USED FUEL DISPOSITION CAMPAIGN

Review of Used Nuclear Fuel Storage and Transportation Technical Gap Analyses

Fuel Cycle Research & Development

Prepared for

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Used Fuel Disposition Campaign

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EXECUTIVE SUMMARY

This report fulfills the M2 milestone M2FT12PN0803042, "Review of Technical Data Gaps Relative to Similar External Studies," under Work Package Number FT-12PN080304.

The U.S. Department of Energy Office of Nuclear Energy (DOE-NE), Office of Fuel Cycle Technology, has established the Used Fuel Disposition Campaign (UFDC) to conduct the research and development activities related to storage, transportation, and disposal of used nuclear fuel and high-level radioactive waste. The mission of the UFDC is to identify alternatives and conduct scientific research and technology development to enable storage, transportation, and disposal of used nuclear fuel (UNF) and wastes generated by existing and future nuclear fuel cycles. The Storage and Transportation activities within the UFDC are being developed to address issues regarding the extended storage of UNF and its subsequent transportation. The near-term objectives of the storage and transportation task are to use a science-based, engineering-driven approach to develop the technical bases to support the continued safe and secure storage of UNF for extended periods, subsequent retrieval, and transportation.

While both wet and dry storage have been shown to be safe options for storing UNF, the focus of the program is on dry storage of commercial UNF at reactor or centralized locations. Because limited information is available on the properties of high burnup fuel (exceeding 45 gigawatt-days per metric ton of uranium [GWd/MTU]), and because much of the fuel currently discharged from today's reactors exceeds this burnup threshold, a particular emphasis of this program is on high burnup fuels.

The first step in establishing the technical bases for storage and transportation was to determine the technical data gaps that need to be addressed. The *Gap Analysis to Support Extended Storage of Used Nuclear Fuel* (UFDC 2012a, referred to as the UFDC Gap Analysis) was prepared to document the methodology for determining the data gaps and to assign an initial priority (Low, Medium, High) of importance for additional research and development to close the data gaps. The analysis considered only normal conditions of extended dry storage of commercial light water reactor (LWR) uranium dioxide fuel. An update to the UFDC Gap Analysis report is planned to include data gaps associated with transportation as well as some design-basis phenomena (e.g., design-basis seismic events) and accident conditions (e.g., cask tipover). UFDC also performed a more quantitative prioritization of the research to close the high and medium priority gaps in the *Used Nuclear Fuel Storage and Transportation Data Gap Prioritization* report (UFDC 2012b, referred to as the UFDC Gap Prioritization).

In order to verify that the UFDC identified all of the technical gaps and properly prioritized them, this report was commissioned to compare the UFDC Gap Analysis and UFDC Gap Prioritization reports to those recently published by others, including the U.S. Nuclear Waste Technical Review Board (NWTRB), the U.S. Nuclear Regulatory Commission (NRC), the Electric Power Research Institute (EPRI), and the International Atomic Energy Agency (IAEA). The documents reviewed are:

- *Evaluation of the Technical Basis for Extended Dry Storage and Transportation of Used Nuclear Fuel* (cited as NWTRB 2010)
- *Identification and Prioritization of the Technical Information Needs Affecting Potential Regulation of Extended Storage and Transportation of Spent Nuclear Fuel*, Draft for comment (cited as NRC 2012a)
- *International Perspectives on Technical Data Gaps Associated with Extended Storage and Transportation of Used Nuclear Fuel*, Draft (cited as EPRI 2012)
- *Extended Storage Collaboration Program (ESCP) Progress Report and Review of Gap Analyses* (cited as EPRI 2011)
- *Long Term Storage of Spent Nuclear Fuel - Survey and Recommendations* (cited as IAEA 2002).

The EPRI 2012 report provides the priorities of additional research of Extended Storage Collaboration Program (ESCP) committee members from six countries in addition to the United States: Germany, Hungary, Japan, South Korea, Spain, and the United Kingdom. Priorities given for the six countries are opinions of the EPRI/ESCP International Subcommittee participants and may not represent the official position of the organization or country. Each organization and country has a different focus when evaluating the research needed for closing technical gaps. These differences stem mostly from differences in the storage systems used (e.g., casks, vaults), future waste management needs and strategies, and organizational perspectives (e.g., industry, regulator). Both the NRC report (NRC 2012a) and the international report from EPRI/ESCP (EPRI 2012) are draft reports subject to change.

There are a collective total of 94 technical data gaps identified by the various reports to support extended storage and transportation of UNF. This report focuses on the gaps identified as Medium or High in any of the gap analyses and provides the UFDC's gap description, any alternate gap descriptions or different emphasis by another organization, the rankings by the various organizations, evaluation of the consistency of priority assignment and the bases for any inconsistencies, and UFDC-recommended action based on the comparison. Gaps that are ranked Low by all organizations and countries are not evaluated in this report.

Of the 94 gaps identified in the various gap analyses, there are 14 cross-cutting gaps and 80 structure, system, and component- (SSC-) specific gaps. For the cross-cutting gaps, the UFDC identifies eight and others identify six. Thirteen of the 14 cross-cutting gaps were identified as Medium or High by at least one of the gap analyses. The UFDC assigns a high priority to all the cross-cutting gaps it identified. For most of these, there is general agreement of their high priority. The six gaps identified by others are either covered by other UFDC gaps or are not applicable to UNF storage and transportation in the United States. Therefore, it is concluded that no changes to the UFDC cross-cutting gap analysis are necessary.

For the 80 SSC-specific gaps, the UFDC identifies 52 and others identify 28. The gaps identified by others either do not meet the UFDC's definition of a gap for extended storage and subsequent transportation, are grouped differently by the UFDC, or are given less than low priority by the

UFDC. For example: “Cladding - Oxide Thickness” is a property of UNF, not a degradation mechanism, “Cladding - Propagation of Existing Flaws” is covered by the UFDC under the individual degradation mechanisms, and “Canister - Irradiation Damage” is considered by the UFDC to be insignificant.

Of the 80 SSC-specific gaps, 48 were identified as Medium or High by at least one of the gap analyses. For 25 of these 48 Medium and High priority gaps, there is either consistency in evaluation and priority assignment across the gap analyses or the UFDC assigns a higher priority. Gaps with consistent high priority evaluation receiving five or more high ratings include:

Cross-cutting gaps

- Thermal Profiles
- Examine Fuel After Storage
- Monitoring

SSC-specific gaps

- Cladding – Delayed Hydride Cracking
- Cladding – Hydride Reorientation and Embrittlement
- Casks/Canisters – Atmospheric Corrosion (especially SCC at the welds)

In some instances, the UFDC gives a higher priority for additional research and development to gaps where experts disagree on the mechanisms (e.g., delayed hydride cracking and clad oxidation). Other differences in priorities are mostly because of differences in the various countries’ or organizations’ storage and transportation programs and ultimate waste disposal strategies. For example, the UFDC places a higher priority on many of the cladding gaps in an effort to maintain retrievability at the fuel assembly level.

For four gaps, the evaluation in the UFDC Gap Analysis (UFDC 2012a) is significantly different from that in other gap analyses. UFDC will address these gaps as follows:

- “Basket – Weld Embrittlement” will be evaluated once detailed and realistic thermal profiles have been developed.
- “Bolted Cask – MIC [microbiologically influenced corrosion]” and “Welded Canister – MIC” will be addressed as part of the various container aqueous and atmospheric corrosion gaps.
- “Fuel – Helium and Fission Gas Release” will be considered as part of fuel and cladding gaps.
- “Concrete – Thermal Degradation of Mechanical Properties, Dry-out” will be analyzed as part of existing concrete gaps.

As stated in the UFDC Gap Analysis (UFDC 2012a) and UFDC Gap Prioritization (UFDC 2012b) reports, as more data are obtained, all gaps are subject to reevaluation of priority. Continued collaboration with other organizations and countries will ensure that the UFDC is pursuing the proper course to obtain the data and analyses necessary to develop the technical bases for continued safe and secure storage.

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TABLES

ACRONYMS

AMP	aging management program
ANL	Argonne National Laboratory
BRC	Blue Ribbon Commission on America's Nuclear Future
BWR	boiling water reactor
CASTOR	a trade name that stands for cask for storage and transport of radioactive material
CFR	Code of Federal Regulations
CoC	Certificate of Compliance
CRIEPI	Central Research Institute of Electric Power Industry, a research institute of the Japanese nuclear industry
crud	a colloquial term for corrosion and wear products (rust particles, etc.) that become radioactive (i.e., activated) when exposed to radiation.
DBTT	ductile-to-brittle transition temperature
DCSCP	Dry Cask Storage Characterization Project
DCSS	dry cask storage system
DHC	delayed hydride cracking
DOE	U.S. Department of Energy
DOE-NE	U.S. Department of Energy Office of Nuclear Energy
EPRI	Electric Power Research Institute
ESCP	Extended Storage Collaboration Program
GWd	gigawatt-day
HBS	high burnup structure
HLW	high-level (radioactive) waste
IAEA	International Atomic Energy Agency
INL	Idaho National Laboratory
ISFSI	independent spent fuel storage installation
ISG	interim staff guidance
LWR	light water reactor
MIC	microbiologically influenced corrosion
mm	millimeter(s)
MMC	metal matrix composite
MOX	mixed oxide
MTU	metric tons (Tonnes) of uranium
MVDS	modular vault dry storage
N/A	not applicable
NRC	U.S. Nuclear Regulatory Commission

NUREG	publication prepared by staff of the U.S. Nuclear Regulatory Commission
NWTRB	Nuclear Waste Technical Review Board
PCI	pellet–clad interaction
PNNL	Pacific Northwest National Laboratory
PWR	pressurized water reactor
R&D	research and development
ROK	Republic of Korea (South Korea)
SCC	stress corrosion cracking
SFST	Spent Fuel Storage and Transportation (a division of the NRC)
SSC	structure, system, and component
UFDC	Used Fuel Disposition Campaign
UK	United Kingdom
UNF	used nuclear fuel
U.S.	United States (adjective)

USED FUEL DISPOSITION CAMPAIGN
Review of Used Nuclear Fuel Storage and Transportation Technical Gap Analyses

1. INTRODUCTION

The U.S. Department of Energy Office of Nuclear Energy (DOE-NE), Office of Fuel Cycle Technology has established the Used Fuel Disposition Campaign (UFDC) to conduct the research and development (R&D) activities related to storage, transportation, and disposal of used nuclear fuel (UNF) and high-level radioactive waste (HLW). Within the UFDC, the storage and transportation task has been created to address issues of extended or long-term storage and transportation. The near-term objectives of the storage and transportation task are to use a science-based, engineering-driven approach to

- develop the technical bases to support the continued safe and secure storage of UNF for extended periods
- develop the technical bases for retrieval of UNF after extended storage
- develop the technical bases for transport of high burnup fuel, as well as low and high burnup fuel after dry storage.

These objectives will help formulate the technical bases to support licensing for extended storage of UNF that will facilitate a wide range of disposition options. Under current regulations, it is not sufficient for UNF to simply maintain its integrity during the storage period, it must maintain its integrity in such a way that it can withstand the physical forces of handling and transportation associated with restaging the fuel and moving it to a treatment/recycling facility or a geologic repository. While both wet and dry storage have been shown to be safe options for storing UNF, the program will focus on dry storage at the reactor site or centralized locations with storage times exceeding the current longest licensed dry storage period. Although the initial emphasis of the program will be on commercial light water reactor (LWR) uranium-oxide fuel, DOE-owned research and defense UNF and alternative and advanced fuel concepts being investigated by DOE will be addressed later in this program. Because limited information is available on the properties of high burnup fuel (exceeding 45 gigawatt-days per metric ton of uranium [GWd/MTU]), and because much of the fuel currently discharged from today's reactors exceeds this burnup threshold, a particular emphasis of this program will be focused on high burnup fuels.

The first step in establishing the technical bases for continued safe storage and transportation was to determine the technical data gaps that need to be addressed. The *Gap Analysis to Support Extended Storage of Used Nuclear Fuel* (UFDC 2012a, also known as the UFDC Gap Analysis) was prepared to document the methodology for determining the data gaps and to assign an initial priority (Low, Medium, High) of importance for additional R&D to close the data gaps. The analysis was based on normal conditions of extended storage and informed by subsequent transportation needs. An update of the UFDC Gap Analysis report is planned for fiscal year

(FY) 2012 to fully evaluate data gaps associated with transportation as well as design basis phenomena (e.g., design-basis seismic events) and accident conditions (e.g., cask tipover). UFDC performed a second, more quantitative prioritization of the research to address the High and Medium priority gaps in the draft report *Used Nuclear Fuel Storage and Transportation Data Gap Prioritization* (UFDC 2012b). This prioritization report also considered anticipated high and medium priority gaps associated with transportation and the design-basis phenomena and accident conditions during extended storage.

Other organizations including the U.S. Nuclear Regulatory Commission (NRC), the Nuclear Waste Technical Review Board (NWTRB), and the Electric Power Research Institute (EPRI) performed independent gap analyses to support extended storage and transportation and, in some instances, prioritized these gaps. Several international organizations including those in Germany, Hungary, Japan, South Korea (Republic of Korea [ROK]), Spain, and the United Kingdom (UK), also performed similar independent gap analyses to support extended storage and transportation, and prioritized these gaps as part of the EPRI Extended Storage Collaboration Project (ESCP). The International Atomic Energy Agency (IAEA) also published a survey and recommendations of member countries' long-term storage needs as part of one of its coordinated research projects.

Among the various analyses performed, there are differences, in some instances significant, in both the gaps identified and in their assigned priorities. These differences stem mostly from differences in the storage systems used (e.g., casks, vaults), future waste management needs and strategies, and organizational perspectives (e.g., industry, regulator). This report compares the various gap analyses to determine if changes to the UFDC Gap Analysis and prioritizations are necessary or recommended. This comparison report, the issued UFDC Gap Analysis (UFDC 2012a) and draft UFDC Gap Prioritization report (UFDC 2012b) present a comprehensive picture of UFDC's current position on the gaps in the technical basis for safe storage and transport of used nuclear fuel. It is important to emphasize that as additional data are gathered and predictive models are developed, it is possible that the priority of identified gaps will change, or new gaps may be identified.

1.1 Purpose and Scope

The purpose of this report is to compare the UFDC gap analyses and priorities to those recently published by other organizations and countries including:

- *Evaluation of the Technical Basis for Extended Dry Storage and Transportation of Used Nuclear Fuel* (cited as NWTRB 2010)
- *Identification and Prioritization of the Technical Information Needs Affecting Potential Regulation of Extended Storage and Transportation of Spent Nuclear Fuel.* Draft for comment (cited as NRC 2012a)
- *Extended Storage Collaboration Program (ESCP) Progress Report and Review of Gap Analyses* (cited as EPRI 2011)

- *International Perspectives on Technical Data Gaps Associated with Extended Storage and Transportation of Used Nuclear Fuel* (cited as EPRI 2012). This draft report provides the priorities of additional research of EPRI/ESCP committee members from six countries in addition to the United States: Germany, Hungary, Japan, ROK, Spain, and the United Kingdom. The priorities of committee members from these countries are considered separately in this report. It is important to note however, that these priorities represent the opinions of the EPRI/ESCP International Subcommittee participants and do not represent any official position of the participant's country.
- *Long Term Storage of Spent Nuclear Fuel – Survey and Recommendations* (cited as IAEA 2002). This report surveyed long-term storage in over 20 countries that had, or planned to have, wet and/or dry storage. These included: Belgium, Bulgaria, Canada, Czech Republic, France, Germany, Hungary, India, Italy, Japan, Lithuania, Mexico, Netherlands, People's Republic of China, ROK, Romania, Russian Federation, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Ukraine, United Kingdom, and the United States. Discussions from these countries did not lend themselves to separate representation within this report, so they are discussed collectively.

Section 2 of this report summarizes the combined gaps and assigned priorities from the gap analyses developed by the various U.S. organizations (UFDC, NWTRB, NRC, EPRI), participants of the EPRI ESCP International subcommittee (Germany, Hungary, Japan, ROK, Spain, and the United Kingdom), and the IAEA.

If a gap is ranked Medium or higher by any organization or country, the following is presented in Section 3 for that gap:

- UFDC's gap description
- alternate gap description or different emphasis by another organization
- the rankings by the various organizations that discussed this gap
- an evaluation of the consistency of priority assignment in the various gap analyses and the bases for any inconsistencies. Because this report is intended to evaluate UFDC's gaps and their priorities against others, particular emphasis is placed on the reason for the inconsistency from UFDC's perspective. More significant elaboration is presented for those gaps where UFDC's priority is lower than others.
- UFDC-recommended action based on the comparison.

For gaps that are ranked Low by all organizations and countries that addressed the gap, no additional discussion is provided.

1.2 Background

Dry storage of commercial LWR fuel in the United States is accomplished at independent spent fuel storage installations (ISFSIs), where two types of storage systems are used: direct-loaded bolted casks and welded canisters housed in overpacks or storage modules. Both systems are deployed outside on concrete storage pads. Both systems have baskets to hold multiple assemblies and neutron absorbers, and use helium to promote heat removal and to provide an inert environment for the fuel. Shielding is provided by the metal shell and borated polymer/resin of the bolted casks and by a reinforced concrete overpack or storage module for the welded canisters. Most welded canisters are designed for both storage and transport. Most direct-loaded bolted casks are for storage only.

In 1986, the first U.S. ISFSI was licensed at the Surry power plant site in Virginia for a period of 20 years, and the license was subsequently renewed for an additional 40 years through an exemption process. Effective May 17, 2011, the storage regulation (10 CFR 72.42(a)) was officially changed to allow an initial license period of up to 40 years and license extensions of up to 40 years. In addition to the safety functions of confinement, shielding, and subcriticality, the U.S. regulations currently include retrievability at the assembly level as important to safety, in order to support all UNF disposition options (reprocessing/recycling and/or geologic disposal).

DOE-NE has established the UFDC to conduct the R&D activities related to storage, transportation, and disposal of UNF and HLW. The near-term objectives of the storage and transportation task within the UFDC are to use a science-based, engineering-driven approach to develop the technical bases to support the continued safe and secure storage of UNF for extended periods, subsequent retrieval, and transportation. Retrievability of UNF at the assembly level is important to DOE in providing safety and flexibility in potential interim storage and final disposition scenarios, whether they be reprocessing or disposal in a geologic repository.

UFDC's current priorities for research are provided in the UFDC Gap Analysis and the Gap Prioritization Reports (UFDC 2012a and 2012b). For the UFDC Gap Analysis (UFDC 2012a), the criteria used to determine the priority for gaps specific to a structure, system, or component (SSC) are:

- Data Needs
- Regulatory Considerations
- Likelihood of Occurrence
- Consequences
- Potential for Remediation
- Cost and Operations
- Future Waste Management Strategies.

The Gap Prioritization report (UFDC 2012b) narrowed this list to

- Likelihood of Occurrence
- Consequences

- Remediation

and added Timing of Data Needs.

Table A-1 shows the results of the Gap Prioritization report (UFDC 2012b, Table 5.5) with the column "Priority" added for this report. Since the score and rank are difficult to use when comparing priorities, they have been converted to priorities of Very High, High, Medium High, and Medium. These gap priorities are combined with the Low priority gaps of the UFDC Gap Analysis report (UFDC 2012a) to obtain the UFDC priority. For the gaps that are prioritized differently in the two reports, the Gap Prioritization report was given precedence.

The NWTRB is tasked to independently evaluate DOE technical activities for managing and disposing of UNF and HLW. The NWTRB report (NWTRB 2010) provides a comprehensive discussion of the U.S. technical issues and research needs for extended dry storage and transportation. In Table 9 of NWTRB 2010, the nine highest-priority research needs are listed. In a few cases, the NWTRB indicated that filling a data gap had low priority, but in most cases, priority is not assigned to the research needs discussed.

The NRC is the U.S. regulatory agency and determines whether an applicant's license meets the regulatory requirements. In this role, the NRC also pursues technical information to inform licensing decisions. Their purpose is not to address the technical issues themselves, but to identify and understand the technical issues that may arise during the review of license applications. Engineering solutions or additional research are both viable means to ensure safety.

NRC staff used two main priority criteria in developing their draft report (NRC 2012a): level of knowledge and regulatory significance. For level of knowledge, the NRC considers the level of knowledge for the time it takes for a degradation mechanism to initiate, the propagation rate of the degradation, and the time when the degradation will result in the component losing its ability to perform its safety functions. NRC staff also considers the capability for monitoring and inspection. For regulatory significance, the NRC considers the potential impact of the degradation phenomena on six safety areas: criticality, thermal, confinement, structural, shielding and retrievability. The overall rankings are provided in Table 5-1 of NRC 2012a. Those degradation phenomena that are rated high in Table 5-1 are further prioritized in Table 6-1 into those that should be addressed first (H1) and those that should be addressed next (H2).

EPRI pursues data needed by the utilities to present their safety cases in their license applications for UNF dry storage and transportation. Since DOE, not the utilities, is responsible for final dispositioning of the UNF, data gaps associated with long-term waste management strategies (e.g., retrievability of the fuel assembly) are ranked less important for EPRI than for UFDC.

In EPRI's report (EPRI 2011), the priority criteria are:

1. the importance to maintaining the safety functions with a particular emphasis on confinement
2. the amount of existing data
3. the amount of ongoing research
4. the ability to fairly easily detect, inspect, or mitigate degradation of the safety functions.

The safety functions listed by EPRI in Table 4-1 of EPRI 2011 are confinement, subcriticality, thermal performance, radiological protection, and retrievability. Table 4-2 of EPRI 2011 provides EPRI's priorities for research to close the gaps in knowledge on the SSC-specific degradation mechanisms. EPRI did not directly discuss any cross-cutting issues.

Within the IAEA, the program on Radioactive Waste and Spent Fuel Management provides support to the Member States by establishing safety standards for the management of spent fuel and providing assistance to the Member States on the use and application of these standards. In the technical document *Long Term Storage of Spent Nuclear Fuel – Survey and Recommendations* (IAEA 2002), the IAEA provides an overview of the used fuel storage programs in over 20 of its Member States. "Member States have similar regulatory objectives regarding the management of spent nuclear fuel. Those objectives are to protect public health and safety, by implementing regulations to:

- maintain subcriticality of spent fuel
- prevent the release of radioactive material
- ensure that radiation rates and doses do not exceed acceptable limits
- maintain retrievability of the spent fuel throughout the lifetime of the storage facility." (IAEA 2002, p. 11).

Retrievability is listed as a safety objective even though many of the countries reprocess their used nuclear fuel. "The key conceptual aspect of the long term storage is that it must not be regarded as a final disposal option or solution. This entails the capability to safely re-handle the spent fuel at any point in time after initial storage." (IAEA 2002, p.3) "Retrievability is strongly dependent on the conditioning route for the fuel after storage, individual licensing situation, and licensing practices in Member States, and characteristics of the fuel (e.g., type of defects). Therefore, requirements may depend on the ultimate back end solution for the fuel. Nevertheless, an aspect of retrievability is the integrity of the spent fuel including its structural components." (IAEA 2002, p.1).

In Germany, dry storage of used nuclear fuel employs bolted casks, which are stored in buildings, tunnels, or concrete canopies (IAEA 2007). Dry storage started in 1993 and current storage licenses are for 40 years, but the possibility of longer storage is being investigated.

The United States allows for storage-only licenses (up to 40 years) and requires a separate license for transportation with a 5-year renewal (recertification) requirement. Unlike the United States, some European member states including Germany, require that a transportation license, renewed every 3 to 5 years, must remain valid throughout the storage period, even if the cask is in storage with no transport planned.

The present solution for dry storage in Hungary is based on modular vault dry storage (MVDS) facilities. The MVDS consists of robust concrete rooms with vertical tubes that hold single fuel assemblies. Each fuel assembly is stored in a steel fuel tube that is sealed and rendered inert with nitrogen gas. The first dry storage was licensed in 1997 for a 50-year period.

Japan has been storing used boiling water reactor (BWR) fuel in dual purpose (storage and transport) bolted metal casks within storage buildings since 1995. In addition, Japan has been actively pursuing the use of multipurpose welded canisters. The dry storage period in Japan is 50 years.

While the ROK started dry storage of pressurized heavy water reactor spent fuel in 1992, dry storage of LWR fuel has not yet started. The type of dry storage system for pressurized water reactor (PWR) fuel is not yet decided. The planned storage period in the ROK is 50 years.

Spain’s first dry storage Certificate of Compliance (CoC) was issued in July of 1995 with a license period of 20 years and a possibility of 20-year renewal. Spain stores its used fuel in both welded canisters (HI-STORM 100) and dual-purpose bolted metal casks, but plans for a centralized repository vault system are under way.

Currently, there is no dry storage of used fuel in the United Kingdom. However, for PWR fuel, the intent is to store the fuel in a canister and cask system designed by Holtec International for up to 100 years.

2. GAP COMPARISON EVALUATION

Table 2.1 presents the priorities for R&D to close the gaps as necessary to form the technical bases for safe storage and transport of UNF for each of the organizations or countries. Included in the table are both cross-cutting gaps and SSC-specific gaps. The cross-cutting gaps are those that influence the degradation of more than one SSC or are other gaps in knowledge affecting more than one SSC. For example, thermal profiles affect the degradation rates of all the SSCs, while additional research in monitoring could provide further information on many degradation mechanisms.

In some cases, the different organizations or countries grouped the gaps differently. Thus there are general gaps as well as specific gaps. In addition, some of the gap titles were modified to be more general or more specific to facilitate comparison. For example, the UFDC gap "Examination of the fuel at the Idaho National Laboratory (INL)" has been generalized to "Examine fuel after storage". The list of SSCs is somewhat country-dependent and has been expanded to accommodate all the countries included in the EPRI ESCP report (EPRI 2012).

In Table 2.1, when a cell is blank, the organization or country did not specifically identify that gap for prioritization. This may be because the organization rated this gap very low, or because they organized their gaps differently. For example, in general the German authors did not identify specific concrete degradation mechanisms, but did identify concrete degradation as a medium priority. They also stated, "Fields are left blank in cases where a substantial expectation on necessary investigation programs and their importance is not possible by the involved parties at present." (EPRI 2012, p. 59).

In general, the priorities are indicated by an "H" for high, "M" for medium and "L" for low; but there are some exceptions. The UFDC provides greater specificity so priorities of very high and medium high are indicated by "VH", and "MH." Similarly, the NRC highest and second-highest gap priorities are indicated by "H1" and "H2." The NWTRB and IAEA gaps, which are discussed but not prioritized, are indicated by an "X." Finally, Japan presented a number of gaps that it has addressed and now considers closed. These are indicated with a "C" in Table 2.1.

The priorities presented in Table 2.1 are those reported in, or inferred from, the reviewed documents and may not represent the official position of the organization or country. In particular, priorities given for the six countries are opinions of the EPRI/ESCP International Subcommittee participants. For the sake of brevity, the analyses and priorities presented by the authors of these reports will be referred to by the author's organization or country. Finally, both the NRC report (NRC 2012a) and the international report from EPRI/ESCP (EPRI 2012) are draft reports subject to change.

Table 2.1. Comparison of Gaps and Priorities

		UFDC[a]	NWTRB[b]	NRC[c]	EPRI[d]	IAEA[e]	Germany[f]	Hungary[f]	Japan[fg]	ROK[f]	Spain[f]	UK[f]
Cross-Cutting	Ability of Assembly and Canister to Transport after Storage											M
	Activity Transport in Canister											H
	Burnup Credit	H						H				
	Dry Transfer Development		H			X					M	
	Drying Issues	VH	H	H1		X		H	C			M
	Examine Fuel after Storage	H	H			H		H	H		M	M
	Fuel Classification									H	H	H
	Fuel Modeling											H
	Fuel Transfer Options	VH						H		M		
	Moderator Exclusion	H										
	Monitoring	VH	H	H2		H		H	H			
	Stress Profiles	VH	H			X			C			
	Tests of Extreme Transportation Accidents		X									
	Thermal Profiles	VH	H	H1		X		H	C	H	M	H

Table 2.1. (contd.)

		UFDC[a]	NWTRB[b]	NRC[c]	EPRI[d]	IAEA[e]	Germany[f]	Hungary[f]	Japan[f,g]	ROK[f]	Spain[f]	UK[f]
Fuel	Helium and Fission Gas Release		X	H1		X						L
	Fission Product Attack on Cladding	L	X		L		M					
	Fragmentation	L	X	H1	L				M	L	M	L
	Oxidation	L	X	L	L	X				L	L	M
	Restructuring/Swelling	L	X	H1		X						

Table 2.1. (contd.)

		UFDC[a]	NWTRB[b]	NRC[c]	EPRI[d]	IAEA[e]	Germany[f]	Hungary[f]	Japan[f,g]	ROK[f]	Spain[f]	UK[f]
Cladding	Annealing of Radiation Damage	MH	L	M	M	X		M	C	M	M	
	Corrosion - Galvanic	L		H2	L		M					
	Corrosion - Pitting	L	X	L	L		M					
	Corrosion - SCC	L		H2	L	X	M					
	Coupled Mechanisms		X									
	Creep - High Temperature		X	L	L	X			C	M		
	Creep - Low Temperature	MH	L	H2	L	X	M	M		M	M	L
	Crud or Oxide Spallation				L						H	M
	Delayed Hydride Cracking	H	H	H2	M	X		M		H	M	H
	Diffusion-controlled Cavity Growth				L							
	Emissivity Changes	L										
	Grid-to-rod Fretting		X		L							
	Helium Pressurization		X	H1	L	X						
	Hydride Reorientation	H	H	L	M	X		H	C	H		H
	Hydride Embrittlement	H	H	L	M			H	C	H	H	H
	Metal Fatigue Caused by Temperature Fluctuations	L		L	L							
	Microbiologically Influenced Corrosion (MIC)		X	L								
	Oxidation	M	X	L	L	X	M	M		M		
	Oxide Thickness								C		L	
	Pellet-Cladding Interaction		X		L	X			M	L	M	
	Phase Change	L										
	Propagation of Existing Flaws			H2		X					L	

Table 2.1. (contd.)

		UFDC[a]	NWTRB[b]	NRC[c]	EPRI[d]	IAEA[e]	Germany[f]	Hungary[f]	Japan[f,g]	ROK[f]	Spain[f]	UK[f]
Assembly Hardware	Bowing or twisting									M		
	Corrosion Including SCC	MH		H2	L	X		M		H		
	Creep	L		L	L							
	Hydriding Effects	L		L	L							
	Metal Fatigue Caused by Temperature Fluctuations	L		H2	L							
Baskets	Corrosion	L		M	L		M					
	Creep	L		L	L							
	Metal Fatigue Caused by Temperature Fluctuations	L		H2	L							
	Weld Embrittlement			H2								
Moisture absorbers	Thermal and Radiation Damage						M					

Table 2.1. (contd.)

		UFDC[a]	NWTRB[b]	NRC[c]	EPRI[d]	IAEA[e]	Germany[f]	Hungary[f]	Japan[f,g]	ROK[f]	Spain[f]	UK[f]
Neutron Poisons	Corrosion and Blistering	M	X	M	L			M			M	
	Creep	M	X	H				M				
	Embrittlement and Cracking	MH		L				M				
	Metal Fatigue Caused by Temperature Fluctuations	L		M								
	Poison Burnup	L	L	L								
	Thermal Aging Effects	H		H2				M		M	M	
Neutron Shields	Corrosion	L		L								
	Poison Burnup	L		L								
	Radiation Embrittlement	L		L	L		M					
	Thermal Embrittlement, Cracking, Shrinkage, and Decomposition	L		L	L		M					

Table 2.1. (contd.)

		UFDC[a]	NWTRB[b]	NRC[c]	EPRI[d]	IAEA[e]	Germany[f]	Hungary[f]	Japan[f,g]	ROK[f]	Spain[f]	UK[f]
Bolted Cask	Coatings Degradation					X	L					
	Corrosion of Body and Lid			L		X						
	Corrosion of Bolts	VH	X	H1	M		M					
	Corrosion of Metal Seals	VH	X	L	M	X				H		
	Embrittlement of Elastomer seals	L	X	L	L		L					
	Irradiation Damage			L								
	Microbiologically Influenced Corrosion (MIC)			H2	M							
	Thermomechanical Degradation of Bolts	VH	X	H1	M		H			H		
	Thermomechanical Degradation of Seals	VH	X	L	L/M	X	H		H	H		
Welded Canister	Aqueous Corrosion	VH	X									
	Atmospheric Corrosion	VH	X	H1	H				H	H	L	VH
	Integrity under Accident Conditions											H
	Irradiation Damage			L								
	SCC Code, Prevention, and Mitigation								H			
	Microbiologically Influenced Corrosion (MIC)			H2	M							
Fuel Storage Tube	Corrosion							H				

Table 2.1. (contd.)

		UFDC[a]	NWTRB[b]	NRC[c]	EPRI[d]	IAEA[e]	Germany[f]	Hungary[f]	Japan[f,g]	ROK[f]	Spain[f]	UK[f]
Concrete Structures	Aggregate Growth	L	X									
	Aggregate Reaction	L	X	L								
	Calcium Leaching	L	X	L								
	Carbonation		X	L						M		
	Chemical Attack	L	X	L	L							
	Corrosion of Embedded Steel	M	X	M/H2	L			M		M		
	Coupled Mechanisms			M/H2								
	Creep	N/A	X	L								
	Decomposition of Water	L	X									
	Fatigue	L		L								
	Freeze–Thaw	M	X	L	L	X	L			M	L	
	Marine Degradation											M
	Radiation Damage	L	X	L								
	Shrinkage	N/A	X	L	L							
	Spallation				L							
	Thermal Degradation of Mechanical Properties, Dry-out	L	X	M/H2	L	X						
	Unspecified Concrete Degradation						M	M				

[a] DOE 2012a and 2012b, [b] NWTRB 2010, [c] NRC 2012, [d] EPRI 2011, [e] IAEA 2002, [f] EPRI 2012, [g] Email message from K Shirai (CRIEPI) to Christine Stockman (Sandia National Laboratories), "Storage Gap Priorities," June 18, 2012, Sandia National Laboratories, Albuquerque, New Mexico.

VH = Very High, H = High, H1 = NRC highest, H2 = NRC second highest, MH =- Medium High, M = Medium, L = Low, N/A = Not applicable, C = Gap addressed and closed, X = Gap discussed but not prioritized

3. DISCUSSION OF GAPS AND PRIORITIES

The priorities presented in Table 2.1 and discussed here are those reported in, or inferred from, the reviewed documents and may not represent the official position of the organization or country. In particular, priorities given for the six countries are opinions of the EPRI/ESCP International Subcommittee participants. For the sake of brevity, the analyses and priorities presented by the authors of these reports will be referred to by the author's organization or country. Finally, both the NRC report (NRC 2012a) and the international report from EPRI/ESCP (EPRI 2012) are draft reports subject to change.

3.1 Cross-Cutting Gaps

The cross-cutting gaps represent a more diverse set of issues than the gaps in knowledge about the degradation mechanisms for the SSCs. A little more than half of the cross-cutting gaps are identified by UFDC, with the remaining are added in response to highly rated issues identified by others. There has been some debate whether particular issues should be considered gaps. For example "examine fuel after storage" is not a gap in knowledge, but a means of addressing gaps. However, it is a significant task that is highly rated by many, so it is retained in the list. Because there is some subjectivity in determining what constitutes a cross-cutting gap, and because the participants were not asked to rate a full list of gaps, there are many blanks in the individual comparisons. For EPRI and Germany, they did not discuss any cross-cutting gaps, and thus blanks do not necessarily indicate a low priority.

3.1.1 Ability of Assembly and Canister to Transport after Storage

<table>
<tr><td rowspan="1">UFDC's Gap Description</td><td colspan="11">The UFDC did not identify this specifically as a gap. However, the ability of the assembly and canister to be transported after storage is one of the stated objectives of the UFDC program (see Section 1.0). UFDC uses the cross-cutting gap "Stress Profiles" as the means of addressing this gap.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">The United Kingdom identified the need to determine the condition of the fuel for transportation after approximately 100 years of storage and the ability of the fuel and canister to withstand normal and accident transport conditions (EPRI 2012). This gap is similar to the stress profiles gap (see Section 3.1.12) and closing it requires research into closing the individual SSC degradation gaps as well as the stress profiles gap.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>M</td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">The United Kingdom is the only country to give priority to this gap.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">This gap is adequately covered by addressing the SSC-related gaps, especially for cladding, assembly hardware, and the cask/canister, as well as the "Stress Profiles" gap. No additional gap will be added and the priorities for the UFDC gaps remain the same.</td></tr>
</table>

3.1.2 Activity Transport in Canister

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">The UFDC did not identify this as a gap.

In the United States, regulation requires an “analysis of the potential dose equivalent or committed dose equivalent to an individual outside the controlled area from accidents or natural phenomena events that result in the release of radioactive material to the environment or direct radiation from the ISFSI…” (10 CFR 72.24(m)). Table 5-2 of NUREG-1536 rev 1 (NRC 2010) (Table 7.1 of rev 0), provides fractions of radioactive materials available for release from spent fuel that “should be used in the confinement analyses to demonstrate compliance with 10 CFR Part 72” (NRC 2010). However, because of the lack of a credible event that could breach confinement, license applicants either do not perform such a calculation or use conservative release fractions such as those provided in NUREG-1536 for non-mechanistic hypothetical events to show even those conditions result in doses well within the 10 CFR 72.106 limit.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">In the United Kingdom, the regulator does not publish specific requirements of the utilities other than a list of 36 general License Conditions. “In the UK the utility is required to demonstrate ownership of all aspects of the safety case, and to justify the technical bases of the safety case as well as demonstrating compliance with them.” (EPRI 2012). As a consequence, requirements for specific calculations such as those required in 10 CFR 72.24(m) do not exist, and the utility must determine which calculations are necessary to demonstrate safety.

For this reason, the United Kingdom is interested in the “need to develop a model of activity transport/behavior in canister following fuel failure” (EPRI 2012). This includes “fission gas transport in the fuel matrix during a fault situation (i.e., can gap release be enhanced by other mechanisms,” and the need to determine the actual releases to the environment following a fault scenario (EPRI 2012).</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>H</td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">The United Kingdom is the only country or organization to identify this as a gap.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">The release fractions assumed in NUREG-1536 (NRC 2010) are conservative and thus R&D to provide more realistic release fractions under various conditions would be of benefit, but is considered to be of low priority. This priority could increase if further analyses show that such an approach is necessary to counter potential increased failure rates because of materials degradation over extended periods.</td></tr>
</table>

3.1.3 Burnup Credit

<table>
<tr><td rowspan="1">UFDC's Gap Description</td><td colspan="11">Burnup credit is allowance in the criticality safety analysis for the decrease in fuel reactivity resulting from irradiation. The level of burnup credit depends on the isotopes modeled in the criticality analysis. Actinide-only burnup credit generally refers to calculations employing only actinides with the highest reactivity worth. Full burnup credit refers to a combination of the uranium and plutonium isotopes evaluated in actinide-only burnup credit, plus a number of fission products and minor actinides.

Although some data are available and have been used to validate and attain regulatory approval for a burnup credit argument, additional data are needed to attain "full burnup credit;" reduce the bias and bias uncertainty in the isotopic concentration predictions, reactivity worth, and cross sections; and reduce the uncertainty/penalty in the assembly burnup assignment.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">Description of burnup credit is consistent in all the gap reports that discuss it.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>H</td><td></td><td></td><td></td><td></td><td></td><td>H</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">All the gap analyses that identified burnup credit as important to dry storage and transportation are consistent in priority assignment.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is needed, based on this comparison. However, if Revision 3 of ISG-8 (NRC 2012b) is implemented as in its current draft form, the need for additional data to support storage and transportation licenses will be lessened and the priority will be lowered. Additional R&D for burnup credit could be necessary to support geologic disposal efforts.</td></tr>
</table>

3.1.4 Dry Transfer Development

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">With the closing of the INL test area north facility, the ability to load and unload assemblies to or from dry storage casks in a dry environment was lost in the United States. There are two categories of needs for dry transfer facilities: retrieval of limited amounts of fuel to support research, and the ability to handle larger amounts of fuel as needed to repackage stored fuel for further storage, transportation, or disposal. The need for the first of these is covered under the fuel transfer options gap (see Section 3.1.9). The second is less immediate but is suggested for: repackaging fuel from “ISFSI-only” sites if needed, post-accident recovery of damaged fuel (NUREG-1536, NRC 2010), and a consolidated storage facility that could have “flexible, safe, and cost-effective waste handling services (i.e., repackaging or sorting of fuel for final disposal) and could facilitate the standardization of cask systems” (BRC 2012).</td></tr>
<tr><td>Alternate Description</td><td colspan="11">The NWTRB recommends the “design and demonstration of dry-transfer fuel systems for removing fuel from casks and canisters following extended dry storage” (NWTRB 2010, p. 14 and p. 125).

Spain notes the need for development of “Inspections, methods and tools required to open the cask and transfer the fuel from the individual (container) to the centralized repository (vault)” (EPRI 2012).</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td></td><td>H</td><td></td><td></td><td>X</td><td></td><td></td><td></td><td></td><td>M</td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">There is no consensus on the priority of this gap among those who rate it.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">This gap will not be added explicitly as it is already one of the options under the “Fuel Transfer Options” gap and is being considered as one of the means to address closure of gaps through an engineering-scale demonstration program.</td></tr>
</table>

3.1.5 Drying Issues

<table>
<tr><td rowspan="2">UFDC's Gap Description</td><td colspan="11">Many degradation mechanisms of the SSCs within the confinement boundary are dependent on or accelerated by the presence of water. Because the cask or canister is loaded in a pool, it is important to remove as much water as possible during the drying process. While there is no direct evidence that the amount of water that remains in a cask after a normal drying process is of concern, there is a lack of data to validate just how much water remains.</td></tr>
<tr></tr>
<tr><td>Alternate Description</td><td colspan="11">All analyses discussing drying issues are consistent in their description of the gap.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>VH</td><td>H</td><td>H1</td><td></td><td>X</td><td></td><td>H</td><td>C</td><td></td><td></td><td>M</td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">Except for Japan and the United Kingdom, this gap has been assigned a high priority by those that rate it. The Japanese have a different drying method than the United States, and consider this issue closed.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison.</td></tr>
</table>

3.1.6 Examine Fuel after Storage

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">This item was expanded from "examine the fuel at INL" to the more general "examine fuel after storage," which was identified by a number of organizations and countries. The purpose of this gap was to obtain a second data point on low burnup fuel that has been in dry storage, but applies as well to high burnup fuel after it has been in storage for some period. While there is emphasis on the fuel and cladding, closing this gap includes examining the entire dry cask storage system (DCSS) after storage, including the fuel, cladding, assembly hardware, baskets, neutron poisons, canister/cask, overpack if applicable, and pad. This activity will provide data used in evaluating performance models of all the SSCs.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">There is a universal need to examine fuel and the DCSS after a period of storage to validate models.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>H</td><td>H</td><td></td><td></td><td>H</td><td></td><td>H</td><td>H</td><td></td><td>M</td><td>M</td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">There is relative consensus that this is a high-priority activity.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison.</td></tr>
</table>

3.1.7 Fuel Classification

UFDC's Gap Description	Fuel classification or damage definitions are important because typically fuel cannot be put into dry storage if it is "damaged," without special treatment such as placement in a damaged fuel can. In the United States, fuel is classified in the NRC ISG-1 Revision 2 as "damaged," "undamaged," or "intact" (NRC 2007). UNF is determined to be damaged or undamaged based on its ability to meet all fuel-specific and system-related functions. These functions are those imposed on the fuel rods and assemblies by the applicant to meet a regulatory requirement for storage and/or transport. Intact fuel is undamaged fuel that is also not breached.										
Alternate Description	The ROK, Spain, and the United Kingdom all express the need to develop the means to better inspect fuel assemblies for classification purposes. In the United Kingdom, this is necessary because only intact fuel is to be placed in dry storage.										
Priority	UFDC	NWTRB	NRC	EPRI	IAEA	Germany	Hungary	Japan	ROK	Spain	UK
									H	H	H
Consistency of Priority	In those countries that rate fuel classification and damage definition, it is assigned a high priority.										
UFDC Action	At present, there is no evidence that the U.S. industry is not able to properly characterize and classify fuel per the definitions of ISG-1, Revision 2 (NRC 2007). Thus, this gap will not be added to the UFDC Gap Analysis.										

3.1.8 Fuel Modeling

UFDC's Gap Description	The UFDC does not identify this as a gap, but considers it an activity that must be pursued in order to license dry cask storage. UNF cladding modeling to evaluate condition of fuel as a function of dry storage is clearly identified as one of the options to close cladding gaps (UFDC 2012b, Appendix A).										
Alternate Description	The United Kingdom identified the "Need to develop fuel characterization technique i.e., determine fuel is intact," and the "need to develop fuel modeling under dry store conditions accounting for periods spent in reactor and the fuel pond" (EPRI 2012).										
Priority	UFDC	NWTRB	NRC	EPRI	IAEA	Germany	Hungary	Japan	ROK	Spain	UK
											H
Consistency of Priority	The United Kingdom is the only country to identify this issue as a specific gap.										
UFDC Action	The UFDC agrees that fuel modeling is an important option to closing gaps. However, this gap will not be added to the UFDC Gap Analysis.										

3.1.9 Fuel Transfer Options

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">The R&D proposed to close the fuel transfer options gap examines the effects of wetting and drying on cladding properties. Fuel samples, needed for research to close the cladding gaps, would most likely need to be transported from a utility site to a research laboratory. If coming from dry storage, and in the absence of a dry transfer system (see Section 3.1.4), the fuel would be rewetted for unloading from the dry storage cask and loading into a transportation cask, and then re-dried for transport. Both these processes have the potential to change the cladding properties, thus obfuscating any data obtained from those samples. The proposed research will determine if rewetting and re-drying can be done in such a way as to preserve the state of the cladding from storage enough to obtain interpretable data from those samples. This analysis will then help determine the pros and cons of the different transfer options (wet or dry) and allow researchers to make informed decisions on the preferred methods for transfer of fuel.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">Hungary uses the same description as UFDC, whereas the ROK is more concerned about the effects of transferring fuel between reactor pools as a means of maintaining pool capacity.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>VH</td><td></td><td></td><td></td><td></td><td></td><td>H</td><td></td><td>M</td><td></td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">This gap is rated medium or high priority by those who rate it.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison.</td></tr>
</table>

3.1.10 Moderator Exclusion

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">If the geometry of the fuel or the baskets, including neutron poisons, cannot be demonstrated for normal conditions of transport and hypothetical accident conditions, moderator exclusion may be a viable way to demonstrate subcriticality. There does not seem to be a general technical or a regulatory path to demonstrating subcriticality during normal conditions of transport and hypothetical accident conditions after a period of storage. The basis will likely be a demonstration of moderator exclusion along with structural integrity of the fuel, baskets, and neutron poisons, combined with a validated full burnup credit methodology. This issue, which requires further technical R&D as well as regulatory engagement, is relevant to all UNF in dual-purpose dry storage systems.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">UFDC is the only organization that discussed moderator exclusion.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>H</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">UFDC is the only organization that discussed moderator exclusion.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison.</td></tr>
</table>

3.1.11 Monitoring

<table>
<tr><td rowspan="1">UFDC's Gap Description</td><td colspan="11">Monitoring/Inspection can be applied for research purposes in demonstration projects, or more generally at the utilities. At the utilities in the United States, monitoring of the confinement boundary for bolted casks is required. This is usually done by monitoring the pressure between the redundant seals. Other routine monitoring/inspection activities include daily surveillance of overpack inlets and outlets for blockage, periodic radiation surveys, and visual inspection of the exterior of the cask or overpack. For research purposes, monitoring/inspection can provide data to provide input to and evaluation of SSC degradation models.

The gaps in monitoring capability include the lack of field-ready sensors that are adequate with respect to sensitivity, environmental compatibility, physical compatibility, and longevity. Monitoring inside the cask/canister without compromising the confinement barrier, is particularly challenging, requiring field-ready technologies for sensor power transmission/generation and data transmission.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">Germany recommends investigation into pressure monitoring devices that failed during storage operation.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>VH</td><td>H</td><td>H2</td><td></td><td>H</td><td></td><td>H</td><td>H</td><td></td><td></td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">This activity has a high priority to all those that rate it.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison.</td></tr>
</table>

3.1.12 Stress Profiles

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">The stress profiles gap is a gap in the experimental data and detailed calculations needed to determine the types of stresses (magnitude, frequency, duration, etc.) imparted to various SSCs under various conditions. These conditions include normal cask handling, cask drop, seismic events (including up to design basis), cask tipover, and normal transportation. Accurate inputs and quantification of the primary stresses (from pressure and thermal loadings), secondary stresses (from residual stresses from fabrication), and external loadings (from vacuum drying, handling, and vibratory loads during transportation) are important for evaluating the material and structural response of an SSC subjected to extended storage and transportation conditions.

The structural analyses performed for the license applications typically use bounding approximations in order to demonstrate that the SSCs maintain their safety functions through design basis storage events and normal transportation. However, these analyses do not use degraded material properties, so it is difficult to determine how much degradation can occur and still have the SSC meet its safety functions. R&D to close the stress profiles gap will provide this information and thus provides inputs to, and outputs from, the research to close gaps on the effect of the degradation mechanisms on the structural properties of SSCs.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">All analyses discussing stress profiles are consistent in their description of the gap.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>VH</td><td>H</td><td></td><td></td><td>X</td><td></td><td></td><td>C</td><td></td><td></td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">There is inconsistency between the UFDC and Japan. Japan considers this gap closed as a result of the testing performed by the Central Research Institute of Electric Power Industry (CRIEPI) between fiscal year (FY) 2001 to FY 2008. Demonstration tests included thermal, drop impact, missile impact, and seismic tests with full-scale concrete cask and metal cask systems.[a]</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison.</td></tr>
</table>

[a] Shirai K. 2012. Email message from K Shirai (CRIEPI) to Christine Stockman (Sandia National Laboratories), "Storage Gap Priorities," June 18, 2012, Sandia National Laboratories, Albuquerque, New Mexico.

3.1.13 Thermal Profiles

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">Because nearly all degradation mechanisms are temperature-dependent, thermal profile histories are needed to predict SSC performance. Therefore, temperature data are needed for all SSCs from the time the fuel is loaded into the cask, dried, through the storage period, and during subsequent transportation. The NRC issued guidance on temperature limits based on the need to maintain the integrity of the cladding (NRC 2010b). Therefore, when making approximations for modeling, most modelers have used conservative ones to ensure cladding does not exceed those limits. However, because some degradation processes only occur as the dry cask storage system (DCSS) cools below a threshold temperature, more realistic thermal calculations are needed. Similarly, conservatively high temperatures would over-predict various degradation rates.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">All analyses discussing thermal profiles are consistent in their definition.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>VH</td><td>H</td><td>H1</td><td></td><td>X</td><td></td><td>H</td><td>C</td><td>H</td><td>M</td><td>H</td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">Except for Japan, which considers the thermal profiles it currently has as adequate, there is consensus that more thermal modeling is needed. Regulations in Japan limit peak cladding temperature to only 275°C, much lower than the 400 °C peak cladding temperature limit in the United States.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison.</td></tr>
</table>

3.2 Fuel

Typical UO_2 fuels undergo significant changes during reactor operations. The fission process generates a myriad of fission products, many of which are soluble in the UO_2 matrix. Those elements that are not soluble in the matrix tend to either diffuse out of the grains to the grain boundaries and eventually out of the fuel pellet to the fuel–clad gap or they form separate metallic or oxide phases within the fuel. As a general rule, the quantity of fission gases, such as xenon and krypton, released from the fuel pellet increases with increasing burnup. In reality, the duty cycle, which is a combination of parameters such as the operating power level, temperature, and other factors, has a larger direct effect than burnup. Actinides such as plutonium, americium, and curium are also generated in the fuel by neutron capture reactions. The quantity of both fission products and higher actinides increases roughly linearly with burnup.

Other changes that occur with irradiation are an initial densification of the fuel pellet, followed by swelling that is primarily a result of buildup of fission products and radiation damage. The thermal conductivity, which is relatively poor for UO_2 and results in very large temperature gradients across the pellet diameter, decreases with increasing burnup, again as fission products and radiation damage increase and disrupt the UO_2 lattice. The nonuniform heating rates and large temperature differentials leads to uneven thermal expansion that first results in cracking of the fuel pellets, followed by possible deformation. The thermal expansion and swelling of the fuel pellet combined with cladding creepdown closes the fuel–clad gap so that the fuel and cladding are in contact with each other. Local stresses on the cladding, combined with chemical reactions between the fuel pellet and cladding can result in pellet–clad interaction (PCI) failures.

Another major change occurs when the local pellet burnup reaches about 40 GWd/MTU. At this burnup, the fuel undergoes a microstructure change with the formation of the high burnup structure (HBS) or pellet rim (Lassman et al. 1995). Typical LWR fuel pellets have grain sizes between 7 µm and 14 µm, whereas the HBS forms subgrains on the order of 0.1 µm to 0.2 µm and a fine network of small (~1 µm) fission gas bubbles. The HBS is highly porous, yet it still does not release a significant portion of the fission gases, which remain trapped in the high-pressure bubbles within the fuel matrix.

Because the fuel pellet serves only an indirect role in providing or maintaining safety functions, unless the cladding is breached, its importance to licensing is low, and thus all of the UFDC gaps directly associated with fuel were given a low priority.

3.2.1 Helium and Fission Gas Release

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">Helium and fission gas release, either during normal extended storage or during accidents, is not identified as a gap by the UFDC.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">NRC identifies helium release resulting from alpha decay over extended periods as a potential means of increasing the internal pressure of the fuel rod. This gap is given a high priority because knowledge of athermal release is limited. Similarly, release of fission gas and helium during accident conditions was prioritized as a high because the amount of release resulting from mechanical fracture of the fuel was characterized as having a low level of knowledge.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td></td><td>X</td><td>H1</td><td></td><td>X</td><td></td><td></td><td></td><td></td><td></td><td>L</td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">NRC considers rod pressurization as a means of promoting further clad degradation. The UFDC is examining low-temperature, low-stress (i.e., low pressure) mechanisms that suggest that additional rod pressurization is not required to promote mechanisms such as delayed hydride cracking. The release rates assumed in NUREG-1567 (NRC 2000, Section 9) are considered sufficient. It should be noted that the United Kingdom ranks this gap a low priority stating it can be modeled, but verification would be useful.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">This gap will not be added to the UFDC Gap Analysis. If future work or analyses indicate that the assumed release rates result in exposure above regulatory limits, then R&D to better quantify release will be warranted. It should be noted that this gap will be addressed directly through a long-term engineering scale demonstration.</td></tr>
</table>

3.2.2 Fission Product Attack on Cladding

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">Fission products are known to promote PCI and stress corrosion cracking (SCC) of the cladding. Because additional fission product release is not expected under extended storage conditions and because newer cladding designs tend to reduce PCI failures, this is considered a low priority.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">This gap is considered by Germany as a potential means of corrosion of the fuel cladding, which is the same as the PCI and SCC mechanisms.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>L</td><td>X</td><td></td><td>L</td><td></td><td>M</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">This gap is given a low priority by UFDC and EPRI, but a medium priority by Germany without additional information as to why they considered it more important.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison.</td></tr>
</table>

3.2.3 Fragmentation

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">Fuel pellets crack during reactor operation because of the large temperature gradients across the pellet diameter. Additional fractures could occur either as a result of mechanical force, such as under accident conditions, or from internal pressurization such as by generation of helium by alpha decay. Release rates of fission gases, volatiles, and fuel fines under normal and hypothetical accident conditions are specified in NUREG-1567 (NRC 2000).</td></tr>
<tr><td>Alternate Description</td><td colspan="11">The focus of the fragmentation gap by other organizations is on impact accidents.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>L</td><td>X</td><td>H1</td><td>L</td><td></td><td></td><td></td><td>M</td><td>L</td><td>M</td><td>L</td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">The prioritizations assigned to the fragmentation gap vary from Low to the highest priority. But those with higher priorities are focused on the results of an impact accident.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison. While transportation accidents are necessary analyses to be conducted to obtain a license, it is first necessary to determine how the cladding fails, and how much cladding fails in such an accident after extended storage. This will be examined as part of the "Stress Profiles" gap.</td></tr>
</table>

3.2.4 Oxidation

<table>
<tr><td rowspan="1">UFDC's Gap Description</td><td colspan="11">Fuel oxidation is only possible if the cladding is breached and the fuel is exposed to an oxidizing environment at high enough temperature for long enough times. The oxidizing environment is only present in the case of mistaken backfill of the container, excess water present after drying, or breach of the container. The mechanisms and kinetics of fuel oxidation are well understood and documented.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">All analyses use the same description of the fuel oxidation gap.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>L</td><td>X</td><td>L</td><td>L</td><td>X</td><td></td><td></td><td></td><td>L</td><td>L</td><td>M</td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">All organizations with the exception of the United Kingdom agree that the level of knowledge is sufficient to support a low priority. The United Kingdom is focused on post-accident oxidation when breaches are possible.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison.</td></tr>
</table>

3.2.5 Restructuring/Swelling

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">Fuel pellets swell as fission gas and helium are produced. The swelling can cause PCI. At higher burnups, the fuel undergoes a restructuring with new grains forming that are submicron in size.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">The focus of the NRC gap is on helium production from alpha decay that may cause the fuel to swell and become a source for stress to cause delayed hydride cracking (DHC).</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>L</td><td>X</td><td>H1</td><td></td><td>X</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">There is a significant disparity in the priorities assigned by UFDC and NRC. UFDC has examined analyses (e.g., Ferry et al. 2005) that have shown that helium production in UO_2 fuels is not an issue, even at extended times. It is, however, a potential concern for mixed oxide (MOX) fuels.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison.</td></tr>
</table>

3.3 Cladding

Although the NRC does not explicitly consider cladding as a confinement barrier, as evidenced by failed fuel assemblies being allowed in DCSSs as long as they are in a damaged fuel can, the state and material properties of the cladding are still important to licensing. In fact, the NRC regulations require (10 CFR 72.122(h)) that "spent fuel cladding must be protected during storage against degradation that leads to gross ruptures or the fuel must be otherwise confined such that degradation of the fuel during storage will not pose operational safety problems with respect to its removal from storage." Gross ruptures or breaches are defined in NUREG-1536 (NRC 2010) as any cladding breach greater than 1 mm.

For the purposes of the UFDC program, retrievability and operational safety concerns also apply to the fuel after transportation so that the fuel can be transloaded into waste packages for disposal or handled in a reprocessing facility. While the industry is interested in redefining retrievability at the canister (and not fuel assembly) level, the NRC regulations and the uncertainty in the final disposition of UNF dictates that protecting cladding against degradation is of high importance. The UFDC continues to pursue alternatives to individual fuel assembly retrievability (e.g., canning individual or small numbers of assemblies). Such alternatives may facilitate the demonstration of subcriticality in the case of cladding damage and fuel relocation. However, until regulations change and it can be demonstrated that for future waste management needs it is no longer necessary, fuel assembly retrievability remains a key feature for the UFDC.

The mechanical properties of cladding are very interrelated with numerous factors (e.g., radiation damage and annealing, hydride content and orientation, amount of creep and ductility, and oxide layer thickness) affecting cladding performance. There are limited publicly available data on properties of high burnup cladding and the associated newer cladding alloys. Until such data are obtained, it will not be clear whether the listed factors are a concern.

3.3.1 Annealing of Radiation Damage

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">Radiation damage of cladding during reactor irradiation is known to affect the strength and ductility of the cladding. Annealing of radiation damage can decrease the hardness and increase ductility, thus lessening the chance of breakage from mechanical shock, but potentially facilitating additional creep. Recent studies have indicated that annealing of much of the radiation damage is possible at the temperatures experienced during dry storage. The extent of annealing could potentially affect other mechanisms and be an important factor in long-term performance.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">All analyses use the same description for annealing of radiation damage.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>MH</td><td>L</td><td>M</td><td>M</td><td>X</td><td></td><td>M</td><td>C</td><td>M</td><td>M</td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">The priorities assigned range from closed to medium high. The biggest factor in this variation is the organization's understanding of the temperature at which annealing can occur. For example, the NWTRB (NWTRB 2010) cites a report that states that annealing is not expected at temperatures below 400 °C. This seems supported by the results of the Dry Cask Storage Characterization Project (DCSCP) (EPRI 2002) where little, if any, annealing occurred during testing and 15 years of storage. The UFDC higher priority is assigned because the results of Ito et al. (2004) showed nearly 50 percent recovery over almost one year in dry storage conditions at 360 °C. Additional work is necessary to understand and reconcile these differences.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison.</td></tr>
</table>

3.3.2 Corrosion – Wet (Galvanic/Pitting)

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">Wet corrosion can only occur when water is present in the DCSS. There will always be residual water remaining even after a successful drying operation. If sufficient water is present to promote a galvanic coupling between different metals, corrosion could occur. Radiolysis of water can result in production of highly oxidizing species that could promote pitting corrosion, especially in weld materials.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">All analyses use the same description for wet corrosion of cladding.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>L</td><td>/X</td><td>H2/L</td><td>L</td><td></td><td>M</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">The NRC assigns an H2 priority for galvanic corrosion, stating that this is only high if the drying task (Section 3.1.5) indicates that sufficient water remains in the canister and that it may revert to low if sufficient water is not present. Conversely, the UFDC assigns a low priority unless the drying task shows there to be sufficient water to promote wet corrosion. Both organizations agree to change the priority based on the results of the drying gap. NRC rates pitting as a low priority. Germany lists wet corrosion as a medium.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison.</td></tr>
</table>

3.3.3 Corrosion – Stress Corrosion Cracking

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">The UFDC does not explicitly cite SCC of cladding as a gap, but rather it is included as part of "Fission Product Attack on Cladding" in Section 3.2.2 and "Corrosion – Wet" in Section 3.3.2. In order for SCC to occur, there must be a stress (residual or applied), a promoting environment, and a susceptible material.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">The NRC does not believe that there is sufficient stress in the absence of pellet swelling, as discussed in Section 3.2.5, for SCC.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>L</td><td></td><td>H2</td><td>L</td><td>X</td><td>M</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">The NRC rates the priority for SCC as an H2, but states that this depends on a source of stress that comes from pellet swelling. The UFDC does not believe that pellet swelling is an issue, based on results in the literature.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">SCC will not be added explicitly as a gap for cladding, but will continue to include it in the "Fission Product Attack on Cladding" (Section 3.2.2) and "Corrosion – Wet" (Sections 3.3.2) gaps. No change in the UFDC priority is recommended, based on this comparison.</td></tr>
</table>

3.3.4 Creep – High Temperature/Low Temperature

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">The main driving force for thermal (high temperature) creep is the hoop stress caused by internal rod pressure. This will decrease over time as the temperature decreases, unless helium or fission gas release from the pellets increases. As the cladding creeps, the internal volume increases and the hoop stress will decrease, so thermal creep is considered self-limiting. Typically, thermal creep has not been observed at temperatures below 300 °C. In the DCSCP (EPRI 2002), only about 0.1 percent creep was observed over about 15 years. Thermal creep is generally well understood, however, questions remain about the effects of extended storage periods and of radiation damage annealing (see Section 3.3.1).

Low-temperature creep mechanisms have been studied and modeled, but there is little to no information on long-term behavior.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">The NRC states that even low-temperature creep will depend on a source of stress that would come from pellet swelling.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>/MH</td><td>X/L</td><td>L/H2</td><td>L</td><td>X</td><td>/M</td><td>/M</td><td>C/</td><td>M</td><td>/M</td><td>/L</td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">Because of differing views on the sources of stress and on the applicability of the various low-temperature creep mechanisms, the priorities of the organizations and countries are quite varied. Japan considers the creep issue closed, mostly because their drying and storage temperatures are so much lower than in the United States. However, it is not clear whether Japan has considered the low-temperature creep mechanisms in this assessment.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison.</td></tr>
</table>

3.3.5 Crud or Oxide Spallation

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">The UFDC does not explicitly account for crud or oxide spallation as a gap.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">During reactor operations, if crud or the oxide layer spalls, it will affect the local temperature and may promote hydrogen blisters. The UFDC considers this as part of the initial characterization of fuel going into dry storage. If the crud or oxide layers spall during dry storage, that will again affect local temperatures through effects such as emissivity changes and could result in localized hydride effects. The concerns of Spain and the United Kingdom seem to be focused on the initial characterization of the cladding going into storage and the potential for localized hydride concentrations.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td></td><td></td><td></td><td>L</td><td></td><td></td><td></td><td></td><td></td><td>H</td><td>M</td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">EPRI states that additional spallation during storage is not likely, but any spallation could increase the source term in the event of a container breach. Spain is concerned with localized hydride blisters formed during reactor operations because of crud or oxide spallation that may result in additional cladding failures during storage.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">This gap will not be added to the UFDC Gap Analysis as it is considered sufficiently covered by the gaps related to hydrides or emissivity changes.</td></tr>
</table>

3.3.6 Delayed Hydride Cracking

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">DHC is a time-dependent mechanism traditionally thought of as diffusion of hydrogen to an incipient crack tip, followed by nucleation, growth, and fracture of the hydride at the crack tip. The process continues as long as a sufficient stress exists to promote hydrogen diffusion. Kim (2009) proposed a new model for DHC where creep deformation, prior creep strain, higher burnup, the solvus hysteresis, and a hydride phase transition all play roles in DHC. This new model, which does not have consensus among experts, predicts that DHC may be more of a factor at lower temperatures.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">The NRC states that DHC is possible, but depends on a source of stress that would come from pellet swelling.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>H</td><td>H</td><td>H2</td><td>M</td><td>X</td><td></td><td>M</td><td></td><td>H</td><td>M</td><td>H</td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">The differences in prioritization stem mainly from differing opinions as to whether Kim's model is valid and whether fuel swelling is necessary to provide additional stress.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison.</td></tr>
</table>

3.3.7 Helium Pressurization

See Sections 3.2.1 and 3.2.5.

3.3.8 Hydride Reorientation/Embrittlement

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">Hydrogen is taken up on the waterside of the cladding during reactor operations. As the concentration of hydrogen in zirconium exceeds the solubility, which is highly temperature-dependent, zirconium hydrides are formed. Typically, there is a thick hydride layer at the outer surface of the cladding and lower concentrations towards the inner surface. Depending on the size, distribution, and orientation, these hydrides can embrittle the cladding and reduce ductility. There are many factors, including the cladding alloy composition, that influence hydride behavior.

Cladding hydrides are typically aligned in the circumferential direction, but may reorient to the radial direction under a stress, especially when cooled from a higher temperature, such as occurs in the drying process. Radial hydrides can facilitate through-wall cracking of the cladding.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">The description of hydride reorientation and embrittlement is consistent among the various organizations that analyzed it.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>H</td><td>H</td><td>L</td><td>M</td><td>X/</td><td></td><td>H</td><td>C</td><td>H</td><td>/H</td><td>H</td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">There is fairly good agreement that hydride embrittlement and reorientation warrant a high priority for additional R&D. The NRC gives these mechanisms a low priority on the basis that the level of knowledge is high, yet states "In the NRC staff's opinion, the wide number of variables that affect the degree of hydride reorientation make it difficult to produce a detailed parametric description of the formation of radial hydrides, and efforts should be made to determine conditions under which the mechanism is benign" (NRC 2012a). They also give the low prioritization based on temperatures remaining above the ductile-to-brittle transition temperature (DBTT); however, that may not be feasible for extended storage. Japan considers this issue closed because their regulations limit the temperatures during drying sufficiently low to supposedly prevent radial hydride formation.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison.</td></tr>
</table>

3.3.9 Oxidation

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">During reactor operations, the zirconium cladding reacts with water or steam to form an oxide layer on the cladding. The oxide layer is brittle, compared to the metal, and thus affects the overall mechanical properties, depending on the thickness of the oxide. Under normal conditions in dry storage, the assemblies are stored in an inert environment, so oxidation can only occur if residual water remains. The UFDC rates cladding oxidation as a medium until the cause for the rapid fuel-side oxidation of cladding observed in tests at Argonne National Laboratory (ANL) is found.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">All analyses use the same description for oxidation of cladding.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>M</td><td>X</td><td>L</td><td>L</td><td>X</td><td>M</td><td>M</td><td></td><td>M</td><td></td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">Prioritization of this gap is fairly consistent. However, the NRC gives cladding oxidation a low priority based on a high level of knowledge. Overall, the UFDC agrees with the NRC. However, it is necessary to determine the cause of the rapid oxidation observed in the ANL tests to be assured that this will not happen under prototypic dry storage conditions.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison.</td></tr>
</table>

3.3.10 Pellet-Cladding Interaction

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">PCI is typically thought of in terms of fission product release from the fuel (or contact of the fuel with the cladding) that then promotes degradation of the cladding through SCC (see Section 3.2.2). However, it can also be a mechanical interaction of the pellet with the cladding, resulting in localized stresses. The UFDC does explicitly identify a gap in knowledge about PCI, but includes mechanical interactions of the pellet and cladding as part of the creep gap (see Section 3.3.4).</td></tr>
<tr><td>Alternate Description</td><td colspan="11">Spain sees this issue in terms of the overall mechanical response of the cladding-pellet system under pinch loads.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td></td><td>X</td><td></td><td>L</td><td>X</td><td></td><td></td><td>M</td><td>L</td><td>M</td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">The UFDC agrees with the assessment by Spain, and testing of cladding (including ring compression tests) with the fuel still in the cladding are planned.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">PCI will not be added explicitly as a separate gap to the UFD Gap Analysis based on this comparison, but remains a key part of the cladding creep gap.</td></tr>
</table>

3.3.11 Propagation of Existing Flaws

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">The UFDC does not include propagation of existing flaws as an explicit gap, but rather as part of the "Stress Profiles" and "DHC" gaps.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">The NRC (NRC 2012a) states that "There is little current knowledge of the initial flaw size distribution in high burnup cladding, and as a result, it currently cannot be determined whether the cladding will fail in the long term."</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td></td><td></td><td>H2</td><td></td><td>X</td><td></td><td></td><td></td><td></td><td>L</td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">NRC and Spain both identify this as a gap, but Spain is focused on identification of incipient cracks.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">While the UFDC agrees that it is important to determine how incipient cracks may lead to failure, it will be extremely difficult to determine the existing crack size distribution in cladding. The UFDC approach in the "Stress Profiles" gap is to model the maximum crack size for the cladding to maintain its safety functions under normal and design basis conditions of handling, storage, and transportation. This gap will not be added explicitly to the UFDC Gap Analysis.</td></tr>
</table>

3.4 Assembly Hardware

The fuel assembly hardware is defined as the balance of fuel assembly materials other than fuel pellets and fuel cladding. The primary components of fuel assembly hardware that serve a safety function for dry storage of UNF are grid spacers, guide and instrumentation tubes, and assembly channels (BWR assemblies only). Other hardware connected to these components lends structural support, such as tie plates, spacer springs, tie rods, and nozzles. Assembly hardware includes a variety of designs, materials of construction, and types of connections that continue to evolve.

Grid spacers are composed of a zirconium alloy (similar to fuel cladding), Inconel®, or both. The construction of grid spacers includes straps and springs to maintain the spacing between fuel rods, control rod vibration, and provide lateral support. Springs made of Inconel® have low stress relaxation rates; whereas springs made of zirconium alloys have higher stress relaxation rates with irradiation. Generally, zirconium alloys are used in the intermediate grid spacers whereas Inconel® is used for the top and bottom grid spacers. However, some assembly designs use Inconel® in the intermediate grid spacers, and others use a zirconium alloy for all the grid spacers including the top and bottom ones.

It is important to note that in-reactor service substantially alters the condition and material properties of assembly hardware. These altered material properties establish the initial conditions for dry storage. The most significant changes to assembly hardware condition and material properties resulting from reactor service are structural growth, creep, stress relaxation, corrosion, and hydriding.

3.4.1 Bowing or Twisting

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">UFDC does not evaluate this degradation mechanism.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">Some fuel assemblies after long exposure in a reactor (three cycles) may undergo deformation that could cause handling issues. For fuel assemblies that experienced hard operational history, pool side examination is essential (EPRI 2012).</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>M</td><td></td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">The gap analysis conducted by the ROK is the only one that identifies this as an important degradation mechanism. Based on their gap description, this mechanism is influenced by reactor operations and is considered an initial condition prior to dry storage. Therefore, it is not clear that any additional R&D is needed beyond assembly inspection prior to dry storage.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">This gap will not be added to the UFDC Gap Analysis.</td></tr>
</table>

3.4.2 Corrosion Including Stress Corrosion Cracking

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">Assembly hardware is subject to corrosion during the off-normal condition of moisture presence inside the canisters because of inadequate drying or waterlogged rods. The rate and extent of corrosion are expected to be highest during the initial period of storage. Once the moisture has been expended, wet corrosion would stop. Therefore, because of the lower temperatures and absence of moisture during extended storage, wet corrosion is expected be a minor contributor to assembly hardware degradation for extended storage; however, its impact during the initial period of dry storage needs to be better evaluated. Similarly, corrosion and stress corrosion cracking that initiated and occurred during reactor operations, but may not be detected, may be exacerbated during extended storage.

Degradation of a few grid spacers or guide tubes may not constitute a failure during normal and off-normal conditions if enough spacers and guide tubes remain intact to hold the fuel pins and maintain axial support. However, their performance may no longer be acceptable under design basis accidents.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">Description of assembly hardware corrosion and stress corrosion cracking is consistent in all the gap reports that discuss it.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>MH</td><td></td><td>H2</td><td>L</td><td>X</td><td></td><td>M</td><td></td><td>H</td><td></td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">All the gap analyses that identified assembly hardware corrosion and stress corrosion cracking as important to dry storage and transportation are consistent in priority assignment, with the exception of EPRI. The basis EPRI provides for the low priority is that the industry is already dealing with how to handle PWR fuel subject to top nozzle separation because of SCC. EPRI does not address grid spacers.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison.</td></tr>
</table>

3.4.3 Metal Fatigue Caused by Temperature Fluctuations

<table>
<tr><td rowspan="1">UFDC's Gap Description</td><td colspan="11">With longer storage times, there are more summer–winter temperature fluctuations and increased likelihood of extreme weather conditions. However, the temperature of the assembly hardware is not expected to be significantly affected by those fluctuations, given the relatively large heat capacity of storage systems and the fact that assembly hardware is an integral component of the heat-generating fuel. Although temperature fluctuations may result in changes in material properties of assembly hardware, they are not likely to result in a failure. Material property changes are important in evaluating assembly hardware performance during design basis accidents and transportation hypothetical accident conditions.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">The NRC notes that cumulative stress cycles of sufficient magnitude can lead to a change in material properties, metal fatigue, and failure below yield strength. Metal fatigue because of temperature fluctuations of fuel assembly hardware would likely be more operative during extended storage beyond 40 years, resulting from an increasingly accumulated number of stress/temperature cycles over time (NRC 2012a).</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>L</td><td></td><td>H2</td><td>L</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">All the gap analyses that identified assembly hardware metal fatigue caused by temperature fluctuations as important to dry storage and transportation are consistent in priority assignment, with the exception of the NRC. The NRC bases its higher priority in part on the fact that additional information on temperature profiles during storage is necessary to improve estimates of the magnitude of temperature changes and fatigue on fuel assembly hardware.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">The UFDC agrees with the need for more detailed and realistic thermal profiles. No change in the UFDC priority is recommended, based on this comparison, however, if further analysis shows the temperature cycling to be significant, then the priority could change.</td></tr>
</table>

3.5 Fuel Baskets

The safety function of fuel baskets is to hold the fuel assemblies and neutron poisons in a set geometry to meet the subcriticality requirement and thermal performance functions and to allow for fuel loading and retrieval. Baskets are made from a variety of metals such as stainless steel, carbon steel, and aluminum alloys, and have both base metal and welds. Some basket materials, such as Metamic™, an aluminum-boron-carbide metal matrix composite, also serve as the neutron poison material.

3.5.1 Corrosion

<table>
<tr><td rowspan="1">UFDC's Gap Description</td><td colspan="11">Basket components are subject to corrosion during off-normal conditions if sufficient oxygen and/or moisture are present inside the canisters because of inadequate drying or waterlogged rods. The rate and extent of corrosion are expected to be highest for carbon steel and aluminum components during the initial period of storage. Once the moisture has been expended, wet corrosion would stop. Therefore, because of the lower temperatures and absence of moisture during extended storage, wet corrosion is expected be a minor contributor to fuel basket component degradation.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">The description of neutron poisons wet corrosion and blistering is consistent in all the gap reports that discuss it.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>L</td><td></td><td>M</td><td>L</td><td></td><td>M</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">There is inconsistency between the gap analyses for the priority assignment of fuel baskets corrosion. The basis for the inconsistency is that UFDC is reserving judgment on the significance of this issue until the higher-priority drying gap and confinement gaps are addressed, which will determine the extent of moisture presence after drying and during storage. The NRC's priority assignment links these gaps.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison. The priority may change if results of drying tests and analyses indicate that residual water is an issue.</td></tr>
</table>

3.5.2 Metal Fatigue Caused by Temperature Fluctuations

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">With longer storage times, there are more summer–winter temperature fluctuations and increased likelihood of extreme weather conditions. Fuel basket degradation influenced by the temperature fluctuations may not necessarily affect any of the safety functions. For example, observed cracked welds in the Dry Cask Storage Characterization Project (EPRI 2002) appeared to be nonstructural and were intended only to provide additional stability during loading and testing. The investigation concluded that the cracks were not relevant to normal long-term storage and presented no adverse safety implications on the cask or components to perform their safety functions during storage.</td></tr>
<tr><td>Alternate description</td><td colspan="11">Description of fuel baskets metal fatigue caused by temperature fluctuations is consistent in all the gap reports that discuss it.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>L</td><td></td><td>H2</td><td>L</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Consistency of priority</td><td colspan="11">The NRC assigns a higher priority for fuel baskets metal fatigue caused by temperature fluctuations. This priority is based on the same observation discussed above, indicating that there is potential for degradation by metal fatigue in structural components, which is strongly dependent on material properties of thermal expansion coefficients and fatigue resistance. The NRC also identifies that additional data are needed on temperature fluctuations during drying and extended storage, which would enhance the ability to model the magnitude of temperature changes and assess fatigue.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">The UFDC agrees with the need for more detailed and realistic thermal profiles. No change in the UFDC priority is recommended based on this comparison, however, if further analysis shows the temperature cycling to be significant, then the priority could change.</td></tr>
</table>

3.5.3 Weld Embrittlement

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">UFDC does not identify this gap.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">This gap is only identified by the NRC. Long-term exposure of austenitic stainless steel welds containing ferrite to elevated temperatures (300–400 °C [572–752 °F]) results in spinodal decomposition of the α-ferrite phase and precipitation of an intermetallic G-phase (Alexander and Nanstad 1995; Chandra et al. 2011). Both of these mechanisms—the spinodal decomposition and precipitation—have the potential for embrittling the weld metal of stainless steel baskets in spent nuclear fuel casks.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td></td><td></td><td>H2</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">The NRC assigns this gap a high priority because of the limited available data on low-temperature weld embrittlement. Although, it is unclear whether the ductile-to-brittle behavior of welds would affect the transportation safety basis, additional data are needed to evaluate its effect.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">This gap and its priority will be reevaluated once detailed and realistic thermal profiles have been developed. Because the peak cladding temperature is limited to 400 °C, it is unlikely that any basket welds will experience long-term exposure to the elevated temperatures of concern presented in the NRC's evaluation (300-400 °C).</td></tr>
</table>

3.6 Moisture Absorbers

In Germany, the absence of free water in the storage cask is ensured by one of two methods. In the usual case, assemblies are confirmed to be intact by sipping tests prior to loading, so there are no waterlogged rods, and drying is straightforward. "In cases where fuel rod defects are identified or no sipping test results are available, encapsulation or the use of additional moisture absorber represent suitable solutions" (Völzke and Wolff 2011).

3.6.1 Thermal and Radiation Damage

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">The UFDC does not identify this as a gap.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">Elevated temperatures and radiation may cause degradation of the moisture absorbers.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td>M</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">Germany was the only country/organization to identify this issue.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">This gap will not be added to the UFDC Gap Analysis. If drying tests and analyses indicate that residual water is a significant issue and if the option is to include moisture absorbers, then this gap will need to be addressed.</td></tr>
</table>

3.7 Neutron Poisons

The safety function of neutron poisons, in conjunction with the geometry control provided by the fuel structure and baskets, is to maintain subcriticality for flooded configurations. Flooded configurations are credible only during loading and potentially, retrieval operations. Consideration of flooded configurations is presently required for normal conditions of transport and transportation hypothetical accident conditions (unless a moderator exclusion argument is pursued).

Neutron poisons used in dry storage casks are made primarily from borated aluminum alloys, metal matrix composites, aluminum boride carbon cermets, and borated stainless steel materials (limited domestic use). Historically, neutron poisons materials in dry storage casks served only a neutron absorption subcriticality function. However, more recently, with advancements in borated aluminum alloys and borated metal matrix composites, these neutron poison materials serve a load-bearing structural function, maintain the required separation between the fuel assemblies, and provide for heat transfer.

Degradation of neutron poisons during extended storage could affect the storage and transportation safety functional areas by reducing neutron absorption characteristics, reducing heat transfer properties, or changes in material properties resulting in failure to provide the necessary structural support, specifically for accident conditions. For load-bearing alloy and metal matrix composite (MMC) neutron poison materials, no degradation mechanism can change the poison isotope areal density. However, thermal aging effects and creep can reduce the spacing. For non-load bearing cermet neutron poison materials, thermal embrittlement and cracking can reduce poison isotope density, whereas blistering can reduce the spacing.

3.7.1 Corrosion and Blistering

<table>
<tr><td rowspan="1">UFDC’s Gap Description</td><td colspan="11">Corrosion and blistering are important only for non-load-bearing encased cermet materials. The mechanism for blister formation is based on water entering the relatively porous poison material during loading operations. During dry storage at elevated temperatures, water in pores causes internal corrosion and the production of Al_2O_3 and hydrogen causing internal pressure buildup and blistering of the casing or cladding around the poison material. Although blisters do not change the poison isotope areal density, they can cause the clad plate to deform, reducing the free clearances in the fuel baskets, thus potentially affecting retrievability and reducing neutron moderation. Cermets with greater as-fabricated core porosity are less likely to experience blister formation because water that enters the core during the wetting cycle can exit the core through interconnected porosity during the subsequent drying cycle without internal pressure buildup and blister formation.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">Description of neutron poisons wet corrosion and blistering is consistent in all the gap reports that discuss it.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>M</td><td>X</td><td>M</td><td>L</td><td></td><td></td><td>M</td><td></td><td></td><td>M</td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">All the gap analyses that identified wet corrosion and blistering as important to dry storage and transportation are consistent in priority assignment, with the exception of EPRI. The basis EPRI provides for the low priority assignment is that once dry, neutron absorber degradation ceases to be a significant mechanism.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison.</td></tr>
</table>

3.7.2 Creep

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">Creep is only important for load-bearing structural aluminum-based alloy or metal matrix composite materials. Creep of borated aluminum neutron poison materials must be considered because of their inherent low ductility and generally unknown creep properties. Available tests evaluating creep for structural borated aluminum components were limited to short duration. Consequently, the applicability of the results for extended storage is not known. Creep would not affect the neutron absorption characteristics of the neutron poisons, but could reduce the spacing between the fuel assemblies through deformation, which affects neutron moderation and potentially hinders fuel assembly removal.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">Description of neutron poisons creep is consistent in all the gap reports that discuss it. The NRC identified that creep processes may be exacerbated by neutron irradiation and is influenced by temperature, therefore, the NRC limits the likely period of interest to 40 years.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>M</td><td>X</td><td>H</td><td></td><td></td><td></td><td>M</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">Creep of load-bearing neutron poisons is assigned a higher priority in the NRC's evaluation, even though the NRC assigns a high level of knowledge for initiation time, propagation rate, and degradation or failure complete. The NRC (2012a) seemed to have applied their criteria inconsistently for this gap, mainly "Areas with a high (H) level of knowledge, irrespective of the safety implications, are given an overall rating of low (L) for regulatory need for further research."</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison.</td></tr>
</table>

3.7.3 Embrittlement and Cracking

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">Thermal and radiation embrittlement is important only for non-load-bearing encased cermet neutron poison materials. Thermal and radiation stresses and subsequent cracking could reduce the efficacy of neutron poisons by allowing for neutron streaming. Although thermal and radiation embrittlement is not expected to worsen for longer storage times because of decreasing temperature and neutron source term, the long-term effects and broader ranges associated with extended storage have not been evaluated.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">Description of neutron poisons embrittlement is consistent in all the gap reports that discuss it.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>MH</td><td></td><td>L</td><td></td><td></td><td></td><td>M</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">The NRC assigns a lower priority for neutron poison embrittlement because of the high level of knowledge for initiation and propagation rate based on sufficient testing that has been conducted on neutron poison materials, with the exception of cermet absorber materials. UFDC's position is that the MH priority is warranted because, as acknowledged by the NRC, there are insufficient data to evaluate the extent of embrittlement and cracking for cermet materials. Cermet materials are present in a significant fraction of currently loaded casks. Quantifying the extent of embrittlement and cracking is important for demonstrating subcriticality for both normal conditions of transport and hypothetical accident conditions.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison.</td></tr>
</table>

3.7.4 Metal Fatigue Caused by Temperature Fluctuations

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">With longer storages times, there are more summer-winter temperature fluctuations and increased likelihood of extreme weather conditions. However, the temperature of the neutron poisons is not expected to be significantly affected by those fluctuations, given the relatively large heat capacity of storage systems and the fact that neutron poisons are integrated between the heat-generating fuel assemblies. Additional data are desired for load-bearing neutron poison materials to evaluate their structural properties and response for storage design basis accidents and transportation hypothetical accident conditions.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">Description of neutron poisons metal fatigue caused by temperature fluctuations is consistent in all the gap reports that discuss it.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>L</td><td></td><td>M</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">The NRC's medium priority for neutron poisons metal fatigue caused by temperature fluctuations is based on the medium level of knowledge of initiation time and propagation rate, which are heavily influenced by the thermal profiles. The NRC (NRC 2012a) states "This [metal fatigue caused by temperature fluctuations] should be easily calculated once the variation of the temperature distributions is determined from the thermal modeling crosscutting effort."</td></tr>
<tr><td>UFDC Action</td><td colspan="11">The UFDC agrees with the need for more detailed and realistic thermal profiles. No change in the UFDC priority is recommended, based on this comparison, however, if further analysis shows the temperature cycling to be significant, then the priority could change.</td></tr>
</table>

3.7.5 Thermal Aging Effects

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">All metals undergo changes in their mechanical properties when exposed to elevated temperatures. Aluminum-based materials typically exhibit a decline in properties at temperatures above about 93 °C. These property changes are generally reversible after exposure to short-duration moderate temperature excursions; however, long-duration elevated temperature exposure generally results in permanent decrease of mechanical properties such as yield and tensile strength. Heat-treated alloys are more susceptible to changes in material properties than non-heat treated alloys.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">The description of neutron poison materials thermal aging effects is consistent in all the gap reports that discuss it.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>H</td><td></td><td>H2</td><td></td><td></td><td></td><td>M</td><td></td><td>M</td><td>M</td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">The gap analyses for UFDC and NRC are consistent in priority assignment; however Germany, the ROK, and Spain assign only a medium priority to this gap. The basis for the medium priority is not provided.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison.</td></tr>
</table>

3.8 Neutron Shields

The function of neutron shields is to provide radiation protection by slowing down and absorbing neutrons. Neutron shielding for most storage systems is provided by the concrete overpack. For some dual-purpose (storage and transportation) systems, which make up approximately 15 percent of the currently loaded casks, neutron shields are made from a variety of polymer-based materials composed of an effective neutron moderator, such as hydrogen and carbon, and a neutron poison, such as boron. There are variations within each material based on specific polymer-resin type and fabrication technique, which could have significant impact on material performance.

3.8.1 Radiation Embrittlement

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">Radiation (primarily neutron) stressors could cause embrittlement of neutron shielding polymer and resin materials. Radiation embrittlement leading to cracking could reduce the efficacy of neutron shielding and the radiological protection function it provides. Radiation embrittlement of neutron shielding could occur throughout the period of spent fuel storage. The threshold for radiation embrittlement is about 10^6 rad for polyethylene and potentially lower for other borated polymers or resins. Depending on the fuel, neutron shields could reach this dose by 100 years. Therefore, embrittlement of polymeric neutron shields during extended storage is expected. The rate of damage will be greatest in the short term, when radiation levels are highest, and decrease during extended storage as radiation levels decrease.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">The description of neutron shields corrosion is consistent in all the gap reports that discuss it. The NRC notes that there is potential for higher poison burnup levels with MOX fuel because of the higher neutron source term.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>L</td><td></td><td>L</td><td>L</td><td></td><td>M</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">With the exception of the German gap analysis, where CASTOR[a] systems are predominantly used, all the gap analyses agree that although there is potential for radiation embrittlement of neutron shields because of the ability to inspect/monitor its performance and remediate it if necessary, radiation embrittlement of neutron shields is assigned a low priority. For the CASTOR systems, neutron shielding is not as easily accessible for remediation, hence the Medium priority.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison.</td></tr>
</table>

[a]CASTOR is a trade name that stands for cask for storage and transport of radioactive material.

3.8.2 Thermal Embrittlement, Cracking, Shrinkage, and Decomposition

UFDC's Gap Description	The nature of the degradation of neutron shielding materials at higher temperatures depends on the specific material. For example, polyethylene rods may experience some shrinkage, which could lead to gaps and local loss of neutron shielding. Other neutron-shielding materials can experience loss of hydrogen at higher temperatures. The lower temperatures associated with extended storage will likely lead to a lower rate of degradation.										
Alternate Description	Description of neutron shields thermal embrittlement, cracking, shrinkage and decomposition is consistent in all the gap reports that discuss it. The NRC notes that there might be higher potential for embrittlement, cracking, shrinkage, and decomposition of neutron shields with higher burnup and MOX UNF.										
Priority	UFDC	NWTRB	NRC	EPRI	IAEA	Germany	Hungary	Japan	ROK	Spain	UK
	L		L	L		M					
Consistency of Priority	With the exception of the German gap analysis, where CASTOR[a] systems are predominantly used, all the gap analyses agree that although there is potential for thermal embrittlement, cracking, shrinkage, and decomposition of neutron shields, because of the inspection/monitoring of its performance and ability to remediate it, it is assigned a low priority. For the CASTOR systems, neutron shielding is not as easily accessible for remediation, hence the medium priority.										
UFDC Action	No change in the UFDC priority is recommended, based on this comparison.										

[a]CASTOR is a trade name that stands for cask for storage and transport of radioactive material.

3.9 Containers

The container provides the primary confinement boundary for DCSSs. It provides a physical barrier to prevent release of radionuclides, maintains an inert atmosphere of helium (or nitrogen in Hungary) for the container internals to prevent chemical degradation and enhance heat transfer, and prevents ingress of moderator (water) to provide additional criticality protection. There are two generic types of storage confinement containers currently used in the United States: bolted metal casks and welded metal canisters. In addition, fuel storage tubes are used in vault system of Hungary.

There are a number of key differences between the varieties of storage systems. Welded canisters are stored or transported within a separate overpack that provides both neutron and gamma shielding and physical protection. In contrast, bolted direct-load casks have integral gamma and neutron shielding with a thick metal body and polymer–resin neutron shields. The bolted direct-load casks are mechanically sealed via a combination of lids, bolts, and physical seals (e.g., gaskets to maintain the pressure boundaries). In addition, a weather cover is positioned over the bolts and seals to protect them from rainwater. The bolted casts were thick-walled vessels (10 to 12 inches thick) made of a variety of ferrous alloys including nodular cast iron, carbon steel, and low-alloy steel, while the more recent welded canisters have been constructed with stainless steels. Both the welded canisters and bolted casks contain multiple assemblies, while the steel fuel storage tube contains only one.

The priority given to specific container types varies by country. For example, Germany uses only bolted casks, Hungary uses only fuel storage tubes, the United Kingdom uses only welded canisters, and Spain is converting to a vault system. The countries only give priority to the degradation mechanisms of the container types they use for long-term storage.

3.9.1 Bolted Cask – Corrosion of Bolts

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">Because bolts provide the pressure on the seals necessary for sealing, they are a crucial part of the confinement sealing system of bolted casks. Bolts used to secure the lid/cover on bolted casks are primarily constructed of stainless and low-alloy steels. They are protected from the environment by a weather cover. If failure of the weather cover allows water and/or deliquescing atmospheric contaminants to contact the bolts, then corrosion can occur. The active corrosion mechanisms include SCC and general, galvanic, pitting, and crevice corrosion, depending on the material and the environment. Failure of the bolts has been detected by inter-seal pressure drops (EPRI 2002, p. 4-3), but more direct monitoring of bolts is not routinely conducted.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">The NRC also notes the possibility of embrittlement of the bolts because of the uptake of H_2 generated by corrosion.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>VH</td><td>X</td><td>H1</td><td>M</td><td></td><td>M</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">There is some inconsistency in rating corrosion of bolts. The UFDC and the NRC assign a high priority, while EPRI and Germany assign a medium priority. Germany and Japan house their casks in buildings, thus dramatically reducing the likelihood of wet conditions on the bolts, and thus reducing the priority for new research. EPRI assigns medium priority to this gap, noting that periodic inspection and replacement of bolts can be performed if necessary.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison.</td></tr>
</table>

3.9.2 Bolted Cask – Corrosion of Metal Seals

<table>
<tr><td rowspan="1">UFDC's Gap Description</td><td colspan="11">Metal seals may corrode if exposed to moisture, as has occurred upon the initiating events of insufficient drying, failure of secondary seals, or failure of the weather cover. The active corrosion mechanisms may include SCC and general, galvanic, pitting, and crevice corrosion, depending on the material and the environment. Because the inter-lid pressure is monitored, failure of the seals is quickly detected. However, degradation prior to failure is not routinely monitored.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">Description of corrosion of metal seals is consistent in all the gap reports that discuss it.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>VH</td><td>X</td><td>L</td><td>M</td><td>X</td><td></td><td></td><td></td><td>H</td><td></td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">UFDC and the ROK assign a higher priority to corrosion of seals than others. UFDC considers the likelihood of the initiating events leading to moisture at the seals to be "unknown," and the consequences of breach of confinement as "high" resulting in a rating of "very high" for the gaps on the aqueous and atmospheric corrosion of bolted casks. The ROK states (EPRI 2012) that the "metal gasket degradation due to cask lid load and bolting and atmospheric corrosion should be analyzed in domestic environment condition for long time." In contrast, the NRC (2012a) rates the knowledge of initiation, propagation and expected degradation from corrosion of seals as "high," resulting in a "low" rating for this degradation mechanism. It is not clear to the UFDC why the NRC rates the level of knowledge for corrosion of seals (high) so differently from that of corrosion of bolts (low) (see above). In UFDC's opinion, the uncertainties are similar and high for both. EPRI assigns a medium priority to investigations of corrosion of seals, citing the research already performed internationally, and the ability to return the casks to the pool for seal replacement if leaks are detected.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison.</td></tr>
</table>

3.9.3 Bolted Cask – Microbiologically Influenced Corrosion

See Section 3.9.10, Welded Canister – Microbiologically Influenced Corrosion.

3.9.4 Bolted Cask – Thermomechanical Degradation of Bolts

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">Thermomechanical degradation of bolts considered here includes creep and thermal fatigue. Because they are under stress, bolts may creep resulting in loss of sealing pressure and thus confinement. The creep rate is highly temperature-dependent, decreasing as the cask cools. Fatigue of the bolts because of thermal cycling during drying and between summer and winter during storage, accumulates with time.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">Description of thermomechanical degradation of bolts is consistent in all the gap analyses that discuss it.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>VH</td><td>X</td><td>H1</td><td>M</td><td></td><td>H</td><td></td><td></td><td>H</td><td></td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">Except by EPRI, this mechanism is consistently assigned a high priority by those that rated it. EPRI assigns medium priority to this gap, noting that periodic inspection and replacement of bolts can be performed if necessary.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison.</td></tr>
</table>

3.9.5 Bolted Cask - Thermomechanical Degradation of Seals

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">Thermomechanical degradation of seals considered here includes creep, thermal fatigue, and loss of ductility of seals at lower temperature. These degradation modes are dependent on the temperature history. Creep of the seals in response to the sealing pressure occurs most rapidly at high temperatures where it is well studied. Creep at lower temperatures for long periods of time is being studied by the French, Germans, and Japanese. The Japanese (Shirai et al. 2011) concluded that as long as the initial temperatures remain below $134\ ^{o}C$ for aluminum-covered seals and below $125\ ^{o}C$ for silver-covered seals, sealing performance would be ensured for 60 years. Fatigue of the seals because thermal cycling during drying and between summer and winter during storage, accumulates with time. Loss of ductility in metals at lower temperatures is a well-studied phenomenon.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">Description of thermomechanical degradation of seals is consistent in all the gap reports that discuss it.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>VH</td><td>X</td><td>L</td><td>L/M</td><td>X</td><td>H</td><td></td><td>H</td><td>H</td><td></td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">This mechanism is assigned a high priority from UFDC, Germany, Japan, and the ROK, however the NRC and EPRI rate it lower. The NRC assigns creep a low priority, because it considers the knowledge level to be high (NRC 2012a, p. A6-13): "Sufficient data exist to make initial long-term predictions…Additional long-term creep testing data, which are expected to be available as ongoing tests are completed, may be used to refine these predictions." In contrast, the UFDC identifies the need for realistic thermal calculations to determine the likelihood of thermomechanical degradation of seals. EPRI assigns a low priority to investigating metal fatigue, citing the research already done and the ability to detect and remediate degradation if it occurs. It assigns a medium priority to investigating the loss of ductility at low temperatures, because of the lower temperatures that may occur in countries other than Germany and Japan. While there are differences in priorities between the UFDC and the other organizations, there are no significant technical differences.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison.</td></tr>
</table>

3.9.6 Welded Canister – Aqueous Corrosion

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">In aqueous corrosion, bulk water is present at the metal surface and promotes corrosion. This water may contact the surface by any of several ways including: condensation and dripping from the overpack, failure of the overpack to protect the canister from rain, and flooding. Contaminants in the water may come from the water source as in flooding, or be atmospherically delivered such as salt in a coastal location. Depending on the material and environment, corrosion may be general or localized. On stainless steel canisters, the corrosion of concern is generally localized including: pitting, crevice, galvanic, and SCC. Aqueous corrosion rates are well studied and depend on the material and environment. The canister materials are known, but the environment, including the likelihood of aqueous conditions, is not.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">The NRC also points out microbiologically influenced corrosion (MIC) may also occur if there are sufficient nutrients at the surface.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>VH</td><td>X</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">The UFDC is the only one to prioritize this degradation mechanism. Other organizations and countries do not specifically call out aqueous corrosion as distinct from atmospheric corrosion, which is discussed in Section 3.9.7.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison.</td></tr>
</table>

3.9.7 Welded Canister – Atmospheric Corrosion

<table>
<tr><td rowspan="1">UFDC's Gap Description</td><td colspan="11">In atmospheric corrosion, sorption of water vapor from the air provides the water at the surface for corrosion to occur. This process is significant when atmospherically deposited contaminants deliquesce, forming a concentrated electrolyte solution that promotes corrosion. On stainless steel canisters, the corrosion of concern is localized including: pitting, crevice, galvanic, SCC, and if conditions are sufficient, MIC. Contaminants may include aggressive species such as chlorides from marine locations or oxidized sulfur species from polluted areas; organics can be significant, providing the nutrients needed for MIC. Research has shown that with deposited sea salt, relative humidities of 15 percent and above can support deliquescence and corrosion of the canister steels. In the presence of untreated welds, residual stresses are high enough to support SCC. Rates of all types of corrosion are highly dependent on the temperature. The research into atmospheric corrosion is mature enough to identify the conditions necessary for corrosion, but it is not clear if these conditions exist now, or will exist, at specific ISFSIs.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">The description of atmospheric corrosion is consistent in all the gap reports that discuss it.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>VH</td><td>X</td><td>H1</td><td>H</td><td></td><td></td><td></td><td>H</td><td>H</td><td>L</td><td>VH</td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">All organizations that prioritize, and all countries that use welded canisters for long-term storage, assign a high priority to additional research.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison.</td></tr>
</table>

3.9.8 Welded Canister – Integrity under Accident Conditions

UFDC's Gap Description	UFDC does not identify this as a gap. It is a condition for U.S. licensing.										
Alternate Description	The United Kingdom indicates the need to determine canister integrity under accident conditions (dropped load, aircraft crash). They propose a dropped cask test and modeling of accident conditions and heat transfer.										
Priority	UFDC	NWTRB	NRC	EPRI	IAEA	Germany	Hungary	Japan	ROK	Spain	UK
											H
Consistency of Priority	The United Kingdom is the only country identifying this as a gap.										
UFDC Action	This gap will not be added to the UFDC Gap Analysis.										

3.9.9 Welded Canister – Stress Corrosion Cracking – Code, Prevention, and Mitigation

UFDC's Gap Description	UFDC does not identify these as gaps, however, UFDC would group these needs under "Welded Canister – Atmospheric Corrosion," Section 3.9.7.										
Alternate Description	Japan identified the following (EPRI 2012): "1. Code or guideline to evaluate initiation and propagation of Stress Corrosion Cracking (SCC) of stainless steel canister in a marine environment is needed. 2. SCC data of normal stainless steel in a realistic marine environment are needed. 3. Demonstrative tests of preventive measures for SCC of normal stainless steel with reduced residual stress are needed. 4. Monitoring of salt deposition on canister surface storing spent fuel on real sites near the sea is needed. 5. Formula to estimate the salt deposition on canister surface using salt concentration in the air at the site is needed. 6. Non destructive measurement method of the salt deposition on canister surface is needed. 7. Technology to mitigate salt concentration in the air of canister environment is needed."										
Priority	UFDC	NWTRB	NRC	EPRI	IAEA	Germany	Hungary	Japan	ROK	Spain	UK
								H			
Consistency of Priority	Japan is the only country to identify these gaps.										
UFDC Action	This gap will not be added to the UFDC Gap Analysis as it is considered covered by the more general "Atmospheric Corrosion" gaps.										

3.9.10 Welded Canister – Microbiologically Influenced Corrosion

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">UFDC does not mention this mechanism but concurs it may occur if conditions are sufficient.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">MIC may occur on steels when there are sufficient water and nutrients to support microbial growth. The microbes modify the local chemistry, rendering it more corrosive.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td></td><td></td><td>H2</td><td>M</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">The NRC and EPRI identify this mechanism, which may be active during aqueous or atmospheric corrosion. UFDC concurs that if the conditions include sufficient water and nutrients then MIC may occur and result in accelerated corrosion.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">MIC will be added as a possible mechanism during aqueous and atmospheric corrosion and will need to be addressed through testing and analyses.</td></tr>
</table>

3.9.11 Fuel Storage Tube – Corrosion

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">Like the bolted casks and welded canisters, atmospheric and aqueous corrosion may occur on the steel fuel storage tubes if conditions are conducive.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">Only Hungary discusses this gap.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td>H</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">Hungary identifies investigation of corrosion of their fuel storage tubes as a high priority. This is consistent with the priority given to investigating degradation of their container by all countries.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">This gap will not be added to the UFDC Gap Analysis.</td></tr>
</table>

3.10 Concrete Structures

Reinforced concrete structures include: overpacks, storage modules, vaults, and pads. In most cases concrete structures are outdoors and are exposed to the environment. The concrete overpacks, storage modules, and vaults provide radiation shielding and protection of the casks or canisters from the environment. The temperatures and radiation levels are high for overpacks, storage modules, and vaults, but lower for the pad. In most cases a medium to low priority is assigned to investigating the degradation mechanisms of concrete, because these mechanisms are well understood and can be relatively easily detected and remediated. However in cases where the concrete is inaccessible to monitoring, the NRC ranked investigations into four degradation mechanisms as high priority. These are corrosion of embedded steel, coupled mechanisms, dry-out and thermal degradation of mechanical properties, which are discussed below.

3.10.1 Carbonation

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">Carbonation occurs as CO_2 from the air dissolves into water and reacts with the calcium hydroxide in the concrete, producing calcium carbonate. The main deleterious effect of carbonation is the reduction of pH that can lead to the loss of passivation of the reinforcing steel, especially if the steel is not epoxy-coated. The rate of carbonation depends on several factors including the concrete composition, porosity, permeability, and moisture content. Sindelar et al. (2011) state "Carbonation is expected to occur in concrete and penetrate to depths of the reinforcement steel well within the exposure time of 300 years."</td></tr>
<tr><td>Alternate Description</td><td colspan="11">Description of carbonation is consistent in all the gap reports that discuss it.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td></td><td>X</td><td>L</td><td></td><td></td><td></td><td></td><td></td><td>M</td><td></td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">The priority determination by the NRC is self-contradicting. In NRC 2012a Table 5-1, the NRC indicates the level of knowledge is high and the overall priority as low. However in Section A8.5 it rated the level of knowledge of the expected effects as "low." This suggests that carbonation may be one of the mechanisms referred to in Table 6-1, which are assigned a high priority if monitoring cannot reliably detect early degradation. The UFDC does not specifically prioritize carbonation, but discussed its role in corrosion of embedded steel. UFDC recommends additional work on the aging management programs (AMPs) addressing concrete degradation, which is consistent with the emphasis the NRC gives to the monitoring of concrete. The ROK gives a medium priority to carbonation and the resulting corrosion of embedded steel, indicating that carbonation may be accelerated because of higher levels of CO_2 produced by many factories. Other organizations and countries gave no priority to carbonation research.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">UFDC will not add carbonation as a separate gap, but will continue to include it as one of the degradation mechanisms that may lead to corrosion of embedded steel.</td></tr>
</table>

3.10.2 Corrosion of Embedded Steel

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">The reinforcement used in ISFSI concrete structures is typically carbon steel, which is passive as long as the concrete remains highly alkaline. However, if this alkaline environment is altered because of leaching of calcium hydroxide, carbonation, or acid attack, this passivity may be lost and corrosion of the steel reinforcement may result. Similarly, if a solution rich in aggressive anions such as chloride reaches the reinforcement, corrosion may initiate despite the pH being highly alkaline. In order to delay corrosion until after the licensing period, it is important that the concrete overlying the reinforcement is maintained to ensure low permeability to aggressive species, CO_2, and oxygen. However Sindelar et al. (2011) indicate that within 300 years carbonation of the overlying concrete is likely. If corrosion takes place, the larger-volume corrosion products induce stress in the concrete, causing it to crack. Once cracked, transport of oxygen and aggressive species to the steel accelerates, causing increasing corrosion leading to further degradation of the concrete. By the time corrosion of embedded steel is detected, damage may be significant.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">The description of corrosion of embedded steel is consistent in all the gap reports that discuss it.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>M</td><td>X</td><td>M/H2</td><td>L</td><td></td><td></td><td>M</td><td></td><td>M</td><td></td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">UFDC's medium priority is consistent with that of all countries and organizations that prioritized corrosion of embedded steel except the NRC. The UFDC assignment is to the enhancing of the AMPs to inspect and remediate the concrete overlying the embedded steel. The NRC assigns a priority for research as medium or high, depending on the reliability of monitoring for early detection of degradation. Thus, while the UFDC and NRC priorities are somewhat different, monitoring is key to both organizations.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison.</td></tr>
</table>

3.10.3 Coupled Mechanisms

<table>
<tr><td rowspan="1">UFDC's Gap Description</td><td colspan="11">UFDC does not specifically discuss coupled processes as an individual gap, however some interactions are noted. For instance calcium hydroxide leaching, carbonation, acid attack, and cracking can lead to corrosion of embedded steel.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">The NRC notes that thermal, hydrodynamic, mechanical, chemical, and radiation processes may all act on the concrete at the same time. They give the example of cracking from other degradation modes influencing the progression of carbonation.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td></td><td></td><td>M/H2</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">The NRC considers the priority for research to be medium if the component is accessible to monitoring, but high if the component is not easily monitored. This emphasis on monitoring is consistent with the medium priority UFDC gives to the AMPs to inspect and remediate concrete surface damage before significant freeze-thaw or corrosion of embedded steel can occur, and with the high priority given for monitoring development to detect damage well before it is visible.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">This gap will not be added to the UFDC Gap Analysis.</td></tr>
</table>

3.10.4 Freeze–Thaw

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">Damage from freeze-thaw occurs when water within the pores of the concrete freezes, creating expansive stresses. It occurs mainly where water may pond, such as on horizontal surfaces. Damage typically initiates at the surface where cracking and scaling are easily discovered and remediated. Freeze-thaw damage may also occur at structural features, such as the roof bolt holes at the ISFSI containing Three Mile Island fuel at INL, where freezing of the water in the holes caused extensive cracking. Initiation of freeze-thaw damage can be minimized through proper design and construction, and propagation can be halted with an adequate AMP.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">Description of freeze-thaw is consistent in all the gap reports that discuss it.</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td>M</td><td>X</td><td>L</td><td>L</td><td>X</td><td>L</td><td></td><td></td><td>M</td><td>L</td><td></td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">The UFDC assigns a low priority for new research, but a medium priority to proper remediation of bolt holes and AMPs to detect and remediate damage. This is consistent with the medium to low priority assigned to this mechanism by all other organizations and countries that prioritized it.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">No change in the UFDC priority is recommended, based on this comparison.</td></tr>
</table>

3.10.5 Marine Degradation

<table>
<tr><td>UFDC's Gap Description</td><td colspan="11">UFDC did not identify this as a gap.</td></tr>
<tr><td>Alternate Description</td><td colspan="11">"Concrete exposed to a marine environment may deteriorate as a result of combined effects of chemical action of sea water constituents on cement hydration products, alkali-aggregate expansion if reactive aggregates are present, crystallization pressure of salts within concrete if one face of the structure is subject to wetting and others to drying conditions, frost action in cold climates, corrosion of embedded steel reinforcement, and physical erosion due to wave action or floating objects." (Naus 2007, p. 39).</td></tr>
<tr><td rowspan="2">Priority</td><td>UFDC</td><td>NWTRB</td><td>NRC</td><td>EPRI</td><td>IAEA</td><td>Germany</td><td>Hungary</td><td>Japan</td><td>ROK</td><td>Spain</td><td>UK</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>M</td></tr>
<tr><td>Consistency of Priority</td><td colspan="11">The United Kingdom is the only country to identify this as a gap. UFDC did not specifically identify this gap, but covers all the degradation mechanisms except crystallization pressure of salts and physical erosion, which are not likely at ISFSIs in the United States.</td></tr>
<tr><td>UFDC Action</td><td colspan="11">This gap will not be added to the UFDC Gap Analysis.</td></tr>
</table>

3.10.6 Thermal Degradation of Mechanical Properties, Dry-out

UFDC's Gap Description	At least since 1997, when NUREG 1536 (NRC 2010) was published, the industry has used ACI-349 (ACI 2007) for design and construction of dry storage concrete structures. ACI-349 provides limits to concrete temperatures: ≤ 150 °F for general locations under normal conditions, ≤ 200 °F for local areas under normal conditions, and ≤ 350 °F for surface locations under accident conditions. ASTM C1562-10 indicates that long-term exposure to temperatures above these limits under normal conditions may cause changes in concrete material properties such as the compressive strength, tensile strength, and modulus of elasticity. Long-term exposure above 149 ºC (300 °F) may cause concrete surface scaling and cracking. (ASTM, 2010 A5.4.7) However, Bertero and Polivka (1972) and others report that if the free moisture is able to escape at temperatures below 149 °C, the mechanical characteristics of the concrete are not significantly degraded. Under normal conditions, peak temperatures of concrete in DCSSs are not expected to go above 93 ºC (EPRI 2002) and dry-out is the only significant thermal degradation mechanism. Concrete dry-out is a well-studied phenomenon. Exposure to elevated temperatures (100 °C) results in a loss of pore water from within the concrete, followed by dehydration of chemically bound water (EPRI 2002; Naus 2005 and 2007). This dehydration causes weakening of the bond between the gel and cement phases within the concrete, resulting in lower strength. However, if the concrete is rehydrated after the temperature has decreased (e.g., from rainwater), research has demonstrated that the changes in the chemical and physical properties of the concrete will be reversed (Farage et al. 2003; Alonso and Fernandez 2004). If the temperatures remain below 93 ºC, the consequences of dry-out at ISFSIs are expected to be at most a temporary and slight reduction in concrete strength and shielding. NUREG 1536 (NRC 2010) indicates that the accident condition of blockage or air inlets and outlets should be evaluated in safety analysis reports. Applicants have typically used bounding parameters when evaluating the thermal response to this accident, including high ambient temperatures, design basis heat loads, and greater than 24-hour duration, while still remaining below the 350 °F limit for accident conditions. However, ACI 349-06 (ACI 2007) indicates that "After exposure to these temperatures, the serviceability of the structure needs to be assessed before resuming the operation…."
Alternate Description	The NRC discusses higher-temperature degradation mechanisms, including changes in aggregate and cement paste physical (e.g., thermal conductivity and thermal expansion) and chemical (e.g., chemical stability at temperature) properties between room temperature and 1000 ºC. Although they note that "Any degradation due to temperature effects, if possible, would be operative only in the short term." (NRC 2012a).

Priority	UFDC	NWTRB	NRC	EPRI	IAEA	Germany	Hungary	Japan	ROK	Spain	UK
	L	X	M/H2	L	X						
Consistency of Priority	The NRC is the only organization to give significant priority to thermal degradation including dry-out. The NRC (2012a) states "The effects of temperature on the properties of concrete have significant variability and are known to be dependent on concrete chemistry and construction practices." As a result, the NRC gives research on thermal degradation a medium or high priority depending on whether the concrete is accessible to monitoring. The UFDC considers the likelihood and consequence of thermal degradation of concrete during normal operations to be low. Minor cracking would only be significant if it accelerated another degradation mode such as corrosion of embedded steel. UFDC assigns a medium priority to enhancement of the AMPs to identify and remediate significant damage to concrete overlying embedded steel. In the case of off-normal or accident conditions that result in higher temperatures, however, the concrete should be inspected at the locations of the highest temperatures.										
UFDC Action	No change in the UFDC priority is recommended, based on this comparison. Inspection and remediation of damage from this and other mechanisms are covered under the AMPs for corrosion of embedded steel.										

3.10.7 Unspecified Concrete Degradation

UFDC's Gap Description	UFDC does not identify this as a separate gap.										
Alternate Description	This gap includes all concrete degradation mechanisms operative in the identifying country.										
Priority	UFDC	NWTRB	NRC	EPRI	IAEA	Germany	Hungary	Japan	ROK	Spain	UK
						M	M				
Consistency of Priority	Germany and Hungary indicate medium priority for research into concrete degradation without specifying the individual mechanisms. This is in the middle of the range of priorities for the specific mechanisms.										
UFDC Action	No action necessary as UFDC has considered multiple concrete degradation mechanisms.										

4. CONCLUSIONS

This report compares the UFDC Gap Analysis (UFDC 2012a) and UFDC Gap Prioritization (UFDC 2012b) reports to those recently published by others, including the NWTRB (2010), the NRC (2012a), the IAEA (2002), and EPRI (2012). The EPRI report (2011) provides the priorities of additional research of ESCP committee members from six countries (Germany, Hungary, Japan, ROK, Spain, and the United Kingdom). It is important to note that these priorities represent the opinions of the EPRI/ESCP International Subcommittee participants and do not represent any official position of the participant's country. Both the NRC and EPRI reports are still in draft form as of this review and are subject to change.

There are a collective total of 94 technical data gaps identified by the various reports to support extended storage and transportation of UNF. This report focuses on the gaps identified as Medium or High in any of the gap analyses and provides the UFDC's gap description, any alternate gap descriptions or different emphasis by another organization, the rankings by the various organizations, evaluation of the consistency of priority assignment and the bases for any inconsistencies, and UFDC-recommended action based on the comparison. Gaps that are ranked Low by all organizations and countries are not evaluated in this report.

Of the 94 gaps identified in the various gap analyses, there are 14 cross-cutting gaps and 80 SSC-specific gaps. For the cross-cutting gaps, the UFDC identifies eight and others identify six. Thirteen of the 14 cross-cutting gaps were identified as Medium or High by at least one of the gap analyses. The UFDC assigns a high priority to all the cross-cutting gaps it identified. For most of these, there is general agreement of their high priority. The six gaps identified by others are either covered by other UFDC gaps or are not applicable to UNF storage and transportation in the United States. Therefore, it is concluded that no changes to the UFDC cross-cutting gap analysis are necessary.

For the 80 SSC-specific gaps, the UFDC identifies 52 and others identify 28. The gaps identified by others either do not meet the UFDC's definition of a gap for extended storage and subsequent transportation, are grouped differently by the UFDC, or are given less than low priority by the UFDC. For example: "Cladding – Oxide Thickness" is a property of UNF, not a degradation mechanism; "Cladding – Propagation of Existing Flaws" is covered by the UFDC under the individual degradation mechanisms; and "Canister - Irradiation Damage" is considered by the UFDC to be insignificant.

Of the 80 SSC-specific gaps, 48 were identified as Medium or High by at least one of the gap analyses. For 25 of these 48 Medium and High priority gaps, there is either consistency in evaluation and priority assignment across the gap analyses or the UFDC assigns a higher priority. Gaps with consistent high priority evaluation receiving five or more high ratings include:

Cross-cutting gaps

- Thermal Profiles
- Examine Fuel After Storage
- Monitoring

SSC-specific gaps

- Cladding – Delayed Hydride Cracking
- Cladding – Hydride Reorientation and Embrittlement
- Casks/Canisters – Atmospheric Corrosion (especially SCC at the welds)

In some instances, the UFDC gives a higher priority for additional R&D to gaps where experts disagree on the mechanisms (e.g., DHC and clad oxidation). Other differences in priorities are mostly because of differences in the various countries' or organizations' storage and transportation programs and ultimate waste disposal strategies. For example, the UFDC places a higher priority on many of the cladding gaps in an effort to maintain retrievability at the fuel assembly level.

For four gaps, the evaluation in the UFDC Gap Analysis (UFDC 2012a) is significantly different from that in other gap analyses. UFDC will address these gaps as follows:

- "Basket – Weld Embrittlement" will be evaluated once detailed and realistic thermal profiles have been developed.
- "Bolted Cask – MIC" and "Welded Canister – MIC" will be addressed as part of the various container aqueous and atmospheric corrosion gaps.
- "Fuel – Helium and Fission Gas Release" will be considered as part of fuel and cladding gaps.
- "Concrete – Thermal Degradation of Mechanical Properties, Dry-out" will be analyzed as part of existing concrete gaps.

As stated in the UFDC Gap Analysis (UFDC 2012a) and UFDC Gap Prioritization (UFDC 2012b) reports, as more data are obtained, all gaps are subject to reevaluation of priority. Continued collaboration with other organizations and countries will ensure that the UFDC is pursuing the proper course to obtain the data and analyses necessary to develop the technical bases for continued safe and secure storage.

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APPENDIX A

UFDC Top Priority Storage and Transportation Gaps

Table A-1. UFDC Top Priority Gaps Sorted on Rank

Gap	Rank	Priority
Thermal profiles	1	Very High
Stress profiles	1	Very High
Monitoring – External	2	Very High
Welded canister – Atmospheric corrosion	2	Very High
Fuel Transfer Options	3	Very High
Monitoring – Internal	4	Very High
Welded canister – Aqueous corrosion	5	Very High
Bolted casks - Fatigue of seals & bolts	5	Very High
Bolted casks - Atmospheric corrosion	5	Very High
Bolted casks - Aqueous corrosion	5	Very High
Drying issues	6	Very High
Burnup credit	7	High
Cladding – H_2 Effects: Hydride reorientation & embrittlement	7	High
Neutron poisons – Thermal aging	7	High
Moderator exclusion	8	High
Cladding – H_2 Effects: DHC	9	High
Examination of the fuel at the INL	10	High
Cladding – Creep	11	Medium High
Fuel Assembly hardware – SCC for lifting hardware and spacer grids	11	Medium High
Neutron poisons – Embrittlement	11	Medium High
Cladding – Annealing of radiation damage	12	Medium High
Cladding – Oxidation	13	Medium
Neutron poisons – Creep	13	Medium
Neutron poisons – Corrosion (blistering)	13	Medium
Overpack - Freeze–thaw	14	Medium
Overpack - Corrosion of embedded steel	14	Medium