

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

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Spent Fuel and Waste Science and
Technology***

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SUMMARY

The Department of Energy (DOE), Office of Nuclear Energy (NE), Spent Fuel and Waste Science and Technology (SFWST) program is performing research and development in the area of commercial spent nuclear fuel (SNF) long term storage and transportation. This program is being conducted under the provisions of the Nuclear Waste Policy Act (NWPA) of 1982 and its amendments that require the DOE to take title to and manage SNF after storage at the utility reactor site.

This report is a condensed version of previous gap reports (Hanson 2012 and Hanson 2019) with up-dated gap priority assessments. The gap priorities have been updated from Hanson 2019 because 2019 is 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 2012/2019, 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 2019.

Table ES-1 provides a complete list of the identified technical gaps and their associated priorities, as they appeared in Hanson 2012, Hanson 2019, and updated to 2019 in this report. Four changes have been made in gap priorities from 2017 to 2019 and are highlighted in red. They are significant and reflect the progress made in the post-2017 R&D work as well as the operational status that effects how the DOE will manage SNF once it takes title to it for transportation, potential additional storage, and disposal.

The focus for R&D funding will remain on the 1 – 3 priority gaps. 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. Gap Priority Listing

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 a near-term 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	The change in priority from 2012 to 2017 is mostly because other gaps that had been higher, dropped 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 CISCC.
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	
Bolted Casks - Thermomechanical Degradation of Metallic Seals and Bolts		N/A	5	
Welded Canister – Aqueous Corrosion		N/A	5	Gaps have been downgraded per Hanson 2019 to Low and thus are no longer prioritized.
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	

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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	

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REVISION HISTORY

ACRONYMS

AMP	Aging Management Program
BWR	boiling water reactor
CISCC	chloride-induced stress corrosion cracking
DCSS	dry cask storage system
DOE	Department of Energy
EOL	end of life
EPRI	Electric Power Research Institute
ESCP	Extended Storage Collaboration Program (EPRI)
HAC	hypothetical accident condition
HAZ	heat affected zone
IFBA	Integral Fuel Burnable Absorber
IRP	Integrated Research Program
ISG	Interim Staff Guidance
ISFS	Independent Spent Fuel Storage Installation
ITS	important to safety
NCT	normal conditions of transport
NDE	nondestructive examination
NE	Office of Nuclear Energy
NEUP	Nuclear Energy University Programs
NRC	Nuclear Regulatory Commission
NWPA	Nuclear Waste Policy Act
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

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GAP ANALYSIS TO GUIDE DOE R&D IN SUPPORTING EXTENDED STORAGE AND TRANSPORTATION OF SPENT NUCLEAR FUEL: AN FY2019 ASSESSMENT

1. INTRODUCTION

1.1 Background and Purpose

The Department of Energy (DOE), Office of Nuclear Energy (NE), Spent Fuel and Waste Science and Technology (SFWST) program is performing research and development in the area of commercial spent nuclear fuel (SNF) long term storage and transportation. This program is being conducted under the provisions of the Nuclear Waste Policy Act (NWPA) of 1982 and its amendments that require the DOE to take title to and manage SNF after storage at the utility reactor site.

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, and as required by the NWPA, 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 2012) listed 24 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 2019) reflects this advancement in the knowledge base. During the five years between these two reports, the number of “high” and “medium” ranked gaps has been reduced to 15 from 26. While the 2019 report was published in January of 2019, the rankings were based on R&D progress up to 2017. In the past two years, significant progress has been made in quantifying loads during normal conditions of transport (stress profiles), results have been attained from the demonstration cask 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 Centralized Interim Storage Facilities, all point to the need to up-date 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 up-dated 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 and a re-ranking of several existing gaps have been made. The new gap will focus efforts on the determination of the radiological consequence of a through-wall crack in a canister.

The focus of this report is on the high and medium ranked gaps. While the gaps that are ranked as low are identified, it is not expected that significant work will be done on any of these gaps in order to properly address the high and medium ranked gaps.

1.2 Criteria for Identifying and Prioritizing Gaps (Hanson 2019)

A systematic approach was used to identify gaps in the technical bases for extended storage of used nuclear fuel in ISFSIs, for storage and transportation of low burnup fuel after dry storage, and for transportation of high burnup fuel. Dry storage systems are divided into ten Structure, Safety, 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 the 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 research and development needs to address the data as Low, Medium, or High. To assign a rank, the following questions were answered for every identified degradation mechanism:

1. Is there sufficient data to evaluate the degradation mechanism and SSC performance?
2. What are the current regulatory considerations?
3. What is the likelihood of occurrence of the degradation mechanism warranting evaluation of impact on safety functions?
4. What are the consequences of the degradation mechanism?

5. Can the SSC be remediated or managed in an aging management program (AMP)?
6. Would any costly design and operational difficulties be endured due to the degradation mechanism?
7. Would the degradation mechanism limit or complicate future waste management strategies?

Each gap is 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 over the past five years and seeing how this work has affected the answers to these seven questions. The new rankings are then used to develop a new prioritization.

Several 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 providing an alternate means of demonstrating compliance with specific regulatory requirements. Each of these seven areas was given a High rank for R&D in Hanson 2012.

1.2.1 Data Gap Prioritization

Once the data gaps have been 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.

1.2.2 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, ISG-2 for retrievability) and NUREGs (e.g., NUREG-1927) 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 High Burnup Spent Fuel Data Project (aka Demo Project)
- Evaluation of stress profiles under normal conditions of transport (NCT) for various transportation modes
- Inspections and single effects tests and studies for several SSCs including canister welds and cladding
- ISG-2, Rev. 2 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 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 high burnup fuel on the basis of moderator exclusion under hypothetical transport 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.

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 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
- Long-term needs such as data needed 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), repackaging of the SNF, and disposal of existing canisters.

1.2.3 Importance to Licensing

Seven criteria were considered in obtaining a rank for the SSC-specific gaps. Because only the High and Medium rank gaps were selected for prioritization, two criteria rated High for all these gaps. These were Data Needs and Regulatory Considerations. 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. Future 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.

1.2.4 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 over the past five years, building on the review provided by Hanson 2019 and Stockman 2014. The new rank for the gap is then determined and a description of the remaining work is given. Since the issuance of Hanson 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.

2. Identified gaps in order of priority

These tables list priority and rank as equivalent, based on the discussion in Section 1.2.1, 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 – 3 gaps. These are the gaps that 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				

	<p>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, the NRC, Pacific Northwest National Laboratory, Centro de Investigaciones Energeticas, Medioambientales y Tecologicas (CIEMAT), and Empresa Nacional del Uranio, SAS (ENUSA) was able to calculate the measured temperatures inside the dry cask storage simulator within ~1-20 °C, though all were biased higher. Additionally, the high burn-up demo 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 113°C) than the peak temperature calculated by industry using standard conservative practices (TN 2017, Hanson 2018). PNNL conducted a best practice attempt at modeling the temperatures within the high burn-up demo cask and was able to model within 30°C of the PCT, but again biased higher (Hanson 2019).</p>
	<p>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.</p>

Table 2-2. 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
	<p>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.</p>			

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 (Chu 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, salt loads were low (the sampled canisters were not long in storage), but the salts were dominantly chloride-rich sea-salt aerosols (Bryan 2014). At other sites sampled, on the U.S. east coast (Calvert Cliffs (Enos 2013), Hope Creek (Bryan 2014; Bryan 2015); and Maine Yankee (Bryan 2017, Bryan 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 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 Sandia National Laboratories 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 2016; Bryan 2017; Bryan 2018; Bryan 2019)

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. 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 (NRC 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 2016). 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 stress corrosion cracking.

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 2018).

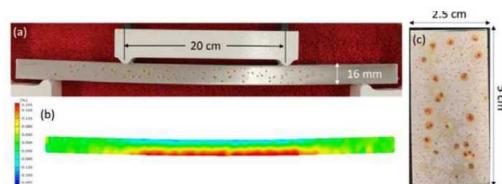


Figure 38. (a) Stressed 304L 4-point bend specimen; (b) digital image correlation stress map of the same specimen; and (c), unstressed coupon after depositing $400 \mu\text{g}/\text{cm}^2$ sea-salt and exposing for 50 days at 50°C and 35% RH.

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 sites for SCC susceptibility (Bryan 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 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 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 cracking 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 SRNL. 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

	<p>transport through through-wall SCC cracks, to estimate the potential dose consequences of such a feature.</p> <p>This gap has been up-graded to a high priority due to the timing need to acquire data on several experimental fronts that support chloride-induced stress corrosion cracking (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.</p>
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2.2 Priority 2 Gaps

Table 2-3. Drying Issues

Gap	2019 Rank	2017 Rank	2012 Rank	Recommended R&D for the Next 3 Years
Drying Issues	2	2	6	Ongoing
<p>What we have learned: There is anecdotal evidence that residual water remains in the canister after success purging of water and drying according standardized test procedures. How much water and the physical state of the water (free water v. chemically absorbed) has not been determined. The University of South Carolina (Knight 2018) led a DOE NEUP IRP (2014-2018) to experimentally evaluate residual water in a test mock-up of a dry canister application after both cold vacuum and forced He drying procedures.</p> <p>General results showed evidence of freezing on the spacer discs and siphon tube, as well as small amounts of bulk water in the simulated failed fuel rod, and the spacer discs siphon tube (Knight 2018).</p> <p>Gas samples were also pulled from the DOE Demo Cask after it was dried and sealed in the operational storage condition. These samples tested for water in the He backfill. Water in concentrations up to 17,000 ppm_v, corresponding to about 100 ml water in the cask atmosphere (Bryan 2019a, 2019b; EPRI 2019).</p>				
<p>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 Demo gas sampling does not cause immediate concern. However, this conclusion needs to be verified.</p> <p>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.</p>				

2.3 Priority 3 Gaps

Table 2-4. Monitoring

Gap	2019 Rank	2017 Rank	2012 Rank	Recommended R&D for the Next 3 Years
Monitoring	3	3	2	Ongoing
<p>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 stress corrosion cracking 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.</p> <p>DOE has also engaged in this area through a series of NEUP projects that have focused more on stretching current accepted 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.</p>				
<p>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 2019a).</p>				

Table 2-5. Cladding Effects: Hydride Reorientation and Embrittlement

Gap	2019 Rank	2017 Rank	2012 Rank	Recommended R&D for the Next 3 Years
Cladding Effects: Hydride Reorientation and Embrittlement	3	3	7	Confirmatory PWR Testing and Testing of BWR and IFBA rods. R&D Ongoing
<p>What we have learned: Arguably, this is the gap that has seen the most 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 the NRC draft (NUREG-2224) 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 (Billone 2018), fatigue data obtained from the CIRFT tests (NUREG/CR-7198), data obtained from thermal measurements taken after</p>				

	<p>loading and drying of the High Burnup Demo Cask (Fort 2018), and data obtained from the Normal Conditions of Transport load quantification tests (Kalinina 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.</p>
	<p>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 BWR and IFBA fuel cladding. Work will also continue to build upon the PWR database through the Sister Rod Test Program.</p>

Table 2-6. Consequence Assessment of Canister Failure

Gap	2019 Rank	2017 Rank	2012 Rank	Recommended R&D for the Next 3 Years
Consequence Assessment of Canister Failure	3	N/A	N/A	Initiating
<p>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.</p>				
<p>What we still need to learn to close this gap: Development of test and analytic objectives is part of the 2019 R&D plan. 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.</p>				

Table 2-7, Fuel Transfer Options

Gap	2019 Rank	2017 Rank	2012 Rank	Recommended R&D for the Next 3 Years
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

	<p>What we have learned: Recent work on the Thermal 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.</p>
	<p>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.</p>

2.4 Priority 4 Gaps

Table 2-8. 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 2-9. Examination of the fuel at 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: Two casks are proposed to be opened as part of a campaign with the HBU confirmatory demonstration cask. 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 2-10. 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
<p>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 Demo Cask 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.</p>				
<p>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.</p>				

Table 2-11. 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
<p>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.</p>				
<p>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.</p>				

Table 2-12. 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
<p>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.</p> <p>The Demo cask 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.</p>				
<p>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.</p>				

Table 2-13. 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
<p>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.</p>				
<p>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.</p>				

Table 2-14. 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
<p>What we have learned: This gap was not specifically evaluated in Hanson et al. (2012). However, the draft MAPS Report (NRC 2016), Section 3.2.2.3 states:</p>				

<p>“galvanic corrosion occurs when two dissimilar metals or conductive materials are in physical contact in the presence of a conducting solution (Baboian, 2003; Hack, 1993). 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</p>	<p>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.</p>
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Table 2-15. Cladding – H₂ Effects: DHC

Gap	2019 Rank	2017 Rank	2012 Rank	Recommended R&D for the Next 3 Years
Cladding – H₂ Effects: DHC	4	4	9	No change in priority
<p>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.</p>				
<p>What we still need to learn to close this gap: There is no near-term R&D planned for this gap.</p>				

2.5 Lower Priority Gaps

The following gaps are listed as low priority. This ranking has not changed from the Hanson 2019 report. They are shown for completeness and tracking of all the gaps that have been identified in the Hanson 2012 report.

Table 2-16. Lower Priority Gaps

Gap	2019 Rank	2017 Rank	2012 Rank	Recommended R&D for the Next 3 Years
Bolted Casks - Thermomechanical Degradation of Metallic Seals and Bolts	N/A	N/A	5	Gaps have been assigned Low per Hanson 2019 and thus are no longer prioritized.
Welded Canister – Aqueous Corrosion	N/A	N/A	5	
Bolted Casks - Aqueous Corrosion	N/A	N/A	5	

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Bolted Casks - Atmospheric Corrosion	N/A	N/A	5	
Subcriticality - Moderator Exclusion	N/A	N/A	8	
Fuel Assembly Hardware – SCC for Lifting Hardware and Spacer Grids	N/A	N/A	11	
Cladding – Creep	N/A	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	

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 CISCC.
Fuel Transfer Options	3	4	4	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	
Bolted Casks - Thermomechanical Degradation of Metallic Seals and Bolts		N/A	5	Gap has been downgraded per Hanson 2019 to Low 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. 5 Years

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.

In-progress Work scope

- The highest priority R&D activity was to complete the loading of the Research Project Cask (EPRI 2014), 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 Research Project Cask after 10 years of storage is ongoing.
- The new identified activity of assessing the feasibility of Direct Disposal will be initiated with studies associated with operational boundary criteria assessments (e.g., thermal and criticality requirements between storage, transportation, and disposal regulations).
- 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 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 Research Project Cask of the High Burnup Spent Fuel Data Project using multiple methodologies
 - Phase IIb: the thermal analyses of the Research 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.
- 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 IRP and analyze data together with gas samples from the Research 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 – H₂ Effects: Hydride Reorientation and Embrittlement
 - Perform Phase 1 testing of sister rods as outlined in a technical memo (Saltzstein 2018)
- 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.
- Consequence Assessment
 - Conduct initial tests with engineered components to obtain data on crack parameter influence and fine particle deposition.

Next 2-5 Years

- Continue monitoring and data collection of the Research Project Cask
- Continue studies on Direct Disposal
- 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
- 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 – H₂ Effects: Hydride Reorientation and Embrittlement
 - Develop Phase 2 Test Plan and perform work as outlined
- Stress Profiles
 - Complete testing, modeling, and analyses previously identified
 - Continue development of cumulative effects models for each SSC
- Consequence Assessment
 - Continue tests with engineered components to refine data on crack parameter influence and fine particle deposition.

Next 5+ Years

- Continue monitoring and data collection of the Research Project Cask and prepare for cask transportation and opening
- Continue assessment of Direct Disposal feasibility
- 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 – H₂ Effects: Hydride Reorientation and Embrittlement
 - Complete Phase 2 testing
 - Based on results, determine if IFBA and/or BWR rods need to be tested
- Stress Profiles
 - Complete cumulative effects models for each SSC
- Examination of the fuel at the INL
 - Begin planning of opening a cask in preparation of opening the Research 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 NRC NUREG-2224 [NRC 2018] which states that high burnup fuel will maintain its integrity under transportation Normal Conditions of Transport.

As fuel behavior has become better understood and is expected to maintain its integrity under storage and transport conditions, emphasis is shifting to DCS 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 DCS 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 up-dated to reflect this increased understanding.