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Making the Case: Demonstrating the Integrity of Spent Nuclear Fuel During Long-term Storage and Subsequent Transportation

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ABSTRACT

The U.S Department of Energy (DOE), Office of Nuclear Energy (NE), Spent Fuel and Waste Science and Technology (SFWST) program is conducting R&D to gather data to assess the viability of long-term storage of commercial spent nuclear fuel (SNF), as well as transportation after storage. The goal of this research is to determine if SNF will maintain its integrity during long-term storage and transportation operations.

The SFWST program works collaboratively with organizations directly involved in the dry storage of commercial spent fuel. These organizations include the U.S. Nuclear Regulatory Commission, the DOE national laboratories, the Nuclear Energy Institute, the Electric Power Research Institute, utilities, cask and fuel vendors, industry contractors, international organizations, standards committees, and universities. This broad technical community ensures that the most important technical issues are being addressed and that the identified R&D priorities are defensible and directly related to the safe management of SNF.

Within this collaborative framework, work has been conducted to address material and mechanical properties of SNF and storage system components, environmental conditions that effect these systems, and load conditions that are expected to impact the storage and transportation components and the SNF directly. This approach allows for a composite assessment of spent fuel integrity given all the factors that affect the dry storage system and and the spent fuel directly.

Important insights across all technical fronts have been obtained that indicate SNF can be stored and transported safely, even after extended periods of storage.

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1.0 Introduction

The DOE initiated the R&D program to investigate the feasibility of long-term dry storage and subsequent transportation of commercial SNF in 2009 under the Spent Fuel and Waste Science and Technology (SFWST) program and its predecessors. Beginning in 2009, DOE took a deliberate step to partner with industry through the Electric Power Research Institute Extended Storage Collaboration Program (EPRI ESCP) to leverage technical expertise across the DOE laboratories and industry. The NRC also participates on ESCP which provides an important licensing perspective.

The initial effort of the SFWST was to conduct a technical gap analysis to help establish a path forward in a way that focused the R&D on issues directly affecting safety and licensing (Hanson 2012) of dry storage systems. As R&D progressed and understanding of the various degradation issues evolved, the identified gaps were revised to reflect the progress that was made. The initial SFWST focus was on cladding degradation and the affect that hydrogen had in the degradation process. However, based on results from this focusa, the remaining work on hydrogen effects on cladding degradation is of a confirmatory nature to ensure our current understanding of fuel behavior under relevant conditions. R&D that has increased in importance over the past several years is environmental effects on the degradation of the stainless steel canister used in the U.S. to dry store SNF. Two up-dated gap reports have been issued in 2019 to reflect these R&D priority changes (Hanson 2019a, Saltzstein 2019).

Identification of the technical gaps led to an engineering approach to assess the safety of SNF in extended dry storage and subsequent transport. In general, the high priority R&D work has focused on mechanical properties of irradiated SNF and the environmental conditions that affect specific degradation processes of the cladding, environmental conditions and manufacturing processes that affect the degradation processes of the stainless steel canisters used to dry store SNF, and regulatory mechanical loading conditions that create a dynamic response of the SNF during normal operational activities. Each of these focus areas will be discussed to show how the discrete areas of focused R&D have evolved to knit together a broad-based judgment that extended storage and subsequent transportation of SNF is safe.

The remainder of this report will be is formatted in sections as follows:

- Gap Analysis
- Cladding Mechanical Properties
- Thermal Loading on SNF
- Mechanical Loading on SNF
- Canister Environmental Investigations
- Conclusions

The overall SFWST R&D program is broader than what is represented in the above 5 focus technical areas. However, these five general areas have made the biggest impact on the judgment of the feasibility of demonstrating safety of SNF in dry storage for extended periods of time followed by transportation.

2.0 Gap Analysis

The initial gap analysis report was published in early 2012 (Hanson2012) after two years of focused study of technical gaps associated with the safety and licensing of SNF for extended storage. The high priority gaps were identified as:

- Hydride effects on SNF cladding
- Atmospheric and aqueous corrosion of stainless steel canisters used to dry store SNF for extended periods of time
- Atmospheric and aqueous corrosion of bolted casks
- Monitoring
- Temperature profiles
- Drying issues
- Subcriticality/Burnup credit
- Examination of fuel in the Idaho National Laboratory casks
- Fuel transfer options

Due to funding and priority assessments, the R&D focused on hydride effects on SNF cladding, atmospheric corrosion of the SS canisters (i.e., stress corrosion cracking), and temperature profiles. Aqueous corrosion of SS canisters was ranked lower in this category as funding limitations pointed to the need to immediately start work on the atmospheric corrosion. Bolted casks are not a large part of the U.S. fleet inventory, so work in this area was focused on a collaboration with the German Bundesanstalt fur Materialforschung und -Prufung (BAM) through Savannah River National Laboratory. Both organizations have a strong program in this area. Monitoring, while very important, was a focus for the industry effort through the ESCP program. Drying issues were addressed through the DOE Nuclear Engineering University Program (NEUP). The remainder of the high priority gaps were not initially funding based on ranking and available funding. This division of labor emphasizes the collaborative nature of managing a large portfolio of work in the most efficient manner possible. In addition, the multiple organizations, spanning government laboratories, industry, regulatory and foreign organizations provided a technical platform for rigorous review and final consensus.

The final two updated gap reports (Hanson2019a and Saltzstein2019) provide a re-assessment of the gaps and their relative rankings. Importantly, these reports recognize the progress made over the past 7 years and adjusted the ranking accordingly. The gap assessment in Hanson2019a covered R&D results through 2017. Significant progress has been made in both data collection and analyses to warrant an updated gap assessment. Saltzstein2019, while not yet published, has been through internal review and is ready for publication. Therefore, the high priority gaps in the SFWST program are:

- Thermal profiles
- Stress profiles
- Welded canister – atmospheric corrosion

Since Hanson2012, important progress has been made on several of the initial high priority gaps. In particular, work on irradiated SNF cladding properties and the forces affecting their degradation processes (e.g., thermal and stress profiles) have shown that SNF cladding will maintain its integrity for periods of extended storage. While work on cladding is on-going, the focus is on confirmatory work and building on the experimental database. Montioring and drying issues have made significant progress through industry and university efforts (EPRI for monitoring and NEUP for drying). While not complete, existing work has built a foundation for continued R&D to better direct near-term efforts.

Welded canister – atmospheric corrosion, has increased in priority due to the timing need to better understand the environment and the mechanisms that affect pit initiation and growth, conversion from pit corrosion to cracks, crack growth, and finally canister breach. Accelerated aging mechanisms are difficult to design for this type of mechanism. Therefore, long term testing is on-going to gather the needed data.

3.0 Cladding Mechanical Properties

Since 2009, a focus of the cladding work has been on obtaining ductility data on de-fueled irradiated cladding from Ring Compression Tests (RCT) that were developed by, and performed at, Argonne National Laboratory (ANL). Important parameters of these tests include; hydrogen content, temperature conditioning to represent the thermal spikes seen during drying when transferring fuel from wet to dry storage, and internal pressure in the fuel that creates the hoop stress that effects radial hydride reorientation during drying.

Figure 1, Billone2018, shows a representative RCT ductility test on irradiated Zirlo cladding as a function to temperature conditioning, hydrogen content, and hoop stress as induced from initial internal rod pressure. The 2% offset strain has been chosen as the transition from ductile to brittle behavior for this material Hydrogen content, stress, and temperature all play an important role in hydride effects on irradiated cladding.

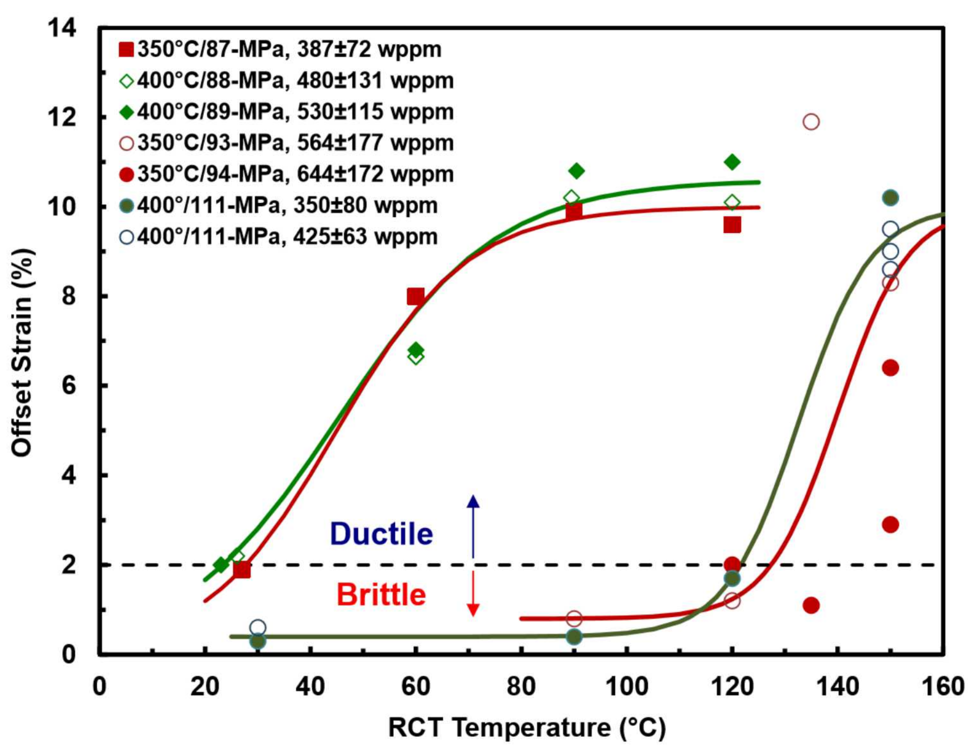

Figure 1. Zirlo® RCT Test Results

Regulatory thermal and stress limits have been suggested for the cladding in ISG-11.3 (NRC2003). This guidance limits the Peak Cladding Temperature during drying to 400° C and the hoop stress to 90 MPa. This provided the upper bound test conditions for temperature and stress for the RCT testing as shown in Figure 1.

Figure 2, Billone2018, shows the internal rod pressures as a function of burnup for irradiated fuels. EOL RIP has a direct effect on the hoop stresses induced in the cladding. Figure 2 indicates that for burnups up to 60 GWD/MTU, RIP remains below 5 MPa. This relates to a hoop stress of < 50MPa, well below the 90 MPa suggested as a limit in ISG-11.3. The lower RIP and resultant lower hoop stresses tend to shift the curves to the left in Figure 1, thereby lowering the 2% ductile to brittle transition behavior. This results in more ductility at temperatures of interest.

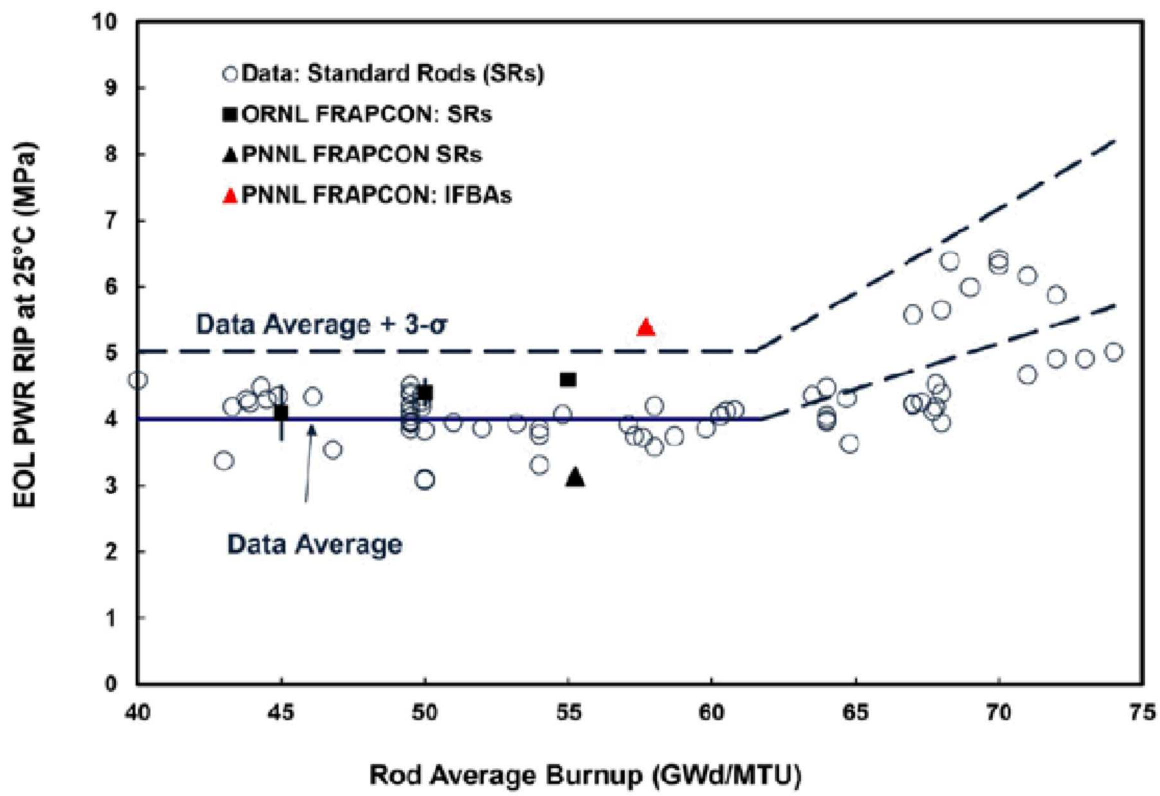

Figure 2. End-of-Life (EOL) Rod Internal Pressure (RIP) as a Function of Burnup

As a result of these tests, Billone2018 states; "Data collected during the past five years suggest that radial-hydride-induced embrittlement may not occur in standard PWR fuel-rod cladding because EOL RIP values (< 5 MPa at 25° C), PCTs (< 400° C), average gas temperatures (< 400° C), and average assembly discharge burnups (< 50 GWd/MTU) are all much lower than previously anticipated." The "average gas temperatures (<400° C)" cited in the above quote will be discussed in Section 4.0.

4. 0 Thermal Loading on SNF

As part of the SFWST program, DOE collaborated with industry to conduct a field demonstration of loading, drying, and dry storing high burnup spent fuel (EPRI2014). One goal of this demonstration was to obtain thermocouple data of commercial high burnup rods as they were transferred from pool storage to dry storage. The test was designed to represent current operational practices of transferring high burnup fuel to dry storage and to obtain important SNF cladding temperature data as the fuel underwent the transfer and during thermal stabilization at the on-set of dry storage. The first goal was to observe how close the cladding came to the 400° C temperature limit imposed by ISG-11.3. Secondly, the thermal data was used to benchmark modeling in order to use analyses to estimate overall fuel thermal behavior and to assess analytically the PCT.

Table 1 (Hanson2019b) shows the results of the analysis and testing data of the Peak Clad Temperature (PCT) of the hottest assembly (and associated fuel rod) loaded in the demonstration cask. The results were both positive and striking. The maximum PCT recorded from the thermocouple data was 229° C, well below the ISG-11.3 threshold of 400° C. While the modeling estimates varied, they did error on the high side. Actual PCTs were below all the modeling estimates. The last row in Table 1 refers to how gaps between materials in the cask may effect the heat transfer process. All the analyses modeled design drawing gaps in the cask. For the actual cask, manufacturing tolerances along with differential expansion of materials during the drying and stabilization process made in impossible to model the actual gap conditions within the cask.

Parameter	FSAR	LAR	Best-Estimate	HBU Cask Measurements
PCT (model vs data)	348°C	318°C	254-288°C	229°C
Heat Loadouts	36.96kW	32.934kW	30.456kW	30.456kW
Ambient Temperature	100°F	93.5°F	75°F	75°F
Design Specifics	Gaps	Gaps	Gaps	No Gaps?

Table 1. Measurement data and analytic estimates of PCT in the demonstration cask
FSAR: Final Safety Analysis Report
LAR: License Amendment Report

Implications from the results of this thermal work are significant as they have a direct effect on the performance of the SNF cladding in the dry storage and transportation operational environment. The lower PCTs mean:

- Less hydrogen is dissolved during the drying process. This means that less hydrogen is available to precipitate into a radial orientation during thermal stabilization thereby reducing the ductile-to-brittle transition effects on the cladding.
- The Rod Internal Pressure (RIP) is lower. This directly effects cladding hoop stress which is also a negative factor in hydride reorientation during the drying process.
- Industry loading of high burnup fuel have margin relative to the 400° C regulatory threshold.

These results are valid for the specific design of the demonstration cask; vertical, bolted lid, bare fuel storage. Other designs need to be evaluated to determine the specific thermal performance of the fuel based on the specifics of the fuel that is loaded and the design of the dry storage system. Benchmarking of the PCT data from the demonstration cask supports the ability to model other dry systems without having to perform testing for each specific vertical design.

For horizontal dry storage systems, SFWST is conducting thermal test on a simulated system to capture thermocouple data of surrogate spent fuel rods and gain a better understanding of thermal management of these systems. The data will also prove valuable for benchmarking computer models, as has been done for the vertical systems. Durbin2019 provides a detailed test plan for this work.

5.0 Mechanical Loading on SNF

The industry has a good understanding of how casks will behave under regulatory normal operations and hypothetical accident conditions. What is not well understood is how the fuel itself performs to these mechanical loadings. SFWST conducted a three-year program to understand fuel response to normal conditions of transport (NCT) loadings. These tests included shaker table tests that represented over-the-road vibratory and acceleration conditions, truck transport of a simulated assembly, and a multi-modal test including highway, ocean, and rail transport of a licensed cask with instrumented surrogate fuel assemblies. NCT conditions were selected for this test program because transport loadings under normal conditions are more severe that storage loading conditions.

Table 2 (Hanson2019b) show the results of this test program in terms of strain and accelerations on the surrogate fuel rods. The maximum recorded peak strain was 96 $\mu\varepsilon$. Measured yield strain data for irradiated SNF cladding is 7000-9000 $\mu\varepsilon$. NCT test data (including operational handling data) show that NCT loadings are well below the yield limit for the cladding. Work is still being evaluated for the NCT 30 cm drop loading condition (Larson2019).

	Highway	Ship	West Rail	TTCI	East Rail
Peak Strain (uE)	17	7.2	46	96	74
Peak Fuel Assembly Acc.	0.6	1.5	1.4	15.1	2.3
Peak Basket Acc	0.2	1.3	0.3	0.8	1.2
Peak Cask Acc	0.2	0.17	0.3	1.2	0.7
Peak Cradle Acc	0.2	0.17	0.6	6	2.8
Peak Deck Acc (ends/mid)	15/5	1.6	8/0.9	27/7	24/5

Table 2. Peak Strain and Acceleration Data from the Multi-modal Test Program

West Rail – rail data from Baltimore to Pueblo, CO.
TTCI – Transportation Technology Center, Inc. (Pueblo, CO)
East Rail – rail data from Pueblo, CO to Baltimore

The NRC and the DOE SFWST programs also sponsored laboratory testing at Oak Ridge National Laboratory to obtain structural response data on real high burnup spent fuel. This data is significant because it provides response characteristics of the irradiated cladding with the fuel as it came out of the reactor. Results have shown the fuel system (i.e., irradiated cladding with the fuel) provides added stiffness to the fuel rod, thereby increasing its strength during mechanical loading events.

Figure 3 shows a fatigue-type diagram (cladding strength vs. loading cycles) relating the ORNL data with other, earlier tests to understand how SNF cladding responds, as a class of material, to mechanical loadings. The heavy black line represents a failure line, above which failure may be expected to occur. The ORNL data is represented by the green and red circles, green indicating no failure and red indicating failure. Fig. 3 shows no experimental data falling below the heavy black line which validates it to be a good metric for a failure criterion. Importantly, the multi-modal test data is represented by the horizontal red line with the associated number of loading cycles estimated for the indicated tests. The loading maximum, 1300 psi, for all the tests up to a million cycles indicate that the maximum stress of 1300 psi is well below the failure threshold indicated by the heavy black line.

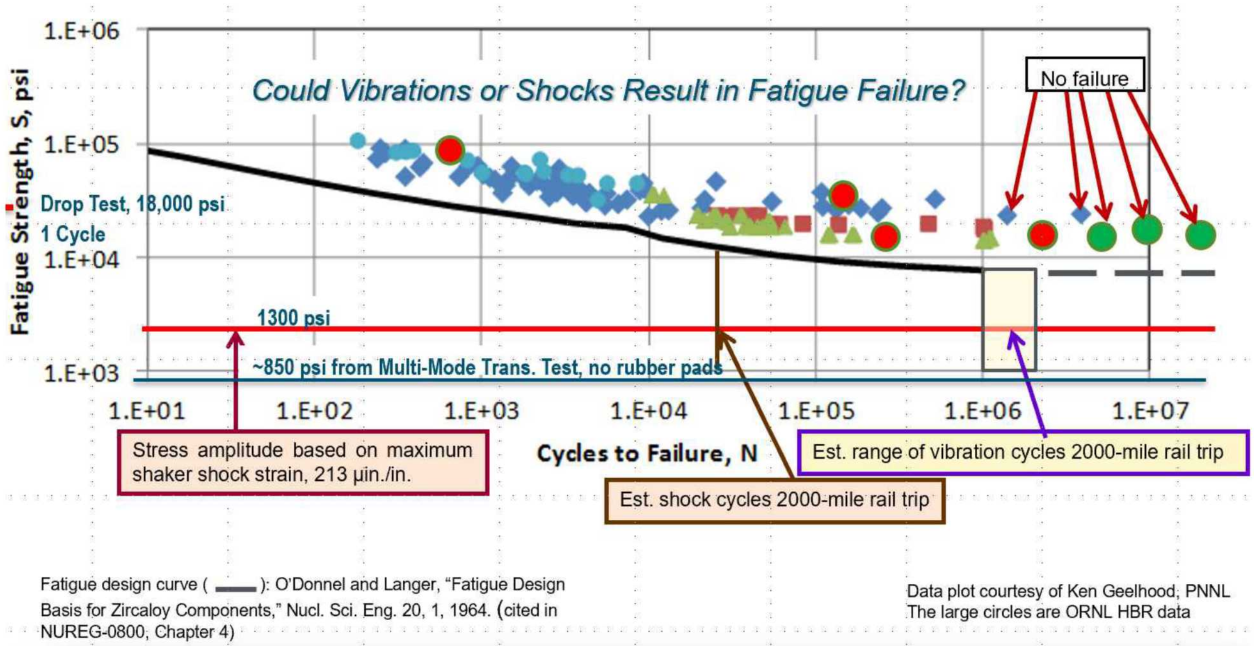

Figure 3. Strength vs. Loading cycles for Spent Fuel Cladding

Current work in this area is focused on developing an expanded database of important clad properties and behavior under stipulated mechanical and thermal loading conditions. This work is being conducted in hot cell laboratories at PNNL and ORNL under the SFWST program. Detailed discussions of this program is provided in Shimskey2019 and Montgomery2019.

6.0 Canister Environmental Investigations

The potential for dry canister degradation through chloride-induced stress corrosion cracking (CISCC) is an important degradation mechanism that is in a relatively early R&D investigation stage. This an important technical gap, particularly at storage sites located near a marine environment. While this gap is not directly associated with the SNF, it is a safety component associated with the overall dry storage system of much of the U.S. fleet.

SFWST has conducted a multi-year R&D program focused on better understanding of this important gap. Figure 4 (Bryan2018) provides a timeline of the CISCC degradation process as well as the organizations involved in performing the various parts of the R&D test program. As shown in Fig. 4, there are several degradation processes that must be evaluated separately to understand how the degradation mechanisms on the canister perform as a whole. That is, how long, and under what conditions is it necessary to initiate CISCC and to eventually produce a through-wall crack in a dry storage canister? A focus of the current R&D work is to assess both the chemical and physical environments on the canister surface, as well as how the relationship between these two environments act to affect the corrosion processes.

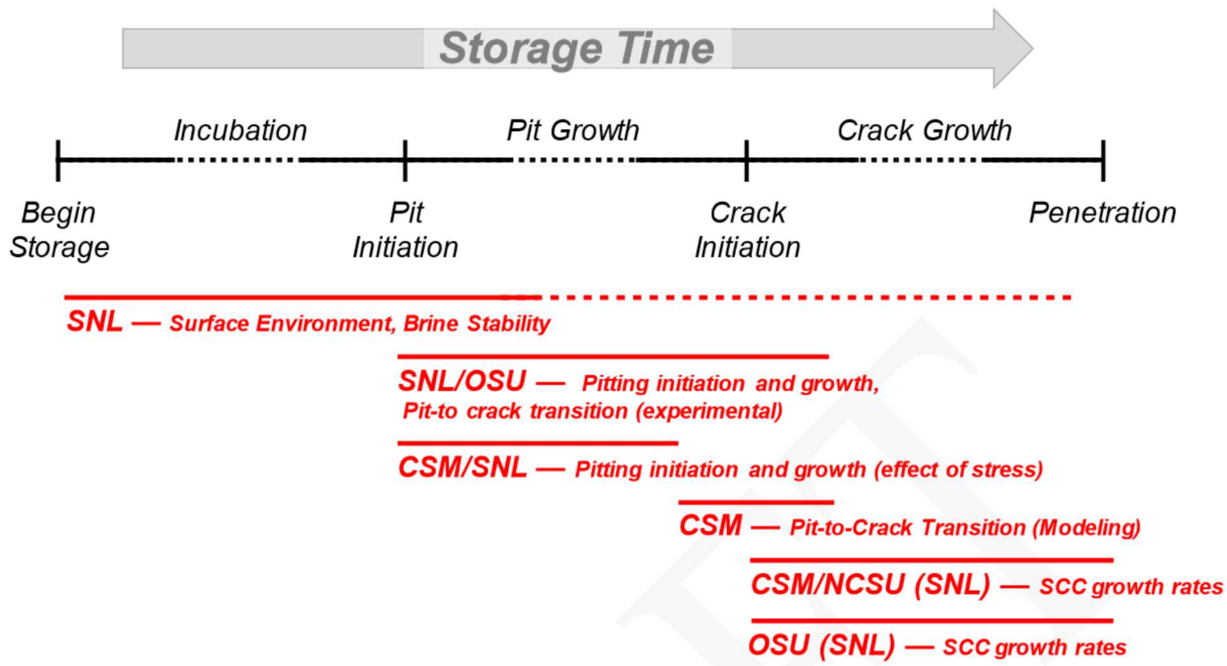

Figure 4. Timeline for stress corrosion cracking, showing current experimental work being carried out by SNL and collaborators

CSM – Colorado School of Mines
NCSU – North Carolina State University
OSU – Ohio State University
SNL – Sandia National Laboratories

7.0 Conclusions

The SFWST program, in conjunction with collaborators from the U.S NRC, industry, and universities, has made substantial progress over the last 7 years in assessing safety of SNF under extended storage and transportation conditions. Given important data obtained and confirmatory analyses that have been made to date, a general assessment can be made the high burnup fuel can be safely stored for extended periods of time and subsequently transported. This assessment has been validated by the NRC in their draft regulatory guide, NRC2018.

Given this assessment, there is still important work needed to be done to better understand canister CISCC and thermal management of various dry storage systems, and to develop an expanded data base of cladding behavior as is being done under the sister pin testing programs at PNNL and ORNL.

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