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BWR Spent Nuclear Fuel Acquisition and Testing to Support the DOE-NE High Burnup Spent Fuel Data Project

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March 2020

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MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

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Reactor & Nuclear Systems Division

BWR SPENT NUCLEAR FUEL ACQUISITION AND TESTING TO SUPPORT THE DOE-NE HIGH BURNUP SPENT FUEL DATA PROJECT

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1. INTRODUCTION

The Office of Spent Fuel and Waste Disposition (SFWD) within the US Department of Energy (DOE) Office of Nuclear Energy (NE) established the Spent Fuel and Waste Science and Technology (SFWST) campaign to conduct research and development (R&D) activities related to the storage, transportation, and disposal of spent nuclear fuel (SNF) and high-level radioactive waste.

The SFWST program was created within SFWD to address issues of extended or long-term SNF storage and transportation. Some near-term objectives of SFWST are to use a science-based, engineering-driven approach to:

- Support the enhancement of the technical bases to support the continued safe and secure dry storage of SNF for extended periods
- Support the enhancement of the technical bases for retrieving SNF after extended dry storage
- Support the enhancement of the technical bases for transporting high burnup (HBU) fuel and transporting low burnup fuel and HBU fuel after dry storage

DOE-NE, in partnership with the Electric Power Research Institute, developed the High Burnup Spent Fuel Data Project to perform a large-scale demonstration and laboratory-scale testing of HBU pressurized water reactor (PWR) fuels (exceeding 45 gigawatt-days per metric ton of uranium [GWd/MTU]). Under this project, 25 sister rods—which are rods that have the same design, power histories, and other characteristics—were removed from assemblies at the North Anna Nuclear Power Station and sent to Oak Ridge National Laboratory (ORNL) in January 2016. ORNL performed detailed nondestructive examination (NDE) on all 25 rods. The NDE consisted of visual examinations, gamma and neutron scanning, profilometry and rod length measurements, and eddy current examinations. After completing the NDE, 10 of the sister rods were delivered to Pacific Northwest National Laboratory (PNNL) in a NAC International, Inc. legal-weight truck cask in September 2018 for destructive examination (DE).

To date, SFWD work has focused on the PWR fuel that is part of the Sister Rod Test program. No boiling water reactor (BWR) fuel has been tested in the program, and the data needs that were identified for the PWR fuel have not been collected for BWR fuel. The goal to obtain six to nine BWR rods and test them at ORNL will support closing this important data gap.

BWR fuel comprises approximately 56% of the total fuel assemblies currently in storage at nuclear power plants in the United States. BWR nuclear fuel and cladding designs and manufacturing are significantly different from PWRs. Differences include the following:

- BWR fuel pellets are larger than PWR pellets.
- Variations of Zircaloy-2 (including liners) are used instead of the Zircaloy-4 cladding materials used in PWRs.
- Clad manufacturing and stress-relief processes are different between PWRs and BWRs.
- The fuel rod dimensions are different because larger rod diameters and thicker cladding are used in BWRs.
- BWR fuel typically has lower internal rod pressures and sees vastly different operating conditions than PWR fuel (i.e., two-phase flow).
- BWR assemblies are “canned,” meaning each assembly is surrounded by a metal fuel channel.
- BWR cladding is often composed of an inner pure Zr liner that has widely different mechanical properties than the Zircaloy-2 alloy and exhibits a stronger affinity for hydrogen.
- The BWR SNF generally has more total hydrogen in the cladding/liner than typical PWR fuel.

- The construction of the PWR and BWR assemblies is vastly different; BWR rods are solidly attached to the assembly nozzles and experience a much different vibration and shock load than PWR rods, which are "floating" within a grid system attached to guide tubes, and the rods sit loosely on the bottom end plates.

These numerous differences will affect the way the BWR SNF responds under dry storage preparation processes (e.g., vacuum drying) and during transportation. The results collected in the PWR experimental program must be compared with a subset of similar data collected on BWR SNF to establish a technical basis for whether the larger PWR database is sufficient to bound the BWR SNF end-of-life conditions as is currently assumed for several fuel/clad properties.

Changes that occur in both fuel types at HBU could exacerbate any mechanical property differences. As the fuel burnup increases, several changes occur that might affect the performance of the fuel, cladding, and assembly hardware in storage and transportation. These changes include increased cladding corrosion layer thickness, increased cladding hydrogen content, increased cladding creep strains, increased fission gas release, and the formation of the HBU structure at the surface of the fuel pellets. The Nuclear Regulatory Commission (NRC) limits the current maximum rod-averaged burnup to 62 GWd/MTU due to these changes and the lack of data at higher burnups.

2. DATA GAPS FOR BWR SNF

Initial SFWST work focused on identifying the technical data gaps that, if addressed, could be used to support the continued safe storage of SNF for extended periods and support licensing activities. Given the number of gaps that were identified, the gaps that were initially assigned a *high* or *medium* rank were further prioritized to focus resources on areas that most needed additional data.

SFWST has made significant progress toward these objectives since its inception. SFWST performed an analysis to identify the technical data gaps (Hanson and Alsaed 2012, updated in 2019), prioritized R&D to close these gaps (Used Fuel Disposition Campaign [UFDC] 2012a), compared the gaps and associated priorities with those published by other US organizations and countries (UFDC 2012b), developed R&D status reviews and plans (Stockman 2014), and performed R&D with emphasis on the highest priority gaps. Since the issuance of Hanson and Alsaed (2012), SFWST has focused its R&D efforts on the higher priority gaps with an emphasis on determining, testing, and modeling realistic conditions, especially temperature profiles, stress profiles, and cladding characteristics.

Teague et al. (2019) reflects the gaps in the necessary data and reflects the ongoing work being done to examine and publicly document the collected data. The report notes that work to establish a sufficiently large database on the various cladding types must be continued to ensure the cladding inventory will meet its safety functions. In particular, hydride effects data must be obtained for BWR and integral fuel burnable absorber fuel cladding. To collect the information needed to close the knowledge gaps for BWR fuel performance during dry cask storage and transportation, a program similar but smaller than the PWR Sister Rod Test program is needed. The necessary information could be gathered by testing a limited number (possibly six to nine) of BWR HBU SNF rods. Key data gaps to be filled include:

- BWR rod internal pressure
- cladding material properties at different parts of the rod and evaluate whether the properties vary for partial length rods
- extent of fuel-cladding chemical interaction and select mechanical properties of the Zr liner
- effects of hydrogen on cladding and the fuel/clad composite system
- effects of drying the fuel before dry cask storage
- burnup effects on BWR SNF material properties (BWR fuel experiences very different operational/burnup conditions than those in PWR fuel; there could be significant differences between rods in the same bundles due to water channels, edge effects, etc.)
- crud and corrosion effects

- strength and fatigue performance of BWR SNF with new "softer" pellets

Additionally, DOE is currently investigating the feasibility of directly disposing dual-purpose (storage and transportation) canisters (DPCs) in a repository. Criticality during the repository performance period (10,000 years or more) is one of the major concerns related to direct DPC disposal, specifically since the system undergoes degradation in the repository environment and timeframe. ORNL is developing as-loaded criticality analysis methodology using full (actinides + fission products) burnup credit that exploits the inherent criticality margin associated with actual canister-specific loading configurations. Burnup credit criticality analysis requires the validation of the depletion/decay code used to generate the burned isotopic composition of an assembly by comparing it with experimentally measured isotopic data. Currently, measured BWR isotopic information is limited, and additional measurements will be highly beneficial for BWR burnup credit analysis, which is essential to demonstrate the disposability of BWR DPCs.

3. ORNL'S ABILITY TO RECEIVE BWR SNF

A feasibility assessment conducted in 2015 determined that ORNL has the capacity and capability to accept up to 50 full-length HBU commercial-use fuel rods. This material amount was evaluated in 2015 because an NE-5 program was determining if research tasks could be performed at ORNL to support the Fuel Cycle Technologies program, which involved testing 25 full-length fuel rods. If that work were performed in conjunction with the Sister Rod Test program, then there could be 50 full-length SNF rods at ORNL. It was determined that ORNL did have the ability to receive and examine the 50 fuel rods within the current Documented Safety Analysis (DSA) for the Irradiated Fuels Examination Laboratory (IFEL), Building 3525, and the work was determined to be manageable from a criticality safety perspective. Adding this material would not alter the nuclear materials safeguards category or significantly affect other research or the ability to receive additional material to support other programs. The facility has the infrastructure and capability to package and process incidental and secondary waste associated with postirradiation examination (PIE).

Since conducting that analysis, ORNL received the 25 full-length sister rods and conducted NDE on all the rods. Then, ORNL shipped 10 unpunctured, full-length sister rods to PNNL. Also, the waste that was generated from the mixed oxide (MOX) project (four rods' worth of SNF material) and the equivalent of approximately one full-length PWR SNF rod were loaded into canisters and shipped to the Transuranic (TRU) Waste Processing Center (TWPC) for eventual transfer to the Waste Isolation Pilot Plant (WIPP). Figure 1 shows the PWR SNF rods that were shipped to TWPC. The 25 rods from the Fuel Cycle Technologies program were designated to go to Idaho National Laboratory for testing and will not be sent to ORNL.

Figure 1. The PWR SNF rods that were loaded into canisters and shipped to TWPC. *Image by Bruce Balkcom Bevard.*

Related to the Sister Rod Test program, an ORNL National Environmental Policy Act (NEPA) categorical exclusion (CX) currently exists (3059X), which includes preparing, examining, segmenting, and testing nuclear fuel elements. DOE subsequently decided to pursue a supplement assessment of the Environmental Impact Statements that could apply to the work scope described in action review document (ARD) 3934 along with related work scope to be performed at Argonne National Laboratory and PNNL. The conclusion, as described in the SA (DOE/EIS-0203-SA-07 and DOE/EIS-0250F-S-1-SA-02), found that no further NEPA documentation was required. This determination did not significantly affect the ORNL internal review documented in the ARD, so no revision was required.

For the conclusions of the CX to remain valid, ORNL needs an executable final disposition path commitment from the customer. If ORNL does not receive such a commitment, ORNL might need to develop a new CX that justifies that the proposed increase in material inventory does not alter the current environmental risk or overall impact beyond what currently exists.

Building 3525 can support the acceptance of full-length commercial fuel rods transported in an industry-supplied lightweight truck (LWT) cask. The equipment and personnel needed to perform the fuel examinations and characterizations are in place and were recently proven through the destructive and nondestructive PIE of four irradiated MOX fuel rods from the Catawba Nuclear Station and 25 PWR fuel rods from the North Anna Nuclear Power Station.

3.1 DOCUMENTED SAFETY ANALYSIS (DSA)

An evaluation of the impact to the DSA of adding 9 BWR rods to the Building 3525 radioactive material inventory and nuclear criticality safety inventory as of 4/9/2020 was performed. BWR rod assumptions are provided in Appendix B. Adding these nine BWR rods results in the radioactivity material inventory listed in Table 1.

Table 1. Nine BWR rods movement from balance of facility (BOF*) to the east hot cell

	9 BWR rods		**Total inventory**		
	Hot cell	**Outside hot cell (BOF)**	**Hot cell**	**Outside hot cell (BOF)**	**Total facility**
Current inventory (April 9, 2020)			17%	46%	63%
Initial receipt-encased SNF-BOF		7%	17%	53%	70%
Move to east hot cell-encased SNF-HC	2%		19%	46%	65%
In east hot cell-segmented SNF	3%		20%	46%	66%

*BOF: all areas outside the hot cells, charging area, charging area wells for NCS limit considerations

This table evaluates the BWR rods initially entering the 3525 yard (Outside Hot Cell SAR area) and being transferred to the east hot cell. Initially the rods are assumed to be in the Encased Spent Nuclear Fuel (contained in unpunctured cladding) form. Once the rods are transferred into the east hot cell, the limit fraction being applied to the material is reduced from 7% to 2% and thus the total facility limit fraction is reduced to 65%. The rods will then be segmented, and since there is a different facility limit (inhalation dose rem) for encased (non-segmented) and segmented rods, this form change will increase the total facility limit to 66%.

Because all other building 3525 nuclear criticality safety (NCS) areas have a NCS limit of 700g FEM, the BWR rods can only be loaded into the east hot cell where the NCS limit is higher (3450g FEM) due to NCS controls. The NCS impact is evaluated in Table 2.

Table 2. Nuclear criticality safety evaluation for the east hot cell

Nine BWR rods FEM(g)/%	FEM (g) limit	Current FEM* (g)/limit %	FEM (g)/limit after BWR rods
922/27%	3,450	2,278/66%	3,200/93%

*Fissile equivalent mass: determined by taking mass of fissionable isotope and multiplying by a factor to normalize for ability to go critical. ^{235}U=1.

This evaluation demonstrates that Building 3525 SAR/TSR/NCSA can accommodate the addition of 9 BWR rods with no revision.

3.2 NATIONAL ENVIRONMENTAL POLICY ACT

The NEPA CX that currently exists for the IFEL (3059X) includes preparing, examining, segmenting, and testing nuclear fuel elements. However, it assumes that a disposition path currently exists for any wastes generated from these activities. Used fuel waste is planned for disposal at WIPP. To exercise the existing CX, a commitment from the customer regarding waste funding and support for the executable final disposition path for used fuel is needed. If such a commitment cannot be obtained, the only recourse is for ORNL to apply for a new CX on the basis that the proposed increase in material inventory would not alter the current environmental risk or overall impact significantly beyond what currently exists. This basis is supportable, but a new CX has not been applied for or granted.

3.3 CRITICALITY SAFETY

Another issue to be addressed is which criticality safety controls will be needed to allow nine BWR rods with ~1 kg of fissile material to be handled and stored in one location. This material can be handled in the East Hot Cell under existing criticality limits. This hot cell is currently at 66% of this limit, and nine additional BWR rods would increase this to 93%. Specimens could be moved to other hot cells to provide additional capacity, if needed.

3.4 SHIELDING

Protecting research and cell equipment from the radiation associated with large amounts of irradiated material is important to minimize radiation damage and reduced equipment lifespan. Storage arrays also minimizes the cell footprint used for fuel storage and aids in rod retrieval and identification. One shielded storage array had previously been fabricated and installed in the east hot cell to shield instrumentation and equipment from unnecessary exposure to high radiation levels resulting from testing irradiated MOX rods. This “small array” has an eight pin capacity and has been supplemented by a second 10 in. × 10 in. × 14 ft. array shielded with 2 in. of lead (large array) that can hold 19 full-length rods. The two shielded storage arrays currently hold one MOX rod and eight full length PWR rods; open spaces are available to support receipt of six to nine BWR rods. Figure 3 shows the small and large storage arrays.

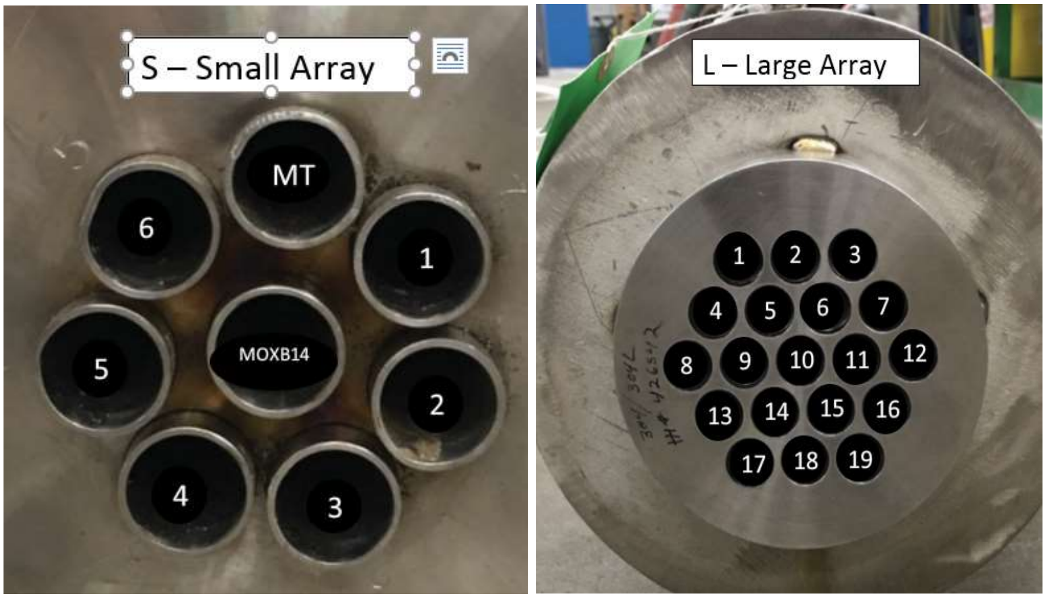

Figure 3. Small and large arrays for storing full length SNF rods in Building 3525 hot cells.

3.5 SAFEGUARDS

The special nuclear materials (SNM) content of the proposed material was calculated to establish the impact to the building material balance area (MBA) and site nuclear material control and accountability (NMC&A) limits. The weight percent of each SNM type was determined separately and evaluated in accordance with DOE-STD-1194-2011, section 6.2.1, "Nuclear Material Categorization," and was verified to be attractiveness level D. Adding this SNM to the facilities' current level D inventory would mean that most of the allowed inventory would remain available for other programs while maintaining the MBA as Category IV. The site MBA would not be significantly impacted.

3.6 WORK ACCEPTANCE REVIEW

Per internal procedures, ORNL must exercise the work acceptance review process, which includes convening the Nuclear Review Panel. This process includes a risk assessment that evaluates a variety of factors associated with the work, such as hazards, facilities, environmental/NEPA considerations, waste generation, safeguards/security considerations, financial considerations, and other considerations. In the evaluation, the panel considers the acceptance of the work relative to safety, the capabilities, the R&D mission, facility and site limits/considerations, impacts to current and future work, and any other relevant factors. The panel must confirm that, based on all these considerations, ORNL could accept and successfully execute this work.

Currently, ORNL facilities can accommodate this material and work, the staff is qualified to perform this work, this work is within the R&D mission, and all of the activities can be performed safely at ORNL. The costs associated with having the material in ORNL facilities, impact to other work, and life cycle management of the material including disposition will be considered once this information is available. DOE must commit to covering the life cycle costs and ultimate material disposition.

4. WASTE DISPOSITION

ORNL's primary challenge is identifying the waste material disposition path once the examinations are complete. Previously, the MOX fuel debris wastes and wastes generated during fuel testing for NRC projects were sent to WIPP for disposal. Under the previous arrangement, the waste was packaged in shielded containers at IFEL. After it was determined to meet the appropriate waste acceptance criteria

(WAC), it was transported by a DOE-EM contractor to their storage facility. The waste containers were then processed, characterized, and certified at TWPC, which is adjacent to the ORNL site, in preparation for shipment to WIPP for disposal. To use this disposal pathway, compliance with the WIPP WAC and other key programmatic areas—such as defense origin determination, removal from NMC&A requirements, and documentation to support the reduction of materials attractiveness from D to E—were addressed.

ORNL can no longer use that exact path. Instead, the waste material will undergo visual inspection by the Central Characterization Program (CCP) when it is packaged at IFEL to ensure the waste content and packaging process is performed in accordance with the approved WIPP acceptable knowledge (AK) summary report. ORNL has a contractual mechanism to procure waste certification services from the National TRU Program (NTP), including the development of AK and performance of VE. While preparing AK, an evaluation of the radiological and chemical characterization requirements will be developed with NTP. The preferred approach is to use only existing information (i.e., process knowledge) to characterize the waste for disposal. However, NTP might require additional information, including the sampling and analysis of critical waste aspects.

The packaging approach that ORNL used for the MOX disposal is anticipated to still be valid for disposing of future waste generated by PIE activities. The packaging approach consisted of using small unshielded cans to collect the high-activity waste. These cans are then packaged into lead-shielded outer containers. The outer containers are subsequently packaged into 55 gal drums and stored by ORNL until the NTP is available to complete the final packaging steps and ship to WIPP. All of the packaging steps will be performed under the CCP surveillance.

The tie to defense waste is established due to the inseparable comingling of sample debris from various programs through the shared use of facilities and equipment. This methodology is currently used and widely accepted for materials that are disposed of as they are generated through the course of testing and examination. Continued use of this method is feasible for portions of PIE performed in conjunction with continued defense-related work, such as the ongoing DE of the remaining MOX full-length fuel rod.

Similarly, the attractiveness would be lowered from D to E once the material is used up through testing. The concentration of SNM contained in a given amount of waste becomes sufficiently low enough that it would require difficult and complex processing before it could be used to construct a weapon or improvised nuclear device.

5. BWR FUEL AVAILABILITY AND SYNERGIES WITH EXISTING PROGRAMS

ORNL as part of the DOE, Office of Nuclear Energy, Advanced Fuels Campaign is actively collaborating with General Electric (GE), Global Nuclear Fuels (GNF), and Southern Company to enable specific technological development activities on the iron-chromium-aluminum (FeCrAl) class of ferritic alloys and coated-Zr alloys for accident-tolerant fuel (ATF) applications. FeCrAl alloys and coated-Zr alloys are leading candidate materials proposed as drop-in replacement cladding solutions for the current generations of light water reactors that can enhance the safe operation of domestic and foreign nuclear power reactor fleets. Collaborations between ORNL, GE, and GNF have developed a tailored alloy FeCrAl composition, called *IronClad*, which is currently under irradiation in a commercial nuclear power plant (Hatch Unit 1). Additionally, GE's coated-Zr cladding, called *ARMOR*, is under irradiation in the same assemblies. Experimental lead test rods of IronClad and ARMOR from one of four assemblies are scheduled to be disassembled poolside and shipped to ORNL in a GE-2000 cask for PIE in early FY 2021. This shipment will include four segmented rods of ARMOR cladding fueled with UO_2 and one segmented rod of IronClad cladding that is unfueled. There is interest from GE to perform additional PIE on the other lead test assemblies that are continuing irradiation at the Hatch Unit 1 nuclear power plant. Assuming a standard operating cycle for the Hatch Unit 1 plant, the second set of lead test rods that contain the IronClad and ARMOR concepts would end irradiation around February 2022. After cooling and poolside exams, the lead test rods from the second Plant Hatch assembly would be ready for potential shipment to ORNL around October 2022 for PIE.

This provides the NE-8 program with a unique opportunity to potentially obtain several BWR fuel rods that can be tested as part of the High Burnup Dry Storage Cask Research and Development Project. A shipment of six to nine BWR fuel rods to ORNL could be coordinated with Plant Hatch to merge with these other planned fuel shipment activities at the facility. This will result in the minimization of fuel shipment impacts at the site. The shipment would most likely require the NAC LWT cask and require a type B shipment due to the presence of irradiated fuel. The exact number of rods will be determined by a balance of isotopic assessment, volume constraints, and PIE funding.

DOE programmatic approval will be necessary before formal interactions/discussions between ORNL, GE, and Southern Company can begin to support the necessary detailed planning and negotiations for the shipment of irradiated BWR fuel to ORNL. The anticipated BWR SNF shipment date from Plant Hatch to ORNL in the fall of 2022 merges well with the existing sister rod PIE and can be accomplished while the ORNL sister rod testing is completed and the residual waste material is shipped to WIPP. Any residual waste material from the BWR SNF examinations is expected to also be appropriately packaged and shipped to WIPP for final disposal.

Although the collaborations to be gained by working with the ATF program are promising, there are other avenues available for obtaining BWR rods for testing to support the NE-8 program. Although detailed discussions have not been initiated, several utilities have expressed interest in supporting DOE testing on HBU BWR rods should the cooperation with the ATF project at Hatch not come to fruition. No details concerning work scope, costs, or schedules with these other utilities are available.

6. PROPOSED WORK SCOPE

Per Teague et al. (2019), cladding hydride effects data must be obtained for BWRs. Additionally, a BWR database similar to the one being developed through the Sister Rod Test program must be built. Also, the BWR SNF burnup credit data is needed to support future waste management strategies. A detailed test plan will be developed once the actual number of rods is known, and testing will be completed as funding is made available. Waste will be removed from ORNL periodically once enough waste is generated to support a shipment campaign.

The detailed examinations are intended to provide performance characteristics, material property data, and mechanical performance properties on HBU BWR rods to establish:

- the baseline condition of the HBU BWR rods (the cladding and fuel pellets in situ), pellets, and cladding, post-operation, and pre-dry storage
- changes in HBU BWR rods, cladding, and pellets resulting from dry storage vacuum-drying activities
- general SNF characteristics data for HBU BWR fuels, including mechanical properties that can be used to expand the applicability of the data across the industry fleet of casks and to support code validation and future analysis needs
- data from HBU BWR SNF exposed to temperatures similar to those experienced during dry storage to expand the applicability of the dry storage project

The detailed test plan will include NDE testing on all BWR rods, and subsequent DE testing will be performed in two phases. Phase 1 of the DE will include the heat treatment of two to three unpunctured full-length rods. These rods will be selected to be similar to other rods that will not be heat treated (i.e., baseline rods). These heat-treated rods will then be sectioned and tested as described below, and the data will be compared with data collected when testing the baseline rods.

ORNL will perform gas communication testing on several full-length punctured rods. The BWR rods are all the same cladding type (i.e., Zircaloy-2). The rods will be heated to 400°C before cooling and puncturing for rod internal pressure measurements, thus preserving the spent fuel rod characteristics before heat treating. A temperature profile will not be used in the Phase 1 tests to reduce the number of test-sample variables and to induce an upper bound of pressure at this elevated temperature relative to stored rods that have an axial temperature profile. The 400°C temperature corresponds to the NRC-recommended limit on peak centerline temperature to ensure cladding integrity. However, prolonged time at this temperature is not desirable for Phase 1 testing since it could lead to excessive annealing of irradiation damage. The effects of annealing will be examined in Phase 2, if necessary. In addition to internal pressure measurements following heat treatment and cooling, gas communication testing will be performed for comparison with the baseline rods.

This work's ultimate goal is to provide the data needed to address the technical gaps associated with HBU SNF and long-term storage (Teague et al. 2019). The DEs are specified to provide sufficient data and allow for more precise analytical predictions of BWR SNF performance during all conditions of transport and storage. Although there are many similarities between PWR and BWR fuel, these examinations are expected to fill the data gaps applicable to BWR SNF that were not closed as part of the HBU program PWR SNF testing.

Table 3 summarizes the data gaps identified for fuel and cladding and the data to be obtained through the BWR NDE and DE for application toward a better understanding of the characteristics of HBU BWR fuel. It also discusses how the data could be applied to support data gap closure. This characterization program addresses the identified gaps in understanding HBU fuel irradiation effects.

Table 3. Summary of technical gaps and the examinations planned for the sister rods.

	Examination type																	
Existing technical gap	ND.01 visual inspection	ND.02 gamma scan	ND.03 fuel rod length	ND.04 eddy current	ND.05 profilometry	ND.06 rod surface temperature	DE.01 fission gas puncture	DE.02 metallographic/hydrogen examination of fuel and cladding	DE.03 clad total hydrogen	DE.04 spiral notch toughness	DE.05 cyclic bending fatigue	DE.06 SEM examination of fuel and cladding	DE.07 four-point bending	DE.08 tube tensile/axial testing of cladding	DE.09 microhardness	DE.10 ring compression tests (fueled and unfueled)	DE.11 cladding and fuel/clad interface TEM	**Application to gap closure**
Stress profiles						X	X			X	X		X	X	X	X	X	Collected data can be used to understand which stresses and conditions result in fuel-rod failure and better define typical conditions for HBU fuel. The data will be used in conjunction with measurements of forces and stresses imposed on the fuel rod to close the stress profiles gap.
Drying issues	Retained water in the canister/fuel rod is currently being addressed through the DOE IRP process. Phase II testing with the BWR rods can be used to supplement the data, if necessary.																	

Table 3. Summary of technical gaps and the examinations planned for the sister rods (continued).

	Examination type																	
Existing technical gap	ND.01 visual inspection	ND.02 gamma scan	ND.03 fuel rod length	ND.04 eddy current	ND.05 profilometry	ND.06 rod surface temperature	DE.01 fission gas puncture	DE.02 metallographic/hydrogen examination of fuel and cladding	DE.03 clad total hydrogen	DE.04 spiral notch toughness	DE.05 cyclic bending fatigue	DE.06 SEM examination of fuel and cladding	DE.07 four-point bending	DE.08 tube tensile/axial testing of cladding	DE.09 microhardness	DE.10 ring compression tests (fueled and unfueled)	DE.11 cladding and fuel/clad interface TEM	**Application to gap closure**
Burnup credit	Important data can be collected through the BWR rod characterization program. Issues to close this gap are related to BWR burnup credit, some of which can be addressed with the planned set of BWR rods; other issues are best addressed with modeling and simulation.																	
Cladding hydride reorientation and embrittlement	X			X			X	X	X	X	X	X	X	X	X			Comparisons of the examination results of corresponding BWR rods before and after heat treatment can be used to address this gap. Several BWR rods will be subjected to heat treatments to examine the separate effects related to rod internal pressure and drying temperature to address this gap.
Cladding creep	X		X					X							X			Axial tension testing can be performed to evaluate creep characteristics of the BWR fuel.
Fuel fragmentation small particles/ aerosols										X	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 oxidation								X				X			X		X	The BWR rod characterization examinations 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 HBU fuel.
Cladding metal fatigue								X						X	X	X		Cladding fatigue caused by temperature fluctuations can be evaluated by comparing segments that have been thermally cycled with segments that have not been cycled.
Cladding oxidation	X			X				X		X	X	X	X	X	X	X		The effects of oxidation can be evaluated by measuring, analyzing, and comparing the DE results for several sister rod samples.

6.1 TESTING TO BE CONDUCTED ON BWR RODS

The rods will be sectioned to support the following tests:

- ASTM axial tube tensile tests
- Cyclic Integrated Reversible Bending Fatigue Tester tests
- ASTM four-point bend tests
- optical microscopy evaluation
- hydrogen content determination
- ASTM micro hardness tests

- defueled-cladding ring-compression tests (RCTs)
- fueled-cladding RCTs

ORNL will also perform tests to quantify the amount and particle size distribution, including the respirable fraction, of fuel released from a failed segment. The same pattern of cuts and testing will be preserved to compare segments of as-irradiated rods and heat-treated rods. Emphasis will also be placed on collecting samples that will provide information on low burnup ends, HBU portions, and grid spacers.

7. SCHEDULE

The desired shipment date of the BWR SNF from Plant Hatch to ORNL is anticipated to be in the fall of 2022 based on the estimated date on which the ATF program will want to ship the second ATF material shipment to ORNL. Other key dates are based on obtaining DOE funding to support coordination work with Southern Company, GE, and GEF; contracting with NAC for use of the LWT; and having funds to support the Southern Company work at Plant Hatch to remove the rods from their parent assemblies and load the rods into the LWT. See Appendix A for schedule details. All NDE is expected to be completed in FY 2023, followed by DE. Testing is planned to be completed by the end of FY 2025, with all waste removed from ORNL by the end of FY 2026.

8. BUDGET

The budget to perform this project is estimated at $6M. This estimate is based on the costs listed in Table 4.

Table 4. Estimated project costs.

Project item	Cost
Development of detailed plans/schedules	$200K
Support from Southern Company	$150K
GNF/GE costs to pull rods	$500K
ORNL costs to plan/receive rods	$150K
Transportation costs	$500K
NDE/DE costs (assume 9 rods)	$3M
Waste costs	$1.5M
Total estimated cost	**$6M**

9. SUMMARY

The proposed test program is similar to but smaller than the PWR Sister Rod Test program. The necessary experimental data can be gathered by testing a limited number (possibly six to nine) of BWR HBU SNF rods. These BWR examinations will develop the data needed to close the technical data gaps that can be used to support the continued safe storage of SNF for extended periods and support licensing activities, including collecting hydride effects data necessary for BWR fuel cladding.

Additionally, the burnup credit criticality analysis information required to validate the depletion and decay codes, which are used to generate the burned isotopic composition of an assembly by comparing it with experimentally measured isotopic data, will be collected. These additional measurements will be highly beneficial for BWR burnup credit analysis, which is essential to show the disposability of BWR DPCs.

The feasibility assessment performed when ORNL was evaluating the capability to accept the 25 sister rods determined that ORNL has the capacity and capability to accept the equivalent of six to nine HBU commercial BWR SNF rods for the purpose of performing research tasks in support of the High Burnup Spent Fuel Data Project. The ability to receive and examine these fuel rods exists within the current DSA for IFEL and is manageable from a criticality safety perspective. Adding this material would not alter the nuclear materials safeguards category or significantly affect other research or the ability to receive additional material to support other programs. The facility has the infrastructure and capability to package and process incidental and secondary waste associated with the PIE. Related to this, a NEPA CX currently exists for this facility, which includes preparing, examining, segmenting, and testing nuclear fuel elements. However, ORNL would need a commitment of an executable final disposition path from the customer for the conclusions of the CX to remain valid.

Building 3525 can support the acceptance of full-length commercial fuel rods transported in an industry-supplied LWT cask. The equipment and personnel needed to perform the fuel examinations and characterizations are in place and were recently proven through the destructive and nondestructive PIE of the 25 sister rods.

10. REFERENCES

DOE/EIS-0203-SA-07 and DOE/EIS-0250F-S-1-SA-02. *Proposed Shipment of Commercial Spent Nuclear Fuel to DOE National Laboratories for Research and Development Purposes*. US Department of Energy Office of Nuclear Physics, 2005.

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Hanson, B. and H. Alsaed. *Gap Analysis to Support Extended Storage and Transportation of Spent Nuclear Fuel: Five-Year Delta*, 2019.

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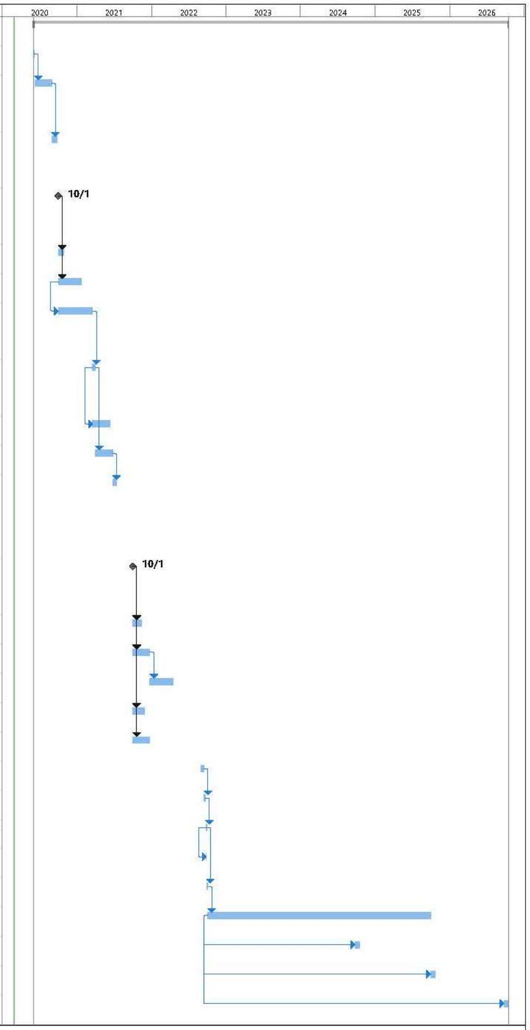
Teague, M., S. Saltzstein, B. Hanson, and K. Sorenson. *Gap Analysis to Guide DOE R&D in Supporting Extended Storage and Transportation of Spent Nuclear Fuel: An FY 2019* Assessment, 2019.

UFDC 2012a. *Used Nuclear Fuel Storage and Transportation Data Gap Prioritization*. FCRD-USED-2012-000109 Draft, PNNL-21360. US Department of Energy Used Fuel Disposition Campaign, Washington, DC.

UFDC 2012b. *Review of Used Nuclear Fuel Storage and Transportation Technical Gap Analyses*. FCRD-USED-2012-000215, PNNL-21596, Prepared for the US Department of Energy Used Fuel Disposition Campaign, Washington, DC.

APPENDIX A. SCHEDULE

ID	Task Name	Duration	Start	Finish	Predecessors
0	**BWR SNF Acquisition and Testing to Support DOE-NE High Burnup Spent Fuel Data Project**	**1664.4 days**	**Mon 6/1/20**	**Thu 10/15/26**	
1	Approval from DOE to engage in discussions with Southern Company, GE, and GNF - needed now	5 days	Mon 6/1/20	Fri 6/5/20	
2	Initiate discussions with Southern Company, GE, and GNF to gage interest and develop a team to identify issues needing resolution	3 mons	Mon 6/8/20	Fri 8/28/20	1
3	Establish a detailed cost estimate for all affected parties and identify cost sharing activities that will affect the costs to each participant	1 mon	Mon 8/31/20	Fri 9/25/20	2
4	Receive DOE funding to develop the detailed plans, documentation, and coordination to proceed with the BWR testing activity; DOE funding may be needed for preliminary Southern Company work at Plant Hatch	0 days	Thu 10/1/20	Thu 10/1/20	
5	Develop a preliminary schedule reflecting key activities at both ORNL and Hatch	1 mon	Thu 10/1/20	Wed 10/28/20	4
6	Identify the specific BWR rods that are (1) available to the SFWD program and (2) of interest to the SFWD program	4 mons	Thu 10/1/20	Wed 1/20/21	4
7	Negotiate with Southern Company, GE, and GNF for operational data on the rods of interest (support modeling of the rods)	6 mons	Thu 10/1/20	Wed 3/17/21	6SS
8	Provide detailed information to the appropriate ORNL organizations to review the criticality safety, safeguards, CX, building inventory limits, and impacts on existing R&D programs	10 days	Thu 3/18/21	Wed 3/31/21	7
9	Exercise the ORNL Work Acceptance Review process once the actual BWR rods are identified	60 days	Thu 3/18/21	Wed 6/9/21	8SS
10	Review the existing AK at ORNL for applicability or revise/develop an AK to support waste removal	60 days	Thu 4/1/21	Wed 6/23/21	8
11	Update the schedule reflecting key activities at both Hatch and ORNL; include ORNL activities such as coordination with other research programs in the IFEL; preparations at 3525 required to receive the LWT (including removal of the "C" zone in room 128)	15 days	Thu 6/24/21	Wed 7/14/21	10
12	Receive DOE approval and funding to contract with NAC and Southern Company for acquisition of the 6-9 BWR rods and receive the DOE commitment to pay for PIE waste removal from ORNL	0 days	Fri 10/1/21	Fri 10/1/21	
13	Support Plant Hatch as appropriate as they plan for the removal of the 6-9 BWR rods from their respective assemblies	30 days	Fri 10/1/21	Thu 11/11/21	12
14	Contract with NAC for use of the LWT to transport both the BWR rods and the ATF fuel to ORNL	3 mons	Fri 10/1/21	Thu 12/23/21	12
15	Coordinate with NAC to modify the LWT rod box to hold both ATF and BWR material	4 mons	Fri 12/24/21	Thu 4/14/22	14
16	Develop a transportation plan for moving the rods from the Hatch plant to ORNL	2 mons	Fri 10/1/21	Thu 11/25/21	12
17	Finalize the draft of the PIE plan for the BWR rods	3 mons	Fri 10/1/21	Thu 12/23/21	12
18	Pull the selected BWR rods from their parent assemblies	10 days	Thu 9/1/22	Wed 9/14/22	
19	Load the BWR rods and the ATF materials into the LWT	5 days	Thu 9/15/22	Wed 9/21/22	18
20	Transport the BWR rods and ATF material to ORNL	2 days	Mon 9/26/22	Tue 9/27/22	19FS+2 days
21	DOE take ownership of the BWR rods as transport is initiated	1 day	Mon 9/26/22	Mon 9/26/22	20SS
22	Remove the BWR rods and ATF material into the hot cell in Bldg. 3525	5 days	Wed 9/28/22	Mon 10/3/22	20
23	Conduct PIE on the BWR rods (3 years)	39 mons	Tue 10/4/22	Mon 9/29/25	22
24	Prepare and ship waste from ORNL - round 1	15 days	Mon 9/23/24	Mon 10/14/24	23SS+66%
25	Prepare and ship waste from ORNL - round 2	15 days	Tue 9/30/25	Mon 10/20/25	23SS+100%
26	Prepare and ship waste from ORNL - round 3	15 days	Thu 9/24/26	Thu 10/15/26	23SS+133%



Project: BWR SNF Acquisition a
Date: Fri 2/28/20

Task		Summary		Inactive Milestone		Duration-only		Start-only	[	External Milestone	◆	Manual Progress			
Split		Project Summary		Inactive Summary		Manual Summary Rollup		Finish-only	]	Deadline	⇩				
Milestone	◆	Inactive Task		Manual Task		Manual Summary		External Tasks		Progress					

APPENDIX B. BWR ROD ASSUMPTIONS

The BWR rod assumptions used to calculate the documented safety analysis include:

- nine BWR rods
- power at 25 MW/MTU constant for 2,000 days
- moderator at 40% void (0.4573 g/cm^3)
- achieving 50 GWd/MTU burnup
- isotopics simulation with ORIGAMI assuming GE10×10-8 design
- maximum 5% enrichment
- stack height of 370 cm
- stack density of 10.42 g/cm^3
- pellet radius of 0.438 cm
- U/UO$_2$ 0.8815
- stack volume of 1,966 cm^3
- initial ^{235}U 922 g