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Visualization of the High-Burnup Spent Fuel Rod Phase 1 Test Plan:

Technical Memo

Spent Fuel and Waste Disposition

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

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1. OVERVIEW

Twenty-five high-burnup fuel rods were extracted from seven different fuel assemblies used for power production at the North Anna nuclear power plant and shipped to Oak Ridge National Laboratory (ORNL) in 2016 for detailed non-destructive examination (NDE) and destructive examination (DE). The spent fuel rods were from 17×17 lattices and consist of four cladding types—Zirlo®, M5®, Zircaloy-4, and low tin Zircaloy-4 (Zirc-4). These spent fuel rods are being tested to provide: (a) baseline characterization and mechanical property data that can be used as a comparison to fuel that was loaded into a modified TN-32B cask in November 2017, as part of the high-burnup confirmatory data project [1] and (b) data applicable to high-burnup fuel rods (>45 GWd/MTU) currently stored and to be stored in the dry-cask fleet. The TN-32B cask is referred to as the "Demo" cask and is currently expected to be transported to a separate location and the internal contents inspected in approximately ten years.

ORNL has completed the NDE of the twenty-five fuel rods [2]. The purpose of this technical memorandum is to present a simplified summary of the first phase of destructive examinations and test conditions that will be used for communicating with various stakeholders. The destructive examinations will leverage the expertise and capabilities from multiple national laboratories for performing independent measurements of relevant data. Close coordination is required to ensure that all examinations follow well-documented procedures and are performed so that measured data and characteristics can be readily compared. Pacific Northwest National Laboratory (PNNL) has published a detailed overview of the test program [3]. ORNL [4] and PNNL [5] developed detailed draft test plans for testing to be performed at their facilities. ORNL and PNNL are in the process of refining these test plans to apply specifically to the testing described in this memorandum. Argonne National Laboratory (ANL) contributed to the ORNL test plan by describing tests to be conducted at ANL. Testing will be based on continuous learning. If a test produces results that are inconsistent with expectations or current trends, further testing will be paused until a path forward is established to understand the results and to identify follow-on testing.

1.1 Objectives

1. Identify types and number of tests to provide a core set of material property and physical data that can be compared to the ten-year stored rods, and develop a simple visual that describes the Phase 1 test plan.

2. Describe a test plan that will generate data to determine if radial hydride-induced embrittlement is an issue for prototypical peak cladding hoop stresses at a peak cladding temperature (PCT) of 400°C.

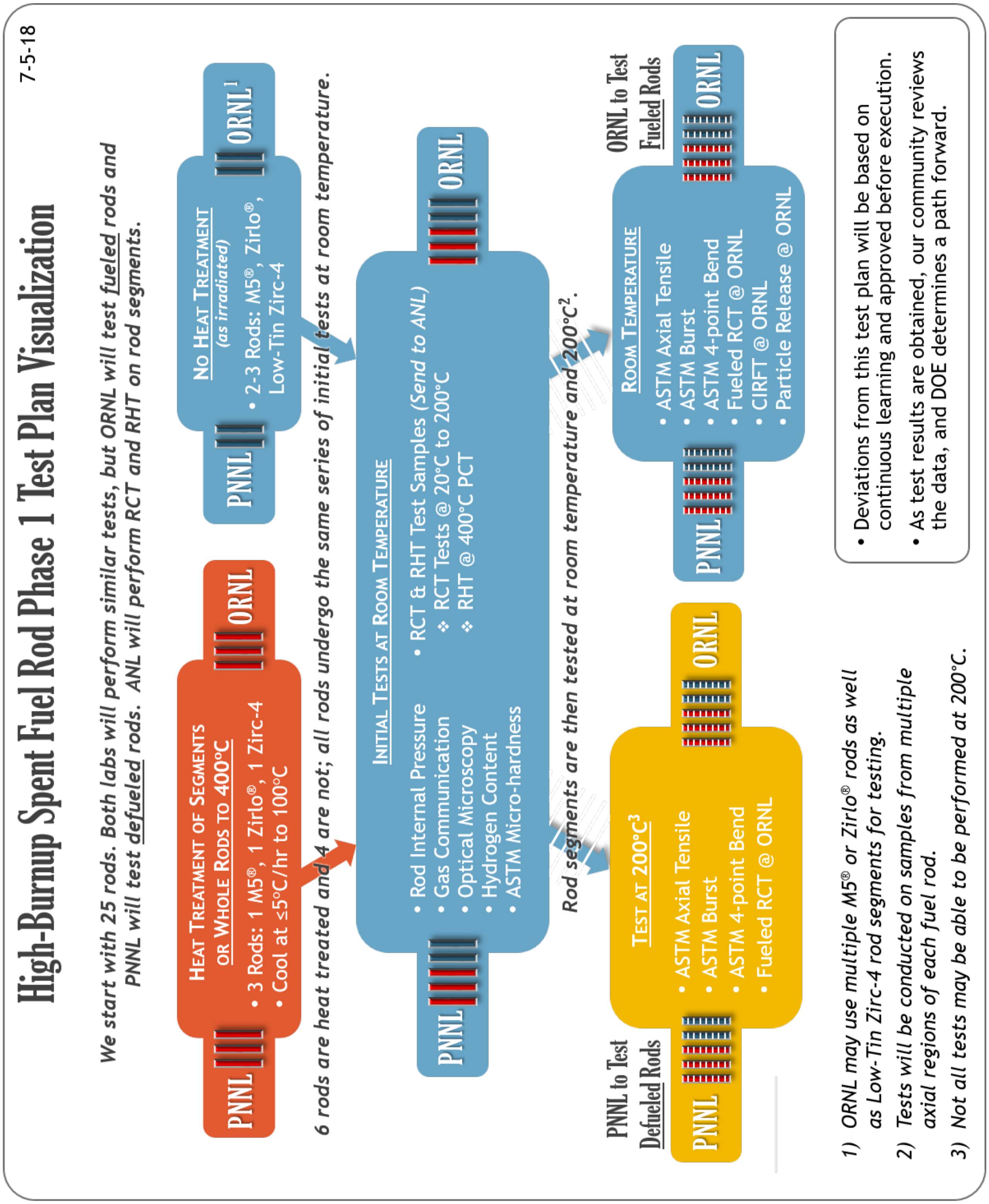

Figure 1. Test Plan Visualization

Ten fuel rods will be shipped to PNNL for DE (five fuel rods for Phase 1 testing) and the other 15 fuel rods will remain at ORNL for DE (about five fuel rods for Phase 1 testing). Approximately one-half rod equivalent (about six feet) of defueled cladding from PNNL and ORNL fuel rods will be shipped to ANL.

1.2 ORNL

ORNL will perform full DE of about five spent fuel rods, from which approximately four feet of defueled cladding will be sent to ANL for DE. ORNL will measure the rod internal pressure in five as-irradiated fuel rods as follows:

- 2 M5®-clad rods
- 2 Zirlo®-clad rods
- 1 low-tin Zirc-4-clad rod
- 3 fuel rods *(after heat treatment at 400°C in a whole-rod heater).*

Two to three rod-length equivalents from as-irradiated fuel rods will be subjected to further DE. ORNL will perform gas communication testing on several full-length punctured rods. One rod of each cladding type (M5®, Zirlo®, and Zirc-4) will be heated to 400°C prior to cooling and puncturing for rod internal pressure measurements, thereby preserving the spent fuel rod characteristics prior to heat treating. A temperature profile will not be used in the Phase 1 tests to reduce the number of test-sample variables and to induce an upper bound of pressure at this elevated temperature relative to stored rods that have an axial temperature profile. The 400°C temperature corresponds to the Nuclear Regulatory Commission recommended limit on PCT to assure cladding integrity. However, prolonged time at this temperature is not desirable for Phase 1 testing because it would lead to excessive annealing of irradiation damage. The effects of annealing will be examined in Phase 2, if necessary. In addition to internal pressure measurements following heat treatment and cooling, gas communication testing will be performed for comparison with the baseline rods.

1.2.1 Heating Rate, Hold Temperature, & Cooling Rates

A heat-up rate of about 10°C/hr will be used up to 400°C. Once the rod reaches 400°C, it will be held at that temperature for about eight hours. It will then be cooled at ≤5°C/hr from 400°C to 100°C at which time a faster cooling rate to ambient temperature may be used.

1.2.2 Test Samples

The rods will be sectioned for the following:

- ASTM axial tube tensile tests
- Cyclic Integrated Reversible Bending Fatigue Tester (CIRFT) tests
- ASTM four-point bend (4-point bend) tests
- Optical microscopy evaluation
- Hydrogen content determination
- ASTM micro hardness tests
- Defueled-cladding ring-compression tests (RCTs)
- Fueled-cladding RCTs.

ORNL will also perform tests to quantify the amount and particle size distribution (including respirable fraction) of fuel released from a failed segment. The same pattern of cuts and testing will be preserved for comparing segments between as-irradiated rods and heat-treated rods. Emphasis will also be placed on collecting samples that will provide information on low-burnup ends, high-burnup portions, and grid spacers. *Note that most ORNL tests will be conducted with fueled-cladding samples*.

1.2.3 Testing Temperatures

The ASTM axial tube tensile and 4-point bend tests will be conducted at two temperatures: room temperature and 200°C. The tests depicted in the blue box on the right in Figure 1 will be conducted at room temperature except for the RCTs, which will be tested at 20°C to 200°C to determine the ductile-tobrittle transition temperature (DBTT). A couple of non-heat-treated segments of M5® and low-Sn Zirc-4 fuel will be tested using past conditions for CIRFT samples on similar materials so that data can be compared to past CIRFT data. It may not be possible to perform the CIRFT tests at 200°C, but it is desirable to compare the mechanical properties obtained in the CIRFT tests to the other mechanical properties obtained in this test plan. The non-heat-treated Zirlo® rod segments will be used to develop a similar fatigue curve as has been done for the other cladding materials. These results will also serve as a baseline for CIRFT tests with heat-treated Zirlo® samples.

1.3 PNNL

PNNL will perform rod internal pressure measurements on the ten rods after they arrive at PNNL. Following rod internal pressure measurement, each rod will be cut into sections and preserved for testing. Additional fuel rod segmenting and defueling of cladding will be performed on one M5®- and one Zirlo®-clad rod for as-irradiated condition testing. About two-feet of cladding from M5® and Zirlo® fuel rods will be defueled and shipped to ANL. Cladding segments from three additional rods (one each of M5®, Zirlo®, and Zirc-4) will be repressurized to previously measured rod internal pressures, sealed and heat treated. The rods will be sectioned and defueled for ASTM axial tube tensile tests, ASTM burst tests, ASTM 4-point bend tests, optical microscopy evaluation, hydrogen content determination, ASTM micro hardness tests, and RCT samples that will be tested at ANL. The same pattern of cuts and testing will be preserved for comparing results for non-heat-treated and heat-treated segments. Emphasis will also be placed on selecting samples that will provide information on low-burnup ends, high-burnup portions, and grid spacers. *Note that all PNNL tests will be performed on defueled rod segments.*

1.3.1 Heating Rate, Hold Temperature, & Cooling Rates

For defueled cladding, heating rates can be higher than 10°C/hr and hold times can be shorter than eight hours (e.g., four hours) to dissolve and diffuse hydrogen. The segments will then be cooled at a rate of ≤5°C/hr until they reach 100°C at which time they may be cooled faster until reaching ambient conditions.

1.3.2 Testing Temperatures

ASTM axial tube tensile, burst, and 4-point bend tests will be conducted at room temperature and 200°C. The 200°C temperature is considered the threshold point where the cladding maintains ductility even if extensive radial-hydride precipitation is present. Mechanical properties at temperatures between room temperature and 200°C can be determined using linear interpolation.

1.4 ANL

ANL will perform RCTs on the samples sectioned from both PNNL and ORNL rods. For the half-rod-equivalent defueled-cladding samples, pre- and post-RHT (radial hydride treatment) hydrogen-content measurement and metallographic examination will be conducted, along with post-RHT metallographic examination. In addition to RCT samples from PNNL, ≤20 segments sectioned from axial locations within the fuel mid-span to the top of the uniform burnup region will be tested in the as-irradiated condition (≤8 segments) and in the post-RHT condition (≤12 segments). The pressures and corresponding hoop stresses used in the ANL 400°C-RHT will correspond to the range of rod internal pressures measured by ORNL and PNNL. Full-length segments (about 90-mm-long) sent to ANL will be from as-irradiated M5® and Zirlo® fuel rods.

2. REFERENCES

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