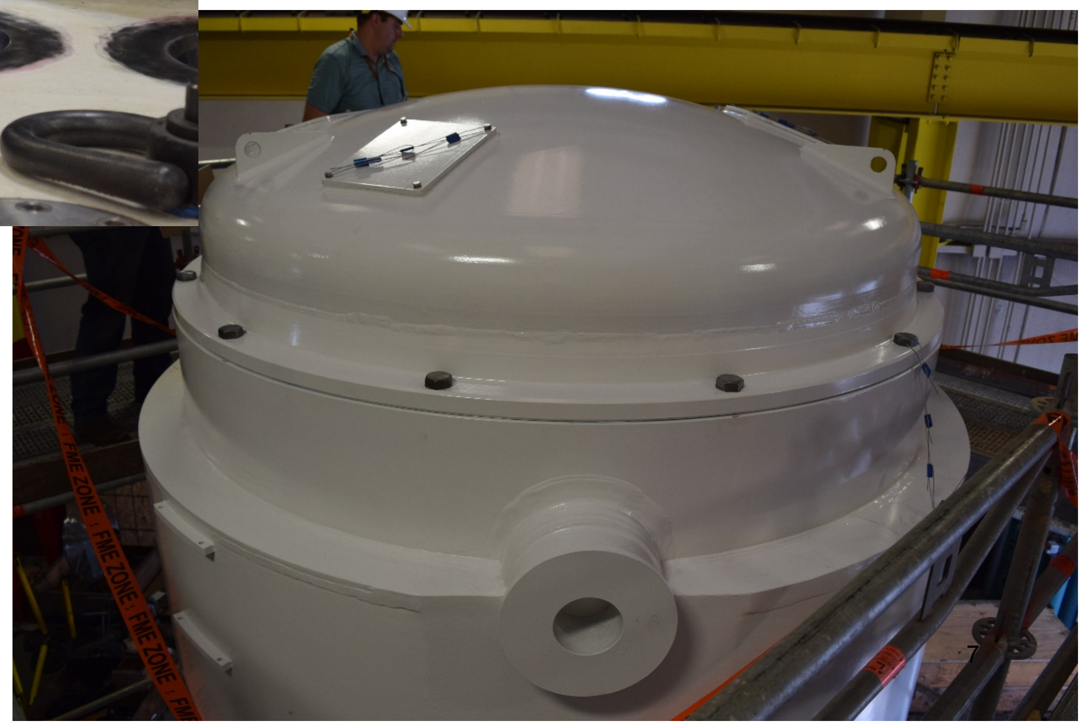
Progress with the Cask

Welding the forgings to the cask

Cask with the security seal



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NRC Approved ISFSI License Amendment

- "(NRC) staff has determined that there is reasonable assurance that: (i) the activities authorized by the amended license can be conducted without endangering the health and safety of the public and (ii) these activities will be conducted in compliance with the regulations in Title 10 of the *Code of Federal Regulations* Part 72 applicable to specific Independent Spent Fuel Storage Installation licenses."
- September 13, 2017

September 13, 2017

Mr. Daniel G. Stoddard
Senior Vice President and Chief Nuclear Officer
Innsbrook Technical Center
5000 Dominion Boulevard
Glen Allen, VA 23060-6711

SUBJECT: AMENDMENT NO. 5 TO MATERIALS LICENSE NO. 2507 FOR THE NORTH ANNA POWER STATION INDEPENDENT SPENT FUEL STORAGE INSTALLATION (CAC NO. L25047)

Dear Mr. Stoddard:

By letter dated August 24, 2015, as supplemented October 8, November 18, November 19, December 1, and December 28, 2015; January 14, March 22, March 23, April 21, June 21, July 26, September 23, November 22, 2016, April 10, and June 14, 2017 you submitted an amendment request for the North Anna Power Station Independent Spent Fuel Storage Installation. You requested an amendment in the form of changes to the Technical Specifications to Materials License Number SNM-2507 for the North Anna Power Station Independent Spent Fuel Storage Installation. The proposed changes would allow storage of spent fuel in a modified TN-32B bolted lid cask as part of the High Burn-up Dry Storage Cask Research and Development Project sponsored by the Department of Energy and the Electric Power Research Institute.

Based on its review of your application, as revised and supplemented, the Nuclear Regulatory Commission (NRC) staff has determined that there is reasonable assurance that: (i) the activities authorized by the amended license can be conducted without endangering the health and safety of the public and (ii) these activities will be conducted in compliance with the regulations in Title 10 of the *Code of Federal Regulations* Part 72 applicable to specific Independent Spent Fuel Storage Installation licenses. NRC staff has further determined that the issuance of the amendment will not be inimical to the common defense and security. These findings are documented in the attached safety evaluation report. Also in connection with the issuance of the license amendment, an Environmental Assessment and Finding of No Significant Impact was noticed in the *Federal Register* on June 30, 2016 (81 *FR* 42743).

The NRC has approved the requested amendment. Changes made to the attached License No. SNM-2507, including technical specifications, are indicated by vertical lines in the right margin. Also attached is a draft of the *Federal Register* notice of the action taken.

In accordance with 10 CFR 2.390 of the NRC's "Rules of Practice," a copy of this letter will be available electronically for public inspection in the NRC Public Document Room or from the publicly available records component of ADAMS. ADAMS is accessible from the NRC Website at http://www.nrc.gov/reading-rm/adams.html.

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3 Results from Non Destructive Analysis

Non-Destructive Results To-Date

Scope: Visual Examinations of the external surfaces and gross dimensional measurements.

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- **Visuals of exterior surfaces with location and appearance of physical abnormalities (e.g. Chemical attack, blisters, cracks, oxide layers, weld failures, etc.)**

- **Results:**
  - No weld failures, cladding breaches or significant defects
  - Barcodes visible
  - Shallow grid-to-rod fretting marks
  - Patches of CRUD and/or spalling oxide
  - long axial scratches from rod removal from the assembly on most rods

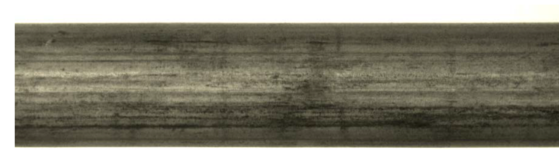
Crud Peeling

M5 cladding

Zirlo cladding

Zircaloy-4 cladding

Pellet-to-Pellet Interfaces



M5 Cladding

Zirlo cladding

Grid to Rod Fretting on M5 cladding

Source: Bevard, ORNL SFWD-SFWST-2017-000088, ORNL/SPR-2017/382

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Non-Destructive Results To-Date

Scope: Gamma Scans to see pellet locations and cracks

- **Gamma Scans (400 to 800 KeV fuel stack and 1100 to 1600KeV for structural components at 1mm increments) to document locations of:**
  - Relative axial burnup profiles
  - Large pellet cracks
  - Pellet stack gaps
  - Pellet stack height
  - Burnup depressions from grid spacers

- **Results**
  - No sign of fission product accumulation or migration
  - Depressions in burnup were easily observed at the spacer grid locations
  - Pellet-pellet interface locations were observable
  - Spring in the plenum region was visible
  - Small fuel stack gaps were observed

	30AK09	30AD05	30AP02	30AG09	30AE14
Measured top end cap	9.9	9.7	9.2	10.1	9.4
Measured stack length	3679.0	3677.0	3679.0	3674.0	3674.0
Measured pellet length	10.2	10.3	10.3	10.2	10.3
measured spring length	178.0	185.0	179.0	185.0	184.0
measured bottom end cap	14.0	14.0	14.0	13.0	14.0
measured total rod length	3880.9	3885.7	3881.2	3882.1	3881.4

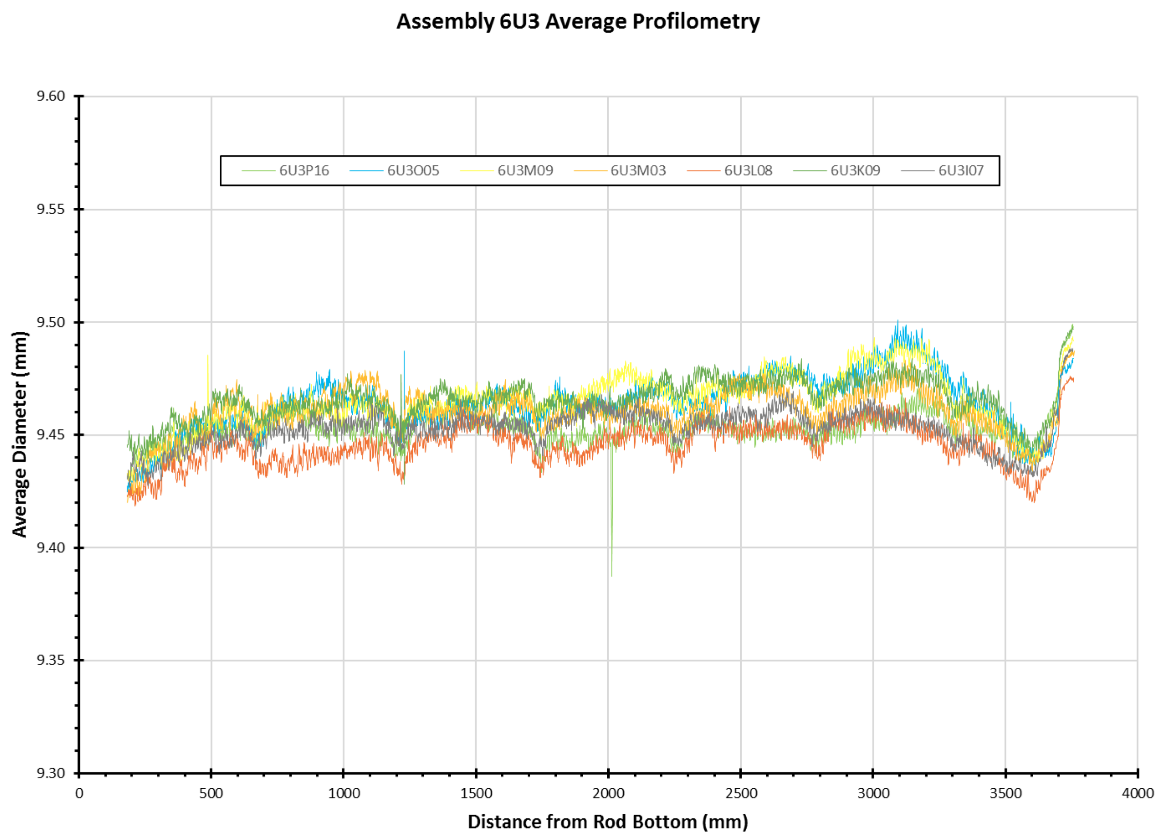
Gamma Scan for one of the 25 Sister Rods

Source: Bevard, ORNL SFWD-SFWST-2017-000088, ORNL/SPR-2017/382

Non-Destructive Results To-Date

Scope: Profilometry to get rod physical measurements

- **Profilometry to measure fuel rod diameter**
- **Results**
  - No significant ovality was noted
  - Some rods with thickest oxide layers have \some erratic diameter measurements
  - Two rods showed



Profilometry Measurement for six of the 25 Sister Rods

Source: Bevard, ORNL SFWD-SFWST-2017-000088, ORNL/SPR-2017/382

Non-Destructive Results To-Date

Next Tests

- **Future NDE**
  - Eddy Current Scans to obtain information on clad mechanical macroscopic defects.
  - Surface temperature

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4 Destructive Analyses is next

PNNL

Heat-Treat Segments of 3 Rods to 400°C:

- 1/M5 + 1/Zirlo + 1/Zirc-4 = 3 rods
  - ✓ Cool rods at 5°C/hr to 100°C

Heat-Treat Segments of 2 Rods to Demo Temps:

- 1/M5 + 1/Zirlo = 2 rods
  - ✓ Heat according to measured Demo Temps
  - ✓ Cool rods at 5°C/hr to 100°C

ORNL

Do Not Heat-Treat Segments of 3 Rods:

- 1/M5 + 1/Zirlo + 1/Zirc-4 = 3 rods

Perform CIRFT Tests on Segments of 2 Rods:

- 1/M5 + 1/Zirlo = 2 rods

Room Temp
1. ASTM Axial Tensile Test
2. ASTM Burst Test
3. ASTM 4-pt Bend

Heat to 200° C
1. ASTM Axial Tensile Test
2. ASTM Burst Test
3. ASTM 4-pt Bend

1. Optical Microscopy
2. Hydrogen-Content
3. ASTM Micro-hardness
4. Rod Internal Pressure
5. Cut for 4 RCT Test

Room Temp
1. ASTM Axial Tensile Test
2. ASTM Burst Test
3. ASTM 4-pt Bend

Heat to 200° C
1. ASTM Axial Tensile Test
2. ASTM Burst Test
3. ASTM 4-pt Bend

1. Optical Microscopy
2. Hydrogen-Content
3. ASTM Micro-hardness
4. Rod Internal Pressure
5. Cut for 4 RCT Test

Rod with Sample Cuts at Top and Middle

15 Rods Remain: 5/M5 8/Zirlo 2/Zirc-4

Then PAUSE… *Our community reviews the data, and we determine a path forward.*

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THOUGHTS? COMMENTS? QUESTIONS?

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Back-up Slides

Contents

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1 Why Are We Here?

Why Are We Here?

- **PROBLEM:**
  Test Plans are too complicated to explain to anyone outside our group
- **PROBLEM:**
  Concerns about the number of tests, types of tests, potential redundancies of tests, and alignment of identified test to technical gaps
- **GOAL:**
  Identify types and number of tests to provide *a core set* of material property and physical data that can be compared within rods, between rods, and later to the 10-year stored rods
- **GOAL:**
  Provide core baseline data of the pre-stored rods for comparison to post-stored rods

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2 Methodology for Simplification

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Methodology

- **I interviewed nine people* from the Labs, NEI, NRC, Consulting, and EPRI and asked the following questions:**
  - *What are the most important sets of data that we need?*
  - *What are your priorities for those data points?*
  - *What tests are best for getting these properties?*
  - *How important is using ASTM methods to you?*
  - *At what temperatures should we test?*
  - *Should we test at T_0, T_0' or both?*
  - *Which rods should be tested?*
  - *Which section of rods?*
  - *Should we use some of the time and budget allocated for PWR sister pin testing to test BWR?*
  - *Any other important things to note?*

*** Machiels, Billone, Kessler, Waldrop, al Saed, Cummings, Csontos, Sorenson, Torres**

3 Results from Interviews

Fundamental Concerns Raised During Interviews

1) **We are proposing too many different tests, including alternate tests designed to measure the same properties.**
   - *Comparison of results may be an issue*

2) **We have turned this into a science project and have missed the fact that we just need a few critical data points.**
   - *We are setting ourselves up for failure with this broad set of parameters*
   - *Fundamentally, we can do without any of this data; scope of the Demo is to see if the fuel can withstand long-term storage; that can be done by opening it in ten years and then performing tests*

3) **The use of the words, “filling gaps” bothers some who state that this is a confirmatory project, not a gap filling project.**

4) **On the other hand, this testing campaign is for more than just confirmatory data, this is our only opportunity now to collect data on this fuel.**
   - *Mechanical properties of cladding with reoriented hydrides*
   - *CIRFT static, fatigue, and cumulative effects testing on M5 and ZIRLO*
   - *Relationship between the RCT-measured DBTT and the actual mechanical properties of the cladding—axial variation and H content dependence*

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Opinions on…

What Are the Highest Priority Data Needs?

1) **High Priority** *(votes)*
   - ***Temperatures*** *(5)*
   - ***Visual measurements of rods*** *(6)*
   - ***Stress strain curve*** *(especially in M5 & ZIRLO) (6)*
     - ***Yield strength*** *(especially in M5 & ZIRLO)*
     - ***Ultimate strength*** *(especially in M5 & ZIRLO)*
     - ***Young's Modulus***
   - ***Rod internal pressure*** *(6)*
   - ***Ductility*** *(especially in M5 & ZIRLO) (6)*
   - ***Microscopy to see hydrides*** *(5)*
   - *Hydrogen content (4)*
   - *Wall and oxide thickness (3)*
   - *CIRFT (especially reoriented M5 and ZIRLO, but also at lower burn-up ends) (3)*
   - *Ductility in fueled segments with a comparison to the ANL RCT results (3)*
   - *Fission gas analysis (2)*
   - *Test at places where there is some grid to rod erosion (2)*
   - *Corrosion properties for long-term storage (1)*
   - *Fracture toughness (1)*
   - *Micro-hardness for annealing (1)*

CONCLUSION:

Highest Priority Data Needs

2) **Don't Test**
   - *Fracture Toughness—NRC doesn't approve because initial crack size is needed*

Opinions on… *What Destructive Tests Are Good For Getting These Properties?*

1) **Optical Microscopy**
   - *Microscopy to see hydrides*
   - *Wall and Oxide Thickness*
2) **Inert Gas Fusion Thermal Conductivity Measurement *(ASTM Standard Method)***
   - *Hydrogen Content*
3) **Micro-hardness**
   - *Annealing*
4) **Standard Puncturing and Evacuation Method**
   - *Rod Internal Pressure*
5) **ASTM Axial Tensile Test using 6” defueled segments and at least one grid spacer**
   - *Stress Strain Curve*
     - ***Ultimate Tensile Strength***
     - ***Uniform Elongation***
     - ***Young’s Modulus***
     - ***Yield Strength***
6) **ASTM Burst Test using 6” defueled segments and at least one grid spacer *(Ring tensile testing if burst testing can not be performed at higher temperatures)***
   - *Stress Strain Curve, yield strength, and elongations in hoop direction*
7) **RCT *(at representative pressures and temperatures; defueled)***
   - *DBTT*
   - *Ductility*
8) **ASTM 4-Point Bend Test using 6” defueled segments and at least one grid spacer**
   - *Modulus of elasticity in bending*
   - *Flexural stress-strain*
9) **CIRFT on standard non-heat treated ZIRLO under realistic conditions**
   - *Fueled mechanical properties*

Opinions on…
How Important Is Using ASTM Methods to You?

1) **Not using ASTM methods puts the onus on the NRC staff to justify to stakeholders why a given non-standardized test was appropriate. If the plan is going to reference non-standardized tests (CIRFT and RCT), then the plan should explain why these are the right test methods (e.g. no standardized method is available to assess "pure bending" of SNF rods-CIRFT allows for that, etc.).**

2) **Use them if you have them, but don't ignore CIRFT and RCT, because they are well vetted.**

3) **Non-ASTM non-vetted test methods should be a lower priority for the scope of this work.**

Opinions on…
What Temps We Should Use for T_0'

1) **400°C for T_0'**
   - *Yes*
     - *There is nothing preventing future applicants from loading fuel that is heated to this temperature and it is the regulatory recommended limit, and is really no different from 375℃.*
   - *No*
     - *Cladding won't realistically get this hot.*
     - *Only a small part of the rod will get this hot, even if the max temp gets to 400℃.*
     - *PNNL modeling show that the inventory is much colder than 400℃.*
     - *Higher temperatures allows for some annealing which can repair damage.*

2) **325-375°C for T_0'** *(bound the inventory)*
   - *375℃*
     - *Based on NRC license applications and amendments, 375℃ will bound a majority of the inventory.*
     - *Test at 350-375℃, but not lower because industry will push temps higher in the future.*
   - *325-350℃*
     - *Above 325℃ annealing of damage occurs.*
     - *At 325 ℃ there is still enough hydrogen in the cladding to create some hydrides.*
     - *There are not enough rods in the inventory that are above 325℃ to make a difference (per PNNL calculations).*
     - *Determine the final temperature between 325-350℃ based on the PNNL modeling.*

3) **Mimic Demo Temperatures for T_0'**
   - *Yes*
     - *Needed to directly compare to demo pins ten years from now.*
     - *Needed to help assess separate effects vs. long-term synergistic effects of multiple phenomena (creep, reorientation, irradiation hardening, oxidation, etc.).*
   - *No*
     - *It will only make a difference if the demo temps are >300℃ and gas pressures are >5MPa.*
     - *If temps are < 300℃ and gas pressures are <5MPa, this will be the same as T_0.*
     - *Don't artificially elevate temperatures because the NRC will never think you did it right.*
     - *Use the modeling results we have to choose temperatures.*

Opinions on… *What Temps We Should Test*

1) **100-200°C for Test Temperatures** *(transportation range)*
   - *Test at 200 ℃ because that is the upper range of cladding temperature when transporting at which hydride structure is frozen.*
   - *Model a few cask systems to 50, 60, or 100 years and choose an average clad temperature for that as a justification for a temperature (PNNL has done this).*
   - *Test at 100 ℃ because that is the temp after ≈100 years when we transport (PNNL MAGNASTOR calculations: PCT @ 100 years = 111 ℃; PCT @ 200 years = 81 ℃).*
   - *Testing below 100 ℃ is not realistic because it will take too many years to get there.*

2) **Test at Room Temperature** *(RT – worst case)*
   - *Worst case*
   - *Important for M5 and medium importance for ZIRLO; Zircaloy-4 alloys are low priority*

3) **Comments**
   - *Sites will try to push it once they find out our temps are so low, so we should test a bit higher.*
   - *Ensure realistic cooling.*
   - *Cool at 5 ℃/hr may be too fast based on Japanese data.*
   - *Keep one at PCT for a long time to see the effect.*

Opinions on… *Heat Treating Rods*

1) T_0 *(no heat treat)*
   - *Yes*
     - *This is the only reason we are doing the sister pin testing, so we can see how drying affects the rods.*
     - *Needed to predict effects of drying and storage. Every rod experiences different drying conditions, so we can't accurately mimic the effects of drying.*
     - *Important for M5 and for ZIRLO, but not as much for others.*
     - *Needed to provide a good reference point for the rods so we don't need to rely on the existing industrial database, which has a lot of variation and is mostly proprietary.*
   - *No*
     - *Testing before drying is not meaningful because there will not be any fuel in the inventory that will not be dried.*
     - *There is so much variability within and between rods, that nothing we do will be representative.*

1) T_0' (*heat treat)*
   - *Yes*
     - *to bound the inventory and to see extend and effects of radial hydrides*
     - *We need data on post-drying*
     - *We don't have non-proprietary as-irradiated data on M5 for important parameters.*

2) **Mimic the Demo**
   - *Yes*
     - *It is very important to mimic the demo because that is what we will compare against when we open the cask in ten years.*
     - *If RPC temperatures are below 350, then these results will be the same as the non-heat treated because radial hydrides will not form.*
   - *No*
     - *We don't need to do this as long as we open the demo in ten years.*

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Our Rod Inventory

1) **Nine AREVA M5® rods**
2) **Twelve Westinghouse Zirlo® rods**
3) **Four Westinghouse Zircaloy-4**
   - *Two Low-tin*
   - *Two Standard*

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Data to Consider *After* Evaluation of the Top Priority Data

1) **Second Priority Data**
2) **Data on Fueled Rod Mechanical Properties**
   - *CIRFT tests*
     - *As-irradiated M5*
     - *Cumulative effects, if we feel we can take credit for fuel in cladding*
   - *Fueled RCT tests*
     - *Compare to ANL method*
3) **Hydrogen Content Variability within Cladding**
   - *Will get some of this with the high priority tests, but may want more*
4) **Microhardness After Extended Time at Temperature**
   - *To understand effects of annealing*
     - *M5 would be best for this, but will only provide data for that cladding and environment*
5) **Full Rod Heater Test**
   - *Store one rod at temperature for one year and cool slowly*

Additional Comments

Targeted Secondary Needs

1) **Tensile properties for as-irradiated M5 and as-irradiated ZIRLO**
2) **Fueled Ring Compression tests**
   – *Do a few to see how they compare to the ANL method (voiced by 3 people)*
   – *There is no database for which to compare*
   – *These details need to be discussed*
   – *We need to develop the method*
3) **CIRFT test should be performed with realistic temperature cycling**
   – *The details need to be discussed*
4) **Cooling rate**
   – *The details and rationale for 5C/hr needs to be discussed with the group*

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4 PROPOSED TEST PLAN

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Proposed Test Plan

1) **Optical Microscopy**
   - *Microscopy to see hydrides*
   - *Wall and oxide thickness*
2) **Hydrogen Content**
3) **Micro-hardness**
4) **Rod Internal Pressure and Gas Analysis**
5) **Ring Compression Tests (defueled)**

Test two of each cladding alloy near top and middle at room temperature and 200°C following heat-treatments at 325-350°C, Demo temperatures, and To.

6) **ASTM Axial Tensile Test using 6" defueled segments**
7) **ASTM Burst Test using 6" defueled segments**
8) **4-Point Bend Test**
9) **CIRFT on as-irradiated ZIRLO**

THEN PAUSE…

Our community reviews the data, and we determine a path forward from there

Proposed Test Plan
(more detail)

1) **Heat-Treating**
   - *Heat-Treat two rods of each cladding at 375 ℃ PCT and pressurize to >5MPa or something bounding to the fleet.*
   - *Heat-Treat one rod of M5, Zirlo, and one Zirc-4 type at temperatures mimicking the Demo. Pressurize at relative pressure.*
   - *Save one rod of M5, Zirlo, and one Zirc-4 to test without heat-treatment.*
2) **Cool at 5°C/hr until ~100°C; faster cooling allowed to room temperature**
   - *This is being tested at PNNL from 5 ℃/hr to 5 ℃/hr to determine the optimal rate.*
3) **Puncture for Rod Internal Pressure and gas analysis** *(at ORNL)*
4) **Perform cuts at ambient temperature**
   a) *Optical Microscopy*
   b) *Hydrogen-Content*
   c) *Micro-hardness*
   d) *Ring Compression Tests*
   e) *Axial and Burst tests*
5) **Test axial tensile, burst tests, 4-pt bend tests at room temperature** *(worst case)* **and ~200°C** *(upper bound for transportation)*
6) **Perform Ring Compression tests for cladding with radial hydrides**
   - *8 rings per rod (4 at top and 4 in the middle)*
   - *determine the ductility transition by testing within room temp. to 200 ℃.*
7) **Test CIRFT on as-irradiated ZIRLO**

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5 Pros & Cons

Pros & Cons

Pros

1) **More comparable data**
   – *Bound the number of tests (7-8)*
   – *Bound the test locations (rod top and middle)*
   – *Bound the temperatures (2 heat treat. 3 testing)*
2) **Saves up to 10 rods for further testing**
   – *4 M5 and 7 Zirlo*
3) **Uses pedigreed methods**
4) **Bounds the inventory storage temps**
5) **Provides data to compare in ten years**
6) **Gets pre- and post-dried data**
7) **Tests at hottest/coldest transportation temps**
8) **Gets data on all four cladding types**
9) **Gets data at different locations on rod**
10) **Gets data at a grid spacer**
11) **Gets mechanical properties at axial and hoop stress** *(most probable failure mechanism)*
12) **Gets more fueled rod data** *(CIRFT)*
13) **Input from nine informed community experts from different entities**

Cons

1) **Won't capture the variability** *(pressure, temperature, hydrides, hydrogen)* **within and between rods**
   – *This can be moved to a later phase after data has been analyzed*
2) **Peak temperatures of 325-400 all have different pros and cons; Many people have strong feelings about this, but a very small percentage of the inventory will ever reach these temperatures**
3) **May have transportation logistical complications**
4) **Expends 15/25 rods; Leaves 10 rods without a specific plan**
5) **Don't get to test-out different methods**
6) **Pushes future data collection decisions out**

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THOUGHTS? COMMENTS? QUESTIONS?