Gap Analysis to Guide DOE R&D in Supporting Extended Storage and Transportation of Spent Nuclear Fuel: An FY2019 Assessment

Spent Fuel and Waste Disposition

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

Melissa Teague[1], Sylvia Saltzstein[1], Brady Hanson[2], Ken Sorenson[3], Geoff Freeze[1]

[1]Sandia National Laboratories
[2]Pacific Northwest National Laboratories
[3]Sandia National Laboratories, Retired

December 23, 2019

SAND2019-15479 R

Sandia National Laboratories

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy National Nuclear Security Administration under contract DE-NA0003525.

SUMMARY

The U.S. Department of Energy (DOE), Office of Nuclear Energy (NE), Spent Fuel and Waste Science and Technology (SFWST) program is performing research and development (R&D) in a number of areas related to the storage, transportation, and disposal of spent nuclear fuel (SNF) and high-level radioactive waste. R&D under the Storage and Transportation control account is addressing issues of extended or long-term storage and transportation of commercial SNF, with a focus on high-burnup (HBU) fuels.

This report is a condensed version of previous reports (Hanson et al. 2012 and Hanson and Alsaed 2019) identifying technical gaps that, if addressed, could be used to ensure the continued safe storage of SNF for extended periods and support licensing activities. This report includes updated gap priority assessments because the previous gap priorities, from Hanson and Alsaed (2019), were based on R&D performed through 2017. Much important work has been done since 2017 that requires a change in a few of the priority rankings to better focus the near-term R&D program. Background material, regulatory positions, operational and inventory status, and prioritization schemes are discussed in detail in Hanson et al. (2012) and Hanson and Alsaed (2019) and are not repeated in this report. One exception is an overview of the prioritization criteria for reference. This is meant to give the reader an appreciation of the framework for prioritization of the identified gaps. A complete discussion of the prioritization scheme is provided in Hanson and Alsaed (2019).

Table ES-1 provides the updated list of the highest priority technical gaps (Priority 1-3 in 2019) along with previous priorities from 2012 (Hanson et al. 2012) and 2017 (Hanson and Alsaed 2019). Three changes have been made between 2017 and 2019; these are highlighted in red. These are significant and reflect the progress made in post-2017 R&D work, as well as the operational status that affects how the DOE will manage SNF in transportation, additional storage (if applicable), and disposal.

The focus for R&D funding will remain on the Priority 1-3 gaps. These gaps are summarized below and detailed in Section 3. Lower priority gaps (Priority 4 and below) are also discussed in Section 3. An overview of near-term R&D plans is provided in Section 4. Work on lower priority gaps may still occur as funding and specific opportunities arise.

Table ES-1. List of Highest Priority Gaps

Gap	2019 Priority	2017 Priority	2012 Priority	Comments
Thermal Profiles	1	1	1	No change in priority
Stress Profiles	1	1	1	No change in priority
Drying Issues	2	2	6	No change in priority
Monitoring - External	3	3	2	No change in priority
Welded Canister – Atmospheric Corrosion	1	3	2	Change in priority due to near-term need to acquire stress corrosion cracking (SCC) data
Cladding – H_2 Effects: Hydride Reorientation and Embrittlement	3	3	7	No change in priority
Consequence Assessment of Canister Failure	3	N/A	N/A	New gap to assess radiological risk due to loss of confinement caused by SCC
Fuel Transfer Options	3	4	3	Change in priority due to need for data for surface storage facility design

Thermal Profiles (Priority 1) – Degradation mechanisms for materials in dry cask storage systems (DCSSs) are temperature dependent. Industry models used to calculate temperatures tend to predict temperatures higher than directly measured. Ongoing work to close this gap includes identifying uncertainties, biases, and sensitivities that can improve the realism of the models. Corresponding validation experiments will also be executed. Recent models of a vertically-oriented dry cask simulator predicted temperatures within ~1-20°C of the measured values. Improved modeling of the demonstration cask from the HBU Spent Fuel Data Project (EPRI 2014c) predicted peak cladding temperature (PCT) within 30°C. In addition, testing is planned for a horizontally-oriented dry cask simulator to support measurement and modeling of temperature profiles.

Stress Profiles (Priority 1) – Structures, systems, and components (SSCs) such as cladding and assembly hardware may be subjected to stresses from external loads (forces, strains, accelerations, etc.) during storage and transportation. A number of transportation tests, including truck, rail, and ship, have been performed on surrogate assemblies, with massive amounts of strain and acceleration data captured for surrogate fuel, assemblies, baskets, casks, and cradles. Ongoing work includes modeling of cladding thinning and pinch loads and a 30 cm drop test.

Welded Canister Corrosion (Priority 1) – Three main parameters have been shown to affect stress corrosion cracking (SCC): environment (salt content, salt stability, humidity, and temperature); material (stainless steel (SS) 304/304L is used in dry storage canisters); and loading (high tensile stresses in weld zones could support through-wall SCC). Surface samples from canisters at several different sites indicated soluble salt deposition, but the concentrations varied widely, and the presence of corrosion-inducing chloride also varied widely. Four-point bend tests on SS 304L coupons loaded with sea salt did not indicate enhanced pitting densities as a function of stress. Ongoing work will continue to focus on the three main parameters. This includes (1) quantifying the brine stability of salts present in the environment, (2) understanding material and surface environment effects on electrochemistry and pit formation, and (3) tensile stress tests to identify characteristic features controlling pit-to-crack transition. A major push will be to evaluate pit formation and SCC initiation and growth rates (i.e., pit-to-crack transition) as a function of environmental parameters (salt load, temperature, and salt/brine composition), material properties (e.g., degree of sensitization, surface roughness, degree of cold work), and stress state and to investigate the consequences of gas and particle transport in through-wall cracks.

Drying Issues (Priority 2) – Anecdotal evidence and samples from the HBU Spent Fuel Data Project demonstration cask suggest that residual water (free and/or chemisorbed and/or physisorbed) remains in canisters after standardized drying/purging procedures. The presence of small amounts of water does not cause immediate concern, however, and additional testing and sampling is necessary to better understand the impacts, if any, of the residual water.

Monitoring (Priority 3) – The focus is on robotic- and sensor-based non-destructive examination (NDE) techniques to detect SCC of canister welds.

Cladding Hydride Effects (Priority 3) – Recent testing indicates that risks associated with hydride reorientation and embrittlement to pressurized water reactor (PWR) cladding integrity are low for current fuel designs, burnups, and reactor operational limits. More data on hydride effects for boiling water reactor (BWR) and Integral Fuel Burnable Absorber fuel (IFBA) cladding is needed.

Consequence of Canister Failure (Priority 3) – The focus is to develop technically defensible assessment of gaseous and particulate releases and radiological consequences through SCC breaches.

Fuel Transfer Options (Priority 3) – Data is needed to support facility design concept for opening a cask for inspection and transfer/repackaging.

ACKNOWLEDGEMENTS

The authors would like to acknowledge and thank the many people who contributed to this report, both those named here and any other who have been a part of this effort.

First, we thank our U.S. Department of Energy Office of Nuclear Energy sponsors Bill Boyle, Ned Larson, Timothy Gunter, and Nancy Buschman.

Second, we would like to thank our Spent Fuel and Waste Science and Technology National Technical Director, Peter Swift, and the work package leads, Brady Hanson (Experiments), John Scaglione (Analysis), Elena Kalinina (Transportation), Sam Durbin (Security) and all the people performing the research, analysis, and writing to get us to where we are today.

Finally, we thank Philip Honnold for technical review.

This page is intentionally left blank.

CONTENTS

LIST OF TABLES

ACRONYMS

BWR	boiling water reactor
CIRFT	cyclic integrated reversible-bending fatigue test
CISCC	chloride-induced stress corrosion cracking
DCSS	dry cask storage system
DHC	delayed hydride cracking
DOE	Department of Energy
ENSA	Equipos Nucleares Sociedad Anónima
EPRI	Electric Power Research Institute
ESCP	Extended Storage Collaboration Program (EPRI)
HAC	hypothetical accident conditions
IFBA	Integral Fuel Burnable Absorber
IRP	Integrated Research Program
ISG	Interim Staff Guidance
ISFSI	Independent Spent Fuel Storage Installation
ITS	important to safety
NCT	normal conditions of transport
NDE	non-destructive examination
NE	Office of Nuclear Energy
NEUP	Nuclear Energy University Programs
NRC	Nuclear Regulatory Commission
PCT	peak cladding temperature
PWR	pressurized water reactor
R&D	research and development
RAI	request for additional information
RCT	ring compression test
SCC	stress corrosion cracking
SNF	spent nuclear fuel
SFWST	Spent Fuel and Waste Science and Technology
SSC	structure, system, and component

This page is intentionally left blank.

1. INTRODUCTION

1.1 Background and Purpose

The U.S. Department of Energy (DOE), Office of Nuclear Energy (NE), Spent Fuel and Waste Science and Technology (SFWST) program is performing research and development (R&D) in a number of areas related to the storage, transportation, and disposal of spent nuclear fuel (SNF) and high-level radioactive waste. R&D under the Storage and Transportation control account is addressing issues of extended or long-term storage and transportation of commercial SNF, with a focus on high-burnup (HBU) fuels.

In 2009, the government ceased licensing activities for the planned Yucca Mountain repository. At that time, it became clear that SNF would need to be stored at the reactor sites longer than had been originally planned, in many cases exceeding the original storage license timeframes granted by the U.S. Nuclear Regulatory Commission (NRC). Immediate questions arose concerning the integrity of the spent fuel being stored for extended periods of time. What would the licensing criteria be for granting extended storage timeframes? What are the degradation processes of SNF and how do they affect fuel integrity in dry storage environments and subsequent transportation? What are the mechanical and thermal loads imparted to SNF during storage and transportation? Could these loads jeopardize spent fuel integrity in their potentially degraded condition? Can SNF be safely transported after extended storage? These, as well as many other technical issues became the focus for a new R&D program initiated by the DOE in 2009 to address SNF long term storage and transportation. As part of this effort, DOE is collaborating with private industry to maximize the R&D effort in a way that focuses the R&D on work that has the biggest impact on licensing for extended storage and subsequent transportation.

The initial part of this R&D effort was to research the current state of knowledge with respect to SNF degradation, dry storage designs, regulatory and operational loadings imposed on these structures, and environmental conditions that may affect the degradation processes and resultant integrity of the spent fuel. This effort led to identification of gaps in the knowledge base. These gaps were then prioritized and ranked. The first gap analysis report (Hanson et al. 2012) listed 26 high and medium priority gaps that needed to be addressed. These gaps and associated rankings were corroborated by industry and the NRC through a peer review process. The focus of the early R&D was on selected high priority gaps and specifically on cladding degradation over extended periods of time. As the R&D program worked through the early issues, significant progress was made, the knowledge base deepened, and a better understanding of degradation processes developed. Over time, the gap analyses and ranking changed due to this increased knowledge. A second gap analysis report (Hanson and Alsaed 2019) reflects this advancement in the knowledge base. The Hanson and Alsaed (2019) report was published in January of 2019, but the rankings were based on R&D progress only up to 2017. During the five years between these two reports, the number of "high" and "medium" ranked gaps was reduced to 15 from 26. In the past two years, significant progress has been made in quantifying loads (stress profiles) during normal conditions of transport (NCT), results have been attained from the HBU Spent Fuel Data Project (thermal profiles and residual water content in a dry storage canister), and important work in inspection and mitigation of canisters juxtaposed with two private initiatives to license, build, and operate consolidated interim storage facilities, all point to the need to update the gap analysis and prioritization of technical issues associated with extended dry storage and transportation.

Considering this progress, the purpose of this report is to provide an updated view of the gap analysis and associated prioritization of these identified gaps. As progress has been made on the R&D work and as operational aspects and policy initiatives have evolved, one new gap has been identified (radiological consequence of a through-wall crack in a canister) and a re-ranking of several existing gaps have been made.

The focus of this report is on the high and medium ranked gaps, now identified by Priority 1-4. The low ranked gaps are also identified, but significant work is not planned for them in order to properly address the high and medium ranked gaps.

1.2 Criteria for Identifying and Prioritizing Gaps

The following subsections are reproduced nearly verbatim from Hanson and Alsaed (2019, Sections 4.3 and 4.4).

1.2.1 Data Gap Analysis and Ranking Approach

A systematic approach was used to identify gaps in the technical bases for extended storage of used nuclear fuel (in Independent Spent Fuel Storage Installations (ISFSIs)), for storage and transportation of low-burnup fuel after dry storage, and for transportation of HBU fuel. Dry cask storage systems (DCSSs) are divided into ten structure, system, and component (SSC) groups: fuel, cladding, fuel assembly hardware, fuel baskets, neutron poisons, neutron shields, welded canister, metal cask, concrete overpack or storage module, and pad. Transportation systems are divided into eight SSC groups: fuel, cladding, fuel assembly hardware, fuel baskets, neutron poisons, neutron shields, welded canister, and casks. To identify the data gaps, the following information was evaluated:

1. For each SSC, determine which safety functional areas are directly impacted or supported.
2. For those functional areas for which the SSC failure does not result in a direct impact, determine whether the SSC's failure or changes in its chemical or physical properties could cause changes in other SSCs, which in turn could impact any of the safety functional areas.
3. For the directly or indirectly impacted safety functional areas, define how the SSC and potential degradation of the SSC affect the safety functions.
4. For each degradation definition, determine the specific degradation modes.
5. For each of four stressors (thermal, radiation, chemical, and mechanical) that contribute to the specific degradation mode identified in step 4, list the specific degradation mechanisms.
6. For each degradation mechanism–SSC combination, identify what is known, what information is lacking, and the importance of new research for extended dry storage and transportation.

Several factors influence the basis for ranking R&D needs to address the data gaps as Low, Medium, or High. To assign a rank, the following questions (presented as criteria) were answered for every identified degradation mechanism:

1. (Data Needs) Is there sufficient data to evaluate the degradation mechanism and SSC performance?
2. (Regulatory) What are the current regulatory considerations?
3. (Likelihood of Occurrence) What is the likelihood of occurrence of the degradation mechanism warranting evaluation of impact on safety functions?
4. (Consequences) What are the consequences of the degradation mechanism?
5. (Remediation) Can the SSC be remediated or managed in an aging management program?
6. (Cost and Operations) Would any costly design and operational difficulties be endured due to the degradation mechanism?
7. (Waste Management Strategies) Would the degradation mechanism limit or complicate future waste management strategies?

Each SSC-specific gap was ranked High, Medium, or Low after assessing the work done by SFWST, including work done by universities under the Nuclear Energy University Program (NEUP)/Integrated Research Program (IRP) grants, NRC, Electric Power Research Institute (EPRI)/Industry, and internationally since 2012 and seeing how this work has affected the answers to the seven questions (criteria). The new rankings were then used to develop a new prioritization.

In addition to the SSC-specific gaps, additional data needs are cross-cutting and could affect multiple important to safety (ITS) SSCs. These cross-cutting needs are important to understanding and evaluating the extent of some of the degradation mechanisms of the ITS SSCs or to providing an alternate means of demonstrating compliance with specific regulatory requirements. These cross-cutting gaps were identified in Hanson et al. (2012) and were also ranked High, Medium, or Low.

1.2.2 Data Gap Prioritization

Once the data gaps were identified and ranked (Low, Medium, High), the Medium and High rank gaps were prioritized so that the limited resources could be best directed to support those gaps that need to be addressed first and are of most importance to a successful program. In order to develop the appropriate prioritization criteria, it is important to identify the relevant considerations for the proposed R&D. The two primary considerations are the timing of data needs and the importance to licensing or to program development. The priorities and rankings reflect the needs of the DOE-NE program, with a focus on the entire waste management cycle including potential for interim storage, repackaging, and geologic disposal; it is possible that the priorities reflecting the needs of the U.S. nuclear industry or of regulatory agencies may be different.

1.2.3 Timing of Data Needs

A wide temporal range was considered in the initial prioritization report (UFDC 2012a), which was necessitated by several factors, including:

- Several license renewals were ongoing with open issues identified in yet-to-be-resolved requests for additional information (RAIs)
- The need to start a demonstration project to support extended storage of high burnup SNF
- The limited data available at the time and the uncertainty of how ongoing activities would impact near-term and long-term performance considerations and licensing needs
- The uncertainty of the collected data would be used in the near-term versus the long-term
- Several NRC guidance documents including Interim Staff Guidance (ISGs) (e.g., ISG-8 for burnup credit (NRC 2012), ISG-2 for retrievability (NRC 2016c)) and NUREGs (e.g., NUREG-1927 (NRC 2016b)) were being revised with potential impacts on data needs
- The uncertainty in program direction regarding length of extended storage, timing of transportation, interim storage, disposability, reprocessing, repackaging, etc.

Over the past five years, several of the timing of data needs issues were initiated or addressed, including:

- The start of the HBU Spent Fuel Data Project (also referred to as the HBU Demo Project) (EPRI 2014c)
- Evaluation of stress profiles under NCT for various transportation modes
- Inspections and single effects tests and studies for several SSCs including canister welds and cladding
- ISG-2, Rev. 2 (NRC 2016c) issuance allowing the definition of retrievability at the canister level as opposed to the fuel assembly (or damaged fuel can) level.
- Issuance of ISG-8 Rev. 3 (NRC 2012) with guidance for “full” burnup credit for pressurized water reactor (PWR) SNF

- Several storage license renewals were approved for both low- and high-burnup SNF
- Several transportation casks for transporting HBU fuel on the basis of moderator exclusion under hypothetical accident conditions (HAC) were approved that took credit for the inner lid (HI-STAR 180) or the welded canisters (MP197HB) as a second barrier per ISG-19 (NRC 2003).

Based on this progress, the timing needs have been reduced from ten in the initial prioritization report (UFDC 2012a) to the following four:

- Prerequisite to addressing other gaps necessary to define the ranges of conditions to which SSCs are subjected during storage and transportation
- Near-term needs such as data to support renewal of dry storage licenses beyond 20 years or transportation of low-burnup fuel after a period of storage as well as transportation of HBU fuel
- Long-term needs such as data to support extended storage beyond the initial renewal period
- SNF management lifecycle needs including interim storage and disposal, which may involve multiple storage and transportation cycles (generally referred to as 72-71-72-71-63, after relevant Parts of the Code of Federal Regulations), repackaging of the SNF, and disposal of existing canisters.

1.2.4 Importance to Licensing

Seven criteria were considered in obtaining a rank for the SSC-specific gaps, as identified in Section 1.2.1. Only the High and Medium rank gaps were selected for prioritization; two criteria rated High for all these gaps: Data Needs and Regulatory. Thus, these are not discriminators for prioritization. The criterion, Cost and Operations, was determined to be too subjective and is not considered in the prioritization analysis. Waste Management Strategies was considered separately from importance to licensing. An additional criterion, Alternatives, was considered but not included because it was not a discriminator. Alternatives exist for almost all gaps, although the alternative may require regulatory changes that cannot be assumed. Thus, three criteria remained and were used to determine the importance to licensing of the SSC-specific gaps: Likelihood of Occurrence, Consequences, and Remediation. The importance to licensing of the cross-cutting gaps is not as straightforward as with the SSC-specific gaps. A subjective prioritization of importance for each was made for each gap.

Metrics for each of the criteria were established in the initial prioritization report. These metrics are not re-evaluated in this report.

1.2.5 Prioritization

The timing needs and importance to licensing established for each gap are combined to compare and prioritize the gaps. Timing needs is given more weight than importance to licensing because program success is defined as having the data to support licensing in time for that specific licensing activity. That is, a data need with a prerequisite need must be addressed first, followed by near-term needs and then long-term needs. Taking these considerations into account, the initial prioritization report (UFDC 2012a) included 13 prioritization criteria. That level of resolution was warranted due to the wide range in timing of data needs as well as the status of the program, industry needs, and ongoing NRC reviews at the time. Based on the progress made thus far, only four prioritization criteria based on the timing needs remain as discriminators across the gaps, which are:

A = Prerequisite to addressing other gaps, for defining the ranges of conditions to which SSCs are subjected during storage and transportation.

B = Near-term High importance needs such as data needed to support renewal of dry storage licenses beyond 20 years or transportation of low-burnup fuel after a period of storage as well as transportation of high-burnup fuel.

C = Long-term High importance needs such as data needed to support extended storage beyond the initial renewal, transportation and storage of SNF at an interim storage facility, repackaging SNF for disposal.

D = Long-term Medium importance such as data that may be needed for special conditions (e.g., specific ISFSI, specific cladding type, a specific canister design) or data that may facilitate a broader range of licensing options.

The relative prioritization of the R&D to address the data gaps is based on the highest importance criteria for which the R&D is needed; a combination of lower importance criteria could not result in a higher priority. For example, a gap that is ranked High and has both a near-term ("B") and a long-term ("C") importance for data is graded as "BC" and results in a higher prioritization than a gap that is ranked High but only has a near-term importance "B". Similarly, a "BC" has a higher priority than a "BD", which has a higher prioritization than a "CD".

1.3 Format for the Remainder of the Report

A summary of each high and medium ranked gap is presented, followed by a very brief summary of the work performed since 2012, building on the review provided by Hanson and Alsaed (2019) and Stockman et al. (2015). The new rank for the gap is then determined and a description of the remaining work is given. Since the issuance of Hanson et al. (2012), SFWST has focused its R&D efforts on the higher priority gaps with an emphasis on testing and modeling realistic conditions, especially for temperature profiles and stress profiles.

This page is intentionally left blank.

2. IDENTIFIED GAPS IN ORDER OF PRIORITY

These tables list priority and rank as equivalent, based on the discussion in Section 1.2, reflecting the needs of the DOE-NE program, with a focus on the entire waste management cycle including potential for interim storage, repackaging, and geologic disposal. High, Medium, and Low priority gaps are part of the lexicon in this and in past reports. For the purposes of the following tables, High and Medium priority gaps are associated with the listed Priority 1-4 gaps. Priority 1-3 gaps have funding plans that define work to address the gaps. Priority 4 and below gaps have no specific plans for R&D, except whenever a unique opportunity presents itself to perform the work. It is possible that the priorities reflecting the needs of the U.S. nuclear industry or of regulatory agencies may be different. Red font in the 2019 rankings in the table below indicates a change from the 2017 ranking.

2.1 Priority 1 Gaps

Table 2-1. Temperature Profiles

Gap	2019 Rank	2017 Rank	2012 Rank	Recommended R&D for the Next 3 Years
Temperature Profiles	**1**	**1**	**1**	**Ranking unchanged. R&D Ongoing**
	What we have learned: Nearly all degradation mechanisms for materials and structures comprising dry storage and transportation systems are dependent on temperature and industry typically employs conservative or bounding assumptions and models when calculating temperature to provide assurance that the SSCs remain below regulatory allowable maximum temperatures. Significant progress in both modeling and experimental efforts has been made in this area over last several years in determining more accurate thermal profiles. A blind round robin validation exercise with participation from Sandia National Laboratories (SNL), the NRC, Pacific Northwest National Laboratory (PNNL), Centro de Investigaciones Energeticas, Medioambientales y Techologicas (CIEMAT), and Empresa Nacional del Uranio, S.A. (ENUSA) was able to calculate the measured temperatures inside the vertical dry cask simulator within ~1-20 °C (Pulido et al. 2019), though all were biased higher. Additionally, the HBU Demo Project cask was loaded in November 2017 giving first-of-a-kind predicted temperature data for an as-loaded dry storage cask, including drying operations to near steady state conditions. The temperatures were significantly lower (by 111°C) than the peak temperature calculated by industry using standard conservative practices (TN Americas 2017; Hanson 2018). PNNL conducted a best practice attempt at modeling the temperatures within the HBU Demo Project cask and was able to model within 30°C of the peak cladding temperature (PCT), but again biased higher (Fort et al. 2019).			
	What we still need to learn to close this gap: Work is planned using a dry cask simulator to study the impact of horizontal orientation on temperature profiles inside dry casks. Additionally, more modeling work is needed to better capture and predict the temperatures inside a real cask, specifically a more accurate and widely accepted methodology for calculating decay heat transfer through the system without excess conservatism.			

Table 2-2. Stress Profiles

Gap	2019 Rank	2017 Rank	2012 Rank	Recommended R&D for the Next 3 Years
Stress Profiles	**1**	**1**	**1**	**Ranking unchanged. R&D Ongoing**
	What we have learned: SSCs may be subjected to external loads (forces, strains, drops, etc.) during storage and transportation. A problem state may exist before a failure occurs. Multiple experimental tests have been performed: 1) a mock 17x17 PWR assembly equipped with strain gauges and accelerometers was subjected to a shaker table to simulate a truck-journey (max strain was 212 microstrain; the elastic limit of Zircaloy-4 is ~7,000 microstrain). 2) the same assembly was placed on a truck and driven throughout Albuquerque, New Mexico (max strain was 143 microstrain). 3) Rail and truck loadings were simulated (max strain was 301 microstrain). Modeling and analyses were performed for each test, and the modeled max strain significantly above test results (744 and 323 for tests 1 and 2). Modeling results indicate a 30cm drop would cause microstrain one order of magnitude greater than that from a truck journey. A large-scale multimodal transportation test was also performed, involving multiple instrument-laden surrogate assemblies. The basket, cask, and cradle were also instrumented. This involved a 395 km drive (in Spain), transportation by both coastal and ocean-going vessel, and shipping by rail. Massive amounts of data were generated in this venture. Modeling was also performed on cladding thinning, cask tipover, stress corrosion crack propagation (in a tipover scenario), handling drop, and seismic response.			
	What we still need to learn to close this gap: 5 major activities are to be completed: 1) Complete the multimodal transportation test and analyze data. Data will be used to guide future modeling ventures and follow-up tests. 2) Conduct 30cm drop tests of Equipos Nucleares Sociedad Anónima (ENSA) cask and SNL surrogate assembly. 3) Develop tests and models to study pinch loads, to validate premise that pinch loads are insufficient to compromise cladding integrity. 4) continue modeling and testing on SSC's. 5) Develop a cumulative effects model for each SSC, to determine how much degradation can occur before failure.			

Table 2-3. Welded Canister - Atmospheric Corrosion

Gap	2019 Rank	2017 Rank	2012 Rank	Recommended R&D for the Next 3 Years
Welded Canister - Atmospheric Corrosion	1	3	2	**Increased priority due to a timing need to acquire SCC data to support experimental initiatives that will help define the path forward and to address increasing community concerns**
	What we have learned: There has been significant work done in this area over the past five years resulting in a few general observations to become clear. First, this is not a technical area that is amenable to time-accelerated types of tests. Second, proper conservative bounding of test parameters needs careful consideration due to the interaction of all processes that may affect the results. Third, there is no standard test specimen, or accepted test procedure, to conduct stress corrosion crack propagation tests under atmospheric conditions. Lastly, understanding and quantifying the progression of stress corrosion crack initiation and growth (deliquescence, general corrosion and pit initiation, pit growth, crack initiation, and crack growth) is critical in defining an operational framework for inspection, mitigation, and repair of canistered systems. Because of these issues, this gap has moved up to a "1" ranking. EPRI published an initial report that defines a process to evaluate the on-site condition of canisters that have been stored for extended periods of time (EPRI 2015). This report was written before much data was available to quantify corrosion processes. Much work has been conducted since then and is discussed based on the three main parameters affecting corrosion: environment, material, and loading (e.g., stresses). 1) Environment: Salt content, salt stability, humidity, and temperature all play important roles in corrosion, crack initiation, and crack propagation in canistered systems. Under the sponsorship of EPRI, there have been 7 site visits (to 4 different plants: Calvert Cliffs, Diablo Canyon, Hope Creek, and Maine Yankee) to assess the amount of general corrosion (visual inspection) and salt loadings deposited on the canisters. In general, there was no indication of any noteworthy corrosion on any of the inspected canisters. After analyzing samples, soluble salt deposition was confirmed at all sites, but the surface concentration of salts varied widely over the canister surface at each site. The amount of corrosion-promoting chloride also varied widely between sites. At the Diablo Canyon site in California, salt loads were low (the sampled canisters were not long in storage), but the salts were dominantly chloride-rich sea-salt aerosols (Bryan and Enos 2014). At other sites sampled, on the U.S. east coast (Calvert Cliffs (Enos et al. 2013), Hope Creek (Bryan and Enos 2014; Bryan and Enos 2015b), and Maine Yankee (Bryan and Enos 2016; Bryan and Enos 2017a; Bryan and Schindelholz 2018), chloride was present, but the soluble salts were dominated by sulfate and nitrate salts. Typical sea-salt aerosols were not observed, and measured chloride surface loads were low. Salt load is an important risk factor for stress corrosion cracking (SCC) and the low chloride salt loads are a positive factor indicating potentially lower risk than previously assumed. The potential role of other soluble components (e.g., sulfates and nitrates) is not known (Bryan and Schindelholz 2018).			

While chloride salts may be deposited on the surface of SNF storage canisters, the timing of deliquescence of those salts and the stability of the resulting brines on a heated canister surface is the subject of current research. Brine stability experiments at SNL have shown that some important salt phases, including ammonium minerals and magnesium chloride, the most deliquescent component in sea-salts, are not stable at elevated temperatures, potentially limiting the conditions at which a deliquescent brine can form, and corrosion can occur (Enos and Bryan 2016b; Bryan and Enos 2017a; Bryan and Schindelholz 2018; Bryan et al. 2019c).

2) Material: There has been much research associated with the corrosion of stainless steel. Since this program is focused on the stainless steel used for dry canisters, the stainless steel is basically limited to 304/304L. It is well known that stainless steels are subject to chloride-induced stress corrosion cracking (CISCC). How the environmental and residual stress conditions affect corrosion on this material is the focus of the R&D.

3) Loading: Finite element modeling by the NRC (Kusnick et al. 2013) indicated that high tensile stresses could occur in weld zones on SNF dry storage canisters. This was confirmed experimentally by DOE-funded research evaluating weld residual stresses in a mockup canister built to the same specifications as a real storage canister (Enos and Bryan 2016a). The study determined that there were high through-wall tensile stresses, in the welds and weld heat-affected zones, that were induced during the manufacturing process. These stresses are potentially sufficient to support through-wall SCC.

   The potential for high stresses to affect the pitting corrosion behavior of 304L stainless steel has also been evaluated. Four-point bend tests were conducted on stainless steel coupons loaded with sea salt at 50° C at 35% RH. These tests showed no difference in pitting densities as a function of stress (Bryan and Schindelholz 2018).

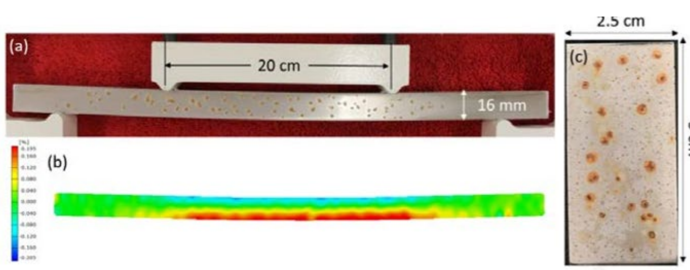

Figure 38. (a) Stressed 304L 4-point bend specimen; (b) digital image correlation stress map of the same specimen; and (c), unstressed coupon after depositing 400 μg/cm² sea-salt and exposing for 50 days at 50°C and 35% RH.

What we still need to learn to close this gap:

1. Environment: Work continues to quantify brine stability of salts present in the environment. Specific goals will be to develop an improved understanding of magnesium chloride stability and secondary phase formation in response to HCl degassing. Additional work will evaluate the effects of well-known aerosol particle-gas conversion reactions on brine chemistry at elevated temperatures. These data will provide a basis for improved screening of sites for SCC susceptibility (Bryan and Schindelholz 2018).

	2. Material: Corrosion work will continue to focus on four thrust areas: a. Understanding how the canister surface environment and different deposited salts contribute to the formation of pits. b. What environmental factors cause a pit to transition to a crack? c. How does the canister surface environment affect the electrochemistry needed to drive canister corrosion? d. Definition of relative governance on material condition and stress relative to surface environmental conditions on electrochemical kinetics and SCC susceptibility (Bryan and Schindelholz 2018) 3. Loading: Tensile tests will be conducted on salt-loaded coupons in realistic temperature and humidity environments to identify characteristic features controlling pit-to-crack transition. If stable cracks can be successfully initiated, crack growth rates on these specimens will be measured (Bryan and Schindelholz 2018). Additional in-service samples of the dust deposited on canisters is needed to obtain a better understanding of the diversity of dust depositions in different geographic areas of the country. 4. Crack Initiation and Growth Rate: A major push in the next few years will be to evaluate stress corrosion crack initiation and growth rates as a function of environmental parameters (salt load, temperature, and salt/brine composition), material properties (e.g., degree of sensitization, surface roughness, degree of cold work), and stress state. This work will be done at SNL, PNNL, and Savannah River National Laboratory (SRNL). 5. Crack Consequence: An additional focus for research is the actual consequence of a through-wall SCC crack. Current studies by EPRI and national laboratories are evaluating gas and particle transport through through-wall SCC cracks, to estimate the potential dose consequences of such a feature. **This gap has been up-graded to a high priority due to the timing need to acquire data on several experimental fronts that support CISCC. These experiments are associated with collecting data for brine stability, deposition rates, incubation time, crack growth rates, consequence analyses, and repair and mitigation of cracks.**

2.2 Priority 2 Gaps

Table 2-4. Drying Issues

Gap	2019 Rank	2017 Rank	2012 Rank	Recommended R&D for the Next 3 Years
Drying Issues	**2**	**2**	**6**	**Ongoing**
	What we have learned: There is anecdotal evidence that residual water remains in the canister after successful purging of water and drying according standardized test procedures. How much water and the physical state of the water (free and/or chemically absorbed and/or physically absorbed) has not been determined. The University of South Carolina (Knight 2017) led a NEUP IRP (2014-2018) to experimentally evaluate residual water in a small-scale mock-up of a dry canister application after both cold vacuum and forced helium drying procedures. General results showed evidence of freezing on the spacer discs and siphon tube, as well as small amounts of bulk water in a simulated failed fuel rod, and the spacer discs siphon tube (Knight 2017). Gas samples were also pulled from the HBU Demo Project cask after it was dried and sealed in the operational storage condition. These samples tested for water in the helium backfill, with water concentrations up to 17,000 ppm_v, corresponding to about 100 ml water in the cask atmosphere (Bryan et al. 2019a; Bryan et al. 2019b; EPRI 2019).			
	What we still need to learn to close this gap: The work initiated in the NEUP IRP needs to be expanded to scale up the test, making it more representative of a full-scale canistered system. The objectives of these tests are to realistically determine the amount of water that remains after the standardized drying procedure in full-scale operational dry storage systems. Currently, the amount of water determined in the NEUP work and the HBU Demo Project gas sampling does not cause immediate concern. However, this conclusion needs to be verified. Additional gas samples from in-service storage systems need to be obtained to get additional residual water data from representative canisters. This should be from both new and older fuel.			

2.3 Priority 3 Gaps

Table 2-5. Monitoring - External

<table>
<tr><th>Gap</th><th>2019 Rank</th><th>2017 Rank</th><th>2012 Rank</th><th>Recommended R&D for the Next 3 Years</th></tr>
<tr><td>Monitoring - External</td><td>3</td><td>3</td><td>2</td><td>Ongoing</td></tr>
<tr><td rowspan="2"></td><td colspan="4">What we have learned: EPRI has taken a lead role and has sponsored projects for the development of robotics and sensors capable of accessing the tight space between the concrete overpacks and welded canisters. The primary focus of these technologies is the detection of SCC of the canister welds. The latest results of this ongoing effort are summarized in EPRI (2016). Inspection techniques include visual, eddy current, ultrasonic, electromagnetic acoustic transducers, as well as surface sampling capabilities. EPRI has also made great strides in applying robotic deployment platforms for these sensor technologies.

DOE has also engaged in this area through a series of NEUP projects that have focused more on stretching current accepted non-destructive examination (NDE) technologies to lesser proven technologies; acoustic emissions, laser induced breakdown (LIBS) spectroscopy, Raman spectroscopy, guided wave technologies, and emission source tomography. These technologies are still in the formative stages.</td></tr>
<tr><td colspan="4">What we still need to learn to close this gap: The majority of the work performed in this gap is better aligned with industry. R&D to support the interrogation of the canister or cask internal components without through-wall penetrations or instruments inside the canister will begin (Hanson and Alsaed 2019).</td></tr>
</table>

Table 2-6. Cladding-H_2 Effects: Hydride Reorientation and Embrittlement

Gap	2019 Rank	2017 Rank	2012 Rank	Recommended R&D for the Next 3 Years
Cladding-H_2 Effects: Hydride Reorientation and Embrittlement	**3**	**3**	**7**	**Confirmatory PWR Testing and Testing of BWR and IFBA rods. R&D Ongoing**
	What we have learned: This gap has seen significant advancement in process understanding. With the exception of confirmatory testing being conducted under the Sister Rod test program, this gap is essentially closed. Confirmation of the progress is supported by draft NUREG-2224 (NRC 2018) which states; "Further, the staff finds that the orientation of the hydrides is not a critical consideration when evaluating the adequacy of cladding-only mechanical properties. Therefore, the use of mechanical properties for cladding in either the as-irradiated or hydride-reoriented condition is considered acceptable for the evaluation of drop accident scenarios." This position is supported by embrittlement data obtained from the ring compression tests (RCT) (Billone 2018), fatigue data obtained from the cyclic integrated reversible-bending fatigue tests (CIRFT) (NRC 2017), data obtained from thermal measurements taken after loading and drying of the HBU Demo Project cask (Fort 2019), and data obtained from the NCT load quantification tests (Kalinina et al. 2018). Results of these tests, examined as integrated effects from actual temperature, actual hoop stress, and realistic external loads, indicate that risks associated with hydride reorientation and embrittlement to cladding integrity of SNF are low for current fuel designs, burnups, and reactor operational limits the United States.			
	What we still need to learn to close this gap: Work to establish a large enough database on the various cladding types needs to be continued to ensure the inventory of cladding will meet its safety functions. In particular, hydride effects data needs to be obtained for boiling water reactor (BWR) and Integral Fuel Burnable Absorber (IFBA) fuel cladding. Work will also continue to build upon the PWR database through the Sister Rod Test Program.			

Table 2-7. Consequence Assessment of Canister Failure

<table>
<tr><th>Gap</th><th>2019 Rank</th><th>2017 Rank</th><th>2012 Rank</th><th>Recommended R&D for the Next 3 Years</th></tr>
<tr><td>Consequence Assessment of Canister Failure</td><td>3</td><td>N/A</td><td>N/A</td><td>Initiating</td></tr>
<tr><td rowspan="2"></td><td colspan="4">What we have learned: This is a new gap that has been identified due to increased awareness of extended dry storage and potential for breach of canister confinement through CISCC. Recognizing there is still much work to do under the Welded Canister: Atmospheric Corrosion Gap, this effort is focused on performing a realistic risk assessment of the radiological consequence of a potential breach of confinement. This work will use experimental tests, coupled with modeling and analysis, to estimate gaseous and particulate release resulting from a through-wall crack caused by CISCC.</td></tr>
<tr><td colspan="4">What we still need to learn to close this gap: Development of test and analytic objectives is planned for 2019. These efforts will focus on the definition of technically defensible release fractions for CISCC scenarios. Currently, the release fraction from the canister to the environment through the CISCC is poorly understood and is of primary importance.</td></tr>
</table>

Table 2-8. Fuel Transfer Options

<table>
<tr><th>Gap</th><th>2019 Rank</th><th>2017 Rank</th><th>2012 Rank</th><th>Recommended R&D for the Next 3 Years</th></tr>
<tr><td rowspan="3">Fuel Transfer Options</td><td>3</td><td>4</td><td>3</td><td>This priority has been raised recognizing the need for data to support a surface facility design concept for a consolidated interim storage facility</td></tr>
<tr><td colspan="4">What we have learned: Recent work on the Thermal Profile and Stress Profile gaps indicate that the fuel should be able to be transferred without returning to the pool for inspection and transfer. Rewetting and redrying spent fuel does not significantly alter the hydride effects. Results from the Thermal and Stress Profile gaps show that factors causing hydride reorientation are less of a concern than previously thought.</td></tr>
<tr><td colspan="4">What we still need to learn to close this gap: This priority has been raised recognizing the need for data to support a surface facility design concept for opening a cask for inspection or repackaging at a consolidated interim storage facility. Work continues on cask drying issues (see Drying Issues gap) and hydride effects through the sister pin testing.</td></tr>
</table>

2.4 Priority 4 Gaps

Table 2-9. Subcriticality – Burnup Credit (BWR SNF only)

Gap	2019 Rank	2017 Rank	2012 Rank	Recommended R&D for the Next 3 Years
Subcriticality – Burnup Credit (BWR SNF only)	**4**	**4**	**7**	**Ongoing**
	What we have learned: BWR SNF burnup credit is mainly needed to support future waste management strategies.			
	What we still need to learn to close this gap: BWR spent fuel burnup credit is needed for degraded, flooded conditions (e.g., disposal).			

Table 2-10. Examination of the fuel at Idaho National Laboratory (INL)

Gap	2019 Rank	2017 Rank	2012 Rank	Recommended R&D for the Next 3 Years
Examination of the fuel at INL	**4**	**4**	**10**	**Ongoing**
	What we have learned: A gas sample of the CASTOR V/21 cask indicated no leaks or evidence of fuel failure. The REA-2023 cask has a leak (breached seal), but only nine fuel rods from the 1999 cask inspection are of interest in this cask.			
	What we still need to learn to close this gap: The CASTOR V/21 and REA-2023 casks are proposed to be opened as part of a campaign supporting the HBU Demo Project. The Castor V/21 fuel will be stored an additional 28 years (42 years total), which could be useful for license extensions and to address issues such as cladding creep over extended periods. Inspection of the REA-2023 cask will yield data on the effect of leaks on fuel condition after decades of storage.			

Table 2-11. Neutron Poisons (load-bearing) – Thermal Aging

Gap	2019 Rank	2017 Rank	2012 Rank	Recommended R&D for the Next 3 Years
Neutron Poisons (load-bearing) – Thermal Aging	**4**	**4**	**7**	**Pending**
	What we have learned: Thermal aging during long term storage of load-bearing structural neutron poison materials could inform loading of future casks based on either modifying the properties of the aluminum alloys to improve their aging properties under thermal conditions of dry storage, or change the dry storage thermal conditions such that the continued performance of the aluminum alloys can be ensured. The results of the significantly lower drying temperatures identified in the HBU Demo Project, coupled with the thermal analyses performed as part of the Thermal Profiles crosscutting gap, indicate that early thermal spikes during the drying process are much lower than the regulatory limit. This will result in the mitigation of thermal aging effects on the aluminum. Note that there is no storage licensing importance for neutron poisons since the primary criticality control during storage is moderator control.			
	What we still need to learn to close this gap: This is a downstream licensing issue for transportation, and thus, still considered a priority rank of 4. As the current R&D informs direction, decisions will be made regarding R&D tasks to fund for this gap.			

Table 2-12. Neutron Poisons – Embrittlement

Gap	2019 Rank	2017 Rank	2012 Rank	Recommended R&D for the Next 3 Years
Neutron Poisons – Embrittlement	**4**	**4**	**11**	**Pending**
	What we have learned: This technical gap is closely associated with the neutron poison thermal aging gap in that it is a structural issue associated with reduced ductility and potential for brittle fracture induced from mechanical loading during transportation and handling operations. The recent results from the Thermal and Stress Profiles gaps have indicated that early thermal spikes during the drying process and mechanical loading events during transportation and handling operations both are much lower than expected and will result in a lower risk to this type of failure.			
	What we still need to learn to close this gap: This is a downstream licensing issue for transportation, and thus, still considered a priority rank of 4. As the current R&D informs direction, decisions will be made regarding R&D tasks to fund for this gap.			

Table 2-13. Neutron Poisons – Corrosion (blistering)

Gap	2019 Rank	2017 Rank	2012 Rank	Recommended R&D for the Next 3 Years
Neutron Poisons – Corrosion (blistering)	**4**	**4**	**13**	**Pending**
	What we have learned: Blistering of encased neutron poison materials may occur for a subset of the neutron poison materials manufactured with the porosity range conducive to moisture retention during wetting. The mechanism causing blistering acts in the early stages of dry storage. There is evidence of this in operating systems and has been brought to the attention of the NRC. NRC has continued to follow this technical issue closely. The HBU Demo Project gas sampling results raised questions about the ability of neutron poisons to trap water during the drying process resulting in a source of water for fuel and hardware corrosion during storage.			
	What we still need to learn to close this gap: This is a downstream licensing issue for transportation, and thus, still considered a priority rank of 4. As the current R&D informs direction, decisions will be made regarding R&D tasks to fund for this gap.			

Table 2-14. Neutron Poisons – Creep

Gap	2019 Rank	2017 Rank	2012 Rank	Recommended R&D for the Next 3 Years
Neutron Poisons – Creep	**4**	**4**	**13**	**Pending**
	What we have learned: Elevated temperatures may be conducive to creep. However, in the early stages of storage, unaged material and limited loads reduce this likelihood. The recent results of the Thermal and Stress Profile gaps corroborate this position.			
	What we still need to learn: This is a downstream licensing issue for transportation, and thus, still considered a priority rank of 4. As the current R&D informs direction, decisions will be made regarding R&D tasks to fund for this gap.			

Table 2-15. Welded Canister – External Galvanic Corrosion (graphite induced)

Gap	2019 Rank	2017 Rank	2012 Rank	Recommended R&D for the Next 3 Years
Welded Canister – External Galvanic Corrosion (graphite induced)	**4**	**4.**	**N/A**	**Pending**
	What we have learned: This gap was not specifically evaluated in Hanson et al. (2012). However, the MAPS Report (NRC 2019), Section 3.2.2.3 states: “galvanic corrosion occurs when two dissimilar metals or conductive materials are in physical contact in the presence of a conducting solution ... In DSSs, graphite is used to lubricate stainless steel subcomponents such as the stainless steel upper trunnion for the TN-68 bolted cask and the interface between the NUHOMS canister shell and support structure, resulting in galvanic contact between stainless steel and graphite. Because graphite is strongly cathodic and the contact is close, the galvanic coupling effect is expected to be strong. These galvanic couples are exposed to sheltered and outdoor environments.”			
	What we still need to learn to close this gap: The importance of this gap to licensing is Medium for both near-term and long-term. The primary basis for this ranking is that although there is credible potential for this degradation mechanism, no significant safety impacts have been observed or predicted.			

Table 2-16. Cladding-H_2 Effects: Delayed Hydride Cracking (DHC)

Gap	2019 Rank	2017 Rank	2012 Rank	Recommended R&D for the Next 3 Years
Cladding-H_2 Effects: DHC	**4**	**4**	**9**	**No change in priority**
	What we have learned: Delayed hydride cracking (DHC) has been shown to be limited to significant pellet swelling, which is unlikely. As temperatures lower over extended periods of time, cladding may be more susceptible to DHC from shock or vibration events. The recent Stress Profiles gap work has shown that induced mechanical loads on the SNF from transport operations are very low.			
	What we still need to learn to close this gap: There is no near-term R&D planned for this gap.			

2.5 Lower Priority Gaps

The following gaps are listed as low priority. This ranking has not changed from the Hanson and Alsaed (2019) report. They are show for completeness and tracking of all the gaps that have been identified sin the Hanson et al. (2012) report.

Table 2-17. Lower Priority Gaps

<table>
<tr><th>Gap</th><th>2019 Rank</th><th>2017 Rank</th><th>2012 Rank</th><th>Recommended R&D for the Next 3 Years</th></tr>
<tr><td>Bolted Casks - Thermomechanical Degradation of Metallic Seals and Bolts</td><td>N/A</td><td>N/A</td><td>5</td><td rowspan="11">Gaps are Low per Hanson and Alsaed (2019) and thus are no longer prioritized.</td></tr>
<tr><td>Welded Canister – Aqueous Corrosion</td><td>N/A</td><td>N/A</td><td>5</td></tr>
<tr><td>Bolted Casks - Aqueous Corrosion</td><td>N/A</td><td>N/A</td><td>5</td></tr>
<tr><td>Bolted Casks - Atmospheric Corrosion</td><td>N/A</td><td>N/A</td><td>5</td></tr>
<tr><td>Subcriticality - Moderator Exclusion</td><td>N/A</td><td>N/A</td><td>8</td></tr>
<tr><td>Fuel Assembly Hardware – SCC for Lifting Hardware and Spacer Grids</td><td>N/A</td><td>N/A</td><td>11</td></tr>
<tr><td>Cladding – Creep</td><td>N/A</td><td>N/A</td><td>11</td></tr>
<tr><td>Cladding – Annealing of Radiation Damage</td><td>N/A</td><td>N/A</td><td>12</td></tr>
<tr><td>Cladding – Oxidation</td><td>N/A</td><td>N/A</td><td>13</td></tr>
<tr><td>Overpack - Freeze–thaw</td><td>N/A</td><td>N/A</td><td>14</td></tr>
<tr><td>Overpack - Corrosion of Embedded Steel</td><td>N/A</td><td>N/A</td><td>14</td></tr>
<tr><td>Monitoring – Internal</td><td></td><td>Closed</td><td>N/A</td><td rowspan="2"></td></tr>
<tr><td>Subcriticality – Burnup Credit (PWR SNF only)</td><td></td><td>Closed</td><td>7</td></tr>
</table>

3. ROLL-UP OF GAP PRIORITIZATION

Table 3-1. Roll-Up of Gap Prioritization
(Red font indicates change from 2017 to 2019 prioritization)

Gap	2019 Priority	2017 Priority	2012 Priority	Comments
Thermal Profiles	1	1	1	No change in priority
Stress Profiles	1	1	1	No change in priority
Drying Issues	2	2	6	No change in priority
Monitoring	3	3	2	No change in priority
Welded Canister – Atmospheric Corrosion	1	3	2	Change in priority due to a timing need to acquire SCC data to support experimental initiatives that will help define the path forward.
Cladding-H_2 Effects: Hydride Reorientation and Embrittlement	3	3	7	No change in priority
Consequence Assessment of Canister Failure	3	N/A	N/A	This is a new gap identified to assess potential radiological risk due to loss of confinement caused by SCC.
Fuel Transfer Options	3	4	3	This priority has been raised recognizing the need for data to support a surface facility design concept for a Consolidated Interim Storage facility
Cladding-H_2 Effects: DHC	4	4	9	No change in priority
Subcriticality – Burnup Credit (BWR SNF only)	4	4	7	
Examination of the Fuel at the INL	4	4	10	
Neutron Poisons (load-bearing) – Thermal Aging	4	4	7	
Neutron Poisons – Embrittlement	4	4	11	
Neutron Poisons – Corrosion (blistering)	4	4	13	
Neutron Poisons – Creep	4	4	13	
Welded Canister – External Galvanic Corrosion (graphite induced)	4	4	N/A	

Gap	2019 Priority	2017 Priority	2012 Priority	Comments
Bolted Casks - Thermomechanical Degradation of Metallic Seals and Bolts		N/A	5	Gaps are Low per Hanson and Alsaed (2019) and thus are no longer prioritized.
Welded Canister – Aqueous Corrosion		N/A	5	
Bolted Casks - Aqueous Corrosion		N/A	5	
Bolted Casks - Atmospheric Corrosion		N/A	5	
Subcriticality - Moderator Exclusion		N/A	8	
Fuel Assembly Hardware – SCC for Lifting Hardware and Spacer Grids		N/A	11	
Cladding – Creep		N/A	11	
Cladding – Annealing of Radiation Damage		N/A	12	
Cladding – Oxidation		N/A	13	
Overpack - Freeze–thaw		N/A	14	
Overpack - Corrosion of Embedded Steel		N/A	14	
Monitoring - Internal		Closed	N/A	
Subcriticality – Burnup Credit (PWR SNF only)		Closed	7	

4. PATH FORWARD

Prioritization is used to determine what scope is funded first under limited funding scenarios. Focus for allocating funds for R&D work is on the Priority 1-3 gaps. Specific recommendations for R&D based on the prioritization above and remaining work identified in Sections 5 and 6 for each gap, are provided here.

4.1 In-Progress Work Scope

- The highest priority R&D activity was to complete the loading of the HBU Demo Project cask (EPRI 2014c), collect the temperature data during drying and initial heat up, and collect the gas samples to help determine if water vapor is present after drying. These tasks were successfully completed in November 2017. Temperature data collection will continue while the cask is on the storage pad. Planning for a facility to open the cask after 10 years of storage is ongoing.

- Thermal Profiles
  - Under the EPRI Extended Storage Collaboration Program (ESCP), round robins between DOE/National Laboratories, NRC, and industry will take place to perform:
    - Phase I: modeling of the vertical aboveground configuration of the BWR dry cask simulator using a variety of codes and methodologies
    - Phase IIa: calculations of the decay heat for the assemblies loaded in the HBU Demo Project cask using multiple methodologies
    - Phase IIb: the thermal analyses of the HBU Demo Project cask using the as loaded configuration, actual ambient conditions and times (e.g., time under vacuum), and proprietary information for the cask and assemblies
    - Phase IIc: sensitivity studies with a focus on mesh size variability and Grid Convergence Index
  - Conduct testing and modeling by orienting the BWR dry cask simulator to the horizontal position.
  - Conduct both small and large scale testing to examine temperatures and flow within large, vertical canister-based systems.
  - Perform modeling to determine how temperatures may change as industry loads shorter cooled fuel assemblies.
  - Perform modeling of canister systems to determine how temperatures change when the canisters are placed into transportation overpacks.
  - Continued support to the Used Nuclear Fuel - Storage, Transportation & Disposal Analysis Resource and Data System (UNF-ST&DARDS) to monitor loaded systems and track estimated temperatures.
- Stress Profiles
  - Complete the ENSA/DOE multi-modal transportation test and analyze data.
    - Perform follow-up tests as necessary
  - Continue modeling of external loads and effects on SSCs during normal conditions, off-normal conditions, and DBAs of extended storage
  - Begin development of cumulative effects models for each SSC
  - Compete analysis of the 30 cm drop tests and modeling on a third-scale ENSA cask.
  - Design and conduct tests and modeling to determine the conditions under which pinch loads occur and the magnitude of these loads.

- Welded Canister – Atmospheric Corrosion
  - Continue gathering data on environmental conditions to determine when chloride induced SCC may initiate
  - Continue performing tests under relevant conditions to determine SCC initiation and crack propagation rates
  - Initiate studies for how to detect potential gas or particulate release from a through-wall SCC
  - Initiate studies for repair and mitigation techniques to address degradation of stainless steel canisters
- Drying Issues
  - Complete the NEUP IRP and analyze data together with gas samples from the HBU Demo Project cask
  - Design and perform lab scale tests to improve sampling and analysis techniques and build the models to link the sampling results to the total water content of the system.
  - Design and perform larger-scale tests using heater assemblies to quantify residual water as a function of drying parameters (temperature distribution, total heat content, pressure, time, hold points, etc.).
  - Design and perform a full-scale test using heater assemblies if necessary.
  - Collect and analyze gas samples from actual DCSS after drying and helium backfill. The goal is to collect samples from various utilities to determine the effect of DCSS design and drying procedure on residual water.
  - Perform a detailed consequence analysis to determine effects, if any, on SSCs resulting from residual water.
- Monitoring
  - R&D to support the interrogation of the canister or cask internal components without through-wall penetrations
- Cladding – H_2 Effects: Hydride Reorientation and Embrittlement
  - Perform Phase 1 testing of sister rods as outlined in a technical memo (Saltzstein et al. 2018)
- Consequence Assessment
  - Conduct initial tests with engineered components to obtain data on crack parameter influence and fine particle deposition.

4.2 Next 2-5 Years

- Continue monitoring and data collection of the HBU Demo Project cask

- Thermal Profiles
  - Complete any outstanding testing and analyses previously identified
  - Perform thermal analysis of other high heat load systems containing HBU SNF to provide assurance that cladding testing parameters are bounded
- Stress Profiles
  - Complete testing, modeling, and analyses previously identified
  - Continue development of cumulative effects models for each SSC
- Welded Canister – Atmospheric Corrosion
  - Continue gathering data on environmental conditions to determine when chloride induced SCC may initiate

  - Continue performing tests under relevant conditions to determine SCC initiation and crack propagation rates
  - Complete studies for how to detect potential gas or particulate release from a through-wall SCC
  - Continue studies for repair and mitigation techniques to address degradation of stainless steel canisters
- Drying Issues
  - Complete testing, modeling, and analyses previously identified
- Monitoring
  - Continue R&D to support the interrogation of the canister or cask internal components without through-wall penetrations
- Cladding – H_2 Effects: Hydride Reorientation and Embrittlement
  - Develop Phase 2 Test Plan and perform work as outlined
- Consequence Assessment
  - Continue tests with engineered components to refine data on crack parameter influence and fine particle deposition.

4.3 Next 5+ Years

- Continue monitoring and data collection of the HBU Demo Project cask and prepare for cask transportation and opening

- Stress Profiles
  - Complete cumulative effects models for each SSC
- Welded Canister – Atmospheric Corrosion
  - Complete tests under relevant conditions to determine SCC initiation and crack propagation rates
  - Complete studies for repair and mitigation techniques to address degradation of stainless steel canisters
- Cladding – H_2 Effects: Hydride Reorientation and Embrittlement
  - Complete Phase 2 testing
  - Based on results, determine if IFBA and/or BWR rods need to be tested
- Examination of the fuel at the INL
  - Begin planning of opening a cask in preparation of opening the HBU Demo Project cask

5. SUMMARY

This series of gap analyses continue to inform the SFWST storage and transportation R&D work. As the work continues to increase our understanding of the fundamental sciences affecting degradation mechanisms, as well as the engineering aspects associated with how specific designs affect the environmental and mechanical loading conditions, ranking of priorities change to reflect this better understanding.

Working with industry, the international community, and the NRC has also provided programmatic confidence in the R&D activities. The combination of performing the R&D with the technical collaboration from outside organizations provides assurance that the correct gaps are being addressed and judgments regarding change in priority of specific gaps are corroborated. As an example, the highest priority gap at the beginning of the program was hydride effects on the ductility of the spent fuel cladding. This gap has been essentially closed as the R&D produced the understanding of response characteristics of spent fuel to storage and transportation thermal and mechanical loadings. The judgement that the gap is essentially closed is demonstrated by the issuance of draft NUREG-2224 (NRC 2018) which states that high-burnup fuel will maintain its integrity under transportation NCT.

As fuel behavior has become better understood and is expected to maintain its integrity under storage and transport conditions, emphasis is shifting to DCSS performance for extended periods of storage. Implicit in this is inspection, mitigation, and repair technologies that will provide confidence in the containment function of the DCSS during extended periods of storage, followed by transportation.

As the R&D continues to inform our understanding of the behavior of spent fuel and associated storage and transportation systems, the gap analysis will continue to be updated to reflect this increased understanding.

6. REFERENCES

Billone, M.C. and T.A. Burtseva 2017. *Results of Ring Compression Tests.* SFWD-SFWST-2018-000510, ANL-18/36. Argonne National Laboratory, Argonne, IL.

Bryan, C.R. and D. Enos 2014. *Analysis of Dust Samples Collected from Spent Nuclear Fuel Interim Storage Containers at Hope Creek, Delaware, and Diablo Canyon, California*. SAND2014-16383. Sandia National Laboratories, Albuquerque, NM.

Bryan, C.R. and D.G. Enos 2015b. *Analysis of Dust Samples Collected from an Unused Spent Nuclear Fuel Interim Storage Container at Hope Creek, Delaware*. SAND2015-1746. Sandia National Laboratories, Albuquerque, NM.

Bryan, C.R. and D.G. Enos 2016. *Analysis of Dust Samples Collected from an In-Service Interim Storage System at the Maine Yankee Nuclear Site*. SAND2016-10266. Sandia National Laboratories, Albuquerque, NM.

Bryan, C. and D. Enos 2017a. *FY16 Status Report: SNF Interim Storage Canister Corrosion and Surface Environment Investigations*. FCRD-UFD-2016-00429, SAND2017-2498R. Sandia National Laboratories, Albuquerque, NM.

Bryan, C. and E. Schindelholz 2018. "Properties of Brines formed by Deliquescence of Sea-Salt Aerosols". *CORROSION 2018*. Phoenix, AZ, NACE International.

Bryan, C.R., R.L. Jarek, C. Flores, and E. Leonard. 2019a. *Analysis of Gas Samples Taken from the High Burnup Demonstration Cask*. SAND2019-2281. Sandia National Laboratories, Albuquerque, NM.

Bryan, C., R.L. Jarek, C. Flores, and E. Leonard. 2019b. "Analysis of Gas Samples Collected from the DOE High Burnup Demonstration Cask". *International High-Level Radioactive Waste Management Conference 2019*. Knoxville, TN, American Nuclear Society.

Bryan, C., E. Schindelholz, A. Knight, J. Taylor, and R. Dingreville 2019c. "Stability of Sea-salt Deliquescent Brines on Heated Surfaces of SNF Dry Storage Canisters". *International High-Level Radioactive Waste Management Conference 2019*. Knoxville, TN, American Nuclear Society.

Enos, D. and C. Bryan 2016a. *Final Report: Characterization of Canister Mockup Weld Residual Stresses*. FCRD-UFD-2016-000064. U.S. Department of Energy, Washington D.C.

Enos, D. and C. Bryan 2016b. "Understanding the Risk of Chloride Induced Stress Corrosion Cracking of Interim Storage Containers for the Dry Storage of Spent Nuclear Fuel: Evolution of Brine Chemistry on the Container Surface". *CORROSION 2016*, Vancouver, BC, NACE International.

Enos, D.G., C.R. Bryan, and K.M. Norman. 2013. *Data Report on Corrosion Testing of Stainless Steel SNF Storage Canisters*. FCRD-UFD-2013-000324. U.S. Department of Energy, Office of Used Nuclear Fuel Disposition, Washington DC.

EPRI (Electric Power Research Institute) 2014c. *High Burnup Dry Storage Cask Research and Development Project: Final Test Plan*. Contract No.: DE-NE-0000593. Palo Alto, CA.

EPRI (Electric Power Research Institute) 2015. *Susceptibility Assessment Criteria for Chloride-Induced Stress Corrosion Cracking (CISCC) of Welded Stainless Steel Canisters for Dry Cask Storage Systems*. Final Report 3002005371. Palo Alto, CA.

EPRI (Electric Power Research Institute) 2016. *Dry Canister Storage System Inspection and Robotic Delivery System Development.* TR-3002008234. Palo Alto, CA.

EPRI (Electric Power Research Institute) 2019. *High Burnup Dry Storage Research Project Cask Loading and Initial Results*. Report 3002015076. Palo Alto, CA.

Fort, J.A., D.J. Richmond, J.M. Cuta, and S.R. Suffield 2019. *Thermal Modeling of the TN-32B Cask for the High Burnup Spent Fuel Data Project*. PNNL-28915. Richland, WA.

Hanson, B. 2018. "Integrated Approach to Closing Cladding Data Gaps; Thermal Analysis, and Hoop Stress". PNNL-SA-139950. Presentation at *NRC Division of Spent Fuel Management Regulatory Conference*, Washington, DC, December 11, 2018.

Hanson, B.D. and H.A. Alsaed 2019. *Gap Analysis to Support Extended Storage of Used Nuclear Fuel: Five-Year Delta*. SFWD-SFWST-2017-00005, Rev. 1, PNNL-28711. U.S. Department of Energy Spent Fuel Waste Science and Technology, Washington, DC.

Hanson, B., H. Alsaed, C. Stockman, D. Enos, R. Meyer, and K. Sorenson 2012. *Gap Analysis to Support Extended Storage of Used Nuclear Fuel*. FCRD-USED-2011-000136 Rev. 0, PNNL-20509. U.S. Department of Energy Used Fuel Disposition Campaign, Washington, DC.

Kalinina, E.A., C. Wright, L. Lujan, N. Gordon, S.J. Saltzstein, and K.M. Norman 2018. *Data Analysis of ENSA/DOE Rail Cask Tests*, SFWD-SFWST-2018-000494, SAND2108-13258R. Sandia National Laboratories, Albuquerque, NM.

Knight, T.W., J. Khan, T. Farouk, and J. Tulenko 2017. "Experimental Determination of Used Fuel Vacuum Drying Using a Mock Fuel Assembly". *International High-Level Radioactive Waste Management Conference*, April 9-13, 2017. Charlotte, NC, American Nuclear Society.

Kusnick, J., M. Benson, and S. Lyons 2013. *Finite Element Analysis of Weld Residual Stresses in Austenitic Stainless Steel Dry Cask Storage System Canisters*. Technical Letter Report, U.S. Nuclear Regulatory Commission, Washington, DC.

NRC (U.S. Nuclear Regulatory Commission) 2003. *Moderator Exclusion under Hypothetical Accident Conditions and Demonstrating Subcriticality of Spent Fuel under the Requirements of 10 CFR 71.55(e)*. Spent Fuel Project Office Interim Staff Guidance (ISG)-19. Washington, DC.

NRC (U.S. Nuclear Regulatory Commission) 2012. *Burnup Credit in the Criticality Safety Analyses of PWR Spent Fuel in Transportation and Storage Casks*. Division of Spent Fuel Storage and Transportation Interim Staff Guidance (ISG)-8, Rev. 3. Washington, DC.

NRC (U.S. Nuclear Regulatory Commission) 2016b. *Standard Review Plan for Renewal of Spent Fuel Dry Cask Storage System Licenses and Certificates of Compliance*. NUREG-1927, Rev. 1. Washington, DC.

NRC (U.S. Nuclear Regulatory Commission). 2016c. *Fuel Retrievability in Spent Fuel Storage Applications*. Division of Spent Fuel Management Interim Staff Guidance (ISG)-2, Rev. 2. Washington, DC.

NRC (U.S. Nuclear Regulatory Commission) 2017. *Mechanical Fatigue Testing of High-Burnup Fuel for Transportation Applications*. NUREG/CR-7198. Washington, DC.

NRC (U.S. Nuclear Regulatory Commission) 2018. *Dry Storage and Transportation of High Burnup Spent Nuclear Fuel, Draft Report for Comment*. NUREG-2224. Washington, DC.

NRC (U.S. Nuclear Regulatory Commission) 2019. Managing Aging Processes in Storage (MAPS) Report, Final Report. NUREG-2214, Washington, DC.

Pulido, R.J.M., E.R. Lindgren, S.G. Durbin, A. Zigh, J. Solis, S.R. Suffield, D.J. Richmond, J.A. Fort, L.E. Herranz, F. Feria, J. Penalva, M. Loret, M. Galbán, J. Benavides, and G. Jiménez 2019. *Modeling Validation Exercises Using the Dry Cask Simulator*. M2SF-19SN010203035, SAND2019-6079R. Sandia National Laboratories, Albuquerque, NM.

Saltzstein, S.J., M. Billone, B. Hanson, and J. Scaglione 2018. *Visualization of the High-Burnup Spent Fuel Rod Phase 1 Test Plan: Technical Memo*. SAND2018-8042, Sandia National Laboratories, Albuquerque, NM. July 18, 2018.

Stockman, C., B. Hanson, S. Marschman, H. Alsaed, and K. Sorenson 2015. *Used Nuclear Fuel Extended Storage and Transportation Research and Development Review and Plan*. FCRD-UFD-2014-00050 Rev. 1, SAND2014-19594R. U.S. Department of Energy Used Fuel Disposition Campaign, Washington, DC.

TN Americas 2017. *TN-32B HBU Demonstration Cask Design/Licensing Basis Document, Revision 8*. ML17109A457, Columbia, MD.

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