Post Irradiation Examination Plan for High Burnup Demonstration Project Sister Rods

Fuel Cycle Research & Development

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

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SUMMARY

This test plan describes the experimental work to be implemented by the U.S. Department of Energy (DOE) Office of Nuclear Energy (NE) to characterize high burnup (HBU) spent nuclear fuel (SNF) in conjunction with the High Burnup Dry Storage Cask Research and Development Project [1] and serves to coordinate and integrate the multi-year experimental program to collect and develop data regarding the continued storage and eventual transport of HBU (i.e., >45 GWd/MTU) SNF. The work scope involves the development, performance, technical integration, and oversight of measurements and collection of relevant data, guided by analyses and demonstration of need.

Twenty-five HBU fuel rods were extracted from seven different fuel assemblies operated at the North Anna nuclear power plant and were shipped to Oak Ridge National Laboratory (ORNL) in 2016 for detailed non-destructive examination (NDE) and destructive examination (DE). These HBU fuel rods are “sister rods” to SNF that is being placed in dry storage in a modified TN-32B cask, the *research project cask (*RCP*)*. The connotation “sister rod” indicates that these fuel rods have characteristics similar to fuel rods that will be loaded in the RPC because they have been extracted from assemblies with the same design and similar operating histories (symmetric partners) or from actual fuel assemblies that will be included in the RPC. The sister rods include four cladding types: Zirlo, M5, Zircaloy-4, and low tin Zircaloy-4. The sister rods are representative of HBU post-operation and pre-dry storage conditions.

The detailed examinations specified within this plan are intended to provide information that can be used to address the previously identified fuel rod data gaps [2] by measuring characteristic data from the sister rods and the fuel contained in the rods under actual and representative dry storage conditions. It should be noted that the existing data gaps are influenced by many variables inherent in the fuel designs, materials used, and operating conditions in the reactor. Hence, a single type of measurement or characterization activity is insufficient to close a gap by itself, but the combination of examinations and data can be used to provide confidence in the understanding of the phenomena of interest and to make informed decisions regarding gap closure with respect to mechanical performance of high burnup fuel. To address the range of environments encountered during canister loading, vacuum drying and dry storage, several rods and specimens will be heat-treated to provide both representative and fleet-bounding conditions based on thermocouple lance measurements from the RPC and analytical predictive models. The DEs are specified to provide sufficient data to allow more precise analytical predictions of pressurized water reactor (PWR) SNF performance during all conditions of transport and storage. While there are many similarities between PWR and boiling water reactor (BWR) fuel, these exams are not expected to be fully applicable to BWR SNF.

Table S-1 summarizes the identified fuel and cladding data gaps, the data to be obtained through the sister rod NDE and DE for application towards a better understanding of the characteristics of high burnup fuel, and discussion of how the data could be applied to supporting data gap closure. While the sister rod characterization program addresses the majority of the gaps in understanding HBU fuel irradiation effects, it is not expected to close all the fuel and cladding related gaps due to dry storage system configuration differences and variability in operational practices.

A summary timeline for performing the various examinations is provided in Figure S-1 based on an assumed budget allocation averaging four million dollars per year. All NDE is expected to be completed by the end of FY17, followed by optical examinations and DE (beginning in FY18). While the majority of the DE will be completed at ORNL, in FY18 selected fueled segments will be shipped to Pacific Northwest National Laboratory (PNNL) for complimentary DE and selected defueled segments will be shipped to Argonne National Laboratory for ring compression testing.

Table S- 1. Summary of Technical Gaps and the Examinations Planned for the Sister Rods

	Nondestructive examination						Destructive examination											
Existing Technical Gap	ND.01 Visual Inspection	ND.02 Gamma Scan	ND.03 Fuel Rod Length	ND.04 Eddy Current	ND.05 Profilometry	ND.05 Rod surface temperature	DE.01 Fission Gas Puncture, Pressure Measurement, Gas Analysis, and Free Volume Estimation	DE.02 Metallographic / Hydrogen Examination of Fuel and Cladding	DE.03 Clad Hydrogen Analysis (hot vacuum extraction method)	DE.04 Spiral Notch toughness	DE.05 Cyclic Bending Fatigue (CIRFT), Dynamic, Static, Shock	DE.06 SEM Examination of Fuel and Cladding	DE.07 4-point bending	DE.08 Tube tensile/Axial testing of cladding	De.09 Ring compression tests (fueled and unfueled)	DE.10 Expanded Plug Wedge	DE.11 Cladding and fuel/clad interface TEM	Application to gap closure
Stress Profiles							X			X	X		X	X	X	X		Data collected from the sister rod characterization program can be used to understand what stresses and conditions result in fuel rod failure. The data will be used in conjunction with measurements of forces and stresses imposed on the fuel rod to close the stress profiles gap with respect to the fuel.
Fuel Transfer Options										X	X		X	X	X	X		Segments will be heat treated and quenched in water. Data from these exams will be compared directly against other data collected from the sister rods that were not quenched and can be used to close this gap prior to reopening the RPC.
Drying Issues (retained water in fuel rods)	Currently being addressed through DOE IRP process. Phase III testing with the sister rods can be used to supplement if necessary.																	
Burnup Credit	Cannot be closed through the sister rod characterization program. A methodology to justify full (actinide and fission product) burnup credit for PWR SNF is provided in ISG-8, Rev 3. Issues to close this gap are with regards to BWR burnup credit which cannot be addressed with the current set of sister rods, and development of a misload analysis approach which can be addressed with modeling and simulation.																	
Cladding Hydride Reorientation and Embrittlement	X			X			X	X	X	X	X		X	X	X	X		Examinations between corresponding sister rods pre- and post-storage can be used to address this gap. The sister rods will be subjected to full length heat treatment to increase the cladding temperatures and corresponding internal pressures beyond those experienced in the RPC to address this gap.
Cladding DHC	X			X														Visual examinations between corresponding sister rods pre and post storage can be used to address this gap. Gap closure not available till after RPC cask is opened.
Cladding Creep	X		X					X										Visual examinations between corresponding sister rods pre and post storage can be used to address this gap.

Existing Technical Gap	Nondestructive examination						Destructive examination											Application to gap closure
	ND.01 Visual Inspection	ND.02 Gamma Scan	ND.03 Fuel Rod Length	ND.04 Eddy Current	ND.05 Profilometry	ND.05 Rod surface temperature	DE.01 Fission Gas Puncture, Pressure Measurement, Gas Analysis, and Free Volume Estimation	DE.02 Metallographic / Hydrogen Examination of Fuel and Cladding	DE.03 Clad Hydrogen Analysis (hot vacuum extraction method)	DE.04 Spiral Notch toughness	DE.05 Cyclic Bending Fatigue (CIRFT), Dynamic, Static, Shock	DE.06 SEM Examination of Fuel and Cladding	DE.07 4-point bending	DE.08 Tube tensile/Axial testing of cladding	De.09 Ring compression tests (fueled and unfueled)	DE.10 Expanded Plug Wedge	DE.11 Cladding and fuel/clad interface TEM	
Cladding Annealing of Radiation Damage								X		X	X	X		X				Data will be collected from a series of separate effects tests on the sister rods and compared against rods from the RPC. The RPC has been strategically loaded to assess this effect on Zirlo cladding. Gap closure not available until RPC is opened.
Fuel fragmentation small particles/ aerosols										X	X							Data will be collected from fuel rod segments breached during testing to address this gap. Aerosolized radionuclide particulates will be collected and measured to address this gap.
Fuel pellet restructuring/ swelling	This is a lower priority gap; no R&D will be performed to specifically address this gap. It is considered a secondary effect that is accounted for in the existing mechanical performance measurements. The data collected through use of actual high burnup fuel rod testing can be used to close this gap.																	
Fission product attack on cladding	This is a lower priority gap; no R&D will be performed to specifically address this gap. It is considered a secondary effect that is accounted for in the existing mechanical performance measurements. The sister rod data collected can be applied to address this gap.																	
Fuel oxidation												X						The sister rod characterization program will collect data on the oxidation behavior of the HBU rim structure. The additional data will enable confirmation of existing rate curves or the generation of new rate curves for high burnup fuel.
Cladding Emissivity changes	This is a lower priority gap that can be addressed though modeling and simulation parametric analyses. No R&D is specified in the sister rod program.																	
Cladding Metal fatigue								X						X	X	X		Cladding fatigue caused by temperature fluctuations can be evaluated through a comparison of DE between segments that have been thermally cycled segments with others that have not been cycled. This gap can be closed prior to the RPC being opened.
Cladding Oxidation	X							X		X	X		X	X	X	X		The effects of oxidation can be evaluated through measuring, analyzing, and comparing the DE results for several sister rod samples. This gap can be closed prior to the RPC being opened.

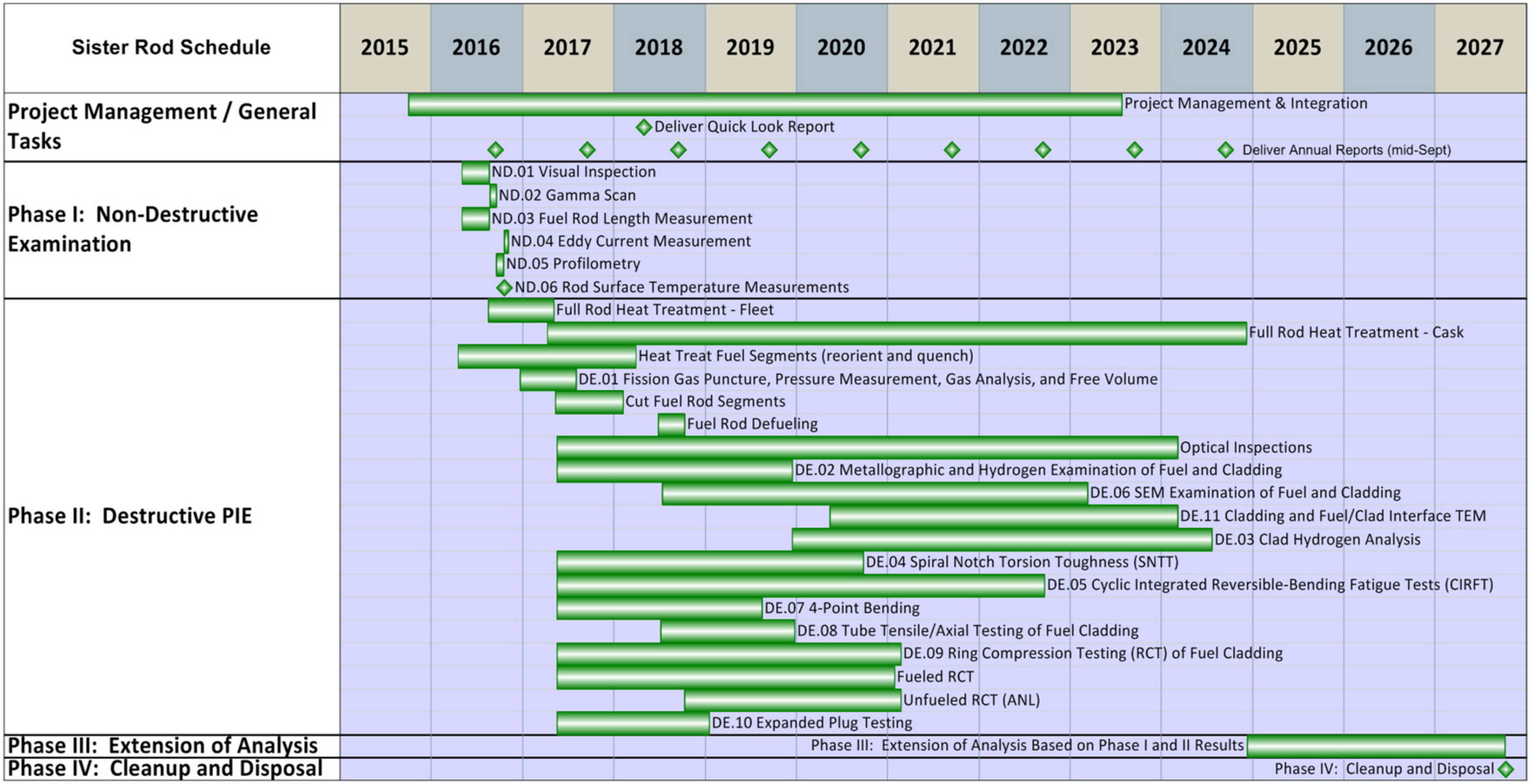

Figure S- 1. Multiyear Examination Timeline

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ACRONYMS

ADEPT	Advanced Diagnostics and Evaluation Platform
AMBW	AREVA's Advanced Mark-BW fuel design
ANL	Argonne National Laboratory
BOL	beginning of life (as-manufactured pre-irradiated condition)
BWR	boiling water reactor
CFR	Code of Federal Regulations
CH	contact handled
CIRFT	cyclic integrated reversible bending fatigue tester
DBTT	ductile to brittle transition temperature
DE	destructive examination
DOE	US Department of Energy
DOE NE	US Department of Energy Office of Nuclear Energy
DOE NR	US Department of Energy Office of Naval Reactors
EOL	end of life (condition at the final reactor discharge date)
EPRI	Electric Power Research Institute
ES&H	environmental safety and health
FCT	Fuel Cycle Technologies
FEA	finite element analysis
FEW	fuel element waste
FHT[C]	full-rod heat treatment - cask
FHT[F]	full-rod heat treatment – fleet
GWd/MTU	gigawatt days per metric ton uranium
GT	guide thimble or guide tube
HBU	high burnup
IFBA	integral fuel burnable absorber
IFEL	Irradiated Fuels Examination Laboratory
ISFSI	independent spent fuel storage installation
KIC	fracture toughness (critical value of stress intensity factor at crack tip)
KID	dynamic fracture toughness
LAMDA	Low Activation Materials Development and Analysis
LOPAR	Westinghouse's low parasitic fuel assembly design
MET	metallographic
NAIF	Westinghouse's North Anna improved fuel design
NAIF/P+Z	Westinghouse's North Anna improved fuel design (Performance+ with Zirlo)
NAPS	North Anna Nuclear Power Station
ND	nondestructive
NDE	nondestructive examination
NRC	Nuclear Regulatory Commission
NRR	NRC Office of Nuclear Reactor Regulation
NSSS	nuclear steam supply system
ORNL	Oak Ridge National Laboratory
PIE	post-irradiation examination
PNNL	Pacific Northwest National Laboratory
PWR	pressurized water reactor
R&D	research and development
RCT	ring compression test
RIP	rod internal pressure
RES	NRC Office of Nuclear Regulatory Research
RH	remote handled

RPC	research project cask
RSICC	Radiation Safety Information Computational Center
SEG	segment heat treatment with slow cooling
SEG-REWET	segment heat treatment with water quench
SEM	scanning electron microscope
SET	separate effects test
SNL	Sandia National Laboratories
SNF	spent nuclear fuel
SNTT	spiral notch torsional fracture toughness
SST	small-scale test
ST	storage and transportation
TBD	to be determined
TC	thermocouple
TEM	transmission electron microscope
TRU	transuranic
UE	uniform elongation
UFD	DOE Used Fuel Disposition Campaign
UNF-ST&DARDS	Used Nuclear Fuel-Storage, Transportation & Disposal Analysis Resource and Data System
UQ	uncertainty quantification
UTS	ultimate tensile strength
WDS	wavelength dispersive spectroscopy
WEC	Westinghouse Electric Company
YS	yield strength

POST IRRADIATION EXAMINATION PLAN FOR HIGH BURNUP DEMONSTRATION PROJECT SISTER RODS

1. INTRODUCTION

This test plan describes the experimental work to be implemented by the U.S. Department of Energy (DOE) Office of Nuclear Energy (NE) to characterize high burnup (HBU) spent nuclear fuel (SNF) in conjunction with the High Burnup Dry Storage Cask Research and Development Project [1]. This test plan serves to coordinate and integrate a multiyear experimental program for the DOE national laboratories to collect and develop data regarding the continued storage and eventual transport of HBU (i.e., >45 GWd/MTU) SNF that is being implemented under fiscal year 2016 work breakdown structure element 1.02.08.02–ST– Storage for the DOE Used Fuel Disposition Campaign (UFD). The work scope involves the development, performance, technical integration, and oversight of measurements and collection of relevant data, guided by analyses and demonstration of need.

Twenty-five HBU fuel rods were extracted from seven different SNF assemblies operated at the North Anna nuclear power plant and have been shipped to Oak Ridge National Laboratory (ORNL) in 2016 for detailed non-destructive examination (NDE) and destructive examination (DE). These HBU fuel rods are "sister rods" to SNF that is being placed in storage in a modified TN-32B cask (i.e., lid has penetrations to allow for limited monitoring inside the cask), the *research project cask* (RPC). The connotation "sister rod" indicates that these fuel rods have similar characteristics to fuel rods in the RPC because they have been extracted from assemblies with the same design and similar operating histories (symmetric partners) or from actual fuel assemblies that will be included in the RPC. The planned loading configuration for the RPC is illustrated in Figure 1.

The detailed examinations specified within this plan are intended to: (1) provide characteristics data on the physical state of the "sister rods" and the fuel contained in the rods including mechanical performance data to provide a baseline of the SNF post-operation and pre-dry storage; and (2) provide HBU fuel data from separate effects tests and small scale testing to understand the mechanical property changes that may occur to the HBU fuel and clad after it has been placed into dry storage. Similar examinations will be performed at the end of the storage period, which may be up to 10 years or longer, to identify any changes in the properties of the fuel rods that may have occurred due to dry storage.

The ultimate goal of the work described in this test plan is to describe the overall framework for obtaining and using the data needed to understand any important changes of the fuel and cladding behavior associated with HBU and long-term storage. As such, this test plan is a high-level planning document used to facilitate the necessary activities to be considered for a multiyear, multi-organizational experimental program. Because this program is expected to be on-going for a period of 10 years or more, programmatic risks must be recognized and managed, to the extent possible, with careful experiment design that includes detailed technical scrutiny, close management, and frequent communication and coordination (technical integration) among the activities. As described in the following sections, a number of the tasks are interdependent and complex. Potential opportunities or issues with unexpected results will necessitate that this test plan be updated periodically as the program matures and data and results are generated. Revisions will be required to accommodate new information such as greater clarity in cost and schedule information and/or emerging issues.

Because of the long-term nature of the test program, the issue of consistent funding is paramount. This program will use specialized facilities and staff for a long period of time, and program continuity and institutional memory will be important to maximize the information obtained. Organizations expected to play a role in this work include, but are not limited to, DOE-NE, ORNL, Pacific Northwest National Laboratory, Idaho National Laboratory (INL), and Argonne National Laboratory (ANL). Interactions are anticipated to share information with the US Nuclear Regulatory Commission (NRC) and the Electric Power Research Institute (EPRI). Other stakeholders may be added with the concurrence of the program manager.

	1 6T0 Zirlo, 54.2 GWd 4.25%, 3cy, 11yr 907 / 727 W	2 (TC Lance) 3K7 M5, 53.4 GWd 4.55%, 3cy, 8yr 983 / 749 W	3 3T6 Zirlo, 54.3 GWd 4.25%, 3cy, 11yr 909 / 729 W	4 6F2 Zirlo, 51.9 GWd 4.25%, 3cy, 13yr 793 / 653 W	DRAIN PORT
5 3F6 Zirlo, 52.1 GWd 4.25%, 3cy, 13yr 795 / 653 W	6 (TC Lance) 30A M5, 52.0 GWd 4.55%, 3cy, 6yr 1039 / 746 W	7 22B M5, 51.2 GWd 4.55%, 3cy, 5 yr 1170 / 754 W	8 20B M5, 50.5 GWd 4.55%, 3cy, 5 yr 1149 / 741 W	9 5K6 M5, 53.3 GWd 4.55%, 3cy, 8yr 977 / 745 W	10 5D5 Zirlo, 55.5 GWd 4.2%, 3cy, 17yr 806 / 668 W
11 Vent Port 5D9 Zirlo, 54.6 GWd 4.2%, 3cy, 17yr 795 / 660 W	12 28B M5, 51.0 GWd 4.55%, 3cy, 5 yr 1162 / 750 W	13 F40 Zirc-4, 50.6 GWd 3.59%, 3cy, 30yr 463 / 397 W	14 (TC Lance) 57A M5, 52.2 GWd 4.55%, 3cy, 6yr 1047 / 752 W	15 30B M5, 50.6 GWd 4.55%, 3cy, 5 yr 1152 / 744 W	16 3K4 M5, 51.8 GWd 4.55%, 3cy, 8 yr 944 / 718 W
17 5K7 M5, 53.3 GWd 4.55%, 3cy, 8yr 979 / 746 W	18 50B M5, 50.9 GWd 4.55%, 3cy, 5 yr 1159 / 747 W	19 (TC Lance) 3U9 Zirlo, 53.1 GWd 4.45%, 3cy, 10yr 918 / 724 W	20 0A4 Low-Sn Zy-4, 50 GWd 4.0%, 2cy, 22yr 641 / 541 W	21 15B M5, 51.0 GWd 4.55%, 3cy, 5 yr 1163 / 750 W	22 6K4 M5, 51.9 GWd 4.55%, 3cy, 8 yr 944 / 717 W
23 3T2 Zirlo, 55.1 GWd 4.25%, 3cy, 11yr 929 / 744 W	24 (TC Lance) 3U4 Zirlo, 52.9 GWd 4.45%, 3cy, 10yr 912 / 719 W	25 56B M5, 51.0 GWd 4.55%, 3cy, 5 yr 1161 / 749 W	26 54B M5, 51.3 GWd 4.55%, 3cy, 5 yr 1162 / 759 W	27 6V0 M5, 53.5 GWd 4.4%, 3cy, 8yrs 989 / 756 W	28 (TC Lance) 3U6 Zirlo, 53.0 GWd 4.45%, 3cy, 10yr 915 / 721 W
	29 4V4 M5, 51.2 GWd 4.40%, 3cy, 8yr 915 / 709 W	30 5K1 M5, 53.0 GWd 4.55%, 3cy, 8yr 970 / 740 W	31 (TC Lance) 5T9 Zirlo, 54.9 GWd 4.25%, 3cy, 11yr 922 / 738 W	32 4F1 Zirlo, 52.3 GWd 4.25%, 3cy, 13yr 798 / 656 W	

Notes on Figure 1:
Each square represents a basket cell with cell identifier in the upper left corner, and the identifying characteristics of the fuel assembly:

- presence of a thermocouple lance (i.e., TC Lance);
- region reference number (assembly identifier);
- cladding material;
- assembly average burnup;
- initial enrichment (^{235}U weight percent);
- number of cycles operated in the reactor;
- cooling period since discharge at the planned cask loading date; and
- utility predicted decay heat at the time of loading and at the end of a 10-year storage period.

Figure 1. Planned *Research Project Cask* Loading Pattern

1.1 OBJECTIVES

The overall technical and performance objectives of this work scope are:

(1) to ensure that the primary goal of the HBU confirmatory data project is realized by collecting data to properly characterize high burnup (>45 GWd/t) fuel rod parameters, and

(2) to support the DOE with developing and/or obtaining the scientific and technical data needed to formulate the bases to support

   a. licensing for an extended storage time (i.e., dry cask storage >20 years), and

   b. subsequent transportation of SNF that has been irradiated to HBU.

An initial data gap analysis of HBU fuel storage is documented in detail in *Gap Analysis to Support Extended Storage of Used Nuclear Fuel* [2] and will be used to aid in identifying what data are needed to accomplish these objectives.

Data needs include validation of computer codes with appropriate clad/fuel mechanical properties to be used to model SNF rod behavior under normal, off-normal, and hypothetical accident conditions as prescribed in Title 10 of the Code of Federal Regulations (CFR) Parts 71 and 72. The essential mechanical properties as a function of rod burnup, dry storage time, and exposure to temperature cycling are considered—clad ductility, modulus of elasticity, Poisson's Ratio, ultimate tensile strength (UTS), yield stress (YS), and uniform elongation (UE). Using the data on these properties, it is possible to predict the stress and strain profile on the fuel rod for a variety of loading conditions during dry storage and transport. Because the rods are subjected to vibrational loads during transportation, it is necessary to establish the fatigue strength and fracture toughness of the HBU rod, along with the effects of rod-to-rod or rod-to-basket impacts resulting from normal transport. To substantiate the expectation for normal performance, it is important to understand the role of the fuel in maintaining rod integrity. Information to be collected through the sister rod evaluations include:

- data to characterize the initial conditions of the fuel post-operation and pre-dry storage,
- measurements of mechanical properties of HBU fuel rod cladding,
- data to understand the effects of expected handling and transportation loads on mechanical performance of the composite fuel and clad system, and
- data on respirable release fractions from HBU fuel.

One primary outcome from the work described in this test plan is the empirical information on the condition of HBU fuel resulting from long-term dry storage. This information is obtained by measuring the change in mechanical properties before and after storage. The direct comparison of the sister rods before and after storage will help identify degradation (or recovery) in mechanical performance of the fuel rods as a result of being placed into dry storage, and it may identify new issues. Additionally, basic material properties will also be developed to allow for analytical prediction of the existing fleet's performance, as well as variants on the current fleet of fuel designs.

Except as required by agreements with owners of existing data, all scientific and technical information developed or obtained under this project will be made publicly available.

2. PRIMARY TASKS

Testing will be conducted over several years and delineated into separate phases:

Phase I NDE that will begin immediately after the sister rods have been delivered to ORNL;

Phase II DE to establish baseline data/information for comparison against; and for performing separate effects tests and small scale testing simulating conditions of drying and storage to understand HBU fuel storage characteristics; and

Phase III performance of follow-on analyses and testing to the Phase I and II activities to address uncertainties or anomalies in the observations or collect additional data whose need is identified during prior examinations or analysis; and

Phase IV clean-up and waste material disposal.

An initial plan for segmenting the fuel rods is provided in Appendix A. The cutting plans will be used to guide the early post-irradiation examination (PIE) planning efforts. The cutting plan specifies the location on each fuel rod of the desired specimens and their utilization in the testing, including:

- metallography/scanning electron microscope (MET/SEM) mount,
- mechanical test specimen, and
- fuel or clad radiochemical/hydrogen analysis.

Once early PIE data have been obtained (i.e., NDE), the program will review the original cutting plans and determine the changes needed prior to moving to Phase II. Additionally, the draft cut plans will aid in materials management, helping to ensure that sufficient material is available for the different programs as other programs/projects and cost sharing opportunities are identified.

Specific objectives for each phase are described in detail in the following sections.

2.1 PHASE I: NON-DESTRUCTIVE EXAMINATIONS

The Phase I PIE work will be performed in the ORNL Irradiated Fuels Examination Laboratory (IFEL) Building 3525 hot cell bank. The major emphasis of the NDE task is visual examinations of the rod external surfaces and gross dimensional measurements. Detailed procedures for the NDE work will be available prior to the performance of the examination and will be approved before use. Work will be performed in accordance with the Fuel Cycle Technologies (FCT) quality assurance plan (DOE-NE, 2010) and all work will be done under the appropriate facility environmental, safety, and health (ES&H) guidelines.

The goal of the NDE task is to experimentally verify the presence or absence of cladding degradation in the non-dry stored test fuel, and to provide characterization information for comparison with post-dry storage conditions. Observations will include:

1) Visual and dimensional inspections reporting any physical abnormalities (e.g., chemical attack, blisters, cracks, heavy or uneven oxide layers, weld failures, or clad distortions) and a digitally-created user-viewable montage of each rod;
2) gamma scanning to non-destructively
   a. obtain relative axial burnup profiles;
   b. identify any gross migration of fission products or large pellet cracks,
   c. identify any pellet stack gaps;
   d. to measure the pellet stack height; and
   e. to identify location and magnitude of any burnup depressions due to grid spacers;
3) eddy current scans to obtain information on clad mechanical macro defects; and
4) rod surface temperature measurements.

These tasks will be conducted in an order that is most efficient for the hotcell. A preliminary “quick-look” PIE report will be made available soon after the rods have been examined, but prior to complete analysis so that the destructive PIE planning can be conducted in a timely manner. A comprehensive ND PIE report will be prepared following completion of all NDE tasks.

2.1.1 NDE DELIVERABLES

Key milestones/deliverables that will be completed during the NDE phase include:

1) video and pictures of ND PIE;
2) final rod segmenting plan that incorporates the data collected from the ND PIE;
3) a preliminary ND PIE report for review; and
4) a final comprehensive ND PIE report.

The NDE results will be evaluated prior to initiating the DEs on a rod-by-rod basis. After acceptance of the Phase I results and the completion of a final cutting plan, DEs will begin.

2.2 PHASE II: DESTRUCTIVE EXAMINATIONS

The goal of the destructive PIE task is to define the mechanical properties of interest for the HBU SNF fuel/cladding and to better understand the mechanical performance of the composite fuel and clad system. These mechanical properties will vary based on cladding type, burn-up, oxide and crud layer thicknesses, hydride content and orientation, radiation damage, annealing, and temperature. Testing will include separate effects tests (SETs) and small-scale tests (SSTs). Not every rod will be subjected to the full suite of DEs; some rods will be used to perform specific kinds of tests.

The DE leverages the expertise and capabilities from multiple national laboratories for performing independent measurements of certain data/information. It is assumed that the appropriate authorizations and funding will be available to allow the supporting laboratories (i.e., ANL and PNNL) to prepare for and receive materials for identified testing. Some of the activities within this primary task are not performed routinely, but they still need to be designed for use with irradiated materials or performed in a hot cell, so they have uncertainties and risks related to cost, schedule, and measurement outcome. Close coordination will be required to ensure that all examinations follow well-documented procedures and are conducted so that resulting data can be readily combined. Hence, the DE includes activities that require detailed planning, decision making, and authorizations.

Samples will be taken as directed by the Appendix A cutting plan (as amended following NDE) from the available fuel rods. The scope of the DE may be adapted as appropriate to capitalize on potential opportunities for cost/schedule sharing with other programs.

Phase II PIE work will consist of DEs delineated into two major subtasks:

1) destructive analyses to provide baseline characteristics data for rods in the RPC for future comparisons against; and
2) destructive analyses
    a. to provide useful information for comparisons of properties after drying and storage, and
    b. to provide general SNF characteristics data for HBU fuels, including mechanical properties that can be used to expand the applicability of this data across the industry fleet of casks of higher temperatures and to support code validation and future analysis needs prior to the cask being opened.

c. This subtask area will have several categories to delineate different sets of test conditions for SET and SST.

A more detailed discussion of these activities is provided in Section 3.3.

2.2.1 DE DELIVERABLES

Key milestones/deliverables to be completed during the DE phase include:

1) annual progress reports summarizing the progress of the testing (no test results) based on milestones and schedule;
2) a report summarizing the results of each primary DE area; and
3) a final comprehensive report summarizing all NDE and DE and providing the primary conclusions reached by the study.

2.3 PHASE III: EXTENSION OF ANALYSIS BASED ON PHASE I AND PHASE II RESULTS

This test plan is designed to coordinate the implementation of a complex multiyear, multi-organization program. Numerous organizations provided input to this plan, including technical, cost, and schedule information. However, this information is not sufficiently complete to govern Phase III experimental activities, as much of the Phase III work will be identified based on data analysis and findings from the Phase I and II activities.

Therefore, task-specific planning documents containing operational details and constraints for Phase III will be developed subsequent to the approval of this document and following the majority of the Phase I and Phase II work. The Phase III program is meant to be phased and adaptive, so that examinations can be implemented to address issues quickly and to support informing program direction as new data becomes available.

These supplemental planning documents will require approval by the federal program manager prior to being implemented. As noted, the Gantt chart in Appendix B presents the elements of Phase I and II and provides an initial working schedule that will be updated and supplemented as Phase III activities are identified.

2.4 PHASE IV: CLEANUP AND DISPOSAL

During fuel testing and characterization at the different DOE national laboratories, it is anticipated that the research and development (R&D) debris wastes will be disposed of at the conclusion of various tests and as sufficient volumes of waste are generated. Each laboratory will be responsible for dispositioning the waste from their allotment of sister rod segments. The fuel element waste (FEW) will be consistent in terms of its makeup, with an expected volume of about 30 cubic feet annually of remote handled (RH)/transuranic (TRU) waste, using the same methodology for disposal as used for other site fuel debris wastes. The DOE national laboratories will dispose of their FEW as approved by specific site procedures and policies. Non-fuel secondary wastes generated in support of the project will include both RH and contact-handled (CH) solid low-level waste and will be disposed of as other similar site waste.

2.5 RESPONSIBLE ORGANIZATIONS

The DOE-NE UFD ST team is responsible for executing the work identified in this plan. The work will be performed by personnel at select DOE national laboratories.

2.6 DATA/INFORMATION TO BE OBTAINED, PRETEST PREDICTIONS, AND BOUNDARY CONDITIONS CONSIDERED

Experimental testing involves nondestructive, destructive, and mechanical examinations of SNF elements. These examinations will provide quantitative and qualitative information concerning the strength of the fuel rod. Examples of the type of information that will be obtained include in situ creep, percentage of fission gas release, internal rod pressure, oxide thickness, hydride morphology and orientation, residual cladding thickness, hydrogen content, tensile strengths, and ductility. Pretest predictions to assist in the design of the experiments and post-test verification of measurements will be performed as appropriate. The primary purpose of the predictions is to enable design and optimization of experimental configurations to ensure applicability for intended use.

A summary of the fuel rods to be examined in the UFD ST program is provided in Table 1. Additionally, Table 1 lists the cask rods paired with each sister rod for direct post-storage comparisons (designated in the column “Sister rod lattice location”). Throughout the remainder of this document the sister rods will be described using the following format XXXYYY, where XXX represents the fuel assembly ID and YYY represents the rod lattice position within the assembly as illustrated in Figure 2. Figure 2 is color-coded denoting lattice positions within an assembly where corresponding sister rods would be located relative to the same or different assemblies.

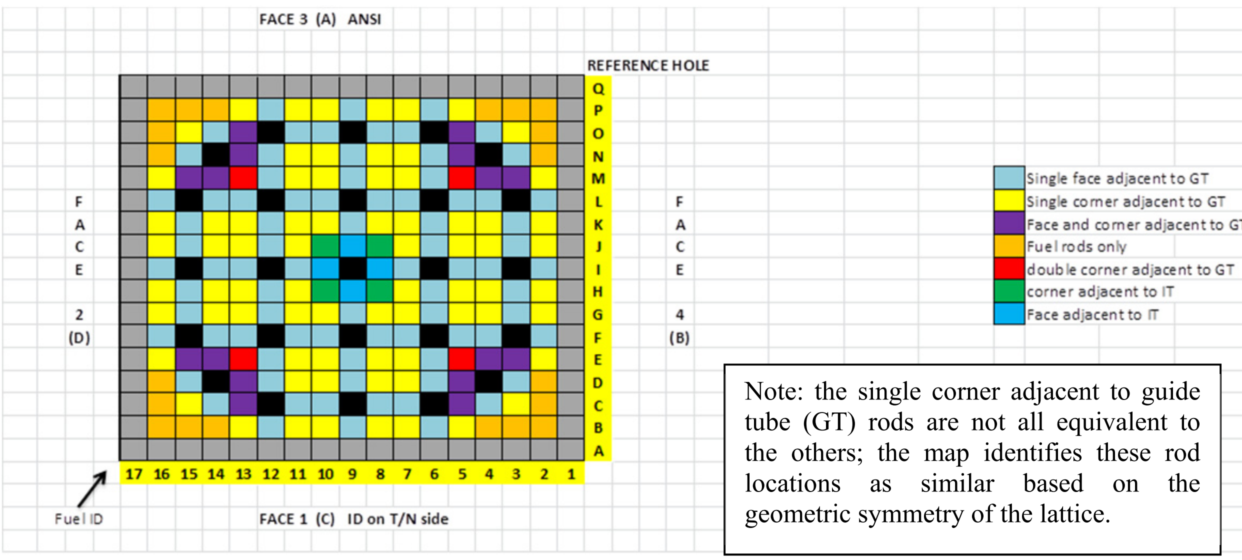


Figure 2. Fuel assembly lattice map with sister locations identified.

The draft cutting plan provided in Appendix A allocates specimens from each rod that will establish the rod average condition with respect to clad oxide layer thickness and hydride content, metallographic structure and fuel condition and structure. For higher priority selected examinations, both pre- and post-mechanical DE includes examinations of total hydrogen content, hydride density, and orientation, as these can be highly variable along the length of the rod and can have a profound impact on the examination results. This is particularly important for heat-treated specimens. For dynamic DE performed with fueled segments, the experiment will be designed to allow for collection of aerosolized radionuclides released on fracture.

Phase II DEs include the collection and evaluation of two major sets of information: baseline characteristics data (T0), and post-drying data prior to opening the cask (T1). The SNF rods are grouped into several categories to delineate different sets of boundary conditions for SETs and SSTs:

- T0 – SNF rods corresponding to the beginning-of-test condition of the fuel being loaded into the dry storage cask at the time prior to drying and being placed on the independent spent fuel storage installation (ISFSI). This is essential data that provide a baseline set of information about HBU SNF prior to being loaded into the RPC for future comparisons.
- T1 – corresponding to the time period after the fuel has undergone drying and helium backfill. This data will allow an understanding of the physical changes that occur to a fuel rod during cask loading, vacuum drying, and cool-down following drying. Tests that replicate the temperatures measured in the RPC will be used to generate data for comparisons against T0 and T1 data to provide an understanding of the mechanical properties changes (or recovery) that occur to the SNF during drying that influence the progression of rod cladding behavior throughout the RPC dry storage period. In addition, the boundary conditions measured from the RPC will be expanded on to encompass predicted temperature histories of other HBU fuel in the dry storage cask fleet to provide mechanical property data for HBU fuel for use in computational models, to expand the applicability of the RPC to higher clad temperatures than will be reached in the project and to support future analysis needs. Data generated representative of this time period will be primarily from SSTs and SETs, with the following boundary conditions:Tests that replicate the conditions (e.g., temperature histories) measured in the RPC will be used to generate data for comparisons against T0 data to provide an understanding of the mechanical properties changes (or recovery) that occur to the SNF during drying that can be confirmed at the end of the RPC dry storage period. In addition, the boundary conditions measured from the RPC will be expanded on to encompass predicted temperature histories of other HBU fuel in the dry storage cask fleet to provide mechanical property data for HBU fuel for use in computational models, to expand the applicability of the RPC to higher clad temperatures than will be reached in the project and to support future analysis needs. Data generated representative of this time period will be primarily from SSTs and SETs, with the following boundary conditions:
    - full-rod heat treat [cask] (FHT[C]) – full length rods that will be thermally heat treated then stored for an extended period of time. The heat treatment will mimic thermocouple readings of the RPC over time up to a period right before transport (i.e. 10 years or longer);
    - full-rod heat treat [fleet] (FHT[F]) – full length rods that will be thermally heat treated to predicted dry storage system peak clad temperatures representative of the dry storage system fleet. Fuel rods will be held at temperature for a specified length of time (TBD), allowed to cool to steady state at ambient hot cell conditions, and then destructively evaluated;
    - Multi-use segments (SEG) – rods that will be punctured and then segmented prior to any conditioning (e.g., heat treating). Individual segments selected for heat treatment (including sealing and repressurization) are identified in Section 3.3;
    - Quenched segments (SEG-REWET) –Individual segments consisting of fueled and defueled samples that will be repressurized, heat treated, and then quenched in water. It is assumed that the quench condition tested will bound the effects of dry storage followed by placement into a pool for fuel transfer.

Data will be collected from sister rods that are stored in the RPC at the end of the dry storage period and used for direct comparisons against the T0 data to evaluate any physical changes that occur to a fuel rod during cask vacuum drying and cool-down during storage, and to confirm the applicable T1 data. These data are referred to as T10 data throughout the plan.

Table 1. Sister Rods Selected for Characterization

Clad material	Donor assembly identifier	Sister rod lattice location	Key characteristics	Planned sister rod testing boundary conditions	Cask-stored sister	
					Assembly Identifier	*Cask rod lattice location*
M5	30A	G9	Sister rod to assembly rod in assembly 57A lance position with close proximity to the peak (hottest) rod position (I-7) in the cask	FHT[C]	57A	I7
M5	30A	K9	Sister rod to assembly rod in assembly 57A lance position with close proximity to the peak (hottest) rod position (I-7) in the cask	T0	57A	I7
M5	30A	D5	D-5 & E-14 represent in-reactor rod operation next to guide tubes with (E-14) and without (D-5) burnable poisons. Because the poisons influence power output during irradiation the rods are expected to have different characteristics, even though they have burnups that are very similar	FHT[F]	57A	E14
M5	30A	E14		FHT[F]	57A	D5
M5	30A	P2	Next to core baffle region which may be susceptible to baffle jetting based on final location in core for last irradiation cycle	SEG (PNNL segments)	57A	B2
M5	5K7	P2	In its last cycle of operation, 5K7 was located near core baffle; sister rod in 3K7 is close to the canister edge that is expected to experience accelerated cooldown	Phase III	5K6 3K7 5K1	P2
M5	5K7	C5	Equivalent to the rod with peak burnup in sister assembly 5K6	SEG (PNNL segments)	5K6 3K7 5K1	5K6O13
M5	5K7	K9	Sister rod to rod with proximity to the thermocouple in assembly 3K7	SEG	5K6 3K7 5K1	3K7K9
M5	5K7	O14	Approximately average assembly burnup	Phase III	5K6 3K7 5K1	5K6C4
Zirlo	6U3	I7	This rod is the sister to 3 different fuel assemblies in the central, middle, and outer regions of the basket	T0	3U4 3U9 3U6	3U4I7 3U9I11 3U6I11
Zirlo	6U3	M9	Rod is next to a lance position	FHT[C]	3U4 3U9 3U6	E9(3U4)
Zirlo	6U3	K9	Rod is next to a lance position	FHT[C]	3U4 3U9 3U6	K9(3U9)

Table 1. Sister Rods Selected for Characterization (continued)

Clad material	Donor assembly identifier	Sister rod lattice location	Key characteristics	Planned sister rod testing boundary conditions	Cask-stored sister	
					Assembly Identifier	*Cask rod lattice location*
Zirlo	6U3	L8	Rod is next to a lance position	SEG (PNNL segments)	3U4 3U9 3U6	3U6F10
Zirlo	6U3	O5	Rod at close to the maximum predicted burnup	FHT[F]	3U4 3U9 3U6	3U4C5; 3U9O13; 3U6C13
Zirlo	6U3	M3	Rod for comparison to 3U4 near the maximum predicted burnup in middle cask basket zone	FHT[F]	3U4 3U9 3U6	3U4E3
Zirlo	6U3	P16	Rod for comparison to rod B-2 that is expected to have the fastest cooling rate in 3U6 (cask basket periphery)	SEG	3U4 3U9 3U6	3U6B2
Zirlo	3F9	N5	Rod for baseline parameters (selected based on matchup with sister assemblies)	SEG (PNNL segments)	4F1 3F6 6F2	4F1N5 3F6N5 6F2N5
Zirlo	3F9	D7	Rod having approximate average assembly burnup	SEG (PNNL segments)	4F1 3F6 6F2	4F1D7 3F6D7 6F2D7
Zirlo	3F9	P2	Rod having approximate lowest burnup in assembly and close to assembly periphery	Phase III	4F1 3F6 6F2	P2
Zirlo	3D8	E14	Rod having approximate highest burnup in assembly	FHT[F]	5D9 5D5	5D5M4 5D9N13
Zirlo	3D8	B2	Rod having close to lowest burnup in assembly (selected based on pulling restriction)	FHT[F]	5D9 5D5	5D5P16 5D9B16
Low tin Zr-4	3A1	B16	Rod having lowest burnup in assembly; close to assembly periphery	SEG	OA4	B16
Low tin Zr-4	3A1	F5	Rod having highest burnup in assembly; reasonably close to center of assembly	SEG	OA4	F5
Zr-4	F35	P17	Rod located on the assembly periphery (postulated as likely to be of most interest for science)	Phase III	None (F40)	N/A
Zr-4	F35	K13	Interior region rod for comparison against other Zirc-4 rods (interesting science but limited applicability to discharge population)	Phase III	None (F40)	N/A

3. SCIENTIFIC APPROACH AND EXAMINATION METHODS

This section describes each of the primary tasks discussed in Section 2. Subtasks and associated descriptions are also provided, and these correspond to elements listed in the program. A Gantt chart to illustrate the schedule, approximate task durations, and how the tasks fit together is included as Appendix B. The Gantt chart is subject to change as planning proceeds, for example to capitalize on unanticipated opportunities, react and overcome unforeseen difficulties, and accommodate new and/or more accurate information (e.g., greater clarity in cost and schedule information) as it becomes available.

An initial plan for segmenting the sister rods is provided in Appendix A. The cutting plans will be used to guide the early planning efforts. The preliminary cutting plan specifies the location of the desired specimens and the associated examinations (e.g., MET/SEM mount, mechanical test specimen, hydrogen analysis). Once the NDE data have been obtained, the original cutting plans will be reviewed to determine if changes are needed. In many cases, some margin has been allowed between specimens (shown as white space in the cutting diagrams) to allow refined selection to obtain desired conditions (e.g., particular burnup, overlap or avoidance of grid marks).

3.1 TEST CONDITIONS AND SAMPLE SELECTION

During Phases I and II, all examinations, with the exception of DE.09 (see Section 3.3.2), will be completed at ambient temperature and humidity, including those specimens that are heat-treated. Phase III examinations may include elevated temperature tests. Hot cell temperature and humidity should be measured and recorded for each examination per test day, or more frequently as necessary, near the location of the test activity.

3.2 PHASE I: NON-DESTRUCTIVE INTACT ROD EXAMINATIONS

After the fuel rods have been loaded into the hotcell, the rods will be examined on a rod-by-rod basis using ORNL's Advanced Diagnostics and Evaluation Platform (ADEPT). A picture of the ADEPT system with selected testing equipment is shown in Figure 3. The planned NDEs are shown in Table 2, and the following sections provide a more detailed description of the NDE tasks.

Once these examinations have been completed, a summary of the results will be reported to the UFD program office. Prior to further sample preparation, including segmentation, the data will be examined to determine if additional NDE are necessary. If deemed necessary, any additional examinations will be completed prior to any DE of the rods.

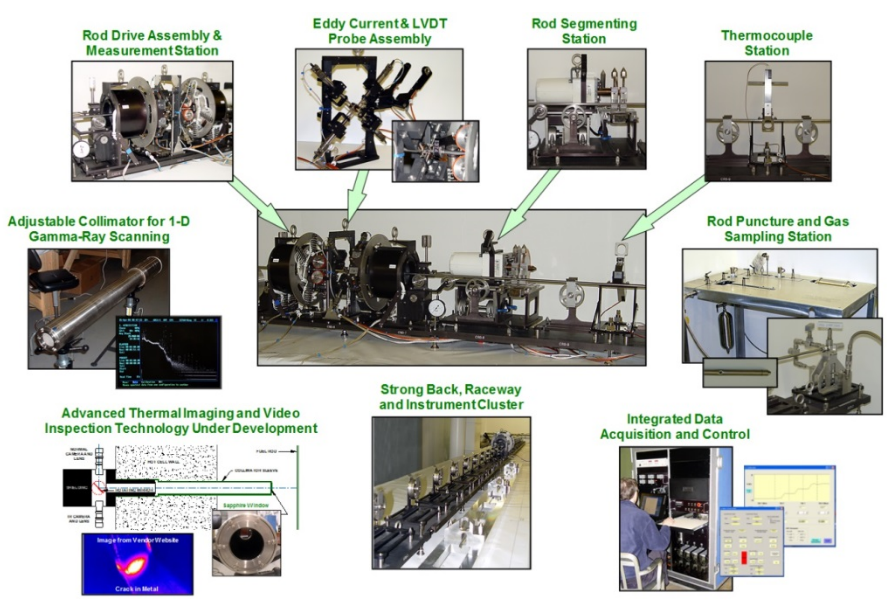


Figure 3. ORNL's ADEPT Spent Fuel Rod Handling and Measurement System, including Select Associated Equipment for Performing Testing

Table 2. Nominal Non-Destructive Examinations

Test No.	Examination	Number	Examination description
ND.01	Visual Inspection	1 per rod 25 total	Verify that the fuel rods are sound and undamaged. Note any CRUD or cladding damage/wear marks. Digitally stitch a series of photographs together to create a user viewable montage of the entire rod
ND.02	Gamma Scan	1 per rod 25 total	Measure relative activity as a function of axial position, determine pellet stack height, and note any gaps between pellets. Note flux (burnup) depressions due to grid spacers
ND.03	Fuel Rod Length Measurement	1 per rod 25 total	Measure rod length, noting the as-discharged in-reactor rod growth. This measurement provides the initial condition for later comparisons relative to cladding creep and growth
ND.04	Eddy Current Measurement	1 per rod 25 total	Note any clad flaw (cracks, holes, other anomalies).
ND.05	Profilometry	1 per rod 25 total	Measure the rod diameter as a function of axial position. Note average diameter, out-of-roundness, and any unusual features.
ND.06	Rod surface temperature measurements	5 minimum per rod 125 total	Measure the surface temperature of each rod at selected positions along the rod axis. This information is needed to confirm heat treatment simulations and provide the initial set points for the heat treatment systems.

ND.01: VISUAL INSPECTION.

This examination will be conducted by placing the fuel on the ADEPT inspection apparatus and using the device camera to view the exterior of the fuel under ambient lighting conditions. The fuel rod will be examined in a systematic manner by moving an axial region of the rod to the camera field of vision and rotating the rod so it can be photographed at all angles. This will be done all along the length of the rod so that the surface of the rod is completely imaged. A digitally-created user-viewable montage of each rod will be assembled for each rod. Regions of interest can be looked at more closely; images of regions clearly indicating damage will be forwarded to the program office. Work on the rod may be suspended until the cause of the damage is determined (i.e., spontaneous or induced during handling).

ND.02: GAMMA SCAN.

The rod will be 1D gamma scanned (resolution of ~1mm) using the ADEPT. The rod will be moved in front of a collimated detector and the activity as a function of rod length will be recorded. Three items will be of specific interest: the activity profile along the rod, the inferred fuel stack height, and the presence of any gaps or irregularities in the fuel stack. In addition, any gross migration of fission products will be noted. If any serious abnormalities are found, this information will be forwarded to the program office. Work on the rod may be suspended depending on the nature of the observed problems.

ND.03: FUEL ROD LENGTH MEASUREMENT.

The axial length of each rod will be measured using ADEPT primarily to infer irradiation growth.

ND.04: EDDY CURRENT MEASUREMENT.

The rod will undergo an eddy current scan using the general rod examination apparatus to determine and locate any macro cladding flaws. Ideally, the resolution should be sufficient to find pinhole type flaws; the actual flaw size resolution will depend on the hardware available. If any serious abnormalities are noted, this information will be forwarded to the program office. Work may be suspended on the rod depending upon the nature of the problem (e.g., accounting for ferro-magnetic interference). A limitation of this measurement is due to the requirement for a small clearance between the sensor coil and the rod;

therefore, serious rod deformations will prevent the rod from entering the coil. Thus, it may not be possible to scan some segments of a deformed rod.

ND.05: PROFILOMETRY.

Profilometry will be conducted by both axial and angular movement of the rod and will be indexed to the other non-destructive measurements. A modest clearance is required between the sensors and the rod so serious rod deformations or defects may be out of measurement range. Thus, it may not be possible to measure some segments of a deformed rod. Software reconstruction of the rod cross section may be pursued if initial measurements indicate that it is significantly out-of-round.

ND.06: ROD SURFACE TEMPERATURE MEASUREMENT.

The surface temperature axial profile of each rod will be measured at selected elevations (minimum of 5) to provide design and initial condition data for the heat treatment applications (see Section 3.3).

3.2.1 DESTRUCTIVE EXAMINATION SAMPLE PREPARATION

The samples are prepared for DE using a combination of processes including heat treatments, cutting, and defueling (selected samples). Heat treatments are applied both before (i.e., full length rods) and after segmentation and are described in Section 3.2.1.1. The segmentation process is described in Section 3.2.1.2, and draft cut diagrams with DE segments identified for each rod are provided in Appendix A. The defueling process to be used is described in Section 3.2.1.3.

It is important to note that the proposed examinations and number of samples per examination are based on the knowledge available in advance of the work; the initial examinations are expected to provide data that may inform the examinations to be completed and/or the number of specimens allocated to each test. This test plan will be revised as necessary to capture any changes.

3.2.1.1 T1 HEAT TREATMENTS TO BE APPLIED TO SELECTED RODS/SEGMENTS

As discussed in Section 1, Phase II heat treatments support the project goal to better understand the effects of temperature and time on the fuel system during dry storage, including producing data representative of the vacuum drying process (T1 data). To achieve the appropriate fuel system properties, conditions mimicking the vacuum drying process will be imposed on full length rods (FHT[F]) and pressurized rod segments (SEG). The effects of heating followed by a quench will also be investigated (SEG-REWET). Laboratory-imposed heat treatments that mimic the conditions of the RPC (FHT[C]) will also be completed to obtain HBU fuel characteristics data paralleling the stored fuel.

The following sections describe the objectives of the heat-treatments, along with the currently proposed method(s) for achieving the desired condition. Note that the heat-treatment methods are currently under investigation and these sections will be updated as the investigations are completed.

FHT[C]: FULL-ROD HEAT TREATMENT - CASK

Heating full-length rods prior to puncture preserves the as-received internal pressure and therefore provides a better method to produce the expected hoop stress distribution under actual drying conditions. Additionally, this method maximizes time and cost efficiencies and reduces uncertainties introduced regarding sample preparation for segments that would need to be individually sealed, pressurized, and heated. Table 3 summarizes the FHT[C] heat treatment application and samples.

The FHT[C] rod treatment will be prescribed based on the measurements from their corresponding TN-32B instrumented cask location. The frequency of data download will necessarily dictate the timing of the heat treatment (at least 1 download cycle of lag).

The heat-treated rods will be segmented per the Appendix A cutting plan, and selected segments will be subjected to destructive testing as specified in Section 3.3 for comparison with T0 test results. Design of the heating system is still conceptual. Considerations include multiple axial heating zones, rod-external helium atmosphere, grid conduction, adjacent rods, and cost/lifetime/maintenance of the heat-treatment equipment. Full-length heat treatment will be accomplished with the rod in a horizontal orientation. Thermocouples will be used at several rod-axial elevations to monitor the external temperature of the rods. At a minimum, three rod-axial zones of external heating will be provided. Temperatures shall be maintained to the prescribed condition within ±5°C.

Table 3. Summary of FHT[C] Heat Treatment Application and Samples

Objective:	Mimic thermocouple readings of the RPC over time up to a period right before transport (i.e. 10y or longer), including the vacuum drying cycle.
Initial Conditions:	Un-punctured, fueled
Sample size:	full length rod
Number of samples:	4 (30AG9, 6U3K9, 6U3L8, 6U3M9)
Information or benefit obtained:	Information on the state of the fuel after the storage period but immediately prior to transportation will be obtained.
	Heat treatment provides an alternative to removal of the cask rods for examination and offers an opportunity for earlier examination.
	Data are expected to support the knowledge base relative to fuel and cladding conditions and vulnerabilities prior to shipment. Additionally, examinations of the heat-treated rods can provide information on the fragility of the pellet/clad bond; thermal creep of rods in horizontal dry storage that could affect vibrational responses during shipment, and further provides data on mechanical performance properties for modeling and simulation.
Prerequisites	NDE rod prep (1 to 6); FHT[F] heat treatment concluded

FHT[F]: FULL-ROD HEAT TREATMENT – FLEET

As discussed in the FHT[C] heat treatment section, heating as full-length rods prior to puncture is preferred to best reproduce the hoop stress distribution. The FHT[F] heating will use the FHT[C] equipment to achieve bounding conditions. Best-estimate thermal calculation results are available from the Used Nuclear Fuel-Storage, Transportation & Disposal Analysis Resource and Data System (UNF-ST&DARDS) [3]; the current estimate of the bounding temperature for the fleet is 325°C. This temperature will be confirmed through additional evaluations; the selected temperature should be slightly higher than what has been currently calculated for the fleet (~10%), while providing a reasonable upper estimate on actual peak clad temperatures expected under realistic modeling conditions. The duration of these heat treatments is anticipated to be consistent with the planned RPC thermal stabilization period; after heat treatment the rods will be allowed to cool to ambient temperatures prior to initiating DE.

The heat-treated rods will be segmented per the Appendix A cutting plan, and selected segments will be subjected to destructive testing as listed in Section 3.3 for comparison with T0 test results. A summary of the FHT[F] heat treatment application and samples selected is provided in Table 4.

Table 4. Summary of FHT[F] Heat Treatment Application and Samples

Objective:	Mimic predicted dry storage system peak clad temperatures representative of the dry storage system fleet. Fuel rods will be held at temperature for two weeks.
Initial Conditions:	Un-punctured, fueled
Sample size:	full length rod

Number of samples:	6 (30AD5, 30AE14, 3D8B2, 3D8E14, 6U3O5, 6U3M3)
Information or benefit obtained:	Data on changes to rods that occur due to [simulated] drying for comparative basis and understanding will be obtained. This intermediate condition is not available from the cask rods, but it is intended to provide data for rods that experience higher temperatures than the cask rods when being placed into dry storage.
Prerequisites	NDE rod prep (1 to 6)

SEG: HEAT-TREATED SEGMENTS

Several sister rods are slated for the SEG or SEG-REWET heat treatment process; however, not all segments from those rods will be heat treated. Some segments will be maintained at the T0 condition, and others will receive the SEG or SEG-REWET heat treatment. For the initial heat treatment process, a subset of the allocated segments will be heat treated (see the cutting plan in Appendix A for a map of the segments allocated for SEG-REWET) and examined (DE.02 through DE.10). If the SEG-REWET heat treatment is found to have no effect when compared with other comparable segments, the SEG-REWET segments will be reallocated to other tests or reserved for later use. The initial subset selections are annotated in the Appendix A cutting plan.

A summary of the SEG heat treatment application and samples selected is provided in Table 5. Fuel segments will be heat treated to temperatures that are bounding for the fleet during drying (see discussion in FHT[F] heat treatment section), and/or to temperatures large enough to induce hydride reorientation, and then cooled at a slow rate (to be determined (TBD), but typically on the order of 1°C/min). Fueled segments tested will have end caps welded on and will be repressurized to the measured rod internal pressure (RIP) (DE.01). Defueled segments will use swage-locked end caps and will also be repressurized to the measured RIP. Different segments may be heat treated to different temperatures and may be cycled through the temperature range more than once (upper temperature limit of 400°C consistent with previous studies [6, 7]). The heat-treated segments will be subjected to destructive testing as listed in Section 3.3 for comparison with T0 test results. The results can also be compared to the full rod heat treatment results to validate the segmented heat treatment is an acceptable approach.

Table 5. Summary of SEG Heat Treatment Application and Samples

Objective:	Mimic predicted dry storage system peak clad temperatures representative of the dry storage system fleet. Fuel rod segments will be held at temperature for two weeks.
Initial conditions:	Punctured, segmented, fueled (segments used by ANL for ring compression tests will be defueled at ORNL prior to heat-treatment, and segments used by PNNL for mechanical property testing will be prepared/defueled at PNNL)
Sample size:	Per the individual DE to be performed, 1 to 6 inches; see cutting plan. Longer segments may be used for heat treatment and cut a second time for a more economical heat-treatment cycle.
Number of samples:	Initially 32 segments from 4 rods (may be expanded or eliminated based on initial segment test results) (6U3P16, 5K7K9, 3A1B16, 3A1F5)
Information or benefit obtained:	The heat treatment imposed is meant to bound the canister drying process for the fleet. Because the in-situ drying process associated with canister loading for dry storage imposes relatively high temperatures, the cladding in particular can undergo several changes in stress state and metallurgical conditions. The full range of mechanical tests will be performed (DE.02 to DE.11) to provide direct comparison between pre-dried (T0) and post-dried fuel (T1) using the SEG heat treated specimens.
	It should be noted that the T1 condition will not be available from RPC rods, since the cask rods won't be destructively examined at T1; thus, the SEG, SEG-REWET, and FHT[F] rods must provide the sum of information on the separate effects of drying.
Prerequisites	NDE and segmentation; end cap welding and pressurization

SEG-REWET: HEAT-TREATED AND QUENCHED SEGMENTS

Several sister rods are slated for the SEG or SEG-REWET heat treatment process; however, not all segments from those rods will be heat treated. Some segments will be maintained at the T0 condition, and others will receive the SEG or SEG-REWET heat treatment. For the initial heat treatment process, a subset of the allocated segments will be heat treated (see the cutting plan in Appendix A for a map of the segments allocated for SEG-REWET) and examined (DE.02 through DE.10). If the SEG-REWET heat treatment is found to have no effect when compared with other comparable segments, the SEG-REWET segments will be reallocated to other tests or reserved for later use. The initial subset selections are annotated in the Appendix A cutting plan.

A summary of the SEG-REWET heat treatment application and samples selected is provided in Table 6. As discussed in the SEG heat treatment section, fuel segments will be heat treated to temperatures that are bounding for the fleet during drying and may be subjected to higher temperatures and cycled to produce hydride reorientation; however, rather than cooling slowly as for the SEG heat treatment, the SEG-REWET segments will be quenched in a water bath (typical spent fuel pool temperature). The heat-treated segments will be subjected to destructive testing as listed in Section 3.3 for comparison with T0 and T1 test results.

This treatment is postulated as bounding the packaging heat/quench scenarios, including transfer of bare fuel from dry storage (e.g., at a consolidated storage facility) where the fuel is placed back into a pool before being repackaged.

Table 6 Summary of SEG-REWET Heat Treatment Application and Samples

Objective:	Mimic predicted dry storage system peak clad temperatures representative of the dry storage system fleet followed by quench (effects of being in dry storage and then placed back into a pool for fuel transfer). Fuel rod segments will be held at temperature, allowed to cool, and then quenched in water (hold times and temperatures TBD). Some of the quenched segments will also be reheated to simulate a secondary drying process that would be performed when the fuel is repackaged.
Initial conditions:	Punctured, segmented, fueled
Sample size:	As specified by the individual DE to be performed, 1 to 6 inches; see cutting plan. Longer segments may be utilized for the heat treatment and cut a second time to achieve a more economic heat-treatment cycle.
Number of samples:	Initially 32 segments from 4 rods (may be expanded or eliminated based on initial segment test results) (6U3P16, 5K7K9, 3A1B16, 3A1F5)
Information or benefit obtained:	Data on changes to the rods that occurs due to [simulated] drying followed by rewetting and re-drying for comparative basis and understanding. This test is designed to provide information to address the fuel transfer options gap. Incremental comparisons will be made on heat treated segments, heat-treated then rewet segments, and heat-treated, then rewet, then re-heat-treated to evaluate if rewetting and re-drying affects the characteristics of the cladding and composite fuel properties.
Prerequisites	NDE and sample prep, excluding heat treatment; end cap welding and pressurization; validate segmented heat treatment approach is acceptable based on data from FHT[F] samples.

3.2.1.2 ROUGH SEGMENTING

ORNL's ADEPT equipment (Figure 3) will be used to segment the rods to smaller samples for further destructive examinations (see Section 3.3). Preliminary cutting plans are provided in Appendix A, and these will be modified as necessary following the NDE. The requirements of each destructive exam (sample size, number of samples, sample conditions desired (e.g., fueled / defueled) are provided with the

DE description. The ADEPT segment cuts are considered "rough"; the specimen preparation required for most other DE will be conducted as a part of that DE.

As the rough cuts are completed all fuel segments will be mechanically marked to indicate the top of the segment, and each segment will be placed into its own sealed container marked with the segment ID (traceable to the assembly, rod, and rod axial elevation to the nearest mm). Containerized segments will be stored with other segments destined for the same DE until the facilities are ready to receive them. Fuel segments to be examined at laboratories other than will be marked and packaged this same way, and then placed into shielded storage until enough segments are collected to warrant a shipment campaign.

3.2.1.3 DEFUELING

Many of the DEs require only the cladding; therefore, the fuel must be removed from those segments without damaging the clad. The majority of the defueling will be accomplished by soaking the segments in nitric acid, as illustrated by Figure 4, and then rinsing to remove residual contaminants on the clad surface providing for a clean surface and lower dose rates.

Zircaloy clad is impervious to nitric acid and therefore will not be damaged during the hot acid defueling. The defueled clad will be routed to the appropriate laboratory for further sample preparation followed by DE. Some segments may be defueled by mechanical means, depending upon the needs of the DE activity and experimentalist.

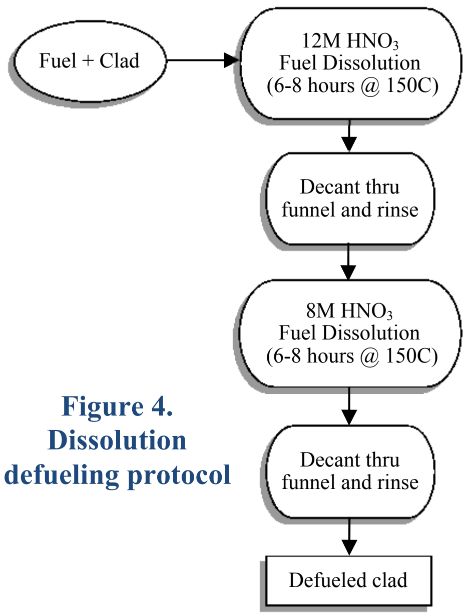


Figure 4. Dissolution defueling protocol

3.3 PHASE II: DESTRUCTIVE EXAMINATIONS

Table 7 describes and prioritizes the nominal planned DE. Prior to beginning the DE, samples of the sister rods must be prepared as described in 3.2.1. The sister rods will be segmented according to detailed cutting diagrams and in accordance with the specifications for the DE. The preliminary cutting diagrams in Appendix A will be reconsidered as the results of the NDE allow for identification and location of landmarks such as pellet/pellet interfaces, the burnup gradients, and wear marks due to in-reactor interface with the grid spacers prior to segmenting. DE will begin after acceptance of the NDE results and development of the final cutting plan (for each rod on a rod-by-rod basis).

As discussed in Section 1, Phase II DE supports three major objectives:

1) establish baseline characteristics data (T0) for later comparison with rods in the RPC;
2) produce heat-treated specimens and test to establish data representative of fuel that has gone through the vacuum drying process (T1 FHT[F] or SEG) with and without rewetting (SEG and SEG-REWET); and
3) produce heat-treated rods in the lab that mimic the conditions of the RPC (FHT[C]) to provide HBU data that is characteristic of HBU rods after storage and immediately prior transport.

The sections following Table 7 summarize each DE, including the number of specimens per test.

Table 8 provides a summary of the total number of tests planned by DE type on a rod-by-rod basis, but these are expected to evolve as the program matures. Note that not all examinations will be performed on all rods and that the DE will be conducted heuristically to determine if any changes to the planned destructive portion of the testing are needed. Hence, the desired examinations for each rod and number of specimens are subject to change as program implementation proceeds.

Other laboratories receiving fueled or defueled segments for testing include ANL and PNNL. ORNL will cut and package segments to meet the receipt requirements of the receiving laboratory. ANL cannot receive fuel and ORNL will defuel ANL segments prior to shipment; PNNL has the capability to receive fueled segments and PNNL segments will be as long as possible given the shipping container. PNNL DE is planned in a separate document, while ANL's proposed DE is included within this document.

Table 7. Nominal Destructive Examinations

Exam No.	Examination/ Operation	Examination objective (primary goal in *italics*)	Related technical gap(s) [2]	Prior -ity
DE.01	Fission gas puncture, pressure measurement, gas analysis, and free Volume estimation	*Rod Internal Pressure, gas volume and composition*	Stress profiles, cladding creep, cladding H_2 Effects: Hydride Reorientation and Embrittlement	1
DE.02	Metallographic / hydrogen examination of fuel and cladding	*Hydride structure, oxide thickness, grain size analysis, fuel radial profile, clad hydride relative density, hydride rim thickness, and orientation*	Cladding H_2 effects: hydride reorientation and embrittlement, cladding oxidation	2
DE.03	Clad hydrogen analysis (hot vacuum extraction method)	Validate and quantify the optical *total hydride content* observations (limited samples)	Total hydrogen content of clad at HBU	3
DE.04	Spiral notch toughness (SNTT)	*Fracture toughness*, interface bonding efficiency Also, Shear resistance/ modulus; Young's modulus, *DBTT in phase III*	Embrittlement, stress profiles;	4
DE.05	Cyclic bending fatigue (CIRFT) *Dynamic* *Static* *Shock*	*Fatigue life (dynamic)* Mechanical properties (static) Shock / impact effect on Fatigue life (dynamic) Also: Young's modulus, fatigue strength, S-N curve, flexural strength, interface bonding efficiency, ultimate tensile strength*, collection of fuel aerosolized particulates that are released on rupture*	Characterize the cumulative effects of extended vibration. Stress profiles, fuel fragmentation/small particles and aerosols	5
DE.06	SEM Examination of Fuel and Cladding	*Microstructure, hydride structure, Oxide thickness, grain size analysis, fuel radial profile, clad thickness*; as needed to validate other observations	Supports the characterization of the cumulative effects of extended vibration, stress Profiles, fuel fragmentation magnitude	6
DE.07	4-point bending	With and without fuel to obtain *flexural modulus, flexural stress, flexural strain* using traditional testing methods. Further validate CIRFT methods; allow for direct data comparison with other measurements and future measurements.	Stress Profiles, Fuel fragmentation – small particles/ aerosols	7
DE.08	Tube tensile/axial testing of fuel cladding	*Axial yield strength, ultimate tensile strength, uniform elongation, total elongation; calculate Young's Modulus, Poisson's ratio. Strain hardening*	Stress profiles, cladding creep, cladding H_2 Effects: Hydride Reorientation and Embrittlement	8
DE.09	Ring compression tests (fueled and unfueled)	S*tress/strain relationship; DBTT when applied as a function of temperature*. On fueled samples s*tress/strain relationship*. *Compare fueled and unfueled results*	Stress profiles, cladding creep, cladding H_2 Effects: Hydride Reorientation and Embrittlement	9
DE.10	Expanded plug wedge testing	*Circumferential stress/strain. Young's modulus, yield stress, uniform elongation, strain hardening behavior in the tangential direction.*	Hoop stress capability of SNF clad.	10
DE.11	Cladding and fuel/clad interface TEM	*Microstructure: hydride type/alignment, general defect microstructure, radiation-induced segregation*. Performed as needed to validate the underlying microstructure inherent in mechanical testing observations	Supports the characterization of the stress profiles and performance of the fuel system during storage and transport.	11

3.3.1 SAMPLE SELECTION APPROACH

The 25 sister rods were selected to provide a representative sample of materials and dry storage conditions. One of the primary objectives of the sister rod selection process was to acquire rods with a wide range of characteristics such that the attributes that result in reducing rod strength could be identified after detailed examination. For this project, all of the fuel rods were manufactured to about the same enrichment and were operated to about the same end of life (EOL) burnup. Generally, from a bird's-eye view, the sister rods and their partners in dry storage are considered to be some 8,500 rods from the same population – that is, zirconium-based alloy cladding with UO_2 fuel pellets operated in a commercial PWR starting with similar ^{235}U enrichments and ending with similar burnups. This type of population characterization is suitable to some applications, but not to all of the applications to which the data derived from the study will be applied.

However, it is well known that the final rod condition is path-dependent and rods having the same initial enrichment and final burnup may not have been subjected to the same duty in reactor. Thus, it is important to characterize not only the final configuration of the as-received sister rods, but also to understand the operating history of the rods in order to draw conclusions or construct empirical relationships for the population of HBU rods.

Within the mechanical DE, it is particularly important to describe the populations of interest and to draw an appropriate number of samples to support the objectives of the program. Too many samples may waste time, resources and money, while too few may lead to incorrect conclusions about the SNF performance. Given the limited amount of materials available, it is clear that samples must be judiciously selected to obtain sufficient applicable data to draw meaningful conclusions.

Therefore, for purposes of selecting an appropriate number of samples and characterizing the test data obtained, the material-based, design/geometry-based, and operationally-based characteristics of the sister rods as discussed in the following sections are considered. Additionally, the test type and data applications themselves are discussed as related to sample size selection. The following segment sizes are required for the various examinations:

- DE.01 (puncture), N/A;
- Optical examinations (DE.02, DE.06 and DE.11),<1.5" total (accounts for blade width on cuts);
- DE.03, 0" (very small sample taken from other samples);
- DE.04, 4" fuel in clad;
- DE.05, DE.07, DE.08, 6" fueled cladding (2 segments per set of tests for a total of 12");
- DE.09, 9.5" (total for fueled and defueled tests with included optical exam); and
- DE.10, 0.5" defueled cladding.

3.3.1.1 MATERIAL-BASED POPULATIONS

Of the 25 fuel rods provided as sister rods, 4 cladding materials are represented: M5 (9 rods), Zirlo (12 rods), Zircaloy-4 (2 rods), and low tin Zircaloy-4 (2 rods). No integral fuel burnable absorber (IFBA) rods are included. Although several of the rods came from the same assembly production batches, there is no evidence that the cladding used came from the same production lots. Thus, similarity for the rod cladding is based upon the fuel vendor's specification for the material.

All rods are fueled with UO_2 pellets with similar enrichments. Like the fuel cladding, although several assemblies were manufactured in the same production batch, there is no evidence that the pellets used came from the same production lots. Therefore, similarity for the fuel pellets must rely upon the fuel vendor's specification and acceptance criteria

3.3.1.2 DESIGN AND GEOMETRY-BASED POPULATIONS

All 12 of the Zirlo rods are the Westinghouse North Anna Improved Fuel (NAIF/P+Z) fuel assembly design; the 9 M5 rods are AREVA's Advanced Mark-BW design (AMBW); the 2 Zircaloy-4 rods are the Westinghouse low parasitic (LOPAR) fuel assembly design; and the 2 low tin Zircaloy-4 rods are the Westinghouse NAIF fuel assembly design. Thus, 16 are Westinghouse-designed and manufactured and 9 are AREVA designed and manufactured.

The AREVA M5 rods were manufactured in two different production batches. The Zirlo rods were manufactured in 3 different production batches. Both low-tin Zirc-4 rods came from the same manufacturing batch and both Zirc-4 rods came from the same manufacturing batch.

3.3.1.3 OPERATIONALLY-RELATED POPULATIONS

All sister rods have an average burnup greater than 45 GWd/MTU. Given the very small variations in beginning-of-life (BOL) enrichment from rod-to-rod, and the relatively small variations in EOL burnup, the sister rods as a collection are generally considered to be 25 samples from the same population of burnup and enrichment.

The location within the fuel assembly lattice influences the irradiation environment. Although the majority of the sister rods were operated in different lattice positions, the assembly lattice positions themselves can be generically classified as corner rods, peripheral rods, guide tube adjacent rods, and typical rods, as illustrated in Figure 2. Using this more generic classification definition, the sister rods include: 9 rods that had a single face adjacent to a guide tube cell; 7 rods that had a face and a corner-adjacent to a guide tube cell; 6 rods that were operated in fuel rod only cells; 2 that were single-corner adjacent to a guide tube cell (considered a typical cell based on grid spring/dimple interfaces, but experienced effects from the guide tube cell); and 1 rod that was a peripheral rod (next to a corner location). It should be noted that the 6 rods labeled as fuel rod cells all came from corner-adjacent positions.

For the 12 rods slated for Phase II examination (excludes FHT[C] and reserved rods), as of January 2017, the range of cooling times is 6 to 22 years, with an average cooling time of 12 years. On average the rod decay heat is approximately 3.5 W for the 12 rods. Three rods have relatively low decay heat (3A1B16, 3A1F5, 3D8B2) and should likely be considered a separate population with respect to examination observations. The predicted axial burnup profiles for the fuel assemblies are expected to be very similar to the axial profile shown in in Figure 5 [11]. Since the axial decay heat profile generally follows the burnup profile, the decay heat as a function of elevation is considered to be consistent among the rods, as scaled by the rod's predicted decay heat.

Because each rod's burnup (and therefore decay heat) varies axially along the rod, the sister rods can each be segregated further into zones based on burnup and decay heat measurements/predictions. Per Figure 5, the burnup decay heat axial profile is fairly flat over the majority of the active fuel region, with roughly 75% of central rod region at the same burnup/decay heat value (typically 110% of the rod average value). The bottom and top ~12% of the active fuel region has a steep burnup gradient, where the exposure drops from the central rod region value to about 75% of the rod average burnup in essentially a linear fashion. The exposure/decay heat generation drops about 7% at spacer grid locations [11] putting those elevations into a separate population. Finally, the cladding in the non-fueled regions of the rods has much lower exposures than the cladding in the active fuel region, and thus must be treated as a separate population.

Axial temperature variations are also expected to occur within the RPC, with the hotter areas located in the central elevations of the RPC. Any effects of this temperature variation should be observed on the FHT[C] heat treated rods and on the cask rods (at T10). The SEG, SEG-REWET and FHT[F] rods aren't expected to be influenced by the cask axial heat variation.

Given these axial variations, the rod populations for Phase II are generally zoned for purposes of sample selection/description as illustrated in Figure 5 and the estimated amount of material available for DE in Phase II (12 rods, excluding the FHT[C] rods and rods allocated to PNNL) are:

Zone 1: high-burnup, hottest, fueled elevations; 888 inches
Zone 2: high-burnup, fueled elevations; 240 inches
Zone 3: variable lower burnup, fueled elevations; 480 inches
Zone 4: under-grid fueled elevations; 144 inches
Zone 5: unfueled elevations; 72 inches.

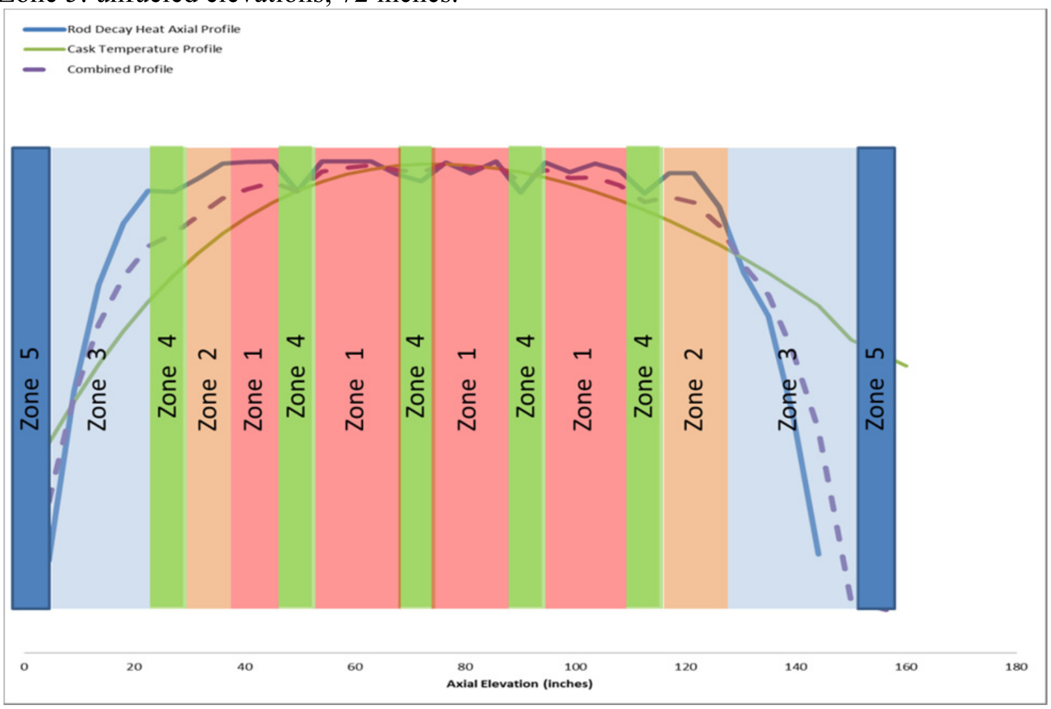


Figure 5. Predicted Axial Burnup Profile and Sample Zoning Approach for the RPC Assemblies and Inferred for the Sister Rods

3.3.1.4 HEAT TREATMENT POPULATIONS

Considering the rod materials and the heat treatments to be applied, there are twelve combinations of cladding type and heat treatment:

1. M5 T0
2. M5 FHT[F];
3. M5 SEG;
4. M5 SEG-REWET;
5. Zirlo T0;
6. Zirlo FHT[F];
7. Zirlo SEG;
8. Zirlo SEG-REWET;
9. low-tin Zirc-4 T0;
10. low-tin Zirc-4 FHT[F];
11. low-tin Zirc-4 SEG;
12. low-tin Zirc-4 SEG-REWET;

The Zirc-4 cladding is not included as the material is in reserve for Phase III or for PNNL use and the FHT[C] heat treatment rods are considered to be in reserve for Phase III as well.

3.3.1.5 TEST TYPE AND DATA APPLICATION CATEGORIES

Each of the Phase II mechanical tests can be categorized by loading/event rate, temperature range, data type, and quantity of previous data available. This information, summarized in Table 8, can be used to further guide the number of samples allocated per test.

The mechanical tests being performed fall into two categories with respect to the loading rate: quasi-static and dynamic. Dynamic testing typically results in more data scatter as a consequence of the greater number of uncertainties inherent in the event (crack propagation, for example) and the data capture rate of the instrumentation. By contrast, quasi-static test events (yield, for example) are slower, are usually section average events, and are easier to capture with accuracy and repeatability. Therefore dynamic testing usually requires more data points to substantiate a trend at a particular confidence level.

Determination of the specimen characteristics as a function of temperature requires that specimens be provided for each temperature to be tested. During Phase II, only DE.09 (defueled) tests will be temperature-dependent. To accommodate this, each DE.09 rough cut sample has been allocated sufficient material for 4 sub-samples, accommodating 4 variations on test temperature.

Data from the testing can be used in several ways:

i. descriptively to characterize the main features of the HBU performance;
ii. investigatively to discover previously unknown behavior;
iii. inferentially to test the current theories on the behavior;
iv. qualitatively to find out what happens to one variable as another is changed; and
v. quantitatively to constructing empirical relationships for the purpose of mechanistically modeling and predicting the specific relationship between variables.

Progressing from i. to v. the requirement for a larger quantity of data and for more specific data is increased. Although the combined data provided by the tests will be applied in all five areas, a primary objective of the tests is to quantify the mechanical material properties to allow modeling and prediction of its performance during storage and transport (item v. above). Additionally, a primary objective is to confirm or reject the postulated impact of bounding storage temperatures and environmental conditions (namely hydride reorientation and vibration effects) on the fuel's performance during storage and transport (item iii. above).

Table 8. Test type and data application categories

Test	Sample Test Loading Type	Temperature of sample during Phase II test	Data Application Type	Quantity of data available for decision-making (not necessarily HBU)
DE.04 SNTT	dynamic	ambient	inferential, quantitative	None
DE.05 CIRFT	dynamic	ambient	inferential, qualitative, and quantitative	32 data points (4 alloys)
DE.07 4-point bending	quasi-static	ambient	quantitative	>17 (Studsvick, JAEA)
DE.08 Axial Tension	quasi-static	ambient	quantitative	many
DE.09 RCT	dynamic and quasi-static	90 to 150°C	Inferential, qualitative, quantitative	18 data points (3 alloys, ANL)
DE.10 Expanded Plug	quasi-static	ambient	quantitative	10 data points (ORNL)

3.3.1.6 SUMMARY OF TEST POPULATIONS AND DISTRIBUTION OF MATERIAL

In order to characterize the populations described in Sections 3.3.1.1 through 3.3.1.4 efficiently, the minimal sample selection has been specified. The distribution of material has been selected primarily based on cladding material, axial zones, and the heat treatment to be applied. Dynamic quantitative tests were allocated 25% more material to accommodate the inherent larger scatter. Where it may be possible to reach conclusions based on results from an initial dataset (for inferential applications, e.g., SEG, SEG-REWET), a smaller number of test samples has been allocated as a starting point, with material reserved for addition studies if results warrant further testing. Higher priority DEs are assigned a larger amount of material based on the testing priorities established in Table 7, with priorities 1 through 6 receiving approximately 50% more material than DE priorities 7 through 11. The FHT[F] heat treated rods are assigned in this same manner; the SEG and SEG-REWET samples are taken from the four rods specifically allocated for that purpose using the same ratios for highest versus high priority tests. Table 9 provides a summary of the material allocated for the various tests (excluding those segments allocated to PNNL; see the cutting plan in Appendix A and the summary in Section 3.3.3).

Each Zone 4 region is necessarily short (grid heights on the order of 2 inches) and the majority of these regions will be reserved. However, a limited number of samples may be cut to accommodate DE.05 testing with a spacer grid region included, extending into the regions on each side of the Zone 4 region. The cutting diagrams provided in Appendix A show the axial elevations of the allocated samples.

Because there is a limited amount of material available and a statistically-based method for allocating the material cannot be used, the data observed from each test will be monitored to determine if a test can be concluded earlier based on the confidence level achieved as the work progresses. If a test can be concluded early, the material can be re-allocated to other tests as necessary. Section 3.3.1.7 discusses the proposed stopping criteria.

3.3.1.7 STOPPING CRITERIA

An objective of the sister rod test program is to determine the mean attributes (e.g., fatigue life, tensile strength, fracture toughness) of the sister rod populations of interest with a high enough confidence level to allow inferences and conclusions based on the measurements. Typically several measurements are made for each load level from a pool of like specimens to determine a mean and standard deviation for the population. In the case of the sister rods, many sub-populations within the pool of material (alloy, operational, etc) are expected. However, it is possible that the sub-populations identified have little effect on the results of the experiments; that is, as an example, it is possible that for certain tests results for M5 T0 and Zirlo T0 will be the same.

In order to ensure the best use of the material in hand, an approach to evaluating the existing data with the additional data provided by each test will be used. Bayesian (highest-density interval region of practical equivalence) or equivalent statistical-based methods will be used to continuously evaluate the state of the knowledgebase regarding each data set, and will be updated as additional data is received. As the data supports or refutes the proposed theories and/or empirical models, the number of allocated samples will be revised. Also, as enough inferential testing is obtained to make a conclusion, those tests may be discontinued and the samples reallocated to other tests.

Table 9. Number of Samples per Destructive Test Type

Rod/ test	Alloy	DE.02[a]	DE.03[b]	DE.04[b]	DE.05[b,g]	DE.06[a]	DE.07[c]	DE.08[c]	DE.09[d, f]	DE.10[d]	DE.11[e]	Heat treatment applied
6U3I7	Zirlo	7	4	5	5	7	4	3	2	3	1	None
30AK9	M5	7	4	5	5	7	4	3	2	3	1	None
6U3P16	Zirlo	2	2	1	1	2	1	1	2[j]	1	0	SEG and SEG-REWET[h]
5K7K9	M5	2	2	1	1	2	1	1	2[j]	1	0	SEG and SEG-REWET[h]
3A1B16	Low tin Zirc	2	2	1	1	2	1	1	1[j]	1	0	None, SEG and SEG-REWET[h]
3A1F5	Low tin Zirc	2	2	1	1	2	1	1	1[j]	1	0	None, SEG and SEG-REWET[h]
6U3O5	Zirlo	7	4	5	5	7	4	3	2	3	1	FHT[F]
6U3M3	Zirlo	7	4	5	5	7	4	3	2	3	1	FHT[F]
30AD5	M5	7	4	5	5	7	4	3	2	3	1	FHT[F]
30AE14	M5	7	4	5	5	7	4	3	2	3	1	FHT[F]
3D8E14	Zirlo	7	4	5	5	7	4	3	2	3	1	FHT[F]
3D8B2	Zirlo	7	4	5	5	7	4	3	2	3	1	FHT[F]
Sample size required		0.5	0	4	6	0.5	6	6	9.5	0.5	0	33
Total length used (in), SEG/SG-REWET		7	0	40	60	7	48	36	38	3	0	239
Total length used (in), FTH[F]		4	0	16	24	4	24	24	57	2	0	155
Total length used (in), T0		21	0	120	180	21	144	108	114	9	0	717
Total length used (in)		32	0	176	264	32	216	168	209	14	0	1111
Total number of samples		64	40	44	44	64	36	28	22	28	8	378

[a] Samples taken from locations spaced axially along the rod in Zones 1, 2, and 3, with one sample from Zone 4.
[b] Samples taken from Zone 1 and Zone 2, as possible.
[c] Samples taken from Zone 1, 2 and 3.
[d] Samples from all Zones.
[e] Samples paired with selected DE.04, DE.05, and DE.08.
[f] Four defueled test sub-samples are derived from each segment allocated.
[g] One static and four dynamic samples per rod allocated.
[h] Initial specimens to evaluate if the heat treatment resulted in a performance difference. If a difference is observed, additional tests may be specified using the reserved segments and/or segments from other rods.
[j] The portion of the segment allocated for defueled RCT will not be heat treated.

3.3.2 DESTRUCTIVE EXAMINATION LISTING (BY EXAM TYPE)

3.3.2.1 FISSION GAS PUNCTURE, PRESSURE MEASUREMENT, GAS ANALYSIS, AND FREE VOLUME ESTIMATION.

Objective:	Obtain the fission gas pressure, total moles of gas present, fission gas constituents, and the fuel rod free volume will be measured. The fission gas sample will be analyzed for the major fission gas isotopes (e.g., Kr and Xe). The sample will also be examined for unexpected gases.
Initial conditions:	Un-punctured, fueled; majority to be punctured in the plenum region, but at least one rod will be punctured in other axial locations to assess axial communicability of the fission gas, as possible
Sample size:	Full rod
Total number of samples:	17 (4 reserved for FHT[C]; 4 reserved for Phase III un-punctured)
Information or benefit obtained:	RIP, free volume, and fission gas composition; gas pressure to be monitored as a function of time during the puncture
Prerequisites	NDE.01 through .06; FHT[F] full rod heat treatments (5 of the 15 rods to be punctured);

The ADEPT equipment will be used for the rod puncture. The rod pressure and plenum volume measurement relies on the ideal gas law as a basis and assumes constant temperature operation; a reference volume is used as the standard and the change in pressures as volumes are valved in and out are used to compute the values of interest. The measurement uncertainty is directly related to the volume of the test fixture. A new apparatus has been proposed for the ADEPT apparatus that improves performance and provides for longer life and better selection of components. The conceptual design, shown in Figure 6, has an estimated uncertainty of 5%.

The puncture apparatus interface must be configured for the rod diameter and end plug length to provide a good seal and minimize fixture volume. Some rods may require more than one puncture, although past experience and studies indicate that there is good communication between the fuel column region and the plenum. Pressure as a function of time will be measured. Detailed drawings of the rod plenum region(s) will be needed to design and fabricate this equipment.

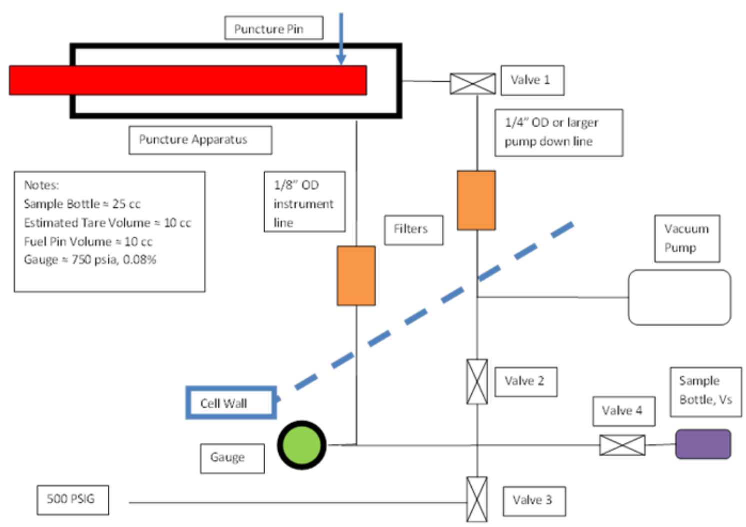


Figure 6. Rod Pressure and Free Volume Equipment Set Up

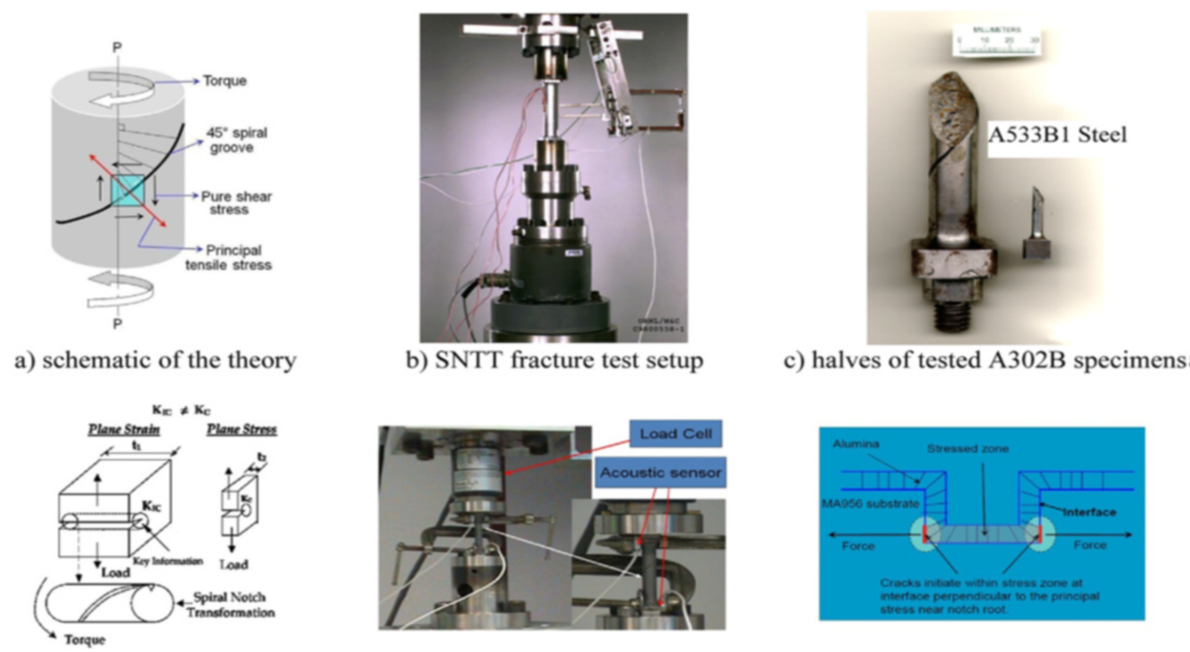
3.3.2.2 MECHANICAL TESTING

All specimens used in the mechanical testing will be characterized for hydride content and orientation via either optical methods (see Section 3.3.2.3) and/or through vacuum testing (DE.03). Where practical, the hydride content and orientation may be inferred through results from nearby samples. When indicated by the test results, additional post-test fractographic or other optical examinations (see Section 3.3.2.3) may be performed to characterize failure regions or other regions of interest.

DE.04: SPIRAL NOTCH TOUGHNESS (SNTT) TESTING.

Objective:	Measure the fracture toughness of the fuel system. Assess, as possible, the strength of the pellet-cladding bond.
Initial conditions:	Fueled segments; heat treated and as-received
Sample size:	4-inch segment
Number of samples:	44
Information or benefit obtained:	Data for simulation and prediction of fuel performance during dynamic conditions (e.g., transportation and off-normal/accident conditions).
	Data on the clad-pellet interface bonding efficiency (torsion).
	Determination of the ductile-to-brittle transition temperature (DBTT) (Phase II provides baseline performance at room temperature conditions; Phase III to provide data with temperature variation)
Prerequisites	ND.01 through ND.06; DE.00 (selected specimens), DE.01, segmentation

Fracture toughness (KIC) and dynamic fracture toughness (KID) tests will be performed using the ORNL Spiral Notch Torsion Fracture Toughness Test (SNTT) system. SNTT is a fracture toughness testing protocol that can determine Mode I (tension) fracture toughness (KIC) using small cylinder specimen. This is a significant breakthrough compared to the conventional approach in that it can be carried out with a much smaller sample. SNTT has been applied to ductile or brittle materials successfully, as well as composite materials [13]. The developed testing protocol based on SNTT methodology and equipment are illustrated in Figure 7. Previous studies showed that the principle tensile stress (opening mode) is perpendicular to the 45° spiral groove line and crack propagation is toward and perpendicular to the specimen central axis. Figure 7c provides an example of a SNTT fractured test specimen; Figure 7d compares and contrasts the SNTT specimen and loads with the traditional CT specimen; and Figure 7e and f illustrate the test setup with an example of and alumina oxide coated SNTT sample.



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

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

Figure 7. SNTT theory and test equipment

The torsion test imposes a pure torsion load to evaluate clad-pellet bonding effects on SNF system performance. The dynamic interaction between the fuel and the clad can result in significant axial shear stress as well as radial shear stress, in addition to the radial normal stress from contact impacts between fuel rods and spacer grids. To ensure the range of burnup and hydride content are sampled, several axial locations of each rod will be tested.

DE.05: CYCLIC BENDING FATIGUE (CIRFT) STATIC, DYNAMIC, AND SHOCK TESTS.

The Cyclic Integrated Reversible-Bending Fatigue Tester (CIRFT) can be used to perform both static and dynamic fatigue tests [4], and will be used to evaluate mechanical properties, fatigue lifetime, and fatigue lifetime after transient shock(s). Tests will be performed in a manner similar to the testing that has already been completed for different fuel rods [5]. The cyclic tests will be performed for a fixed amplitude and frequency to identify the number of cycles to failure. After the test, the broken surfaces (if failure occurs) can be examined using the optical methods described in Section 3.3.2.3. The magnitude and duration of transient shocks applied to the sample will based on previous transport studies (rail and roadway) and will be applied in a consistent manner, and the application site will be marked. Figure 8 provides an example of previously measured transportation shock loads.

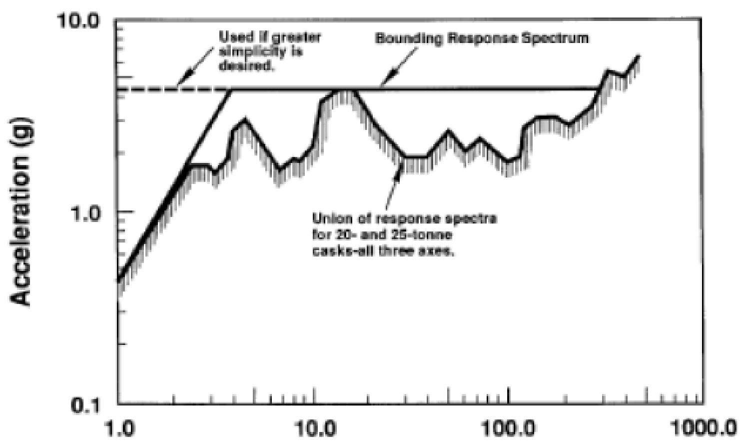


Figure 8. An example of acceleration (shock) loads during roadway transport [14]

Selected segments will be tested over multiple moment amplitude ranges. The samples will be comprised of low burnup segments from near the ends of the fuel rod, intermediate burnup segments, and HBU segments from the central region of the fuel rod. To verify assumptions about performance in regions directly under a grid region, a few segments from Zone 4 may also be tested (e.g., if grid-to-rod fretting marks are observed). To ensure the range of burnup and hydride content are sampled, several axial locations of each rod will be tested. The Phase II tests will be conducted at room temperature and the specimens will be tested to failure or stopped after reaching 10,000,000 cycles

.

Objective:	Apply static and dynamic loads to determine the mechanical properties of the test specimen and to assess the fatigue lifetime of the specimen. Apply a shock commensurate with rod-to-rod or rod-to-basket impacts and determine if there is an impact on fatigue lifetime. If fracture of the specimen occurs, collect any fuel fragments or particles released, as possible.
Initial conditions:	Fueled segments; heat treated and as-received
Sample size:	6-inch segments; one static sample (6”) per rod
Number of samples:	Nominally 44 6-inch samples allocated. Results will be compared against existing data to evaluate trends. Enough samples will be tested to provide an S-N curve indicating load to failure at a given number of cycles. However, as results are evaluated, the number of samples may be reduced.

Information or benefit obtained:	Static data will be used for simulation of SNF for storage, transport, and disposal.
	Static and dynamic data will be used for comparison with previously obtained data to compare and contrast the relative performance of the fuel system and potential failure limits for different stress modes.
	Dynamic data will be used to assess the fatigue lifetime of the fuel for application in fuel transport
	Static and dynamic data are expected to provide insight to the fuel/clad bond composite structure performance (e.g., as it influences strength following handling drops or transient shocks / vibrations).
	Static and dynamic data are expected to provide insight to the complex loading/stress conditions at the pellet-pellet interfaces.
	As possible, aerosolized radionuclides released as a result of specimen cladding breach will be used to assess the release fractions and specific activities for the contribution to the releasable source term limits for HBU fuel.
Prerequisites	ND.01 through ND.06; DE.00 (selected specimens), DE.01, segmentation

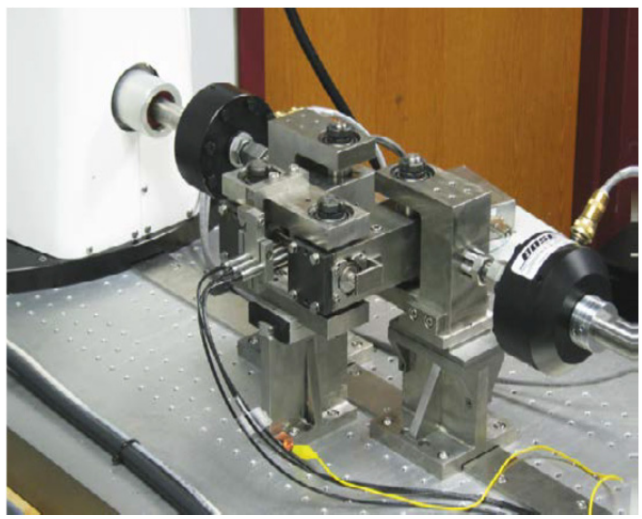


Figure 9. The cyclic integrated reversible-bending fatigue tester (CIRFT)

The CIRFT U-frame, shown in Figure 9 includes two rigid arms, connecting plates, and universal testing machine links. The rod specimen is oriented horizontally and is coupled to the rigid arms through two specially designed grips. Linear motions are applied at the loading points of the rigid arms and these are converted into pure bending moments exerted on the rod. The CIRFT can deliver dynamic loading to a rod specimen at 5 to 10 Hz. Three LVDTs measure rod deflections at three adjacent points within the gage section to determine rod curvature, which is then correlated to the applied moment to characterize the mechanical properties of the bending rod. Online monitoring can capture mechanical property changes to reveal fatigue behavior during testing. A static test is used to identify the moment and curvature at which deformation of the segment occurs and to establish the range of load amplitudes for the dynamic tests.

DE.07: 4-POINT BENDING TESTS.

The four point bending flexural test provides values for the modulus of elasticity in bending, and the flexural stress and flexural strain response, and is the test traditionally used to study brittle materials, where the number and severity of flaws exposed to the maximum stress is directly related to the flexural strength and crack initiation.

Although the information obtained from this test is redundant to other tests, it is needed to provide validation information for those other methods. The 4-point bend test is used across industries, is well understood, and is simple to perform, whereas the other mechanical tests are specific to SNF examinations. Because some of the equipment used in the SNF testing may not be available (or may need to be rebuilt) when the cask rods are retrieved, it is important to provide a test with tried and true reliability as a benchmark for the program to mitigate risk.

Objective:	Apply static loads to determine the mechanical properties of the test specimen
Initial conditions:	Fueled segment
Sample size:	6 inch
Number of samples:	36
Information or benefit obtained:	Static data will be used for simulation of SNF for storage, transport, and disposal.
	Static data will be used for comparison with data obtained using other tests methods to provide an alternate method and to provide validation.
Prerequisites	ND.01 through ND.06; DE.00 (selected specimens), DE.01, segmentation

DE.08: TUBE TENSILE/AXIAL TESTING OF FUEL CLADDING.

To ensure the range of burnup and hydride content are sampled, several axial locations of each rod will be tested. The Phase II tests will be conducted at room temperature and the specimens will be tested to failure. Post-test fractographic examination will be performed to characterize the failure regions using an electron microscope, as needed. To prevent crushing of the specimen at the load application points and to provide a solid grip on the ends, metal plugs (shown in Figure 10) will be inserted into each end of the specimen.

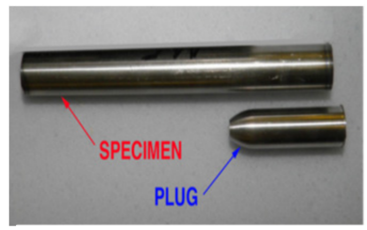


Figure 10. Tensile specimen with filler plug used to

Objective:	Measure the traditional mechanical properties of the cladding, including Young's modulus, yield strength, strain hardening, ductility and ultimate tensile strength in the axial direction.
Initial conditions:	Defueled segments; heat treated and as-received
Sample size:	6 inch
Total number of samples:	28
Information or benefit obtained:	Data will be used for simulation of SNF for storage, transport, and disposal.
	Data will be used for comparison with previously obtained data to compare and contrast the relative performance of the fuel system and potential failure limits for different stress modes.
	Data will be used to determine if the thermal environments imposed during dry storage modify the mechanical properties of the cladding
Prerequisites	ND.01 through ND.06; DE.00 (selected specimens), DE.01, segmentation, defueling

DE.09: RING COMPRESSION TESTING (FUELED AND UNFUELED).

Ring compression test (RCT) loading simulates a "pinch" type loading at grid-spacer springs and fuel-rod contact with grid spacers, with other fuel rods, and with the assembly basket walls. The sample is loaded in lateral compression (i.e., in the radial direction), inducing hoop bending stresses in the cladding. Testing of as-irradiated cladding will provide baseline data and DBTT temperature studies (20°C to 200°C). RCTs will be conducted with as-irradiated fueled and defueled cladding samples. The load-displacement curves for fueled vs. defueled cladding samples will be compared to assess the support provided by the pellet.

Although it is not necessary to test fueled samples to failure, cladding failure (through-wall crack) or partial failure may occur. Selected fueled specimens may be subjected to stepped loads to evaluate hysteresis effects, as illustrated in Figure 11. Selected post-test specimens will be examined optically (see Section 3.3.2.3) to characterize crack surfaces and the extent of radial hydride precipitation.

A RCT database will be generated for fueled cladding samples, as a comparison to defueled cladding samples, in the as-irradiated condition and in the hydride-reorientation-treated condition following cooling from peak temperatures, pressures, and hoop stresses. If the fuel provides enough support to the cladding such that cladding displacement is <<2 mm when the maximum load is reached, then additional tests with cladding containing radial hydrides may be discontinued, as the hydride orientation would no longer be relevant.

For cladding samples subjected to simulated drying temperatures, the extent of radial hydride precipitation will be characterized and RCTs will be performed to determine possible degradation in properties, especially raising of the ductile-to-brittle transition temperature (DBTT), due to radial hydrides. Optical microscopy will be used to determine the extent of radial hydride precipitation and post-RCT cracking. A Finite Element Analysis (FEA) model, which has already been developed and benchmarked, will be used to determine failure stresses and strains in response to RCT hoop loading.

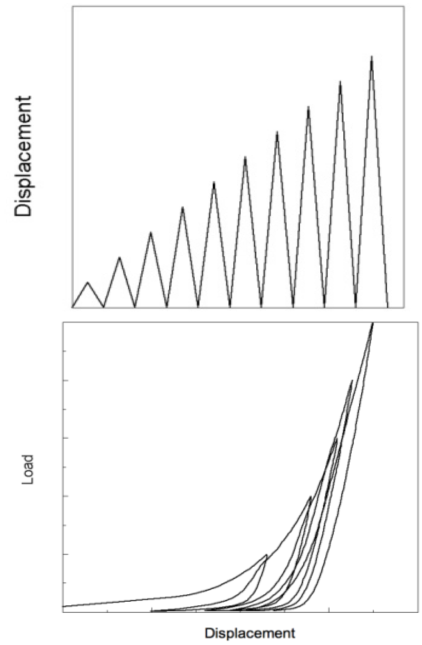


Figure 11. Stepped Loading to Evaluate Hysteresis

RCT of defueled specimens will be performed at ANL in a similar manner to previous RCT [6]. Three and a half inch segments will be defueled at ORNL and shipped to ANL. The segments for the defueled RCT will be further segmented according to Figure 12. Hence, for each three-and-a-half inch segment of cladding, ANL will perform three DE.03, one DE.02, and four DE.09 tests.

RCT with fueled segments is planned to be performed at ORNL. To perform comparable fueled RCT that can be directly compared to the defueled RCT, six-inch fueled rod segments adjacent to the ANL defueled segments will be used. Segments for the fueled RCT will be delineated according to Figure 13.

125E1: Reserved for future use (≈23 mm)
125E2: Ring-compression test sample (25 mm) (DE.09)
125E3: Ring-compression test sample (25 mm) (DE.09)
125E4: Hydrogen content sample (2 mm) (DE.02)
125E5: Met sample (4 mm) (DE.02)
125E6: Ring-compression test sample (25 mm) (DE.09)
125E7: Ring-compression test sample (25 mm) (DE.09)
125E8: Reserved for future use (≈23 mm)

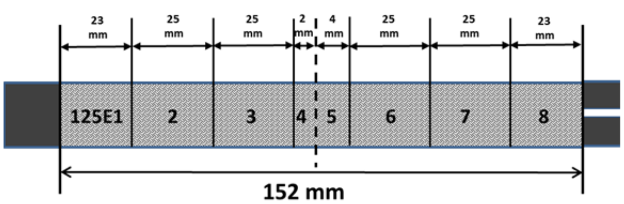


Figure 13. Cutting Diagram for Fueled RCT Rough Cut Segment

105E1: Reserved for future use (≈18 mm)
105E2: Hydrogen content sample (2 mm) (DE.03)
105E3: Ring-compression test sample (8 mm) (DE.09)
105E4: Ring-compression test sample (8 mm) (DE.09)
105E5: Hydrogen content sample (2 mm) (DE.03)
105E6: Met sample (3 mm) (DE.02)
105E7: Ring-compression test sample (8 mm) (DE.09)
105E8: Ring-compression test sample (8 mm) (DE.09)
105E9: Hydrogen content sample (2 mm) (DE.03)
105E10: Reserved for future use (≈17 mm)

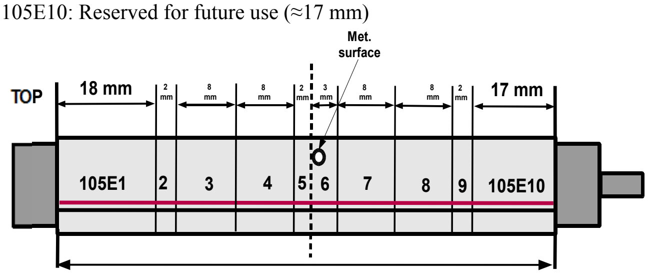


Figure 12. Cutting Diagram for Unfueled RCT Rough Cut Segments

For each six inch segment of fuel, ORNL will perform one DE.02 (MET sample), one DE.08 (hydrogen analysis), and four DE.09 (RCT with fuels) tests.

Objective:	Measure the traditional mechanical properties, including Young's modulus, yield strength, strain hardening, ductility and ultimate tensile strength in the lateral direction.
Initial conditions:	Both fueled and defueled segments; heat treated and as-received; fueled segments to be pressurized to peak RIPs based on measured values including a distribution to account for anticipated variations from sister rods to actual rods in the cask.
Sample size:	1 inch segments (cut from 9.5-inch rough cut segment, see Figures 12 and 13)
Number of samples:	20 fueled (6-in) and 24 defueled (3.5-inch)
Information or benefit obtained:	Fueled and unfueled mechanical properties supporting modeling and simulation of fuel during storage and transportation, including the hoop stress vs. plastic strain properties of the cladding materials, as well as the engineering values for YS, UTS, and UE. It is important to conduct the test with all four cladding alloys because the database is rather sparse for the temperature range of interest.
	For fueled segments subjected to simulated drying-storage, the extent of radial hydride precipitation will be characterized and RCTs will be performed to determine possible degradation in properties due to radial hydrides.
	The test may identify conditions for subsequent fracture toughness conditions (due to an increase in the DBTT induced through the heat treatments applied).
	Mechanical property data is particularly important for M5® cladding for which publicly available data are inadequate. It is also important for the other alloys because the database is rather sparse for the temperature range of interest.
Prerequisites	ND.01 through ND.06; DE.00 (selected specimens), DE.01, segmentation, defueling (selected specimens); capped and pressurized (fueled segments)

DE.10:EXPANDED PLUG WEDGE TESTING.

The test set-up with a test sample is illustrated in Figure 14. This testing will provide an effective means for determining the transverse properties of HBU SNF. This method uses an expandable plug-wedge set-up and dual pistons drivers to stretch a small ring of the clad tubing material. The specimen strain is determined using the measured diametrical expansion of the ring. An in-house developed analytical protocol is used to convert the load-circumferential strain data from the ring tests into material stress-strain curves. This newly developed testing protocol removes many complexities associated with specimen preparation and testing. The advantages are simplicity of test component assembly in the hot cell and the direct measurement of specimen strain. Currently, this method has been successfully applied to Zr-4 and M5 clad tubing materials.

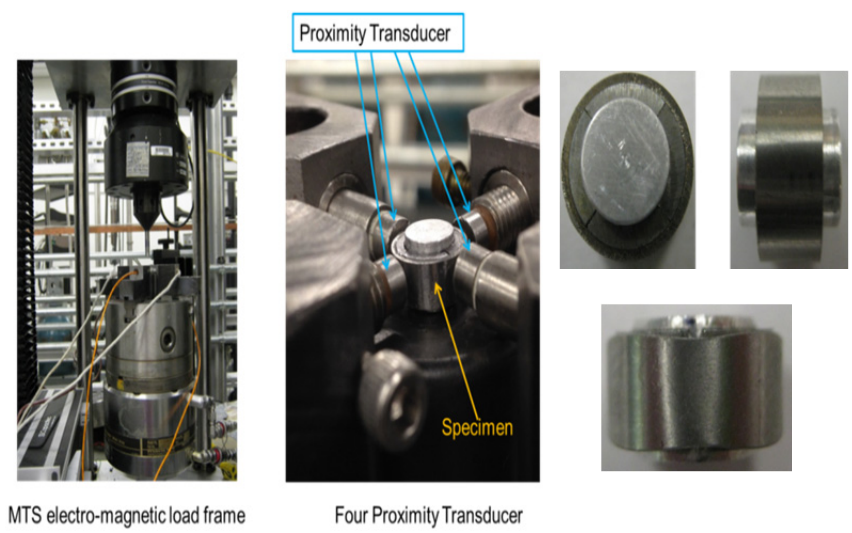


Figure 14. Expanded plug test setup with specimen shown

Objective:	Measure the tensile properties of a tubing structure in the tangential direction, i.e., hoop strength, including Young's modulus, yield stress, and strain hardening behavior.
Initial Conditions:	Defueled segments
Sample size:	0.5 inch
Number of samples:	28
Information or benefit obtained:	Understanding the various stress parameters and the associated mechanical properties, including hoop stress behavior, is important to support modeling of SNF reliability.
	Evaluation of the hoop strength with a uniaxial load application provides more definitive results than biaxial testing.
Prerequisites	ND.01 through ND.06; DE.00 (selected specimens), DE.01, segmentation, defueling

3.3.2.3 OPTICAL EXAMINATIONS

DE.02: METALLOGRAPHIC AND HYDRIDE EXAMINATION OF FUEL AND CLADDING.

Objective:	Characterize general condition of the fuel system: measure clad oxide layer thickness (external and internal), fuel/clad interactions, fuel restructuring, rim effects, and agglomerate behavior. Characterize the orientation and qualitatively quantity of hydrides present in the cladding.
Initial conditions:	Segment for planned MET specimen (see Appendix A cutting plans), rough cut, mounted, polished; or selected from mechanical testing specimen following fracture to provide additional information.
Sample size:	<0.5 inch
Number of samples:	64
Information or benefit obtained:	Provides necessary information to characterize the state of the samples and for correlating performance of the fuel system.
Prerequisites	ND.01 through ND.06; DE.00 (selected specimens), DE.01, segmentation

Metallographic and hydrogen mounts will be prepared, polished, and optically photographed. The mounts may also be etched to provide better resolution of the grain structure and allow analysis of the grain size.

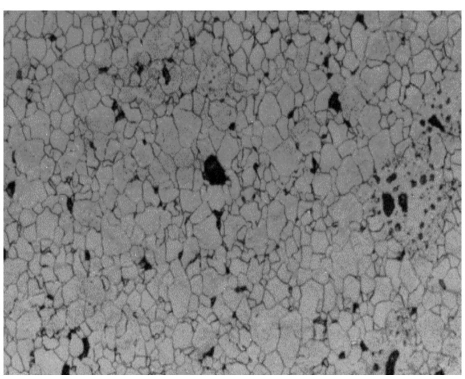


Figure 15. An example of a MET mount after etching showing the grain boundary enhancement

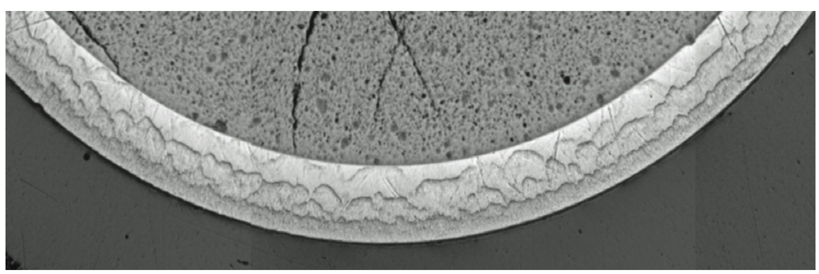


Figure 16. An example of optical hydride morphology examination with a fueled segment

DE.06: SEM EXAMINATION OF FUEL AND CLADDING.

Objective:	Characterize the general morphology of the fuel and cladding. Characterize the amount of bonding between the fuel and the cladding.
Initial conditions:	Fueled and unfueled segments
Sample size:	<0.5 inch
Number of samples:	64
Information or benefit obtained:	Provides necessary information to characterize the state of the samples and to correlate performance of the fuel system.
Prerequisites	ND.01 through ND.06; DE.00 (selected specimens), DE.01, segmentation

The general morphology of the fuel will be examined using low magnification SEM imaging. Selected rough-cut segments will be further segmented, mounted and polished for examination of pellet cracking, pellet-cladding gap and interface, fission gas bubbles, fuel restructuring and rim effects, clad oxide layer thicknesses (pellet-side and water-side), agglomerate behavior, and fission product profiles. Features of interest may be examined in detail at higher magnifications. As possible, thin mounts will be used to control radiation levels to accommodate the SEM facility allowables; size and dose restrictions may limit the size of the regions examined.

Also, SEM microprobe scans using wavelength dispersive spectroscopy (WDS) for Nd will be used to measure local burnup. Nd is a good indicator of burnup due to its low mobility in the fuel. It has been demonstrated that the local concentration of Nd increases almost linearly with local burn-up [8, 9]. However, to maximize signal to noise levels very small samples are required.

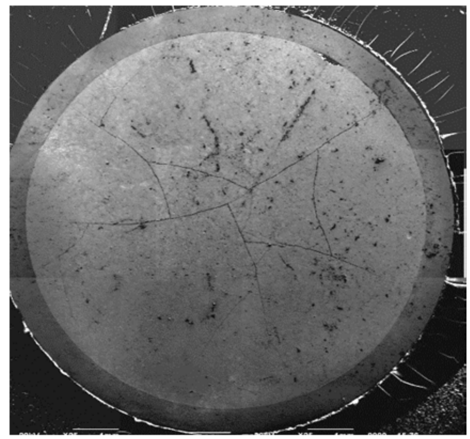


Figure 17. An example of the level of detail possible using low magnification SEM imaging

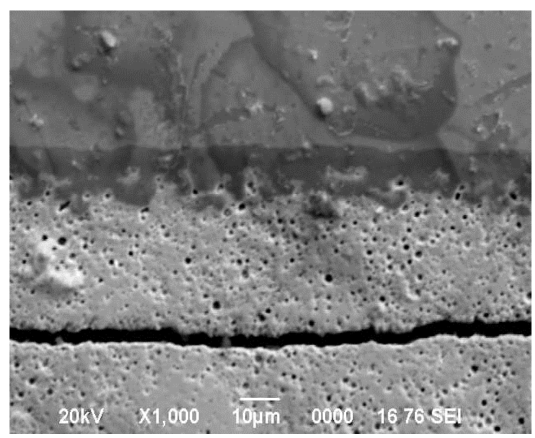


Figure 18. An example of the level of detail possible using high magnification SEM imaging

DE.11: TRANSMISSION ELECTRON MICROSCOPY (TEM).

Objective:	Characterize the general morphology of the fuel and cladding. Characterize the amount of bonding between the fuel and the cladding.
Initial conditions:	Fueled and unfueled segments
Sample size:	<<0.5 inch
Number of samples:	8
Information or benefit obtained:	Provides necessary information to characterize the state of the samples and for correlating performance of the fuel system.
Prerequisites	ND.01 through ND.06; DE.00 (selected specimens), DE.01, segmentation

The TEM is used to examine the long–term aging effects on the irradiated microstructure of the cladding and fuel/clad interface. Specific items to be examined include any changes to radiation-induced defects (a- and c-type component loops) in response to any low strain deformation, hydride development or reorientation, fuel/clad interaction, solute segregation and changes to precipitate structures. Observations with the TEM will be used in conjunction with mechanical test results to better understand how microstructural changes influence mechanical integrity. Work may include some atom probe tomography on select samples or rod conditions to complement the TEM analyses. This portion of the work will involve the Low Activation Materials Development and Analysis (LAMDA) laboratory at ORNL.

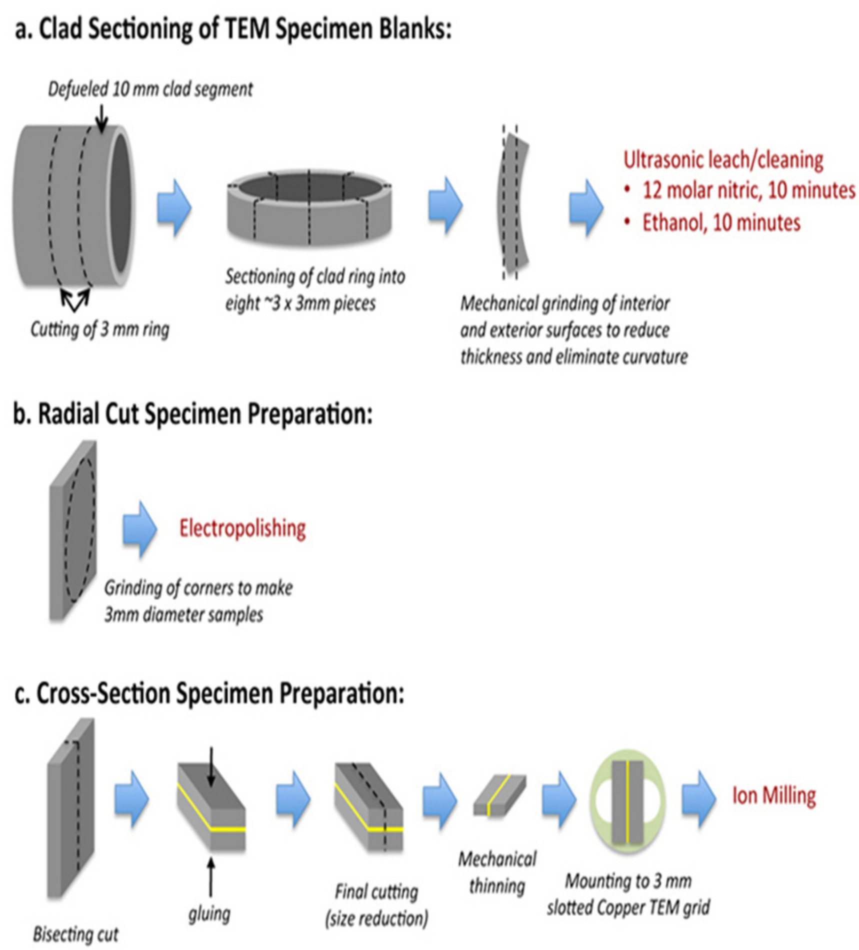


Figure 19. Sample preparation for TEM examination; includes section of the rough cut segment, mechanical thinning to remove curvature and reduce thickness, followed by mounting

3.3.2.4 CHEMICAL ANALYSIS

DE.03: CLAD HYDROGEN ANALYSIS.

Objective:	Characterize the orientation and qualitatively quantity of hydrides present in the cladding.
Initial conditions:	Defueled segments. A very small amount of material is needed and will be taken from selected mechanical test samples.
Sample size:	<<0.5 inch
Number of samples:	40
Information or benefit obtained:	Provides necessary information to characterize the state of the samples and for correlating performance of the fuel system.
Prerequisites	ND.01 through ND.06; DE.00 (selected specimens), DE.01, segmentation, defueling

The clad hydrogen content will be determined by the inert gas fusion process such as that employed by the LECO-type units. Small samples (~100mg) are heated in the analyzer, and the hydrides in the clad are vaporized and released into the analyzer's inert carrier gas. The hydrogen content in the carrier gas is determined based on thermal conductivity measurements of the gas. The uncertainty of the measurement is estimated as ±10% (µg H/g metal).

Selected defueled specimens will be analyzed using full circumference 1mm rod-axial segments, and also using azimuthal sub-sections of the 1mm rod-axial rings. The hydrogen concentration will be calibrated to the metal mass, considering the oxide layer thickness determined in DE.02. Further, the hydrogen content of many specimens will be determined after mechanical testing (e.g., tensile, burst, creep) to further verify correlations between hydrides and structural performance used in simulation models.

3.3.2.5 OTHER TESTS OR EXAMINATIONS

COLLECTION OF FUEL FRAGMENTS OR PARTICLES FOLLOWING TEST SPECIMEN CLAD FRACTURE

It is recommended that during performance of these tests, as possible, aerosolized radionuclides released upon segment breach be captured, quantified, and the particle distribution determined. This data will be used to assess the release fractions and specific activities for the contribution to the releasable source term limits for HBU fuel.

3.3.3 DESTRUCTIVE EXAMINATION LISTING (BY DONOR ASSEMBLY & SISTER ROD)

The following sections provide a summary of the testing performed in Phase II by rod.

3.3.3.1 RODS FROM DONOR FUEL ASSEMBLY 6U3

Seven sister rods were removed from assembly 6U3: 6U3I7, 6U3M9, 6U3K9, 6U3L8, 6U3O5, 6U3M3, and 6U3P16. Fuel assembly 6U3 is a Westinghouse North Anna Improved Fuel (NAIF) fuel assembly irradiated at the North Anna Power Station that will not be stored in the RPC. These SNF rods consist of Zirlo cladding and had an initial enrichment of 4.45 wt% ^{235}U. Rod 6U3I7 is of particular importance, as it will be used to provide baseline characteristics for three other fuel assemblies in the RPC that have been strategically placed in the inner (3U9), middle (3U4), and outer (3U6) zones to provide fuel rods that will have different cooling rates enabling a better understanding cladding annealing. These assemblies will also have thermocouple lances to measure the temperature distributions with respect to the different regions and rates of cooling. Phase II DE will be performed on this rod to collet T0 data.

Rods 6U3L8, 6U3O5, 6U3M3, and 6U3P16 will be examined to collect T1 data.

- Rods 6U3O5 and 6U3M3 will be heat treated to simulate peak clad temperatures predicted in the dry storage cask fleet (FHT[F]) (see Section 3.2.1.1).
- Selected Rod 6U3P16 segments will be subjected to SEG and SEG-REWET heat treatment after rod puncture for separate effects examinations.
- Rod 6U3L8 will be segmented and shipped to PNNL for complimentary mechanical properties testing.

Rods 6U3M9 and 6U3K9 will also be subjected to Phase II DE to collect T1 data.

- These rods will be heat treated to simulate the temperature measurements observed in the RPC (FHT[C]) prior to and following emplacement on the ISFSI. Measurements will be taken by thermocouple lances located in fuel assemblies 3U4 and 3U9 stored in the RPC. The duration of these heat treatments is anticipated to be a minimum of two weeks—consistent with the planned cask thermal stabilization period—and up to the end of the RPC storage period (i.e., 10 years or longer). Rod 6U3M9 will mimic the thermal couple lance reading from assembly 3U9 and Rod 6U3K9 will mimic the thermal couple lance reading from assembly 3U4. These rods are available for testing at any time after thermal stabilization of the cask to observe physical or mechanical property changes that occur to a fuel rod during cask loading, vacuum drying, and cool-down following drying. However, DE of these rods will be deferred until the RPC is made ready for transport away from the North Anna site. This would provide essential information on the state of the fuel immediately before transport for direct comparison to the sister rods in the RPC after transport.

A summary list of the DE for the rods from assembly 6U3 is provided in Table 10. Remaining portions of the rods will be available for follow on testing or made available to other programs.

Table 10. Fuel Assembly 6U3 Donor Rod Phase II Test Summary

Rod	Test/ # of samples
6U3I7	T0 condition; DE.02/7 DE.03/4 DE.04/5 DE.05/5 DE.06/7 DE.07/4 DE.08/3 DE.09/2 DE.10/3 DE.11/1
6U3O5	FHT[F]; DE.02/7 DE.03/4 DE.04/5 DE.05/5 DE.06/7 DE.07/4 DE.08/3 DE.09/2 DE.10/3 DE.11/1
6U3M3	FHT[F]; DE.02/7 DE.03/4 DE.04/5 DE.05/5 DE.06/7 DE.07/4 DE.08/3 DE.09/2 DE.10/3 DE.11/1
6U3P16	T0, SEG and SEG-REWET; DE.02/2 DE.03/2 DE.04/1 DE.05/1 DE.06/2 DE.07/1 DE.08/1 DE.09/2 DE.10/1 DE.11/0

3.3.3.2 RODS FROM DONOR FUEL ASSEMBLY 3A1

Two sister rods were removed from assembly 3A1: 3A1B16 and 3A1F5. Fuel assembly 3A1 is a Westinghouse-designed NAIF fuel assembly irradiated at the North Anna Power Station that will not be stored in the RPC. These SNF rods consist of low-tin Zr-4 cladding and had an initial enrichment of 4 wt% ^{235}U. Differences between the two sister rods are burnup and location within the assembly. Both rods will be subjected to Phase II DE to collect T0 and T1 data (SEG). Because these are the only two low-tin Zr-4 rods, rods 3A1B16 and 3A1F5 will be punctured and cut into segments for various DE to enable flexibility as testing proceeds. Some of the segments will be evaluated as-is to provide T0 data and some will be SEG heat treated. Different segments could be heat treated to different temperatures pending results of the initial tests (see Section 3.2.1.1).

A summary list of the DE for the rods from assembly 3A1 is provided in Table 11. Remaining portions of the rods will be available for follow on testing or made available to other programs.

Table 11. Fuel Assembly 3A1 Donor Rod Phase II Test Summary

Rod	Test/# of samples
3A1B16	T0, SEG and SEG-REWET; DE.02/2 DE.03/2 DE.04/1 DE.05/1 DE.06/2 DE.07/1 DE.08/1 DE.09/1 DE.10/1 DE.11/0 1
3A1F5	T0, SEG and SEG-REWET; DE.02/2 DE.03/2 DE.04/1 DE.05/1 DE.06/2 DE.07/1 DE.08/1 DE.09/1 DE.10/1 DE.11/0

3.3.3.3 RODS FROM DONOR FUEL ASSEMBLY 30A

Five sister rods were removed from assembly 30A: 30AG9, 30AK9, 30AD5, 30AE14, and 30AP2. Fuel assembly 30A is an Advanced Mark BW (AMBW) 17×17 fuel assembly irradiated at the North Anna Power Station that will be stored in the *RPC*. The SNF rods consist of M5 cladding with an initial enrichment of 4.55 wt% ^{235}U. Fuel assembly 30A is a sister fuel assembly to fuel assembly 57A that will also be stored in the *RPC*. Both fuel assemblies will be instrumented with thermocouple lances. Fuel assembly 57A is of particular importance as it is predicted to have the highest fuel clad temperature after the cask is loaded and dried. Rods 30AG9 and 30AK9 are from symmetrical locations within the assembly and are sisters to each other as well as several other rods in assembly 30A and rod 57AI7 that is next to a thermocouple lance. Rod 30AK9 will be used to provide baseline characteristics for the sister pins in assemblies 30A and 57A. Phase II DE will be performed on this rod to collet T0 data.

Rods 30AD5 and 30AE14 will be subjected to Phase II DE to collect T1 data.

- Rods 30AD5 and 30AE14 will be subjected to the FHT[F] heat treatment. Comparisons of results from these two rods are of particular interest in that they have similar end of life burnups, but they experienced different specific powers over time as rod 30AE14 was adjacent to a guide tube location that had a burnable poison rod inserted during the first cycle of irradiation and rod 30AD5 did not. The different irradiation history may result in differences in fuel and cladding characteristics. Data collected from this comparison can be used to understand if neutron spectrum and high specific powers early in life affect the fuel rod mechanical characteristics at end-of-life.
- Rod 30AP2 will be segmented and shipped to PNNL for complimentary mechanical properties testing.

Rod 30AG9 will be subjected to the FHT[C] heat treatment. This rod provides intermediate dry storage test results that can later be confirmed at the end of the *RPC* storage period. However, DE of this rod will be deferred until the *RPC* is made ready for transport away from the North Anna site. This would provide essential information on the state of the fuel immediately before transport for direct comparison to the sister rods in the *RPC* after transport.

A summary list of the DE for the rods from assembly 30A is provided in Table 12. Remaining portions of the rods will be available for follow on testing or made available to other programs.

Table 12. Fuel Assembly 30A Donor Rod Phase II Test Summary

Rod	Test/# of samples
30AK9	T0 condition; DE.02/7 DE.03/4 DE.04/5 DE.05/5 DE.06/7 DE.07/4 DE.08/3 DE.09/2 DE.10/3 DE.11/1
30AD5	FHT[F]; DE.02/7 DE.03/4 DE.04/5 DE.05/5 DE.06/7 DE.07/4 DE.08/3 DE.09/2 DE.10/3 DE.11/1
30AE14	FHT[F]; DE.02/7 DE.03/4 DE.04/5 DE.05/5 DE.06/7 DE.07/4 DE.08/3 DE.09/2 DE.10/3 DE.11/1
30AP2	Reserved for PNNL

3.3.3.4 RODS FROM DONOR FUEL ASSEMBLY 5K7

Four sister rods were removed from assembly 5K7: 5K7P2, 5K7C5, 5K7K9, and 5K7O14. Fuel assembly 5K7 is also an AREVA AMBW 17×17 fuel assembly irradiated at the North Anna Power Station that will be loaded into the *RPC*. The SNF rods consist of M5 cladding with an initial enrichment of 4.55 wt% ^{235}U. Fuel assembly 5K7 is a sister fuel assembly to fuel assemblies 5K6, 3K7, and 5K1 that will also be stored in the *RPC*.

Rods 5K7C5 and 5K7K9 will be subjected to Phase II DE to collect T1 data.

- Rod 5K7C5 will be segmented and shipped to PNNL for complimentary mechanical properties testing.
- Rod 5K7K9 will be subjected to the SEG heat treatment.

Rods 5K7O14 and 5K7P2 will be reserved for Phase III testing. They will remain in the rod box until the DE is completed and results analyzed from the other M5 clad fuel rods from assembly 30A. Individual test plans for the Phase III testing will be developed and approved by the DOE-NE UFD ST team prior to being implemented.

Table 13. Fuel Assembly 5K7 Donor Rod Test Summary

Rod	Test/# of samples
5K7P2	Reserved for Phase III
5K7C5	Reserved for PNNL
5K7K9	T0, SEG and SEG-REWET; DE.02/2 DE.03/2 DE.04/1 DE.05/1 DE.06/2 DE.07/1 DE.08/1 DE.09/2 DE.10/1 DE.11/0
5K7O14	Reserved for Phase III

3.3.3.5 RODS FROM DONOR FUEL ASSEMBLY 3F9

Three sister rods were removed from assembly 3F9: 3F9N5, 3F9D7 and 3F9P2. Fuel assembly 3F9 is a Westinghouse NAIF 17×17 fuel assembly irradiated at the North Anna Power Station that will not be loaded in the *RPC*. The SNF rods consist of Zirlo cladding and the initial enrichment of the fuel was 4.25 wt% ^{235}U. Fuel assembly 3F9 is a sister fuel assembly to fuel assemblies 3F6, 4F1, and 6F2 that will be loaded into the *RPC*. These sister assemblies will be loaded in locations on the outer periphery of the cask basket and are expected to experience some of the most rapid cooling rates following vacuum drying.

Rods 3F9N5 and half of 3F9D7 will be segmented and shipped to PNNL for complimentary mechanical properties testing. The remaining half of 3F9D7 will be subjected to SEG heat treatment.

Rod 3F9P2 will be reserved for Phase III testing. They will remain in the rod box until the DE is completed and results analyzed from the other Zirlo clad fuel rods from assemblies 6U3 and 3D8. Individual test plans for the Phase III testing will be developed and approved by the DOE-NE UFD ST team prior to being implemented.

Table 14. Fuel Assembly 3F9 Donor Rod Test Summary

Rod	Test/# of samples
3F9N5	Reserved for PNNL
3F9D7	Reserved for PNNL
3F9P2	Reserved for Phase III

3.3.3.6 RODS FROM DONOR FUEL ASSEMBLY 3D8

Two sister rods were removed from assembly 3D8: 3D8E14 and 3D8B2. Fuel assembly 3D8 is a Westinghouse NAIF 17×17 fuel assembly irradiated at the North Anna Power Station that will not be stored in the *RPC*. The SNF rods consist of Zirlo cladding and an initial enrichment of 4.2 wt% ^{235}U. Fuel assembly 3D8 is a sister assembly to fuel assemblies 5D5 and 5D9 that will be placed in the *RPC*. Both assemblies are loaded in locations on the outer periphery of the cask basket and are expected to experience some of the most rapid cooling rates following vacuum drying. Rods 3D8E14 and 3D8B2 represent the calculated highest and lowest burnup fuel rods in the assembly, respectively. Comparisons of results between these two rods should provide an indication of the sensitivity to burnup and provide insight into how the DE results can be combined statistically for trending analysis purposes.

Rods 3D8E14 and 3D8B2 will be subjected to the FHT[F] heat treatment to collect Phase II DE.

Rods 3D8E14 and 3D8B2 will be subjected to the SEG and SEG-REWET heat treatment

A summary listing of the DE for the rods from assembly 3D8 is provided in Table 15. Remaining portions of the rods will be available for follow on testing or made available to other programs.

Table 15. Fuel Assembly 3D8 Donor Rod Test Summary

Rod	Test/# of samples
3D8E14	FHT[F]; DE.02/7 DE.03/4 DE.04/5 DE.05/5 DE.06/7 DE.07/4 DE.08/3 DE.09/2 DE.10/3 DE.11/1
3D8B2	FHT[F]; DE.02/7 DE.03/4 DE.04/5 DE.05/5 DE.06/7 DE.07/4 DE.08/3 DE.09/2 DE.10/3 DE.11/1

3.3.3.7 RODS FROM DONOR FUEL ASSEMBLY F35

Two fuel rods from assembly F35: F35P17 and F35K13—were included with the sister rods for characterization purposes. Fuel assembly F35 is a Westinghouse LOPAR fuel assembly irradiated at the North Anna Power Station that will not be stored in the *RPC*. These SNF rods consist of with Zr-4 clad fuel with an initial enrichment of 3.59 wt% ^{235}U. This fuel assembly is not a sister assembly to any that will be loaded into the *RPC*, but does consist of the same cladding material and initial enrichment as fuel assembly F40 that will be stored in the *RPC*. Fuel assembly F35 was a lead test assembly irradiated in four reactor cycles to achieve high burn-up. Fuel rods from F35 were pulled during a pool-side examination campaign performed many years ago at the North Anna spent fuel pool to investigate the effects of corrosion buildup on fuel assemblies subjected to HBU levels and higher temperatures operation [10]. These rods were pulled from the bottom of the fuel assembly (the Zr-4 clad fuel assemblies at North Anna require bottom nozzle removal to extract fuel rods), some were characterized, and four remained stored in the pool. These fuel rods are not considered typical for Zr-4 clad fuel but currently available test data on HBU Zr-4 clad fuel has been from H.B. Robinson, a Westinghouse 15×15 fuel assembly design with a pellet length to diameter ratio that is close to 1.0. Typical fuel pellet length-to-diameter ratios are in excess of 1.5. Longer pellets may exert different stresses on the cladding when the pellet-pellet bonding degrades than exhibited for the H.B. Robinson fuel [5]. Hence, these rods provide material to extend the range of applicability of the existing HBU Zr-4 data to include 17×17 Zr-4 clad fuel rods with typical pellet length-to-diameter ratios.

Pending results of the Phase I examinations for rod F35P17, rods F35P17 and F35K13 are considered low priority from a DE standpoint because these Zr-4 rods are from a lead test assembly with atypical operating history and are not necessarily representative of other Zr-4 clad HBU SNF rods in the fleet. Hence, they are planned to be examined as part of the Phase III DE. Rod F35P17 is of particular interest because it is the only edge rod that was made available for characterization purposes. Rod F35K13 is an inner region rod for comparison purposes to other Zr-4 clad fuel rods.

A summary listing of the DE for the rods from assembly F35 is provided in Table 16. Remaining portions of the rods will be available for follow on testing or made available to other programs.

Table 16. Fuel Assembly F35 Donor Rod Test Summary

Rod	Test/# of samples
F35P17	Reserved for Phase III
F35K13	Reserved for Phase III

3.3.4 EXAMINATION SEQUENCE (BY YEAR)

Each laboratory will perform optical or other examinations of their specimens pre- and post-testing as necessary to characterize the test sample(s). Recognizing that this program will be ongoing for 10 or more years, the sister rod examinations have been planned under an assumed funding constraint per fiscal year. Hence, some exams that may be of high interest to be evaluated in conjunction with other exams may be deferred to be performed at a later time to be cost effective. However, allowances to address emerging issues can be made on a limited basis as needed.

Because of annual funding uncertainties the examinations will be conducted in a prioritized sequence based on obtaining the most important information first while also accounting for efficiencies in how staff and equipment are utilized (e.g., delaying the start for certain examinations so they can be performed in batches or in series). Table 17 shows an overview of the planned examinations by fiscal year. All testing will commence with Phase I NDE. These examinations will be conducted in an order that is most efficient for the hot cell and performed on all 25 rods. Prior to beginning Phase II, the fuel rod segmenting plans will be finalized by evaluating the gamma scans completed in task ND.02 to identify pellet/pellet interfaces, the burnup profile, and locations of grid spacers. Phase II DE will be initiated on 17 SNF rods that are expected to take multiple years to complete. The remaining rods will be reserved for Phase III testing and long-term heat treatment to mimic the RPC thermocouple readings. The 17 rods selected for initial DE are: 6U3I7, 30AK9, 6U3P16, 5K7K9, 3A1B16, 3A1F5, 6U3O5, 6U3M3, 30AD5, 30AE14, 3D8E14, 3D8B2, 5K7C5, 3F9N5, 30AP2, 6U3L8, and 3F9D7.

FY16 and FY17. Activities are to receive the sister rods at ORNL, perform NDE of all rods so that final cut plans can be made, design, acquire, and install full rod heat treatment capability, heat treat the FHT[F] rods (6U3O5, 6U3M3, 30AD5, 30AE14, 3D8E14, and 3D8B2) and perform fission gas puncture (DE.01) on all 17 rods. Once the ADEPT equipment is set up for DE.01, all 17 rods will be processed in sequence. Alternating between puncturing and cutting operations to support early DE is not recommended as significant costs will be incurred for equipment setup. These activities support the milestone to ship fuel and clad segments to the other laboratories in FY18. As indicated previously, three rods (6U3M9, 6U3K9, and 30AG9) will be used to mimic the thermocouple readings from the RPC. These are referred to as the FHT[C] rods, and can be placed into heat-treatment once the FHT[F] rods have been heat treated. These rods would not be put into heat treatment until after the RPC has been loaded. A process for receiving and using the RPC thermocouple measurement results over time must be established. The FHT[C] rods will be DE in conjunction with or after the Phase III testing.

FY18. Activities will be focused on fuel rod segmenting. The fuel rod rough cutting operation will be performed on a per rod basis (i.e., the entire rod will be segmented according to its respective final cut plan). Note that some segments will receive additional sectioning with a fine saw where multiple thin samples are being obtained from a single segment. Once a rod has been segmented, opportunities to pause and evaluate are available prior to initiating the cutting on the next rod. Rod cutting will begin with rods

30AK9 and 6U3I7 which will be used to provide T0 baseline data. After each of these rods is cut, some segments will be prepared and sent for optical examination to assess if there are any unexpected characteristics in the spent fuel rods so that adjustments can be made if necessary prior to segmenting the remaining rods. Rod cutting will then proceed with the remaining rods. All segmenting is planned to be completed in FY18 to support the milestone to ship segments to other laboratories. The planning basis is for ORNL to prepare three shipments in FY18—one on-site to a separate facility (i.e., building 7920) for defueling activities, one off-site to PNNL, and one off-site to ANL. The current candidate package to be used for shipping fueled segments off the ORNL reservation to PNNL is the 10-160B. Shipping the spent fuel material has certain costs associated with it, so materials from the first set of 17 rods that are planned to be shipped will be stored until complete single shipping campaigns to each destination are ready. Note that significant preparatory activities will need to be completed prior to the shipping campaigns to ANL and PNNL.

To capitalize on hot cell usage fees while the cutting operations are being performed, some DE.05 testing will be started focusing on the segments from rods 6U3I7 and 30AK9. Segments from 6U3I7 are Zirlo clad fuel, a cladding material that was previously not available for bending fatigue testing (DE.05). Hence it is important to extend the range of applicability of the cyclic fatigue test data to include Zirlo. Additionally, segments from 30AK9 are M5 clad fuel, which is a cladding material that has had limited bending fatigue testing. Both of these rods are being used to establish baseline data for future comparisons against, so in addition to filling data gaps with respect to these materials, they need to be performed early to establish a baseline for directing future DE. The baseline data are important because trends can be developed to limit the range and subsequent total number of DE.

Focus will also be on preparations for DE.05 (shock) with T1 heat treatment activities to evaluate the impacts of rewetting fuel rod segments. Segments from rods 6U3P16 and 5K7K9 will be prepared for follow-up DE. This information is high priority because it provides an understanding of the impacts of placing fuel that has been dried back into a pool. Specifically, this can support future decision making regarding facility requirements for opening the RCP. FY18 will be used for sample preparation at ORNL.

FY19. Segments should be available at ANL and PNNL to begin DE activities. These examinations will be performed continuously on sample sets such that the optical images, hydrogen content and morphology are known for each segment subjected to testing at ANL and PNNL. DE.05 tests will continue into FY19, with post-DE.05 and optical exams performed as needed. ORNL will prioritize its focus on the segments from rods 6U3P16 and 5K7K9 that were prepared in FY18 to address the rewetting issue, and then move on to examinations of other segments in a time and cost efficient manner. The order and set groupings for the other segments (i.e., non 6U3P16 and 5K7K9) will be defined and coordinated by the project manager prior to the start of work. As work progresses, a running list of Phase III follow-on activities from each laboratory needs to be maintained such that plans for providing additional material can be made in subsequent years.

FY20. Activities will be focused on continuing on-going DE activities. The DE.11 activities are deferred until this FY based on funding constraints and dependence on results of other DE to identify samples of interest. All testing will proceed at a steady rate based on allowable funding and to minimize dead-time. Minimizing dead-time is important in reducing overall program risk because staff and/or equipment resources may not be available after a lull. Hence, stopping and restarting examinations that will be continued can have significant cost impacts (replace/refurbish equipment, train new staff, etc.). By the end of FY20 ANL is expected to complete all Phase II DE.09 activities and submit recommendations for follow-on Phase III examinations.

FY21. Activities will continue at PNNL and ORNL focusing on performing mechanical testing and optical characterizations. Performance of DE.09 using fueled segments was deferred until this year as it will be used in direct comparisons to some of the DE.09 tests with unfueled segment results that needed to be developed in previous years. Testing at each laboratory will proceed at a steady rate based on allowable funding and to minimize dead-time.

FY.22. Activities will continue at PNNL and ORNL focusing on performing mechanical testing and optical characterizations. Testing at each laboratory will proceed at a steady rate based on allowable funding and to minimize dead-time. By the end of FY22 PNNL is expected to complete all Phase II activities on available material. Plans for Phase III activities will be initiated.

FY23. Activities will continue at ORNL focusing on performing mechanical testing and optical characterizations. Testing will proceed at a steady rate based on allowable funding and to minimize dead-time. In conjunction with continuing the on-going Phase II DE at ORNL, activities similar to FY18 segmenting activities will be performed for rods 5K7P2, 5K7O14, 3F9P2, F35P17, and F35K13. Final cut plans for these rods will be developed based on the Phase III needs.

FY24 and beyond. Activities at ORNL will close out the Phase II DE including performing post-test optical examinations on identified segments. Phase III activities will be started that are identified in the Phase II plan. The FHT[C] rods will continue to be heat treated at ORNL until the RPC is ready to be shipped.

The following subsections describe the specific exams that will be performed for each of the sister rods.

Table 17. Planned examination sequence

Exam	FY16	FY17	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27
NDE	X	Done	Done	Done	Done	Done	Done	Done	Done	Done	Done	Done
Sample Prep – heat treatment		X	X	X	X	X	X	X	X	X	X	X
Rod Puncture	X	X	Done	Done	Done	Done	Done	Done	Done	Done	Done	Done
Sample Prep – rod segmentation		X	X	Done	Done	Done	Done	Done	TBD	TBD	TBD	TBD
Defueling selected segments			X	X	Done	Done	Done	Done	TBD	TBD	TBD	TBD
MET / Hydrogen mount		X	X	X	X	X	X	X	TBD	TBD	TBD	TBD
Spiral Notch toughness (SNTT)		X	X	X	X	X	Done	Done	TBD	TBD	TBD	TBD
Cyclic Bending Fatigue (CIRFT) *Dynamic* *Static* *Shock*		X	X	X	X	X	X	Done	TBD	TBD	TBD	TBD
Tube tensile/Axial testing of fuel cladding			X	X	X	X	Done	Done	TBD	TBD	TBD	TBD
Expanded Plug Wedge Testing		X	X	X	X	Done	Done	Done	TBD	TBD	TBD	TBD
Ring compression testing (fueled and unfueled)		X	X	X	X	Done	Done	Done	TBD	TBD	TBD	TBD
4-point bend testing		X	X	X	X	Done	Done	Done	TBD	TBD	TBD	TBD
Vacuum total hydrogen				X	X	X	X	X	TBD	TBD	TBD	TBD
SEM		X	X	X	X	X	X	X	TBD	TBD	TBD	TBD
TEM (as needed)					X	X	X	X	TBD	TBD	TBD	TBD

3.3.5 RECOMMENDATIONS FOR POST STORAGE AND OTHER FUEL ROD COMPARISONS

To provide confidence that the small-scale testing and separate effects test examination protocols used and developed through the sister rod characterization activities (i.e., T1 data) can be applied to other cladding materials and spent fuel rods, some confirmatory examinations will need to be performed with rods extracted from the RPC. The corresponding RPC stored rods for confirmatory evaluations are identified in Table 1. Details of specific confirmatory examinations will be developed as part of the Phase III planning effort. Additionally, several other rod types are present in the spent fuel inventory that include boiling water reactor fuel rods and IFBA rods that should be examined in the future to understand if they are appropriately bounded with respect to fragility by the data generated through the sister rod characterizations program.

3.4 PHASE III: FOLLOW-ON EXAMINATIONS TO PHASE I AND PHASE II

Phase III experimental activities will be identified based on data analysis and findings from the Phase I and II activities. Therefore, subsequent to the approval of this document, task-specific planning documents containing operational details and constraints for Phase III will be developed to implement the follow on activities. These follow-on plans are meant to be phased and adaptive so that they can be implemented to address issues quickly and support informing program direction as new data is available. Current considerations for Phase III involve performing select DE (e.g., DE.04, DE.07, DE.08, DE.10) at elevated temperatures. Also, segments from the FHT[C] heat treatment will become available for testing.

3.5 PHASE IV: CLEAN UP AND MATERIAL DISPOSAL

As required by the hot cell conduct of operations, the following accompanying hot cell operations will be conducted during and/or after the PIE.

HC.01: Waste Handling. During and after the PIE, waste will be identified, segregated, and packaged for disposal. This effort will also require that the appropriate waste paths be identified and disposal documentation produced. This activity will involve both the Building 3525 hot cell and the radiochemical analysis lab.

HC.02: Spent Fuel Packaging. The portions of the fuel rods that will not be used in the PIE task will be cut to an appropriate length for disposal and packaged for handling. This task will also require the preparation of the necessary paperwork for the material transfer to another building or site. This task will be executed at the end of the PIE in case additional test specimens are need from the cut segments.

4. INDUSTRY STANDARDS, FEDERAL REGULATIONS, DOE ORDERS, REQUIREMENTS, AND ACCEPTANCE/COMPLETION CRITERIA

This section discusses applicable standards, level of accuracy of activity results, deliverable acceptance criteria, and other requirements as they apply to the work in this test plan.

4.1 STANDARDS

Applicable consensus standards that have relevance to some of the detailed activities coordinated within this test plan include:

ASTM E8 / E8M - 15a, Standard Test Methods for Tension Testing of Metallic Materials

ASTM E9-09, Standard Test Methods of Compression Testing of Metallic Materials at Room Temperature

ASTM E21 – 09, Standard Test Methods for Elevated Temperature Tension Tests of Metallic Materials

ASTM B811-13e1, Standard Specification for Wrought Zirconium Alloy Seamless Tubes for Nuclear Reactor Fuel Cladding

ASTM E146-83, Methods of Chemical Analysis of Zirconium and Zirconium Alloys (Silicon, Hydrogen, and Copper)

WK47776 New Test Methods for Hydrogen Determination in Steel, Iron, Nickel and Cobalt alloys by Inert Gas Fusion and Hot Extraction

4.2 REGULATORY REQUIREMENTS

Fuel transportation will be in accordance with the provisions of 10 CFR Part 71, *Packaging and Transportation of Radioactive Material* and U.S. Department of Transportation rules in 49 CFR Part 173, *Shippers--General Requirements for Shipments and Packaging*. Transportation will also be subject to requirements of DOE Directive DOE M 460.2-1.

DOE orders that may have relevance to some of the detailed activities coordinated within this test plan, and hence should be reviewed for applicability, include:

DOE G 421.1-1: DOE Good Practices Guide Criticality Safety Good Practices Program Guide for DOE Nonreactor Nuclear Facilities

DOE O 435.1 Chg 1: Radioactive Waste Management

DOE M 460.2-1: Radioactive Material Transportation Practices

DOE O 5660.1: Management of Nuclear Materials

4.3 LEVEL OF ACCURACY, PRECISION, AND REPRESENTATIVENESS OF RESULTS

The accuracy, precision, and representativeness of the testing and analysis work performed are assessed as part of the uncertainty analyses for each of the products developed. The accuracy of the testing results is to be controlled by using appropriate instrument calibrations and reference standards. The precision of individual measurements is to be assessed based on use of replicate measurements and/or the established precision of the measuring and testing equipment used. Test results will be documented in the technical products.

4.4 OTHER REQUIREMENTS

A critical aspect to performing this type of work is providing a quality assurance program that gives confidence to the sponsor that the data derived from the examinations will be useful for any intended purposes, including regulatory review. The FCT quality assurance plan (DOE-NE, 2010) and laboratory specific procedures will be used to govern the work performed in this plan. The quality assurance program has two distinct but related aspects:

1) Assurance of quality in operations in all matters relating to safety in the work place and safety, public health protection, and environmental management in operations involving radiological, nuclear, and hazardous materials and equipment, and
2) Assurance of quality both in special items production activities and in research and development data collection, data generation, analysis, use of software, documentation, and archiving of test samples.

The quality assurance program for operations in nuclear and radiological facilities must also comply with the provisions of other guidance documents such as:

- 10 CFR Part 830, Subpart A, *Nuclear Safety Management: Quality Assurance Requirements*
- DOE O 414.1A *Quality Assurance*

- DOE G 414.1-2 *Quality Assurance Management System Guide for use with 10 CFR 830.120 and DOE O 414.1*

The quality assurance programs for nuclear energy research, development and production activities are tailored to meet sponsor requirements.

5. EQUIPMENT

Measuring and test equipment necessary to conduct the examinations is controlled and calibrated at the facilities performing the work in accordance with approved laboratory procedures.

Major laboratory equipment necessary to conduct the work includes the following: Hot cells, gloveboxes, ADEPT and associated examination equipment, CIRFT, scanning electron microscope, transmission electron microscope, spiral notch torsion test system, and tensile testing machine. Additional equipment that will need to be designed or procured includes the following: full-length rod heat treatment system and aerosolized radionuclide particle collection system. .

6. DATA AND DOCUMENTATION

Observations, photographs, videotapes, digital files, and other data will be recorded on the appropriate medium and documented in laboratory notebooks as the examinations proceed. Progress of the PIE effort will be described in the project monthly reports and informal E-Mails. Consolidated status reports will be prepared annually. The final results of each major examination phase will be documented in a series of formal reports scheduled through the annual UFD planning process.

The raw data and data analysis algorithms will be made available to program participants. Most of this information will consist of computer files readable by commonly available programs such as EXCEL and WORD. Finished reports will be made available in PDF format. Copies of all records including documentation of equipment calibration and validation of software will be stored electronically at curie.ornl.gov.

7. QUALITY VERIFICATIONS

Detailed procedures for the PIE work will be available or written prior to the performance of the subtask and will be approved before use. All procedures used for the various testing will be retained for review and use when the corresponding “sister rods” from the research cask are extracted and examined for changes relative to the baseline properties. It is essential that the testing be performed identically prior to loading and after loading.

Specific hold points have been identified:

- At the completion of the NDE and prior to further characterization and testing, the data will be examined and the UFDC will determine if additional NDE are necessary.
- A draft rod segmenting plan has been developed that specifies the location of the desired specimens and their disposition – MET/SEM mount, mechanical test specimen, fuel density measurement, fuel or clad radiochemical/hydrogen analysis. At the completion of Phase I, results from the NDEs will be evaluated against the draft segmenting plan and confirmed or modified prior to the beginning of the destructive PIE work. The revised segmenting plan will be issued with a revision to this test plan document.

8. REFERENCES

1. Electric Power Research Institute, Contract No.: DE-NE-0000593 High Burnup Dry Storage Cask Research and Development Project: Final Test Plan, 2/27/2014.
2. FCRD-USED-2011-000136 Rev. 0
3. Scaglione, J.M. *A Unified Spent Nuclear Fuel Database and Analysis System*, International Conference on Management of Spent Nuclear Fuel from Nuclear Power Reactors: An Integrated Approach to the Back End of the Fuel Cycle, IAEA, June 2015.
4. Wang, J.-A. et al. *Dynamic Deformation Simulation of Spent Nuclear Fuel Assembly and CIRFT Deformation Sensor Stability Investigation*, ORNL/SPR-2015/662, Oak Ridge National Laboratory, November 16, 2015.
5. Wang, Jy-An and Hong Wang. *Mechanical Fatigue Testing of High-Burnup Fuel for Transportation Applications*, NUREG/CR-7198 ORNL/TM-2014/214, May, 2015.
6. Billone, M.C. et al. *Baseline Studies for Ring Compression Testing of High Burnup Fuel Cladding*, FCRD-USED-2013-000040/ANL-12/58, Argonne National Laboratory, November 23, 2012.
7. Billone, M.C. *Assessment of Current Test Methods for Post-LOCA Cladding Behavior*, NUREG/CR-7139 ANL-11/52, Argonne National Laboratory, August 2012.
8. Walker, C.T. et al. *On the oxidation state of* UO_2 *nuclear fuel at a burn-up of around 100MWd/kgHM*, Journal of Nuclear Materials 345 (2005) 192–205.
9. Kim, Jung Suk et. al. *Analysis of High Burnup Pressurized Water Reactor Fuel using Uranium, Plutonium, Neodymium, and Cesium Isotope Correlations with Burnup*, Nucl Eng Technol 47 (2015) 924-933.
10. Balfour, M.G. et al. *Corrosion of Zircaloy-Clad Fuel Rods In High-Temperature PWRs: Measurement of Waterside Corrosion In North Anna Unit 1*, TR-100408, Tier 2 Research Project 2757-1 Interim Report, March 1992.
11. Godfrey, A.M. et al. VERA Benchmarking Results for Watts Bar Nuclear Plant Unit 1 Cycles 1-12, CASL-U-2015-0206-000, June 30, 2015.
12. Caciapouti, R.J. and S. Van Volkinburg. *Axial Burnup Profile Database for Pressurized Water Reactors,* YAEC-1937, Yankee Atomic Electric Company, May 1997.
13. Wang, Jy-An and Ting Tan. *Using Spiral Notch Torsion Test to Evaluate Fracture Toughness of Structural Materials and Polymeric Composites*, OSTI 1090472, The 19th International Conference On Composite Materials, Montreal, Canada, August 2013.
14. Maheras, S.J. et al. *Transportation Shock and Vibration Literature Review, Used Fuel Disposition Campaign*, Fuel Cycle Research & Development, PNNL-22514, Pacific Northwest National Laboratory, June 2013.

Appendix A Draft Rod Cut Plans

Preliminary segments are selected based on representative burnup profiles for a 17×17 fuel assembly design at high burnups [12]. Note that the axial burnup distribution indicates that the bottom two and the top two and a half nodes are expected to have burnups below the assembly average, with the remainder of the nodes at or above the assembly average.

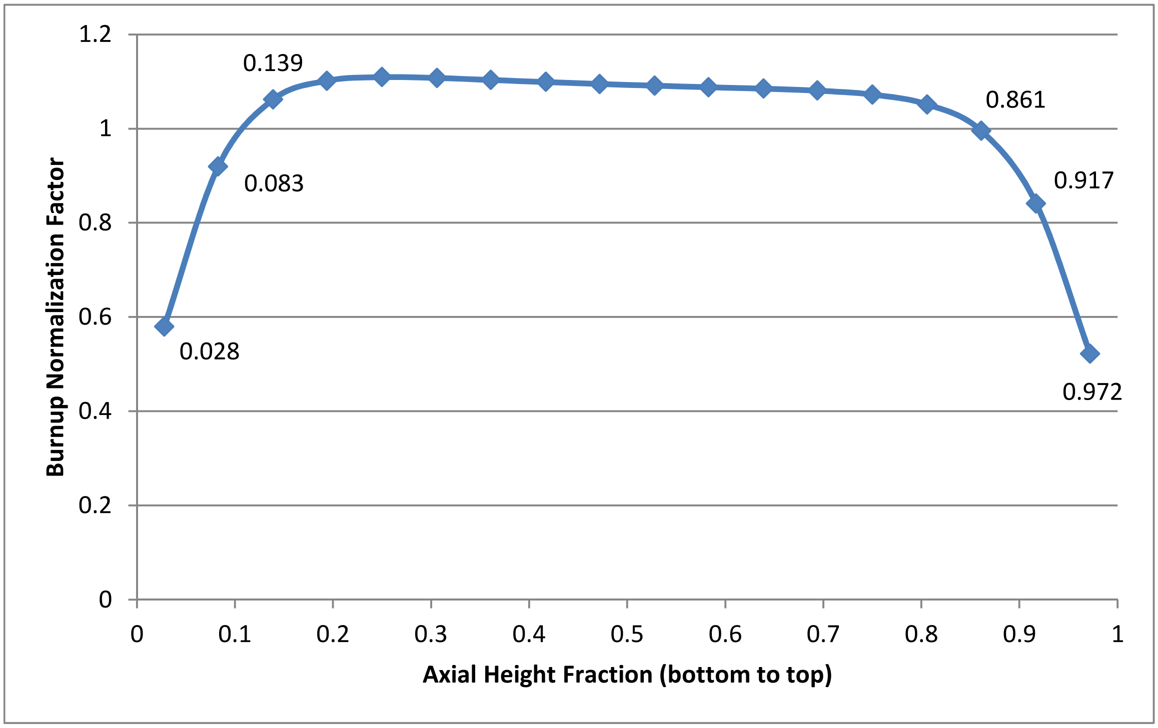
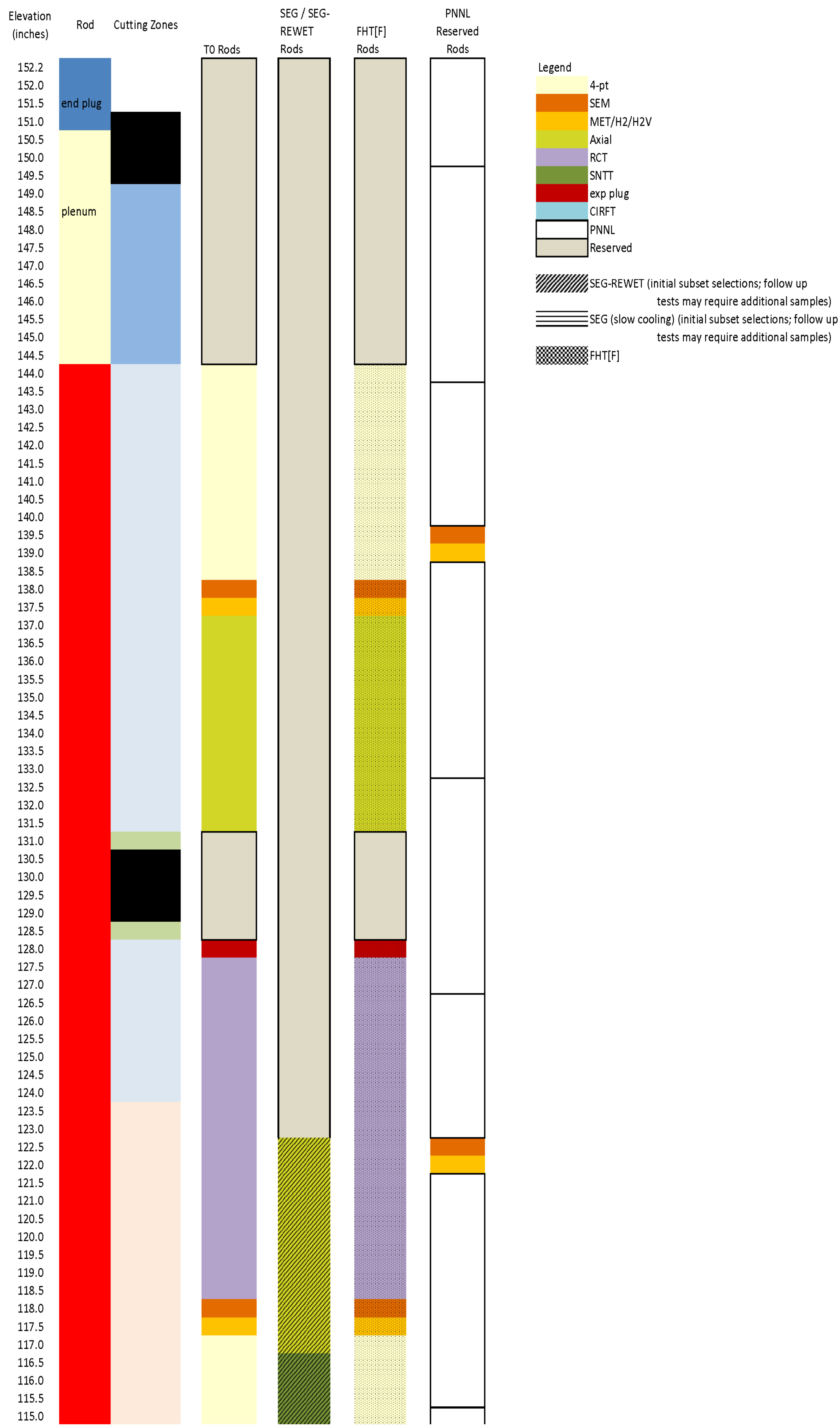
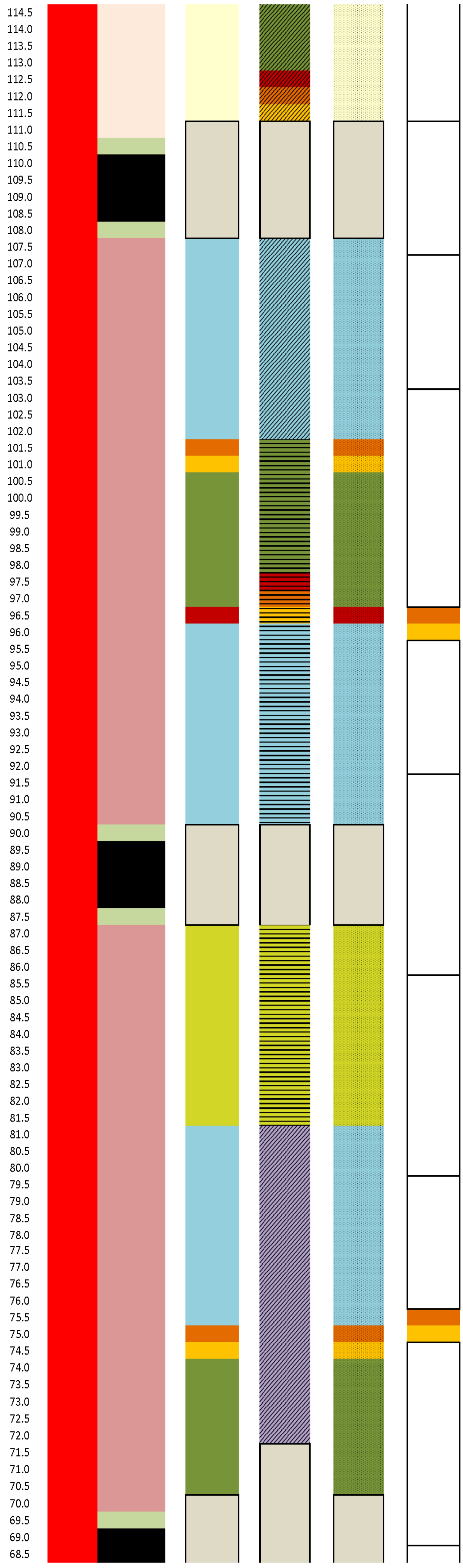


Figure A- 1. Representative axial burnup profile for high-burnup SNF rod

Figure A- 2. Preliminary Segmenting and DE Planned for Phase II Rods

Note that the fuel rod design length might vary slightly from rod to rod, as might the irradiation growth rates. Therefore, these diagrams are provided for general guidance and final cutting plans will be adjusted based on the NDE.

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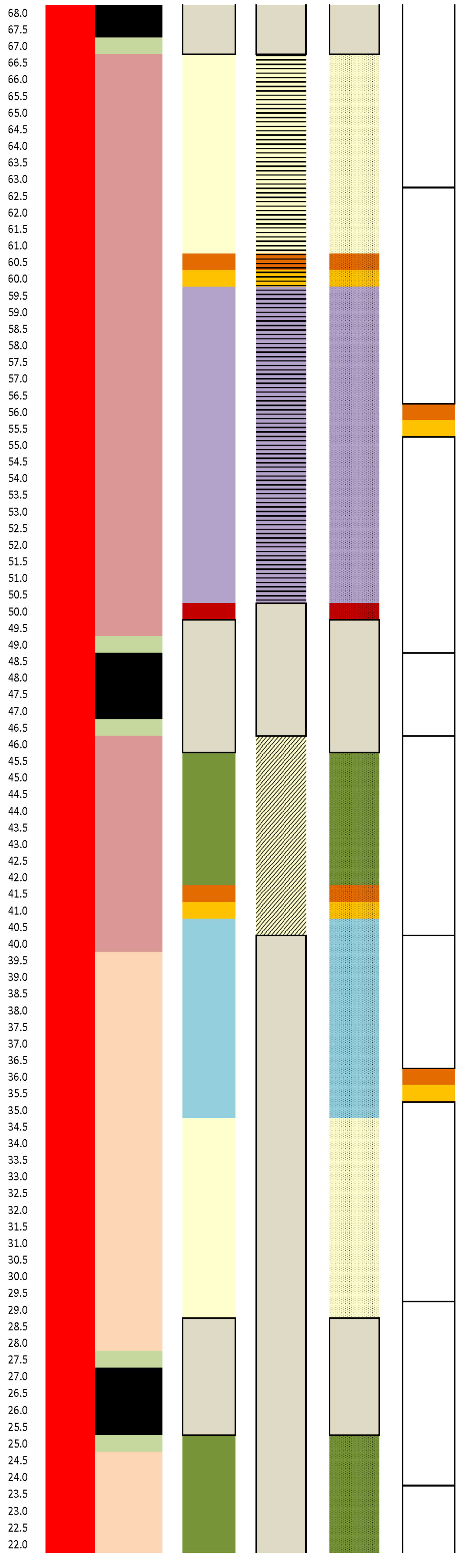
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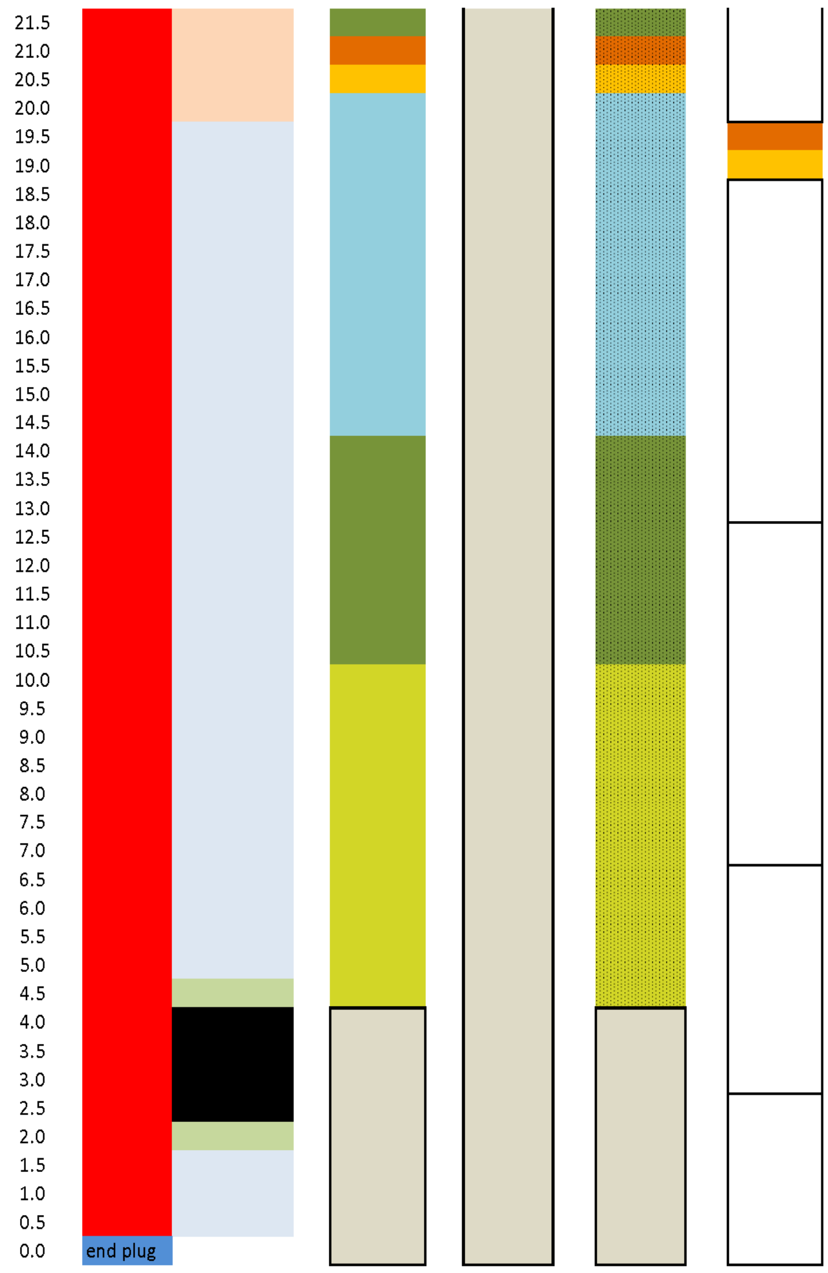
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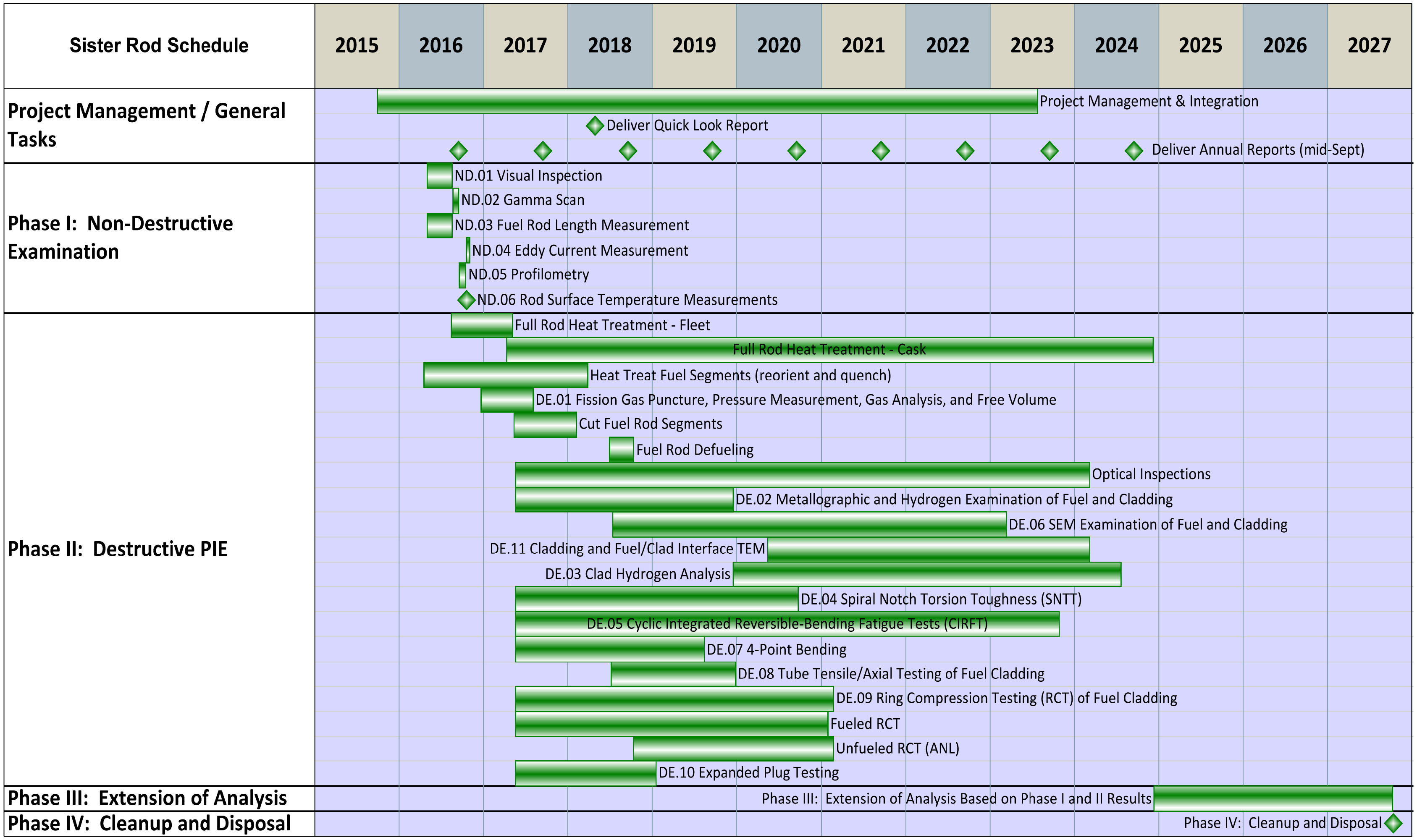
Appendix B Examination Schedule



Appendix C Project Budget

	Fiscal Year	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	Grand Total
Project Management & Integration	Project Management & Integration	$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	Deliver Quick Look Report	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
	Prepare hot cells, receive Sister Rods, Refurbish ADEPT	$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	Equipment repair and replacement	$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	Deliver Annual Report	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Total Project Management		$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Phase 1 (NDE)	NDE Hot Cell Facility	$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	NDE Hot cell experimentalists	$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	ND.01 Visual Inspection	$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	$ [redacted]	[redacted]
	ND.02 Gamma Scan	$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	ND.03 Fuel Rod Length Measurement	$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	ND.04 Eddy Current Measurement	$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	ND.05 Profilometry	$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	ND.06 Rod Surface Temperature Measurements	$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Phase I: Non-Destructive Examination Total		$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	$ [redacted]
Phase II: Destructive PIE	DE Hot cell experimentalists	$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	DE Hot cell facility	[redacted]	$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	Full Rod Heat Treatment - Fleet	$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	Full Rod Heat Treatment - Cask	$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	Heat Treat Fuel Segments (reorient and quench)	$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	DE.01 Fission Gas Puncture, Pressure Measurement, Gas Analysis, and Free Volume	$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	Cut Fuel Rod Segments	$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	Fuel Rod Defueling	$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	DE.02 Metallographic and Hydrogen Examination of Fuel and Cladding	$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	DE.06 SEM Examination of Fuel and Cladding	$ [redacted]	$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	DE.11 Cladding and Fuel/Clad Interface TEM	$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	Optical Inspections Total	$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	DE.03 Clad Hydrogen Analysis	$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	DE.04 Spiral Notch Torsion Toughness (SNTT)	$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	DE.05 Cyclic Integrated Reversible-Bending Fatigue Tests (CIRFT)	$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	DE.07 4-Point Bending	$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	DE.08 Tube Tensile/Axial Testing of Fuel Cladding	$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	DE.09 Ring Compression Testing (RCT) of Fuel Cladding	$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	DE.10 Expanded Plug Testing	$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Phase II: Destructive PIE Total		$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Phase III: Extension of Analysis Based on Phase I and II Results		$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Phase III: Extension of Analysis Based on Phase I and II Results		$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
		$ [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Appendix D Project Milestone Listing

Milestone Description (not necessarily in order; see the schedule in Appendix B for timing of the milestones)
Phase I
Preliminary NDE imaging
Final rod segmenting plan
Comprehensive NDE report
Phase II
Complete design and installation of full rod heat treatment capability
Complete qualification of segment heat treatment method
Complete demonstration of heat treatment methods/capabilities using dummy materials
Develop and design aerosolized radionuclide collection system from clad breach
Complete rod puncturing selected rods
Rod segmentation (selected rods)
Segment defueling (selected segments)
Shipments to PNNL and ANL: complete readiness assessments and approval process for shipping and receiving materials
Shipments to PNNL and ANL: complete rod segmenting
Shipments to PNNL and ANL: obtain shipping containers and prepare shipping paperwork
Shipments to PNNL and ANL: pack segments; ship
Document final examination procedures
Collect RCP temperatures for application to FHT[C] rods
Establish bounding temperatures for application to FHT[F] and SEG/SEG-REWET specimens
Apply heat treatment to selected full length rods (FHT[C] and FHT[F])
Apply heat treatment to selected segments [SEG/SEG-REWET]
Begin mechanical DE
Begin optical DE
Deliver final comprehensive DE report
Prepare Phase III test plan and update rod segmenting plans
Phase III
TBD
Phase IV
Project management activities
Annual status reports