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Protecting People and the Environment

Draft Report for Comment

Identification and Prioritization of the Technical Information Needs Affecting Potential Regulation of Extended Storage and Transportation of Spent Nuclear Fuel

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EXECUTIVE SUMMARY

The U.S. Nuclear Regulatory Commission (NRC) regulates storage of spent nuclear fuel (SNF) from commercial nuclear power plants. An increasing amount of the SNF in storage is in dry storage systems, mostly at current and decommissioned plants. As directed by the Commission (in SRM-COMSECY-10-0007; December 6, 2010), in expectation of continued use of dry storage for extended periods of time, the NRC staff is examining the technical needs and potential changes to the regulatory framework that may be needed to continue licensing of SNF storage over periods beyond 120 years. This report presents the results of NRC staff evaluation of the technical information needs for continued extended dry storage, and for the subsequent transportation of SNF following long-term storage. Staff's evaluation focuses on the degradation phenomena that may affect dry storage systems, and how these phenomena may affect the ability of the systems to fulfill their regulatory functions.

The evaluation in this report focuses on technical information for safety of dry storage systems. Staff will also be evaluating potential security implication of extended storage and transportation (EST) as part of its broader work in this area. The NRC is currently revising parts of its regulations on physical protection in 10 CFR Part 73 that pertain to storage of SNF (Draft Technical Basis for Rulemaking Revising Security Requirements for Facilities Storing SNF and HLW; Notice of Availability and Solicitation of Public Comments, 74 Fed. Reg. 66589, December 16, 2009). Any additional revisions to security regulations that may be needed to address extended storage and transportation will be considered when the current rulemaking for 10 CFR Part 73 is complete, or as new needs are identified.

In identifying and prioritizing potential information needs, NRC staff drew on existing published assessments on the behavior of SNF in storage and the degradation phenomena for dry storage systems, and on staff knowledge and experience in reviewing and licensing dry storage installations and certifying systems for storage and transportation under current regulations (10 CFR Part 72 and 10 CFR Part 71, respectively). For each of the major systems, structures, and components (SSCs) of a dry cask storage system, a set of potential degradation phenomena was developed based on existing assessments, new analyses, and staff experience. For each potential degradation process or issue, staff assessed the current level of knowledge, with particular emphasis on knowledge specifically related to performance of the dry storage SSC. NRC staff with experience in regulatory reviews of dry storage and transportation evaluated each of the SSC degradation mechanisms to determine how it could affect the ability of the SSC to meet the safety regulations for storage and transportation. For the final assessment, the staff prioritized the areas for further technical investigation, using the following criteria: 1)regulatory significance for safety performance: and 2) the level of knowledge about the process or issue. In general, those areas with high safety significance and low level of knowledge ranked highest for further investigation. In addition, the staff identified several crosscutting areas that can aid in understanding conditions affecting several SSCs and degradation processes. These crosscutting areas address effects of residual moisture after drying, thermal modeling, and monitoring methods, and are also given high priority.

For this evaluation, NRC staff has considered performance of the systems over an initial 300 year period following discharge of the SNF from the reactor. The length of this period is defined for analytical purposes only, and does not imply that storage is anticipated for any particular period. Other assumptions concerning future SNF storage and limitations on the scope of the NRC staff evaluation included:

- Only uranium oxide (UOX) fuel and mixed oxide (MOX) fuel are considered.

- Only current modes of storage (concrete or metal overpacks, above and below ground) and transportation are considered.

- Licensed fuel burnup limits in-reactor will not be increased beyond the current limit of 62.5 GWd/MTU peak rod average.

- The current regulatory requirements for maintaining cladding integrity and ready retrieval of intact SNF assemblies during storage apply for extended storage. The cladding provides defense in depth, as a barrier for fission products, and may be important to the safe handling of SNF in various future scenarios for the back end of the fuel cycle.

- Only dry storage systems, at operating reactor sites, at decommissioned reactor sites, or at away-from-reactor sites, are considered. Extended wet storage, either at the reactor site or away from reactor sites, is not considered in this study.

- Certain dry cask storage components under 10 CFR Part 72 (e.g., sealed containers) may be used as transportation package components under 10 CFR Part 71 after extended storage. Transportation requirements under 10 CFR Part 71 for containment, shielding, and criticality safety will not significantly change after extended storage periods, because they are fundamental to safety.

To evaluate the potential regulatory significance of potential degradation, NRC staff considered six areas of regulatory review: criticality, thermal, confinement, structural, shielding, and retrievability. These terms, as used in this report, are defined as follows:

- Criticality is the ability of the system to stay subcritical during every phase of storage and transportation.

- Confinement is the ability of the system to retain radioactive material, including gases and particulates, within the system.

- Shielding is the ability of the system to limit the dose rate at designated locations to acceptable regulatory limits.

- Thermal is the ability of the system to reject heat at a rate that limits the temperature of the materials of construction and contents of the system to a range where the materials and content perform as expected.

- Structural integrity is the ability of the components of the system to remain in a configuration that allows the systems to function as necessary.

- Retrievability is the ability to remove the contents from the storage system in a defined condition.

The staff evaluation of the level of knowledge of the potential degradation of components of the dry storage system, as related to their expected safety functions and regulatory requirements for storage and transportation, identified 14 areas as important for further investigation. NRC staff concludes that the following potential degradation mechanisms or drivers should be addressed first (Priority 1):

- Stress corrosion cracking (SCC) of stainless steel canister body and welds
- Corrosion, SCC, embrittlement, and mechanical degradation of cask bolts
- Swelling of fuel pellets due to helium in-growth, and fuel rod pressurization due to additional fuel fragmentation, helium release, and fission gas release during accidents

The group of phenomena in the last bullet, concerning fuel and cladding, are highlighted for early attention because if they are shown to be unlikely to compromise cladding, other cladding-related mechanisms may become less significant.

NRC staff also recommends that first priority be given to the following crosscutting areas:

- Thermal calculations
- Effects of residual moisture after normal drying
- Development of in-service monitoring methods for storage systems and components

These areas have significance for multiple SSCs and degradation processes. Improvements in thermal calculations, for example, can help enhance understanding of performance of system components both inside (e.g., fuel and cladding) and on the exterior (susceptibility of canisters to SCC). By the same token, residual moisture can affect potential corrosion of cladding or fuel assembly hardware during storage; the potential significance depends on the amount of moisture and how it may interact with the components.

NRC staff considers the ability to monitor system components for degradation to be a valuable tool for ensuring continued safety of SNF storage. The design of any monitoring program depends on what specific degradation processes are of interest, so development of specific monitoring techniques should be closely tied to research on the high-priority degradation phenomena. The monitoring program should also consider the intended safety function of the systems and components, to inform monitoring of the onset and propagation of known degradation mechanisms, and to target unexpected deterioration of performance.

NRC staff recommends that the following potential types of degradation, rated as high overall for further research, should be addressed next (Priority 2):

- Propagation of existing flaws in cladding
- Wet corrosion, SCC, and metal fatigue of fuel assembly hardware
- Metal fatigue of cladding caused by temperature fluctuations, SCC, and DHC
- Low temperature creep and galvanic corrosion of cladding
- Microbiologically influenced corrosion of stainless steel, carbon steel, and cast iron body, welds, lids, and seals

- Embrittlement of fuel basket welds at low temperature, and metal fatigue due to temperature fluctuations

- Thermal aging and creep of neutron absorbers

- Concrete degradation; priority of specific mechanisms depends on availability of monitoring methods and accessibility of the component

This proposed ranking of technical information needs is based on the staff's evaluation of its regulatory needs and is not intended to provide guidance on any specific application. Applicants for new or renewed licenses or certifications should not infer that relevant mechanisms which have been given a low priority in this report should not be addressed in an application. A low priority ranking by staff only indicates that enough information is available for regulatory considerations.

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1 INTRODUCTION

1.1 Current Regulatory Status

The existing regulatory framework of the U.S. Nuclear Regulatory Commission (NRC) for storage and transportation of spent nuclear fuel (SNF) is specified in Title 10 of the Code of Federal Regulations (10 CFR) Part 72, "Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High-Level Radioactive Waste, and Reactor-Related Greater than Class C Waste," and 10 CFR Part 71, "Packaging and Transportation of Radioactive Material," respectively. The effectiveness of these regulations has been demonstrated through significant operational experience in storage and transportation. Regulations for SNF storage cover both the licensing of storage facilities and the certification of dry storage systems for use at those facilities. Currently, more than 1,500 dry storage casks are loaded at 63 independent spent fuel storage installations (ISFSIs) in the United States. The current regulatory framework supports at least the first 80 years of dry cask storage (i.e., a 40-year initial licensing term, followed by a license renewal for a term of up to 40 years, although many of the existing facilities were licensed for an initial term of 20 years under the regulations in place at the time).

The technical basis for the initial licensing and renewal period is supported by the results of a cask demonstration project that examined a cask loaded with lower burnup fuel (approximately 30 GWd/MTU average; all fuel burnup in this paper is given as peak rod average value). Following 15 years of storage, the cask internals and fuel did not show any significant degradation (Einziger et al., 2003). The data from this study can be extrapolated to maintain a licensing safety finding that low burnup SNF can be safely stored in a dry storage mode for at least 80 years with an appropriate aging management program that considers the effects of aging on systems, structures, and components (SSCs). The behavior of these SSCs becomes increasingly less well known over longer periods, due in large part to technical uncertainties about the various degradation mechanisms that can affect their performance. The work described in this report focuses on reducing these uncertainties, so that current licensing practices could be used in future licensing actions.

Security requirements for SNF storage and transportation are addressed in 10 CFR Part 72, Subpart H, "Physical Protection;" 10 CFR Part 73, "Physical Protection of Plants and Materials;" and 10 CFR Part 74, "Material Control and Accounting of Special Nuclear Materials." NRC is currently revising parts of 10 CFR Part 73 that pertain to storage of SNF (Draft Technical Basis for Rulemaking Revising Security Requirements for Facilities Storing SNF and HLW; Notice of Availability and Solicitation of Public Comments, 74 Fed. Reg. 66589, December 16, 2009). Any additional revisions to security regulations that may be needed to address extended storage and transportation will be considered when the current rulemaking for 10 CFR Part 73 is complete, or as new needs are identified. This report focuses on technical information needs for the safety of storage and transportation of SNF over extended periods.

1.2 Potential Need for Extended Storage and This Study

The current regulatory framework for storage of SNF allows for multiple license renewals with aging management. An applicant for storage license renewal must provide appropriate technical bases for identifying and addressing aging-related effects, and develop specific aging management plans to justify extended operations of ISFSIs under potential multiple renewed license terms. The regulatory framework for both storage and transportation are supported by well-developed regulatory guidance; voluntary domestic and international consensus standards;

research and analytical studies; and processes for implementing licensing reviews, inspection programs, and enforcement oversight.

This report identifies, evaluates, and prioritizes the need for additional technical data on the behavior and aging of the systems, structures, and components (SSC) used for dry storage so that NRC can effectively license and regulate spent fuel management for extended periods through multiple dry cask license renewals. NRC staff will use these data to understand (i) systems that must be monitored and inspected, (ii) frequency of the monitoring and inspecting, and (iii) the timeframes in which replacement or repair of systems might be expected. These data will also help determine whether current NRC staff guidance for licensing and renewal of ISFSIs and cask certificates should be revised for use in longer term storage. In addition, the data will be used to support NRC evaluation of aging management plans provided by ISFSI licensees as part of applications for license renewal. This technical information will contribute to maintaining the safety of dry storage of SNF and the capability to transport the SNF at the end of the storage period. Under current regulations, damaged or degraded SNF can be safely and securely transported with appropriate repackaging. Note that while 10 CFR Part 72 covers both SNF and other radioactive waste, and 10 CFR Part 71 covers transportation of a wide range of radioactive material, this report considers primarily technical issues related to storage and transportation of commercial SNF.

1.3 Overall Extended Storage and Transportation Approach

In two staff requirements memoranda (SRM) (NRC, 2010a,b), the Commission directed NRC staff to develop plans for data needs for licensing dry storage of SNF beyond 120 years with subsequent transportation. NRC staff focused on identifying the degradation mechanisms that may be of concern within the first 300 years following discharge from the reactor to consider a reasonably long performance period. The 300-year period is for analytical purposes only. Selection of this time duration for analysis does not imply that spent fuel will be stored for 300 years, that the NRC will license storage for 300 years, or that NRC endorses storage for 300 years.

This report focuses on the technical data needs for the regulation of extended storage and transportation (EST) of SNF. As discussed in Section 2, this report specifically assumes that the future licensing of spent fuel storage will follow current licensing practices. This includes the regulatory requirements in 10 CFR 72.122 that specify, among other criteria, that spent fuel cladding must be protected during storage against degradation that leads to gross ruptures, storage systems must be designed to allow ready-retrieval of spent fuel for further processing or disposal, and that periodic monitoring of storage confinement systems is consistent with its design requirements during the storage period, so that the licensee will be able to determine when corrective action needs to be taken to maintain safe storage conditions.

While this report assumes continued use of current licensing practices for purposes of evaluation of technical information needs, staff acknowledges that these practices may evolve over time in response to improved understanding, operational experience, and Commission policy direction. For example, the staff is currently re-examining the role of cladding integrity and alternate design solutions in the licensing of storage casks as part of its ongoing efforts to reexamine the regulatory framework for extended storage and transportation, as directed by the Commission in an SRM (NRC, 2010a). Changes in licensing practices may affect the needs, or relative priority, for additional technical information.

The NRC staff’s overall regulatory review for EST safety includes five aspects (i) technical information needs and regulatory gap assessments and analyses, (ii) follow-on research and technical analyses, (iii) evaluation of a long-term cask demonstration program, (iv) development and extension of guidance and regulatory technical bases, and (v) implementation of potential rule changes. This report documents the results of the technical information needs assessment and analysis.

In parallel with the technical and regulatory review for EST, the Commission has directed the NRC staff to examine a possible update of the NRC’s Waste Confidence decision and to prepare an Environmental Impact Statement (EIS) for SNF storage beyond the period given in the current Waste Confidence decision (NRC, 2010b). Staff is coordinating its efforts for the EST technical work with the EIS development (NRC, 2011). The information needs identified by staff for EST may also be useful in evaluating the environmental impacts during the period of extended storage, but completion of the impact analyses in the planned EIS does not necessarily depend on new data from the EST efforts. Insights gained in the EST technical studies will be incorporated into the evaluation of the environmental impacts of extended storage to the extent practical.

2 METHODOLOGY FOR IDENTIFYING AND PRIORITIZING POTENTIAL TECHNICAL INFORMATION NEEDS

In identifying and prioritizing potential information needs, NRC staff drew on existing published assessments on the behavior of SNF in storage and the degradation phenomena for dry storage systems, and on staff knowledge and experience in reviewing and licensing dry storage installations and certifying systems for storage and transportation under 10 CFR Part 71 and Part 72. For each of the major systems, structures, and components (SSCs) of a dry cask storage system, a set of potential degradation phenomena was developed based on existing assessments, new analyses, and staff experience. For each potential degradation process or issue on this list, staff assessed the current level of knowledge, with particular emphasis on knowledge specifically related to performance of the dry storage SSC. NRC staff with experience in regulatory reviews of dry storage and transportation evaluated each of the SSC degradation mechanisms to determine how it could affect the ability of the SSC to meet the safety regulations for storage and transportation. For the final assessment, staff used two criteria to prioritize the areas for further technical investigation (i) regulatory significance for safety performance and (ii) level of knowledge about the process or issue. In general, those areas with high safety significance and low level of knowledge ranked highest for further investigation.

To develop its prioritization, NRC staff made several assumptions regarding expectations of future SNF storage and also considered several criteria for the regulatory significance of specific issues. In accord with staff's discussion in COMSECY–10–0007 (NRC, 2010c), the following assumptions were used to define the scope of the analyses:

- Only uranium oxide (UOX) fuel and mixed oxide (MOX) fuel are considered.

- Only current modes of storage (concrete or metal overpacks, above and below ground) and transportation are considered.

- Licensed fuel burnup limits in-reactor will not be increased beyond the current limit of 62.5 GWd/MTU peak rod average.

- The current regulatory requirements for maintaining cladding integrity and ready-retrieval of intact SNF assemblies during storage applies for extended storage. The cladding, as a barrier for fission products, provides defense in depth, and may be important to the safe handling of SNF in future scenarios for the back end of the fuel cycle. Cladding integrity may also serve a secondary criticality safety function in future transportation of spent fuel. Preservation of cladding, as considered in 10 CFR 72.122(h)(1), and hardware integrity are linked to retrievabliity. The NRC staff analysis identifies where this assumption of preserving retrievability drives the conclusion concerning data needs.

- Only dry storage systems, at operating reactor sites, at decommissioned reactor sites, or at away-from-reactor sites, are considered. Extended wet storage, either at the reactor site or away from reactor sites (e.g., the GE-Morris facility), is not considered in this study. Similarly, aging of fuel handling-systems (e.g., cranes, transporters, transfer casks) is not considered in this report.

- Certain dry cask storage components under 10 CFR Part 72 (e.g., sealed containers) may be used as transportation package components under 10 CFR Part 71 after extended storage. Transportation requirements under 10 CFR Part 71 for containment, shielding, and criticality safety will not significantly change after extended storage periods, because they are fundamental to safety.

The overall focus of the NRC staff review is to identify information that will help the staff perform its specific regulatory functions in extended storage and transportation renewal periods. NRC staff needs to:

- Determine whether the regulations are adequate to provide confinement, shielding, and criticality safety, and propose regulatory changes or alternatives through rulemakings where appropriate

- Determine whether an event or mechanism of degradation compromises safety during normal or accident conditions

- Enhance regulatory guidance for design features, maintenance and monitoring needs, and aging management plans for extended storage and transportation

- Provide a technical basis to reviewers so they can determine whether the approach proposed by an applicant is acceptable/adequate

- Develop enhanced inspection guidance for components and systems to verify adequate implementation of aging management programs and identification of premature aging of cask components

The next sections summarize results of the NRC staff's identification and prioritization of the technical needs for extended storage and transportation. Further detail on the staff's evaluation is given in Appendices A and B. Note that NRC staff's identification and prioritization of the technical needs may differ from similar efforts by other parties (e.g., industry groups). These differences may arise, at least in part, from the complementary but distinct roles of the licensee and the regulator in assuring safety of SNF storage and transportation.

3 IDENTIFICATION AND PRIORITIZATION OF POTENTIAL TECHNICAL INFORMATION NEEDS

3.1 Level of Knowledge of Degradation Phenomena

NRC staff's assessment of the level of knowledge drew on several sources, in addition to its own expert knowledge. One primary source is an independent assessment of the level of knowledge developed by the Savannah River National Laboratory (SRNL) under NRC contract (Sindelar, et al., 2011). Staff also drew on similar studies conducted by the U.S. Department of Energy (DOE) (Hanson, et al., 2011), the Nuclear Waste Technical Review Board (NWTRB) (NWTRB, 2010), and the Electric Power Research Institute (EPRI) (EPRI, 2011) through its Extended Storage Collaboration Program (ESCP).

The SRNL study reevaluated the conclusions of earlier EPRI technical gap assessments (Einziger, et al., 1998; Kessler and Einziger, 2002) that had evaluated the information needs and the potential sources of the information necessary to provide a technical basis for the storage of SNF for 100 years. The reevaluation considered changes in fuel properties and types that have occurred since the last evaluation. The study addressed new concerns arising from the longer duration of storage now under consideration (>120 years), decommissioning of reactors that leave legacy sites that may not have adequate fuel handling facilities, and worldwide climate concerns. Examples of the materials and fuel issues considered include

- MOX fuel, new cladding, fuel compositions, and assembly designs that have been and will continue to be put into use
- Condition of fuel and basket in an inaccessible sealed canister during storage
- Degradation conditions that could require repackaging;[1] what they are and when they could be expected to occur
- Required long-term monitoring and aging management requirements
- High burnup SNF, including both current industry practice (up to ~62.5 GWd/MTU) and potential future higher burnups
- Increasing heat loads in dry storage casks systems that change temperatures of the cask components
- Effects from storage underground and in coastal environments
- Degradation of concrete and other system components
- Impacts of very long term storage on transportability[2]
- Transportation issues caused by lower temperature of fuel after extended storage

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[1] As used here, "repackaging" refers to replacing accessible components of the storage system or moving the SNF to a new storage system.

[2] As used here, "transportability" is the ability to transport dual-purpose cask components and SNF from their existing location without requiring handling at the rod or fuel assembly level, in accordance with the requirements of 10 CFR Part 71.

The SRNL study provides a qualitative estimate of the impact of the limited amount of available data on the ability to evaluate storage system performance for regulatory purposes. The report proposes experimental methods to address the data needs identified in the evaluation.

Using the SRNL study and the other available assessments identified above, NRC staff evaluated and identified additional information needs to support the technical basis for extended storage and eventual transportation of SNF for periods up to 300 years. This effort included comparing and evaluating the data sources used in the different existing assessments. Staff's assessment of the level of knowledge for aspects of materials degradation that are of regulatory interest for extended storage and transportation is summarized in Table 3-1. A more detailed analysis of the level of knowledge in each area is in Appendix A. Note that some component degradation mechanisms may be of significance only if other components degrade first.

Table 3-1 shows the component, degradation phenomena, and current ability to monitor the phenomena in a dry storage condition, along with the NRC staff's evaluation of the level of knowledge to address three questions

- When will the degradation initiate?
- How fast will it proceed?
- When will it conclude?

Table 3-1. Level of Knowledge and Availability of Monitoring

Component	Degradation Phenomena	Level of Knowledge			Overall Assessment	Monitoring or Inspection Capability
		Initiation Time	Propagation Rate	Degradation or Failure Complete		
Cladding	Cladding oxidation*	H	H	M	H†	No
	Biocorrosion*	H	NA	NA	H	No
	Pitting corrosion*	H	H	H	H	No
	Galvanic corrosion*	L	L	L	L	
	Stress corrosion cracking (SCC)*	L	M	L	L	No
	Air (off-normal condition) oxidation and corrosion*	H	H	M	H†	No
	Hydrogen embrittlement‡	H	NA	NA	H	No
	Delayed hydride cracking‡	M	H	H	M	No
	Hydride reorientation‡	H	NA	NA	H	No
	Thermal creep§	H	H	M	H†	No
	Low temperature creep§	L	L	L	L	No
	Annealing of irradiation hardening	M	M	L	M†	No
	Irradiation growth	H	H	H	H	No
	Propagation of existing flaws	L	H	M	L	No
	Fatigued cladding due to drying cycles	NA	NA	NA	NA	No

Table 3-1. Level of Knowledge and Availability of Monitoring (continued)

Component	Degradation Phenomena	Level of Knowledge			Overall Assessment	Monitoring or Inspection Capability
		Initiation Time	Propagation Rate	Degradation or Failure Complete		
Fuel-cladding interactions	Air oxidation (off-normal condition)	H	H	M	H†	No
	Fission gas release during accident	H	H	L	L‖	No
	Helium release	H	L	L	L‖	No
	Pellet swelling due to helium generation	L	L	L	L	No
	Additional fuel fragmentation	L	L	L	L‖	No
Fuel assembly hardware and damaged-fuel cans	Creep	H	H	M	H†	No
	Metal fatigue caused by temperature fluctuations	M	M	M	M	No
	Wet corrosion and SCC	M	M	L	M¶	No
	Hydriding effects	H	H	H	H	No
Fuel baskets	Creep	H	H	M	H†	No
	Weld embrittlement	L	L	L	L	No
	Metal fatigue caused by temperature fluctuations	M	M	M	M	No
	Corrosion	M	M	L	M#	No
Stainless steel (SS) canister	Atmospheric SCC	L	M	M	L	No
	Pitting and crevice corrosion	L	H	H	L	No
SS canister and steel/cast iron cask and seals	Microbiologically influenced corrosion	L	M	M	L	No
	Irradiation damage	H	H	H	H	No
Steel/cast iron cask	Atmospheric and aqueous corrosion	H	H	H	H	Yes
Metallic seals	Corrosion from external sources	H	H	H	H	Yes
	Thermal-mechanical degradation—creep	H	M	H	H**	Yes
Polymer seals	Thermal-mechanical or radiation-induced degradation	H	H	M	H†	No
Cask bolts	Corrosion, SCC, and embrittlement	M	M	L	L	No
	Thermal-mechanical degradation	M	M	M	M	Yes
Neutron absorbers	Creep	H	H	H	H	No
	Metal fatigue caused by temperature fluctuations	M	M	L	M†	No
	Wet corrosion and blistering	M	M	L	M††	No
	Thermal aging effects	L	L	L	L	No

Table 3-1. Level of Knowledge and Availability of Monitoring (continued)

Component	Degradation Phenomena	Level of Knowledge			Overall Assessment	Monitoring or Inspection Capability
		Initiation Time	Propagation Rate	Degradation or Failure Complete		
Neutron absorbers (cont.)	Absorber depletion	H	H	H	H	No
	Embrittlement and cracking	H	H	M	H†	No
Neutron shielding	Thermal degradation	M	M	M	M	No
	Poison depletion	H	H	H	H	No
	Radiation embrittlement	H	M	M	H†	No
	Wet corrosion	M	M	M	M	No
Concrete overpack, vaults and pads	Shrinkage cracking	H	H	H	H	No
	Creep	H	H	H	H	Yes
	Fatigue	H	H	H	H	Yes
	Rebar corrosion	M	M	L	M‡‡	Yes
	Carbonation	M	M	L	H‡‡	Yes
	Leaching	H	H	M		Yes
	Sulfate attack	H	H	M		Yes
	Alkali-silica reaction	H	L	L		Yes
	Radiation damage	H	M	M	H‡‡	Yes
	Freeze thaw	H	M	M	H‡‡	Yes
	Thermal dry out§§	M	M	M	M	Yes
	Thermal degradation of mechanical properties§§	M	M	L	M‡‡	Yes
	Coupled mechanisms	M	L	L	L	Yes

H=High
M=Medium
L=Low
NA=Not Applicable
*These degradation mechanisms are discussed in Appendix A, Sections 1.1 and 1.2.
†Degradation mechanism should be addressed before complete degradation or failure occurs, so initiation time and rate are the most important, or degradation mechanism continues indefinitely but may slow down with time and decreasing temperature so end point is irrelevant.
‡These degradation mechanisms are discussed in Appendix A, Section 1.3.
§These degradation mechanisms are discussed in Appendix A, Section 1.4.
‖Continuous degradation mechanism that progressively gets worse with no end point, or the consequences of the degradation, when it does occur, are unknown.
¶Completion will be dependent on drying and amount of water available, so initiation time and rate are most important.
#Rate is most important because it will determine when the deformation of the basket affects retrievability.
**Completion of creep will determine when the seal is lost.
††Only refers to Boral, which is of limited use in the new casks designs.
‡‡Degradation will be visually inspectable long before the degradation is complete, so the initiation time and rate of degradation are most important.
§§These degradation mechanisms are discussed in Appendix A, Section 8.11.

Answers to these three questions are needed for the following reasons:

- The initiation time defines the start of the period when the mechanism should be considered for aging management and thus for inspection and monitoring. Initiation time is also closely tied to the specific conditions under which the degradation could begin.

For example, initiation of some phenomena is more likely at high temperatures, while others require a relatively cold canister for initiation.

- The propagation rate provides guidance on the frequency of monitoring and inspection, and allows suitable conditions to be placed in the license extensions.
- The time at which the degradation will result in a loss of the ability of a component to perform its safety function in the affected phase of operation (such as storage or transportation) is critical for planning remediation actions, such as replacement or repair of the component. This would include the case where degradation during one operational phase impacts a safety function needed in a subsequent phase.
- The availability and type of monitoring and/or inspection capability indicates how easily the degradation process can be detected and its progress assessed. Processes that can be easily monitored or components that are easily inspected can tolerate greater uncertainty.

The extent to which each of the three questions on initiation, progress rate, and conclusion of degradation can be answered, also affects how well aging management plans can address potential degradation, and what regulations and guidance are necessary to ensure that the safety functions are maintained. The overall assessment of the level of knowledge and availability of monitoring given in Table 3-1 is based on expert judgment by NRC staff using the information in Appendix A.

- High (H) level of knowledge indicates that sufficient information on the topic is available to address the criteria for regulatory significance given in Section 2.
- Low (L) level of knowledge indicates that insufficient information is available to address the criteria for regulatory significance given in Section 2, and an applicant may not be able to provide a technical basis that satisfies the current regulations in 10 CFR Part 71 and Part 72.
- Medium (M) indicates an intermediate level of knowledge; a substantial amount of information is available, but it may not be sufficient to address all of the criteria for regulatory significance.
- Not applicable (NA) means that the question does not apply to the degradation mechanism under consideration. For example, this includes cases where the degradation process is continuous and does not have an end point, or where the process happens almost instantaneously so the propagation rate is not the principal concern.

In cases where there is a different level of knowledge of the three phases of degradation (initiation, rate, conclusion), staff used its expert judgment to determine the overall state of knowledge. To determine the overall ranking for the level of knowledge, NRC staff considered the relative significance of the phase of degradation for regulatory decisions (as indicated in footnotes in Table 3-1). In a number of cases, staff considers the initiation time and rate more important than the time of failure. To provide an adequate safety margin, some issues will have to be addressed before complete degradation or failure occurs. In other cases, the process may never end, but slows down with time and decreasing temperature so that a defined failure never occurs. The overall assessment is also influenced by the potential ability to monitor or inspect the dry storage system and components while in service, with minimal intrusion or manipulation. In cases where components can be readily inspected (such as external concrete structures), degradation can be visually identified and remediated long before the degradation is complete.

3.2 Crosscutting Issues

Based on the information provided in Table 3-1, staff has identified three issues that cut across several areas:

- Thermal profiles of the components
- Effects of residual moisture after canister drying
- Monitoring of components

Crosscutting issues are those topical areas that can potentially affect the performance of multiple components of the system.

Staff considers thermal profiles and the effects of residual moisture to be crosscutting issues because several degradation phenomena listed in Table 3-1 are dependent on moisture and temperature, and staff has identified information needs related to both thermal modeling and the effects of residual moisture. For example, corrosion of cladding or fuel assembly hardware depends on a source of water remaining in the canister after drying. Staff considers the level of knowledge of assessing the effects of residual moisture to be relatively low because of (i) the multitude of effects occurring concurrently, (ii) the lack of any drying model accounting for the synergistic effects, and (iii) the lack of a method for either measuring the extent of dryness in the canisters that are dried with vacuum methods or the resulting effects of the residual moisture.

Understanding the temperature evolution of the system has a similar crosscutting impact, because almost all the degradation mechanisms identified in this analysis have an Arrhenius-type temperature behavior, in which the rate of degradation increases with increasing temperature. For example, the hydrogen solubility and internal cladding stress both increase with temperature, making the rods more susceptible to hydride reorientation at the higher temperatures. During transportation, the lower temperature distribution becomes more important, because the cladding could go through a ductile to brittle transition. Most current temperature models, however, are designed to conservatively over predict the expected temperature of the cladding. Improvements in thermal models can also help enhance understanding of performance of other system components, in addition to the fuel and cladding. For example, cool spots on the exterior of the cask (such as near air inlets in shielding overpacks) could be more susceptible to stress corrosion cracking at the lower temperature. The more realistic the modeled temperature distribution, the better the susceptibility to degradation can be determined.

The uncertainties in these two areas directly impact the potential significance of several of the specific degradation mechanisms. For this reason, NRC staff concludes that these crosscutting issues should be resolved early so appropriate studies can be conducted on the affected degradation mechanisms with high importance.

For many of the degradation phenomena listed in Table 3-1, there are no existing capabilities for in-service inspection and monitoring of operating storage systems. Staff considers component monitoring to be a crosscutting issue because the ability to monitor degradation could greatly lessen the need to rely on models and indirect methods to assess the likelihood of degradation. Such methods would be valuable tools for confirming model predictions and for aging management. Operating experience in the United States for the particular monitoring methods needed for long-term storage is limited. Opportunities exist to develop systems that would enable licensees and NRC to assess the performance of dry cask storage systems over prolonged periods of time, as well as establish and validate the technical bases for materials/systems performance.   NRC staff recognizes that this could be an area of continuous improvement over time as methods are developed and refined.

Section 9 of Appendix A provides more detailed discussion of the level of knowledge of each of these crosscutting issues.

4 IDENTIFICATION AND PRIORITIZATION OF POTENTIAL TECHNICAL INFORMATION NEEDS: REGULATORY SIGNIFICANCE AND POTENTIAL IMPACT ON SAFETY

The general design criteria, which include confinement, shielding, and criticality safety for a dry storage system, are in 10 CFR Part 72, Subpart F, General Design Criteria. These criteria cover normal operation, accident conditions, and the effects of environmental conditions and natural phenomena (such as earthquakes, tornadoes, or other hazards). Use of these design criteria helps ensure that performance of the system and components satisfies the safety (and other regulatory) functions of the system. The performance functions of the system and components that contribute to safety include heat removal, fuel geometry control, neutron absorption, moderator exclusion control, and structural integrity, among others. Some design features serve multiple safety functions. Structural integrity of the canister, for example, contributes to confinement, shielding, and criticality control.

As previously mentioned, the design criteria to prevent gross rupture of cladding in 10 CFR 72.122(h), serve purposes beyond a strict safety function. Preservation of cladding is part of the current approach by licensees in assuring compliance with the criteria for retrievability in 10 CFR 72.122(l). Integrity of cladding facilitates safe and effective handling of SNF in the back end of the fuel cycle (e.g., in repackaging for ultimate disposal, or in handling for potential reprocessing). In addition, cladding serves as a barrier to fission products, providing defense in depth. Cladding can also be used in some dual-purpose systems as a means to maintain geometry control during transportation, to demonstrate compliance with package requirements for fissile material (in 10 CFR 71.55).

NRC staff used its expert judgment and experience in dry storage licensing to review the identified degradation processes and other effects of extended storage and determine the regulatory significance of each. The potential impacts of these processes on regulatory and safety functions are summarized in Table 4-1, organized by the potential changes on different system components. The potential safety and regulatory impacts are grouped into six areas: criticality, thermal, confinement, structural, shielding, and retrievability. These terms are defined[3] as follows:

- Criticality is the ability of the system to stay subcritical during every phase of storage and transportation.
- Confinement is the ability of the system to retain radioactive material, including gases and particulates, within the system.
- Shielding is the ability of the system to limit the dose rate at designated locations to acceptable regulatory limits.
- Thermal is the ability of the system to reject heat at a rate that limits the temperature of the materials of construction and contents of the system to a range where the materials and content perform as expected.

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[3] These definitions are those in staff guidance documents (NRC, 2010d, 2010e).

- Structural integrity is the ability of the components of the system to remain in a configuration that allows the systems to function as necessary.

- Retrievability is the ability to remove the contents from the storage system in a defined condition.

Table 4-1. Regulatory Significance for Normal and Off-Normal Storage and Transportation, Including Only Those Degradation Phenomena Judged To Have Potentially Significant Impacts on Safety

Component	Degradation Phenomena	Change in Component Condition	Safety Function
Cladding	Cladding oxidation*	Cladding swelling and rupture and added cladding stress	CO, CR, RE
	Biocorrosion*	Partial or through-wall cracks	CO, RE, SR
	Pitting corrosion*	Partial or through-wall cracks	
	Galvanic corrosion*	Partial or through-wall cracks	
	Stress corrosion cracking (SCC)*	Partial or through-wall cracks	
	Air (off-normal condition) oxidation and corrosion*	Macroscopic degradation in mechanical properties	CO, CR, RE, SR
		Partial or through-wall cracks	
	Hydrogen embrittlement†	Macroscopic degradation in mechanical properties	
		Partial or through-wall cracks	
	Delayed hydride cracking†	Partial or through-wall cracks	CO, RE, SR
	Hydride reorientation†	Macroscopic degradation in mechanical properties	CO, CR, RE, SR
		Partial or through-wall cracks	
	Thermal creep‡	Partial or through-wall cracks	CO, CR, RE, SR
		Cladding swelling and rupture	
	Low temperature creep‡	Partial or through-wall cracks	
		Cladding swelling and rupture	
	Annealing of irradiation hardening	Macroscopic degradation in mechanical properties	CO, CR, RE
	Propagation of existing flaws	Partial or through-wall cracks	CO, RE, SR
	Fatigued cladding due to drying cycles	Macroscopic degradation in mechanical properties	CO, CR, RE, SR
		Partial or through-wall cracks	
Fuel-cladding interactions	Air oxidation (off-normal condition)	Fuel swelling	CO, CR, RE
		Pellet powderization	
		Breach of cladding resulting from internal stress	
	Fission gas release during accidents	Increase in rod internal pressure	CO
		Possible pellet fragmentation due to coalesce on grain boundaries	
		Breach of cladding resulting from internal stress	

Table 4-1. Regulatory Significance for Normal and Off-Normal Storage and Transportation, Including Only Those Degradation Phenomena Judged To Have Potentially Significant Impacts on Safety (continued)

Component	Degradation Phenomena	Change in Component Condition	Safety Function
Fuel-cladding interactions (cont.)	Helium release	Increase in rod internal pressure	CO
		Breach of cladding resulting from internal stress	
	Pellet swelling due to helium generation	Breach of cladding resulting from internal stress	CO
	Additional fuel fragmentation	Increase in rod internal pressure due to fission product gas release and possibly leading to breach of cladding	CO
Fuel assembly hardware and damaged-fuel cans	Creep	Stress relaxation of springs or strain of fuel assembly hardware	SR
	Metal fatigue caused by temperature fluctuations	Property changes or cracking of fuel assembly hardware	CR, RE, SR
	Wet corrosion and SCC	Material loss and cracking	CR, RE, SR
	Hydriding effects	Material embrittlement	CR, RE
Fuel basket	Creep	Strain of fuel basket structure	
	Weld embrittlement	Cracking of fuel basket	CR, SH
	Metal fatigue caused by temperature fluctuations	Property changes or cracking of fuel basket	CR, SH
	Corrosion	Material loss and cracking	CR, SH, TH
Stainless steel (SS) canister body and welds	Atmospheric SCC	Partial or through-wall cracks	CO, CR, RE, SH, TH
	Pitting and crevice corrosion	Partial or through-wall corrosion and initiation of SCC	
SS canister, steel and cast iron casks and seals	Irradiation damage	Material embrittlement and reduced fracture toughness	CO, CR, RE, SH, TH
	Microbiologically influenced corrosion	Partial or through-wall corrosion and initiation of SCC	
Steel and cast iron cask body and lid	Atmospheric and aqueous corrosion	Partial or through-wall corrosion	CO, CR, SH, SR, TH
Metallic seals	Corrosion	Corrosion and loss of seal material	CO, CR, SH, TH
	Thermal-mechanical degradation including creep	Deformation of the seal	CO, CR, SH
Polymer seals	Thermal-mechanical or radiation-induced degradation (creep and/or embrittlement)	Deformation or cracking of the polymer seal	CO,CR, TH
Cask bolts	Corrosion, SCC, embrittlement	Corrosion of bolts	CO, CR, SH, SR

Table 4-1. Regulatory Significance for Normal and Off-Normal Storage and Transportation, Including Only Those Degradation Phenomena Judged To Have Potentially Significant Impacts on Safety (continued)

Component	Degradation Phenomena	Change in Component Condition	Safety Function
Cask bolts (cont.)	Thermal-mechanical degradation including creep	Change in bolt dimensions	CO, CR, SH, SR
Neutron absorbers	Creep	Strain of neutron poison material	
	Metal fatigue caused by temperature fluctuations	Property changes or cracking of neutron poisons	CR
	Wet corrosion and blistering	Material loss and deformation and cracking	CR
	Thermal aging effects	Material property changes	CR
	Poison depletion	Depletion of B-10 atoms	
	Embrittlement and cracking	Material embrittlement	CR
Neutron shielding	Thermal degradation	Property changes, dimensional changes, and loss of material, cracking	SH
	Poison depletion	Depletion of B-10 atoms	
	Radiation embrittlement	Property changes	
	Wet corrosion	Loss of material	
Concrete overpacks and vaults	Cracking due to freeze-thaw, dehydration, and shrinkage	Could lead to loss of structural integrity of concrete cask or vault	SH, SR
	Spallation	Could lead to loss of structural integrity of concrete cask or vault	
	Rebar corrosion	Could lead to cracking of concrete and loss of structural integrity of cask and vault	
	Chemical degradation (carbonation; calcium leaching; chloride and sulfate attack; alkali-silicate reaction)	Could lead to cracking and shrinkage of concrete	
	Radiation	Loss of shielding function of concrete cask and vault	
Concrete pad	Concrete inspection and repair	Need data to assess degradation (e.g., nondestructive evaluation and testing); repair as needed	SR
	Cracking due to freeze-thaw, dehydration, shrinkage	Could lead to loss of structural integrity of concrete cask or vault	
	Spallation	Could lead to loss of structural integrity of concrete cask or vault	

Table 4-1. Regulatory Significance for Normal and Off-Normal Storage and Transportation, Including Only Those Degradation Phenomena Judged To Have Potentially Significant Impacts on Safety (continued)

Component	Degradation Phenomena	Change in Component Condition	Safety Function
Concrete pad (cont.)	Rebar corrosion	Could lead to cracking of concrete and loss of structural integrity of cask and vault	SR
	Chemical degradation (carbonation; calcium leaching; chloride and sulfate attack and alkali-silicate reaction)	Could lead to cracking and shrinkage of concrete	
	Coupled mechanisms	Could increase the rate of degradation of other concrete degradation mechanisms	

CO=Confinement
CR=Criticality
RE=Retrievability
SR= Structural
SH= Shielding
TH=Thermal
BLANK=Regulatory implications identified to be minimal
*These degradation mechanisms are discussed in Appendix A, Sections 1.1 and 1.2.
†These degradation mechanisms are discussed in Appendix A, Section 1.3.
‡These degradation mechanisms are discussed in Appendix A, Section 1.4.

In developing the information in Table 4-1, NRC staff considered how potential degradation of each component could affect its licensing review and inspections for storage and transportation, under both normal and accident conditions. In addition, staff considered how potential degradation might require adding licensing conditions for approval of systems for storage or transportation.

A more detailed discussion of the staff's evaluation of potential impacts on safety function is in Appendix B. For those degradation processes that are determined to have a significant (high) impact on the safety function of the component, Appendix B provides more detail on staff's justification of the ranking.

5 OVERALL PRIORITIZATION FOR FURTHER RESEARCH

NRC staff used the information on level of knowledge (Table 3-1) and the information on safety function impact (Table 4-1) to develop overall priorities for additional research. Staff assign high priority to those topics that have both a potentially high impact on safety functions and a relatively low level of knowledge. A low priority in this ranking does not necessarily mean that the topical area is completely characterized or has no impact on safety. Rather, it means that the staff has determined that sufficient information on that mechanism is available to make regulatory decisions and provide adequate guidance to licensees and applicants.

To prioritize degradation phenomena for further research, staff followed these guidelines:

- Areas ranked high (H) for regulatory safety impact, or high (H) for crosscutting implications, and that have a low (L) or medium (M) level of knowledge are given an overall rating of high (H) for regulatory need for further research.

- 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.

- Areas ranked low (L) for regulatory safety impact are given an overall rating of low (L) for regulatory need, irrespective of the level of knowledge.

- Areas with a medium (M) level of knowledge are given an overall ranking on a case-by-case basis, as influenced by their regulatory need.

Some exceptions to these rules were made in specific cases. For example, the ranking of some phenomena reflects the need for data from other research areas to determine whether a mechanism is active and would require further research. In other cases, the ranking depends on accessibility of a component for monitoring. The bases for exceptions to these rules are indicated in the footnotes in Table 5-1.

Table 5-1. Overall Rankings for Further Research Based on Regulatory Significance, Level of Knowledge, and Use of Data

Component	Degradation Phenomena	Regulatory Significance	Level of Knowledge	Overall Ranking*
Cladding	Cladding oxidation	CO, CR, RE	H	L
	Biocorrosion	CO, RE, SR	H	L
	Pitting corrosion		H	L
	Galvanic corrosion		L	H†
	Stress corrosion cracking (SCC)		L	H‡
	Air (off-normal condition) oxidation and corrosion	CO, CR, RE, SR	H	L
	Hydrogen embrittlement		H	L
	Delayed hydride cracking	CO, RE, SR	M	H‡
	Hydride reorientation	CO, CR, RE, SR	H	L
	Thermal creep	CO, CR, RE, SR	H	L
	Low temperature creep		L	H
	Annealing of irradiation hardening	CO, CR, RE	M	M§

Table 5-1. Overall Rankings for Further Research Based on Regulatory Significance, Level of Knowledge, and Use of Data (continued)

Component	Degradation Phenomena	Regulatory Significance	Level of Knowledge	Overall Ranking*
Cladding (cont.)	Propagation of existing flaws	CO, RE, SR	L	H
	Fatigued cladding due to drying cycles	CO, CR, RE, SR	NA	L‖
Fuel-cladding interactions	Air oxidation (off-normal condition)	CO, CR, RE	H	L
	Fission gas release during accident	CO	L	H
	Helium release			
	Pellet swelling	CO	L	H‡
Fuel assembly hardware and damaged-fuel cans	Creep	SR	H	L
	Metal fatigue caused by temperature fluctuations	CR, RE, SR	M	H¶
	Wet corrosion and SCC	CR, RE, SR	M	H†
	Hydriding effects	CR, RE	H	L
Fuel baskets	Creep		H	L
	Weld embrittlement	CR, SH	L	H
	Metal fatigue caused by temperature fluctuations	CR, SH	M	H
	Corrosion	CR, SH, TH	M	M†
Stainless steel (SS) canister body and weld	Atmospheric SCC	CO, CR, RE, SH, TH	L	H
	Pitting and crevice corrosion			
SS, steel, and cast iron body, welds, lids, and seals	Microbiologically influenced corrosion	CO, CR, RE, SH, TH	L	H
	Irradiation damage		H	L
Steel and cast iron cask body and lid	Atmospheric and aqueous corrosion	CO, CR, SH, SR TH	H	L
Metallic seals	Corrosion	CO, CR, SH, TH	H	L
	Thermal-mechanical degradation	CO, CR, SH		
Polymer seals	Thermal-mechanical or radiation-induced degradation	CO, CR, TH	H	L
Cask bolts	Corrosion, SCC, and embrittlement	CO, CR, SH, SR	L	H
	Thermal-mechanical degradation			
Neutron absorbers	Creep		H (L#)	L (H#)
	Metal fatigue caused by temperature fluctuations	CR	M	M**
	Wet corrosion and blistering	CR		M††
	Thermal aging effects	CR	L	L (H#)
	Absorber depletion		H	L
	Embrittlement and cracking	CR	H	L
Neutron shielding	Thermal degradation	SH	M	L
	Poison depletion		H	
	Radiation embrittlement		H	
	Wet corrosion		M	

Table 5-1. Overall Rankings for Further Research Based on Regulatory Significance, Level of Knowledge, and Use of Data (continued)

Component	Degradation Phenomena	Regulatory Significance	Level of Knowledge	Overall Ranking*
Concrete overpack and vaults and pads	Cracking due to freeze-thaw, dehydration, shrinkage	SH, SR	H	L
	Creep		H	L
	Rebar corrosion		M	M (H‡‡)
	Chemical degradation (carbonation; calcium leaching; chloride and sulfate attack and alkali-silicate reaction)		H	L
	Radiation damage		H	L
	Thermal dry out		M	M (H‡‡)
	Thermal degradation of mechanical properties		M	M‡‡
	Coupled mechanisms		L	M (H‡‡)
Crosscutting for multiple components	Drying	CO, CR, RE, SR	L	H
	Thermal calculations	CO, CR, RE, SR, TH	L	H
	Monitoring	CO, CR, RE, SR, TH	L	H

H=High
M=Medium
L=Low
NA=Not Applicable
CO=Confinement
CR=Criticality
SH=Shielding
SR=Structural
TH=Thermal
BLANK=Regulatory implications were identified to be minimal

*Any degradation mechanism where the knowledge was high was given an overall low rating irrespective of the need for the data.

†High only if there is residual moisture after drying; otherwise, low. Drying is being evaluated as a separate crosscutting issue. Although the input ratings for the fuel assembly hardware and the fuel baskets are similar, the overall rating for the fuel assembly hardware is of higher significance due to different materials and a potentially greater impact on safety functions such as criticality.

‡Will only be high because stress generated from helium swelling of the fuel is shown to be operative.

§Rated medium because annealing has both positive and negative effects on cladding performance.

‖Even though cladding fatigue is important to criticality safety, its overall ranking is low because the number of cycles during drying is limited and the temperature range is above the ductile-brittle transition.

¶Rated high because it can indirectly affect criticality.

#Structural neutron absorbers only.

**This should be easily calculated once the variation of the temperature distributions is determined from the thermal modeling crosscutting effort.

††Only Boral™ will be affected by blistering, and it has limited use in newer canister designs. Currently loaded canisters using Boral will have the issue in the shorter term.

‡‡These mechanisms have structural safety implications but progress relatively slowly. They can be monitored by existing techniques if the component is accessible. They are rated medium if monitoring is available, and high if the component is cannot be easily monitored.

NRC staff considers that all of the high priority information needs are important for developing a sound technical and regulatory basis for extended storage and transportation. Within this group, some of the phenomena may have more direct implications for changes in system fabrication or design, and for use of monitoring for early identification of incipient degradation. Staff therefore recommends that degradation phenomena that impact confinement, shielding, and criticality control be addressed first.

In addition, several of the high-priority phenomena depend on either the initial dryness (residual moisture) of the internal environment, or on cladding stresses that could develop over time (from decay-produced helium or fuel swelling). Staff recommends the initial research focus include work on these two potential driving mechanisms.

Staff considers the ability to monitor system components for degradation to be a valuable tool for ensuring continued safety of SNF storage. The design of any monitoring program depends on what specific degradation processes are of interest, so development of specific monitoring techniques should be closely tied to research on the high-priority degradation phenomena. The monitoring program should also consider the intended safety function of the systems and components, to inform monitoring of the onset and propagation of known degradation mechanisms, and to target unexpected deterioration of performance.

A more detailed discussion of the NRC staff recommendations for priority of the high rated research needs is given in Section 6.

6 CONCLUSIONS

Under conditions of extended storage and subsequent transportation, dry storage systems, structures, and components may experience degradation not observed in storage of shorter durations. These extended degradation phenomena must be evaluated to determine whether additional information is needed to

- Determine whether the regulations are adequate to provide confinement, shielding, and criticality safety, and propose regulatory changes or alternatives through rulemakings where appropriate
- Determine whether an event or mechanism of degradation compromises safety during normal or accident conditions
- Enhance licensing regulatory guidance for design features, maintenance and monitoring needs, and aging management plans for extended storage and transportation
- Provide a technical basis for reviewers to use when determining whether the approach proposed by an applicant is adequate
- Enhance inspection guidance for components and systems to verify adequate implementation of aging management programs and identification of premature aging of cask components

NRC staff has evaluated the level of knowledge of the potential degradation of components of the dry storage system, as related to their expected safety functions and regulatory requirements for storage and transportation. Staff used this evaluation to prioritize the need for further research to meet the previously outlined goals.

NRC staff's rankings in Table 5-1 show 18 entries having an overall ranking of high (H) in the need for further research. Several additional entries have conditional high ranking, depending on their accessibility for monitoring (degradation of concrete components by several mechanisms) or on their role as structural neutron absorbers (creep and thermal aging effects). All of these high-ranked areas are grouped and prioritized for further investigations as those that should be addressed first (Priority 1) and those that should be addressed subsequently (Priority 2). The latter set are important for a complete analysis of the regulatory framework, but rank behind the six top priority areas. In some cases, results of early work on Priority 1 areas may help determine the specific information needs for Priority 2 areas. The staff's prioritized research areas are summarized in Table 6-1.

NRC staff concludes that the following potential degradation mechanisms or drivers should be addressed first (Priority 1):

- Stress corrosion cracking (SCC) of stainless steel canister body and welds
- Corrosion, SCC, embrittlement, and mechanical degradation of cask bolts
- Swelling of fuel pellets due to helium in-growth, and fuel rod pressurization due to additional fuel fragmentation, helium release, and fission gas release during accidents

Table 6-1. Summary of Regulatory Research Areas

Component	Degradation Phenomena	Regulatory Significance	Level of Knowledge	Overall Ranking	Reason for Ranking High	Research Priority
Cladding	Galvanic corrosion	CO, RE, SR	L	H*†	This is only high if the drying task indicates that sufficient water remains in the canister. This may revert to low if sufficient water is not present. The level of knowledge is low.	2
	Stress corrosion cracking (SCC)		L	H§‡	All three mechanisms depend on a source of stress that would come from pellet swelling. If the stress is not present, the mechanisms become benign. If operative, these mechanisms could increase the source term and increase cladding stress. The latter could affect containment, especially if other degradation processes have compromised the canister.	2
	Delayed hydride cracking	CO, RE, SR	M	H§‡		2
	Low temperature creep	CO, CR, RE, SR	L	H‡		2
	Propagation of existing flaws	CO, RE, SR	L	H	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. Breached cladding affects the containment source term.	2
Fuel-cladding interactions	Fission gas release during accident	CO	L	H	Both of these mechanisms will result in an increased pressure in the canister and potential containment issues. The level of knowledge is low.	1
	Helium release					
	Pellet swelling	CO	L	H§	The level of knowledge is low, and swelling of the pellets would be the only source of stress for long duration cladding failure.	1
	Additional fuel fragmentation	CO	L	H	Additional fuel fragmentation will release fission gas to pressurize the rod and result in an increased source term for containment.	1
Fuel assembly hardware and damaged-fuel cans	Metal fatigue caused by temperature fluctuations	CR, RE, SR	M	H‖	Loss of assembly hardware would put the fuel in an unanalyzed state for criticality. The extent of the fatigue will depend on the size of the temperature fluctuations determined from the thermal crosscutting task.	2
	Wet corrosion and SCC	CR, RE, SR	M	H*†	This is only high if the drying task indicates that sufficient water remains in the canister. This may revert to low if sufficient water is not present	2

Table 6-1. Summary of Regulatory Research Areas (continued)

Component	Degradation Phenomena	Regulatory Significance	Level of Knowledge	Overall Ranking	Reason for Ranking High	Research Priority
Fuel baskets	Weld embrittlement	CR, SH	L	H	The knowledge of this mechanism is low and failure of the basket will leave the fuel in an unanalyzed condition for criticality.	2
	Metal fatigue due to temperature fluctuations	CR, SH	M	H	The knowledge of this failure mechanism is medium, and failure will place the fuel in an unanalyzed condition.	2
Stainless steel (SS) canister body and weld	Atmospheric SCC	CO, CR, RE, SH, TH	L	H	The canister is the primary containment vessel in storage and may be needed for moderator exclusion of high burnup fuel in transportation. It may also be the primary means of retrieval. It is currently not known whether conditions are applicable for the mechanism to be active or in what timeframe it will occur.	1
	Pitting and crevice corrosion					
SS, steel, and cast iron body, welds lids and seals	Microbiologically influenced corrosion	CO, CR, RE, SH, TH	L	H	Under the correct conditions, this mechanism could corrode seals and/or the cask body that affect containment. Little is known about whether the conditions are ripe for this mechanism to be operative.	2
Cask bolts	Corrosion, SCC, and embrittlement	CO, CR, SH, SR	L	H	While the level of knowledge is medium, failing or loosening bolts can, in the long term, compromise containment and the inert atmosphere in the canister These cladding degradation mechanisms are inoperative only if the inert atmosphere is maintained.	1
	Thermal-mechanical degradation					
Neutron absorber	Thermal aging effects	CR	L	H#	Displacement of absorbers from their original positions can impact criticality safety in the event of canister breach and water ingress. Absorbers in welded canisters cannot currently be monitored or replaced.	2

Table 6-1. Summary of Regulatory Research Areas (continued)

Component	Degradation Phenomena	Regulatory Significance	Level of Knowledge	Overall Ranking	Reason for Ranking High	Research Priority
Concrete Overpack	Multiple mechanisms	SH, SR	H	H	Concrete is the primary shielding for storage and transportation in most systems. Knowledge of the various degradation mechanisms is variable, but overall has been rated high assuming that monitoring can identify early signs of degradation. If analysis of monitoring methods shows that early degradation cannot be reliably detected, then evaluation of individual degradation mechanisms will have higher priority.	2
Crosscutting for multiple components	Drying	CO, CR, RE, SR	L	H	These crosscutting issues affect many components and mechanisms. Many of the other degradation mechanisms, listed previously, can be eliminated if the canister is dry, there is a good knowledge of the temperatures, and adequate monitoring is conducted. The monitoring task is to gain knowledge of the necessary monitoring intervals and adequacy of monitoring.	1
	Thermal calculations	CO, CR, RE, SR, TH	L	H		1
	Monitoring	CO, CR, RE, SR, TH	L	H		2

H=High
M=Medium
L=Low
CO=Confinement
CR=Criticality
RE=Retrievability
SH=Shielding
SR=Structural
*Rated high because it can indirectly affect criticality.
†High only if there is residual moisture after drying, otherwise low. Drying is being evaluated in a separate task.
‡Will only be high if stress generated from helium swelling of the fuel is shown to be operative.
§These rankings may change based on the results of work on pellet swelling.
‖While the level of knowledge is now medium, this is assigned high priority because it may impact criticality safety.
#Structural absorbers only

The group of related phenomena in the last bullet, concerning fuel and cladding, is highlighted for early attention because if they are shown to be unlikely to compromise cladding, other cladding-related mechanisms may become less significant.

Staff also recommends that first priority be given to the following areas:

- Thermal calculations
- Effects of residual moisture after normal drying
- Development of in-service monitoring methods for storage systems and components

Other potential types of degradation rated as high overall for further research should be addressed next (Priority 2)

- Propagation of existing flaws in cladding[4]
- Wet corrosion, SCC, and metal fatigue of fuel assembly hardware
- Metal fatigue of cladding caused by temperature fluctuations, SCC, and DHC[5]
- Low temperature creep and galvanic corrosion of cladding
- Microbiologically influenced corrosion of stainless steel, carbon steel, and cast iron body, welds, lids, and seals
- Embrittlement of fuel basket welds at low temperature, and metal fatigue due to temperature fluctuations
- Thermal aging and creep of neutron absorbers
- Concrete degradation; priority of specific mechanisms depends on availability of monitoring methods and accessibility of the component

This proposed ranking of technical information needs is based on the staff's evaluation of its regulatory needs and is not intended to provide guidance on any specific application. Applicants for new or renewed licenses or certifications should not infer that relevant mechanisms which have been given a low priority in this report should not be addressed in an application. A low priority ranking by staff only indicates that enough information is available for regulatory considerations.

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[4] This area could be elevated to more immediate priority depending on results from investigation of potential fuel rod pressurization.

[5] This area could be elevated to more immediate priority depending on results from more realistic thermal models.

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APPENDIX A

EVALUATION OF TECHNICAL INFORMATION NEEDS

APPENDIX A: CONTENTS

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APPENDIX A: TABLES

APPENDIX A: EVALUATION OF TECHNICAL INFORMATION NEEDS

A1 CLADDING

Cladding degradation mechanisms include oxidation, corrosion, stress corrosion cracking, hydrogen effects, and mechanical degradation mechanisms. The level of knowledge regarding the degradation mechanisms and the status of monitoring and inspection techniques are summarized in Table A1–1.

Once a storage canister is sealed, there are no known capabilities for monitoring or inspecting the degradation phenomena listed in Table A1–1. Many of the phenomena that occur during storage also take place during reactor irradiation, although the operational conditions are substantially different.

Many of the degradation phenomena important for fuel and cladding are correlated to the condition of the material prior to loading into dry storage (i.e., degradation during storage is related to prior degradation that occurred during irradiation under reactor conditions). A number of cladding degradation phenomena lead to through-wall cracking. These phenomena cannot be monitored in a sealed canister. Radiation monitoring and inspection of spent fuel storage systems for leaks may be revealed if degradation has proceeded to cladding breach that results in fission product release. Although it would then be too late to prevent the breach, detection of cladding breaches provides information to characterize the state of the fuel and cladding system for future handling.

Table A1–1. State of Knowledge and Monitoring Techniques—Cladding

Component	Degradation Phenomena	Level of Knowledge			Monitoring or Inspection Capability
		Initiation Time	Propagation Rate	Degradation or Failure Complete	
Cladding	Cladding oxidation	H	H	M	No
	Biocorrosion*	H	NA	NA	No
	Pitting corrosion	H	H	H	No
	Galvanic corrosion	L	L	L	No
	Stress corrosion cracking (SCC)	L	M	L	No
	Air (off-normal condition) oxidation and corrosion	H	H	M	No
	Hydrogen embrittlement	H	NA	NA	No
	Delayed hydride cracking	M	H	H	No
	Hydride reorientation	H	NA	NA	No
	Thermal creep	H	H	M	No
	Low temperature creep	L	L	L	No

Table A1–1. State of Knowledge and Monitoring Techniques—Cladding (continued)

Component	Degradation Phenomena	Level of Knowledge			Monitoring or Inspection Capability
		Initiation Time	Propagation Rate	Degradation or Failure Complete	
Cladding (cont.)	Annealing of irradiation hardening	M	M	L	No
	Irradiation growth	H	H	H	No
	Propagation of existing flaws	L	H	M	No
	Fatigued cladding due to drying cycles†	NA	NA	NA	No

H=High
M=Medium
L=Low
NA=Not Applicable
*See discussion of these degradation phenomena. The inert atmosphere of a properly sealed canister will be such that this degradation mechanism will likely not be operable.
†Regulatory limits and review of drying operations limit thermal cycling to a level where this degradation mechanism is likely not operable.

A1.1 Outer Diameter Corrosion and Oxidation-Related Phenomena[1]

Description of Degradation Phenomenon

During normal reactor operation, zirconium fuel cladding reacts with water or steam to form a uniform layer of zirconium oxide. Older cladding alloys may have oxide layers as large as 50 to 100 microns. Modern alloys are likely to have oxide layers less than 50 microns. The oxide layer is very brittle in comparison to the unoxidized zirconium metal, and therefore the thickness of the oxide layer impacts the mechanical properties of the cladding. With oxide layers above approximately 80 microns, the oxide has a tendency to locally spall (separate from the unoxidized fuel). Because dry cask storage systems (DCSS) are designed to seal out air and moisture, cladding oxidation beyond that which is developed during operation and pool storage is not expected in a properly sealed dry cask system.

Nonetheless, in a properly sealed cask system, the environment of the dry cask may introduce additional corrosive agents other than air and moisture. Biofilms and microbes are present in nuclear power plant water cooling systems and used fuel storage pools. These may remain on the surface of the cladding after the cask is sealed and may lead to potential biocorrosion during dry storage. A high relative humidity is required to support biocorrosion, and it is unclear whether such high humidity can occur from the limited residual water in a sealed cask environment. In addition, the inside wall of some casks has been painted with a corrosion-resistant coating that contains zinc. Initial testing at temperatures above 300 °C

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[1] These include cladding oxidation, biocorrosion, pitting corrosion, galvanic corrosion, stress corrosion cracking, and air (off-normal) oxidation and corrosion.

[572 °F], showed that zinc vapor can react with unoxidized Zircaloy-4 cladding. Subsequent testing at 300 °C [572 °F] conducted using oxidized Zircaloy-4 and the zinc containing coating did not show evidence zinc-Zircaloy interaction (Tsai and Yan, 2001).

If the dry cask container seal or canister system fails such that the inert atmosphere is lost, the fuel cladding system is exposed to air and/or moisture and further oxidation and corrosion is possible. The corrosion rate is highly dependent on the temperature and makeup of the air and moisture environment of the cask. This would be considered an off-normal condition and only occurs as the result of seal failure.

In general, outer diameter corrosion- and oxidation-related phenomena can cause mechanical properties of the cladding to degrade, leaving the cladding vulnerable to failure under loading or impact. Localized corrosion and oxidation-related phenomena can lead to partial and through-wall cracking of the cladding, resulting in the release of fission gases into the cask environment. Outer diameter corrosion and oxidation can occur during extended storage and transportation (EST) if system breaches occur.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) indicate that external oxidation of the cladding may occur if the DCSS is mistakenly backfilled with air, if a leak allows oxygen into the DCSS, or by reaction with oxygen generated from the radiolysis of residual water (including waterlogged rods). Rothman (1984) examined multiple cladding oxidation conditions and predicted cladding thinning of 4 to 53 microns (up to 9 percent of cladding thickness) after 10,000 years at 180 °C [356 °F]. Based on this assessment, the NRC staff conclude that cladding oxidation would be inconsequential for extended dry storage.

Sindelar, et al. (2011) indicate that dry storage under inert gas conditions leads to no further increase in the oxide layer than existed on final discharge from the reactor. Cladding oxidation may occur as a result of an off-normal condition, such as the failure of seals or weldments that allow air ingress. The oxidation and cladding is strongly dependent on temperature. Above 300 °C [572 °F] in air conditions, cladding oxidation may occur during the storage period. Cladding oxidation at temperatures below 200 °C [392 °F] is not significant. Sindelar, et al. (2011) conclude that because of the strong temperature dependence, fuel cladding oxidation during extended storage is unlikely to be a significant degradation mechanism. This report also recommended that air oxidation be evaluated in a demonstration program to verify lack of significant changes to the cladding.

NWTRB (2010) indicates that as long as the inert gas atmosphere is maintained, pitting or other cladding chemical corrosion should be insignificant during long-term storage. Nevertheless, NWTRB (2010) also indicates that biofilm formation, biofouling, and microbiologically influenced corrosion all have been observed in nuclear power plant water cooling systems and used-fuel storage pools. Whether these microbes would be eliminated in the drying process is not known, but water is necessary for microbial activity and little water is expected in the casks after drying. NWTRB (2010) states that research is needed to better understand these mechanisms and the response of microorganisms to radiation fields and the inert gas environments of dry storage.

NRC Staff Evaluation

Each cladding and fuel vendor has approved models that predict oxide layer thickness as a function of in-reactor operating conditions. Previous studies, including the previous dry cask storage demonstration project, have suggested that the cladding condition related to oxidation does not evolve significantly during dry cask storage over 10–15 years in an inerted cask. What is not well understood is whether these observations can be extrapolated for time scales beyond 15 years and to cladding materials that have had higher burnups. Because the canisters will be inerted and models are available for determining the rate of oxide growth, the NRC staff characterized the level of knowledge of the initiation and propagation rate of outer diameter corrosion and oxidation was characterized as high. Knowledge of the point at which these mechanisms cause cladding failures is low because failures will depend on other considerations, such as internal rod pressure, and existing cladding defects, such as hydride blisters. The exceptions to these rankings are biocorrosion and galvanic corrosion. Therefore, unless there is excessive spallation of the oxide, the zirconium oxide on the cladding surface will prevent biocorrosion. Therefore, the NRC staff determined/prioritized the level of knowledge of initiation of biocorrosion is considered high and propagation rate and complete failure are not applicable. Galvanic corrosion can only occur if residual moisture after drying is present. Because drying is an area that needs further investigation (see crosscutting issues), NRC staff determined/prioritized the galvanic corrosion is evaluated as low for initiation time, propagation rate, and degradation or failure complete. Pitting corrosion is unlikely because of the excellent pitting and crevice corrosion resistance of modern welds; therefore, NRC staff determined/prioritized the level of knowledge is considered high.

However, if the canister leaked or had a broken seal, the drying is incomplete; the ingress of oxygen inside the canister could cause further corrosion in air that can be calculated using the oxidation models, which are well characterized (NRC, 2004). The rate of corrosion in air will depend on temperature, relative humidity, and possibly other parameters such as pressure. Oxidation initiates when the canister breaches and continues at a predictable rate that can be calculated from oxidation models, so the knowledge of the corrosion rate is high. The NRC staff determined that additional studies of the kinetics of cladding oxidation in air are needed, but the current short-term predictions should be confirmed in the demonstration. Because exposure time is critical to oxidation and corrosion degradation, monitoring for air ingress and addressing seal failure immediately could be sufficient to prevent oxidation and corrosion degradation from impacting cladding conditions for extended storage. Therefore, the capability to detect air ingress to the canister is an important monitoring need.

A1.2 Inner Diameter Corrosion and Oxidation-Related Phenomena[2]

Description of Degradation Phenomenon

During reactor operation, fission of uranium fuel produces fission products, some of which exist in a gaseous form, including iodine, cadmium, and cesium. During reactor operation, these gaseous fission products can migrate from the fuel pellet into the void volume of the fuel-cladding system. A number of fission products are known to be corrosive, and therefore the presence of these elements in the fuel-cladding gap can provide a corrosive environment for the inner diameter of the cladding. The presence of these gases alone does not necessarily result in corrosion. However, in combination with cladding stress, corrosion-induced cracking from the inner diameter is possible. Over long storage periods (>100 years), pellet swelling can cause impingement of the pellet against the cladding. This can lead to stresses in the pellet and cladding . Missing pellet surfaces can enhance this phenomenon, leading to increased pellet fragmentation and increased localized release of corrosion-aggressive volatile fission products.

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[2] These include cladding oxidation, biocorrosion, pitting corrosion, galvanic corrosion, stress corrosion cracking, and air (off-normal) oxidation and corrosion.

The combination of stress localization and aggressive fission products can lead to failure by stress corrosion cracking (SCC). This phenomenon can be described as pellet cladding interaction (PCI) under storage conditions.

In general, inner diameter corrosion and oxidation-related phenomena have the potential to lead to the degradation of mechanical properties of the cladding, leaving the cladding vulnerable to failure under loading or impact. Localized inner corrosion and oxidation-related phenomena have the potential to lead to partial and through-wall cracking of the cladding, releasing fission gases into the cask environment.

Synopsis of Previous Gap Assessments

The DOE gap assessment indicates zirconium may scavenge oxygen from UO_2, resulting in an oxide layer forming on the fuel side of the cladding. Hanson, et al. (2011) also cite tests conducted at ANL with defective rod segments in humid air at 175 °C [347 °F]. These tests showed extensive fuel-side corrosion of the cladding and axial splitting after 1.5 years (BSC, 2004a), which may have been the result of the fuel-side corrosion/oxidation of the cladding and formation of ZrO_2 corrosion products. It is unclear whether rapid oxidation could have occurred as a result of deliquescence of fission product salts. Potential deliquescence depends on the relative humidity inside the canister. Hanson, et al. (2011) indicate that the ANL test conditions may have included more oxidizing conditions, such as those expected for a waterlogged rod in dry storage under an inert atmosphere. The oxidation rate observed in the ANL tests is significantly faster than predicted by existing models. Consequently, Hanson, et al. (2011) point out the need to determine the mechanism of this rapid oxidation and whether it could ever occur in dry storage. Also, more realistic calculations are needed as to how much water may remain in the dry cask storage systems after drying. Note that under certain conditions that could exist in water-logged rods, the UO_2 matrix could be hydrolyzed, resulting in large expansion of the fuel and splitting of the cladding surrounding the hydrolyzed fuel.

Hanson, et al. (2011) also address SCC of the cladding caused by PCI with the presence of iodine, cesium, and cadmium fission products. To reduce the occurrence of PCI failures, local cladding strains were reduced by changing the pellet design. In addition, a thin liner was added to the inside of the cladding that has improved corrosion resistance; this is softer than the cladding alloy and reduces the local stresses. Lower fuel temperatures in dry storage should not promote an additional release of fission products that would promote SCC. In addition, as temperatures decrease, rod internal pressures and tensile stresses also decrease. Hanson, et al. (2011) concludes that PCI failures would be expected to be small, such as pinhole or hairline cracks, releasing only fission gas. However, if the fuel is in an oxidized and pulverized state, fuel fines could also be released, and contribute to significantly higher dose. While there are only limited data on the new clad materials compared to Zircaloy-2 and Zircaloy-4, NRC staff expects that the newer clad materials would incorporate design changes, such as the liners, reducing the probability of PCI failure.

Sindelar, et al. (2011) emphasize that many fuel rods without the pure zirconium layer have been placed into dry storage and the potential for SCC recurrence as a result of radiolysis of cesium has not been thoroughly investigated, especially for high burnup fuels. Most of the experimental works in which Zircaloy was exposed to iodine and other chemical elements are within the range of operating temperatures below about 320 °C [about 610 °F] and with short exposure times. Long-term studies have not been conducted to evaluate the radiolysis effects on iodine partial pressures that may promote SCC in fuel with appropriate cladding stress/strain conditions. Sindelar, et al. (2011) suggest that fission products present on the clad inner surface may synergistically contribute to crack propagation with the delayed hydride cracking (DHC) mechanism. Sindelar, et al. (2011) indicate that destructive examination of cladding should be performed with appropriate sampling to check for SCC. Considerations should include zirconium-lined and unlined fuel as well as high burnup fuel. Sindelar, et al. (2011) also analyze the potential for rod pressurization by the helium buildup in the gap, as well as within the fuel matrix itself, as a result of alpha decay. Sindelar, et al. (2011) conclude that helium pressurization will not be significant until after thousands of years of storage and thus is insignificant for a 300-year storage period.

NRC Staff Evaluation

The rate of production and elemental distribution of fission products is a well-understood and well-characterized phenomenon. The migration and release of fission products in a wide range of temperature conditions is also relatively well understood. What is not well understood is the relationship between corrosive elements and stress and how they combine to initiate and propagate cracking in cladding material. Root-cause evaluations of failed fuel have attributed failures to iodine-assisted stress corrosion cracking (IASCC) or generally to stress corrosion cracking (SCC). A number of laboratory studies have been conducted to understand the conditions that are required to induce SCC, but the results to date have been inconclusive and there is speculation that SCC is enhanced by an in-reactor environment. The combined conditions and controlling mechanisms of SCC need be better understood to predict whether this combination will result in cladding failure under dry storage conditions.

SCC requires a certain level of stress, which can be a result of fission gas thermal expansion and pellet swelling from alpha decay during spent fuel storage. The extent of the pellet swelling and stress on the cladding in extended timeframes has not been confirmed. Rondinello, et al. (2010) predicts that the pellets should start swelling in the 100- to 300-year timeframe, but this has not been confirmed. In addition, inner oxidation and corrosion phenomena can be impacted by small amounts of corrosive elements or alloying elements, as well as specific fuel design parameters, such as gap dimensions and predicted gap closure times, so more information is necessary to improve characterization of initiation. The NRC staff does not expect that SCC will be an issue for short-term storage because of insufficient stress conditions. If the prediction that pellet swelling begins in the 100- to 300-year timeframe due to alpha decay is confirmed, then the SCC phenomena would be an issue for EST. Until this is confirmed, the NRC staff characterizes knowledge of the initiation time as low.

For most of the inner diameter corrosion and oxidation-related phenomena discussed in this section, the NRC staff characterized the level of knowledge as medium for propagation rate because there is a substantial amount of research on corrosion and oxidation rates available. However, much of this research is valid for reactor temperatures, time spans, and environments, and it is not clear whether the data can be extrapolated to the temperature and time spans considered for extended storage.

Failure of cladding under applied load due to corrosion and oxidation is highly dependent on temperature and cladding load conditions (including rod internal pressure). More work is needed that focuses on the temperature and loading conditions expected during storage and transportation. Therefore, for most of the inner diameter corrosion and oxidation-related phenomena discussed in this section, the NRC staff characterized the level of knowledge as low for degradation or failure.

A1.3 Hydrogen-Related Phenomena[3]

Description of Degradation Phenomenon

During normal operation, zirconium fuel cladding reacts with water or steam to form zirconium oxide, resulting in a thin layer of zirconium oxide on the surface of the fuel cladding. When this reaction takes place, hydrogen is liberated and a portion of these hydrogen molecules are absorbed into the cladding material. The amount of hydrogen absorbed into the cladding material is proportional to the amount of oxidation that takes place during operation. For zirconium cladding alloys in use today, approximately 10–20 percent of the hydrogen liberated by the corrosion during in-reactor operation is absorbed into the cladding material. Some alloys, particularly older cladding alloys, may have hydrogen contents greater than 600 weight parts-per-million (wppm) hydrogen. Alloy design has been improved over the years, and modern alloys are likely to have far less hydrogen pickup.

At reactor operating temperatures, hydrogen is soluble in zirconium up to around 200 wppm. As the temperature decreases, the solubility also decreases. When the hydrogen content exceeds this amount, the hydrogen begins to precipitate into hydrides, circumferential for a pressurized water reactor (PWR), and random and radial for a boiling water reactor (BWR). Hydrogen and hydrides are related to a number of degradation mechanisms, including general hydride embrittlement, delayed hydride cracking, and hydride reorientation.

Delayed hydride cracking is a phenomenon in which the localized cracking of a hydride within zirconium produces high stress conditions at the crack tip that enhance hydrogen migration. Soluble hydrogen migrates to the localized high stress crack trip region, resulting in brittle conditions ahead of the crack tip. If there is a sufficient sustained loading condition, the crack then propagates easily into fresh material and the cycle begins again until a crack penetrates the cladding.

Hydride reorientation is a phenomenon that requires a heating and cooling cycle combined with cladding hoop tensile stress. During operation, the hydrides that form in cladding material form in plane with the cladding surface. This orientation is favorable because through-thickness cracks are effectively blunted by cracked in-plane hydrides located in a plane perpendicular to the direction of the crack propagation. In conditions expected during the vacuum drying of dry cask storage systems, the cladding temperature will increase causing a portion of the hydrides to dissolve into the metal matrix. As the cladding cools down, the hydrogen will again precipitate out as hydrides and, in the presence of cladding hoop tensile stress, the hydrides will have a tendency to precipitate in a plane normal to the localized stress (i.e., perpendicular to the plane of the cladding surface). This orientation enhances crack growth because the hydrides are in a plane parallel to the direction of the crack propagation.

In general, hydrogen-related phenomena have the potential to lead to the degradation of mechanical properties of the cladding, leaving the cladding vulnerable to failure under loading or impact. Localized hydrogen-related phenomena have the potential to lead to partial and through-wall cracking of the cladding, releasing fission gases into the cask environment.

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[3] These include hydrogen embrittlement, delayed hydride cracking, and hydride reorientation.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011), Sindelar, et al. (2011), and NWTRB (2010) all address hydrogen effects, including hydride reorientation, hydrogen embrittlement, changes to the ductile-to-brittle transition temperature (DBTT), and delayed hydride cracking (DHC). The assessments in these reports are consistent and reference many of the same studies. All reports indicate that hydrogen effects are dependent on many factors including the cladding alloy composition, cladding manufacturing processes, operational history including reactor type, burnup, operational temperatures, and cladding temperatures during the drying process.

All reports indicate that cladding on high-burnup fuels is more susceptible to radial hydride formation as a result of higher decay heat, higher internal pressure, and higher hydrogen content compared to low burnup cladding. Hanson, et al. (2011) indicate niobium-bearing cladding alloys and recrystallized annealed (RXA) alloys are more susceptible to radial-hydride precipitation than tin-bearing, cold-work, stress-relieved annealed (CWSRA) alloys. Hanson, et al. (2011) point out that data [Daum, et al. (2006, 2008), Aomi, et al. (2008), and Burtseva, et al. (2010)] indicate that current temperature and stress limits are insufficient to prevent radial-hydride formation and embrittlement at cladding temperatures less than 200 °C [392 °F]. Sindelar, et al. (2011) cite literature that indicates the precipitation of radial hydrides can reduce the ductility of Zircaloy cladding alloys to essentially zero. NWTRB (2010) indicates that studies over the past 20 years have provided conflicting arguments about what combinations of conditions are necessary to initiate the formation of radial hydrides.

Hanson, et al. (2011) indicate that DHC has traditionally been ruled out as a possible mechanism for cladding degradation during extended storage because as the temperatures decrease, the stress decreases and becomes insufficient to promote crack propagation (BSC, 2004b; EPRI, 2002; Rothman, 1984). More recently, Kim (2009) has proposed a new model for DHC where creep deformation, prior creep strain, burnup, the solvus hysteresis, and the γ to δ hydride phase transition all play important roles in DHC. Hanson, et al. (2011) also cites the results of Holston, et al. (2010), who noted that for the conditions tested, several parameters had to be satisfied for DHC to be observed including high hydrogen levels near the crack tip, temperatures less than 380 °C [720 °F], sufficient stress levels at the crack tip {above 600 MPa [87 ksi]}, and the presence of a stress riser. Sindelar, et al. (2011) indicate that the threshold stress intensity for the initiation of DHC in Zr-2.5 percent niobium alloys suggests values ranging from 9 to 11 MPa $m^{1/2}$ [8.2 to 10.0 ksi $in^{1/2}$] for samples tested between 205 and 283 °C [401 and 541 °F]. Metallurgical and compositional differences among the cladding alloys may alter the threshold stress intensity. Sindelar, et al. (2011) indicate that these observations suggest the possibility of DHC in fuel cladding during extended storage and transport and also that the DHC behavior of zirconium-based alloys is highly variable, especially for high burnup fuels, where sustained loading conditions may exist due to fuel matrix swelling and gap closure. DHC failures would produce small, through-wall cracks rather than catastrophic tears in the cladding. NWTRB (2010) also cites the recently developed model by Kim (2009) and suggests that DHC failures that produce fine pinhole or hairline through-wall cracks may release internal rod helium pressure, reducing the hoop stress acting on the crack and arresting further DHC cracking.

Hanson, et al. (2011), Sindelar, et al. (2011), and NWTRB (2010) all address low temperature embrittlement of fuel cladding. Hanson, et al. (2011) also indicate that the value for emissivity of cladding must be considered in the prediction of ductile to brittle transition. The emissivity value is usually chosen to be conservatively low, thus yielding maximum peak cladding temperatures. However, cladding emissivity is dependent on oxide thickness (Luscher and Geelhood, 2010).

Most of the data used to develop this correlation for emissivity are for Zircaloy in steam at high oxide thicknesses typical of reactor accident conditions. Sindelar, et al. (2011) indicate that (i) the database necessary to analyze the time/temperature/burnup dependence of the ductile-to-brittle transition temperatures for cladding alloys during very long-term storage is insufficient and (ii) the data necessary to couple the ductile-to-brittle transition temperatures with other cladding variables are lacking. NWTRB (2010) states that low temperature brittleness is likely to influence delayed hydride cracking and stress corrosion cracking and that more research is needed to understand this phenomenon.

Hanson, et al. (2011) indicate that significant data are needed to determine (i) the effects of high burnup and different clad alloys on hydrogen embrittlement and reorientation and (ii) the subsequent effect on the ability of cladding to remain in the same condition it was in when emplaced in dry storage. In addition, sensitivity analyses or a determination of the actual cladding emissivity as a function of oxide and crud layer thicknesses under dry storage conditions is necessary to calculate actual temperature profiles. Finally, Hanson, et al. (2011) also pointed out that the model by Kim (2009) (indicating that prior plastic deformation of the cladding may be a preferential site for DHC) needs to be further investigated and the limited data on the potential for DHC in higher burnup fuels and newer clad alloys should be addressed.

Sindelar, et al. (2011) indicate that additional data should be developed and models for hydrogen embrittlement modified to include cladding alloys with radial hydrides and the emerging cladding alloys that may show behaviors that differ significantly from those of Zircaloy. Sindelar, et al. (2011) state that emphasis should be placed on the high burnup fuels because their hydrogen content is expected to exceed that for low burnup fuels. Further, currently available data and models currently are not sufficient to assess the impact of long-term storage on the ductile-to-brittle transition temperatures of cladding alloys. In addition, Sindelar, et al. (2011) state that data are needed to establish the combined effects of alloy content, hydrogen content, irradiation, temperature, and other cladding variables on the ductile-to-brittle transition temperatures (and other measures of fracture resistance) of fuel cladding. Finally, Sindelar, et al. (2011) state that emphasis should be placed on high burnup fuel, and efforts should be made to establish the singular and combined effects of irradiation and hydrogen content on fracture resistance.

NRC Staff Evaluation

Hydrogen absorption is a relatively well-understood and well-characterized phenomenon. Each cladding and fuel vendor has approved models that predict oxide layer thickness as a function of operating conditions and has developed hydrogen pickup fraction models related to this oxidation behavior. Once the cladding cools in the pool, there are three potential degradation mechanisms (i) DHC, (ii) hydride reorientation changing the mechanical properties of the cladding (namely ductility and fracture toughness), and (iii) hydrogen embrittlement. Because the stress on the cladding drives these mechanisms the effect of increased gas-pressure-induced stress and increased hydrogen content due to the higher burnups should be considered when evaluating the operability of these mechanisms. The effects of potential increases of emissivity will be considered further in Section A9.

DHC has been traditionally ruled out as a possible mechanism for cladding degradation during extended storage. This is because as the temperature decreases, the stress decreases and becomes insufficient to promote crack propagation, unless the initial crack is almost the full cladding wall thickness (a condition that would lead to an unstable crack in the reactor).

Uncertainties on the operability of the DHC mechanism have arisen with Kim's (2009) new theories and reinterpretation of stress-related data. The theories of phase transformation to brittle hydride phase pose potential uncertainties that threshold stress for DHC may be lower than traditionally thought. The phase transition theory believes that the phase transition at 180 °C [356 °F] will provide stress for the DHC. The question arises as to why DHC breach was not observed in the 15-year demonstration, where portions of the fuel cladding exceeded 180 °C [356 °F] and cooled below 180 °C [356 °F]. Also, data on the SNF matrix swelling by alpha decay in high burnup SNF suggest that the stress imposed in a longer period of time could be high enough to reach the high threshold stress. More tests are needed to determine whether there are actually sufficient stresses from either the phase transformation or from swelling of the fuel after extended times to cause DHC. Therefore, the level of knowledge of mechanism initiation is rated low. The NRC staff's view is that once DHC has initiated, the rate of propagation and time to failure are well known. Even if a DHC crack does occur, the defect is small and tight and staff considers the level of knowledge of initiation time to be medium.

Even at the temperature and stress conditions recommended in NRC (2003a), radial hydrides have occurred. 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. Cladding with radial hydrides will undergo a ductile to brittle transition somewhere in the temperature range of room temperature to 200 °C [392 °F]. The actual temperature will depend on the stress and temperature under which the radial hydrides were formed, the particular cladding alloy, and its initial cold work state. While additional investigation is needed to determine the actual DBTT for each condition, NRC staff have sufficient information but to recognize that if fuel to be transported exceeds the DBTT, a significant amount of data exists to analyze the fuel behavior. Below the DBTT, few data on the properties of the fuel exist. This is not exclusively an EST issue, but is exacerbated by the decreasing temperatures of EST. NRC staff determined that the level of knowledge of initiation of this degradation is high, and that the effects are not evident if the material remains above the DBTT. For this reason, if cladding is kept above the DBTT, knowledge of the propagation rate and time to failure is not applicable for reorientation of hydrides.

A1.4 Creep

Description of Degradation Phenomenon

After discharge from the reactor, creep of cladding is mainly driven by the rod internal pressure, and is believed to be self-limiting due to decreasing temperatures and increasing rod volume resulting in lower pressures and stress with time. Nonetheless, excessive cladding creep can result in wall thinning, which may weaken the cladding below acceptable levels for transport or storage, during normal or accident conditions.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011), NWTRB (2010), and Sindelar, et al. (2011) indicate that the driving force for creep is associated with rod pressurization and stresses to the cladding as a result of pellet cladding interaction. While these assessments suggest that creep is self-limiting and that creep failures are likely to be small defects rather than gross ruptures, all of these assessments recognize that the combination of other cladding degradation modes, including hydrogen effects with creep, needs to be better understood. For instance, high burnup fuels may be more susceptible due to pellet-cladding gap closure and stresses imposed by fuel swelling.

Hanson, et al. (2011) indicate that the main driving force for cladding creep is the hoop stress caused by internal rod pressure, which will decrease over time as the temperature decreases and the rod volume increases. Hoop stresses are between 30 and 200 MPa [4.4 and 29 ksi] for a 17 × 17 PWR fuel rod and 12 to 130 MPa [1.7 to 19 ksi] for a 10 × 10 BWR rod at 400 °C [752 °F]. Hanson, et al. (2011) consider creep to be self-limiting, and creep failure is expected to result in a very small defect (pinhole or hairline crack) that will release the internal gas, including fission gases. It is unclear whether creep would significantly thin the cladding wall thickness and affect cladding integrity during handling or transportation. Hanson, et al. (2011) indicate that there is a deficit of long-term low temperature creep data and little information to assess the effects of cladding deformation (i.e., bambooing) and the contribution of oxide, crud layers, and hydride concentration and orientation on creep behavior. Long-term low temperature {below 400 °C [752 °F]} data are necessary, especially on high burnup fuels and newer clad alloys.

Sindelar, et al. (2011) agree with Hanson, et al. (2011) on the effects of temperature, time, the self-limiting nature of creep, and the consequences of creep rupture. Sindelar, et al. (2011) also indicate that creep models are available, but these models suffer from the weaknesses described in these two reports and should not be extrapolated into timeframes that extend far beyond the data used to develop the model. Heat treatment and small changes in alloy composition microstructure can significantly change creep rates. Consistent with Hanson, et al. (2011), the effects of other cladding phenomena, including hydride reorientation, should be considered in creep evaluation and modeling to more accurately predict spent fuel performance in very long storage conditions. Finally, although the literature is not in agreement on diffusion-controlled cavity growth as a possible creep mechanism, Sindelar, et al. (2011) indicate that it would be desirable to verify the presence or absence of triple boundary cavitation in materials that have undergone creep in any destructive examination work.

NWTRB (2010) indicates that research is needed to better understand the creep rupture parameters that lead to maximum attainable strains under low stress and low temperature conditions. Most available creep and rupture experiments focus on the behavior of cladding over the first 10 or so years of storage when temperatures are higher. Research is needed that is focused on long-term creep behavior at low temperatures, using irradiated fuel, and under hydrogen-embrittled conditions. NWTRB (2010) also emphasizes the potential source of cladding stress may be related to pellet swelling and creep down.

NRC Staff Evaluation

In-reactor creep under normal reactor operating conditions is a well-understood and well-characterized phenomenon. In fact, fuel vendors have incorporated approved cladding creep models in their fuel behavior codes, which provide reasonable creep strain predictions. In addition, there are several fuel-vendor-sponsored and international collaborative research programs geared at generating additional creep data for operating conditions and improving the creep models in existing fuel behavior codes. The fundamental mechanisms of creep are also well understood and have been studied extensively for creep failure prediction in high-temperature and/or high stress engineering applications. What is not well known is how to predict creep strains and failure for very long-term creep at lower temperatures and stresses. In particular, it is not known whether creep can even occur at stresses well below half of the yield stress of a material or whether there exists a temperature threshold for creep to occur. Finally, if creep can occur over very long periods of time at low temperature and low stresses, its mechanisms are unknown, as are the resulting creep strain rates and creep failure strains under those conditions. What is also not well known is how extended storage conditions would affect material properties that have an impact on creep rates and failure mechanisms.

Creep will initiate as soon as the water is drained and the temperature of the cladding is raised during vacuum drying, so its initiation time is well defined. The creep rate is well known for a number of alloys. Due to the configuration of the spent fuel rod, the creep rate quickly tapers off as the system pressure drops due to radial expansion of the rod. The pressure drop is significant enough to eliminate the driving force for creep, making this mechanism self-limiting. Even if there is a large uncertainty in the creep rate, as may be the case for newer alloys, only the initial rate of creep will be affected as the system pressure drops. However, much of the data for creep is valid only for reactor temperatures, time spans, and environments, and it is not clear whether the data can be extrapolated to the temperature and time spans considered for very long term storage. The NRC staff characterized the level of knowledge of creep degradation or failure as medium because significant wall thinning must occur before creep rupture occurs and the nature of the breach is a hairline crack. There is a substantial amount of research investigating how significant creep must be to result in failure under loading (Sanders, et al.,1992; Pescatore, et al., 1990; Chung, et al., 1985; Herzburg, 1996; Goll, et al., 2001). However, failure is highly dependent on temperature and cladding loading conditions (including rod internal pressure), and more work is needed that focuses on the temperature and loading conditions expected during extended storage and transportation.

The NRC staff ruled out thermally active (high temperature) creep as a short-term degradation mechanism because it is self-limiting. It may be a long-term mechanism if low temperature creep is operative. This is especially true for high burnup SNF, where the gap may disappear and the applied stress becomes higher with alpha decay and fission product accumulation in the SNF matrix. In addition, the NRC staff determined that the low temperature creep is a viable deformation mechanism for long-term storage, which is likely to be subject to near-ambient temperatures. Low temperature creep is an athermal process as demonstrated in titanium and its alloys (Jaworski and Ankem, 2006). Twinning is a primary deformation mechanism. Both titanium and zirconium have a hexagonal close packed crystalline structure primarily responsible for twin formation; zirconium is likely to be susceptible to low temperature creep. The NRC staff characterize the level of knowledge of all aspects of low temperature creep as low because it is not known what stress the high burnup fuel will place on the cladding or when sufficient fuel swelling will occur to apply the stress.

A1.5 Annealing of Irradiation Hardening

Description of Degradation Phenomenon

During normal operation in a reactor, the fuel cladding accumulates fast-neutron fluence and the resulting irradiation hardening accompanied by a reduction in the cladding's elongation to failure. This reduction in cladding elongation-to-failure is often referred to as loss of ductility or embrittlement. The main consequences of irradiation hardening for spent nuclear fuel are increased hardness (which translates into reduced creep) and reduced ductility. Under certain conditions, prolonged periods at elevated temperatures can cause irradiation defects to be annealed. The annealing of irradiation defects may result in the cladding partially or completely recovering its initial mechanical tensile properties, which translates to lower hardness and increased ductility. The loss of irradiation hardening can have the deleterious effect of increased creep in spent fuel. However, the annealing of irradiation hardening is also accompanied by a beneficial increase in ductility, which can prevent brittle failure of the spent fuel in the case of a transportation or storage accident.

Annealing of irradiation hardening is a phenomenon that is operative mostly in the short term (i.e., 40 years), when cladding temperatures are still relatively high.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011), NWTRB (2010), and Sindelar, et al. (2011) indicate that there are little low temperature data on annealing with irradiated cladding.

Hanson, et al. (2011) indicate that the overwhelming majority of annealing studies are performed for very short times (about 1–2 hours) at elevated temperatures {400 °C [752 °F] or higher}, mostly to simulate in-reactor problems like reactivity insertion accidents or loss-of-coolant accidents. Ito, et al. (2004) tested both stress relief annealed Zircalloy-4 and recrystallized annealed Zircalloy-2 as a function of time at annealing temperatures. Hardness continued to recover, albeit quite slowly, at temperatures as low as 330 °C [626 °F] over 8,000 hours. Recovery was faster at 360 °C [680 °F]. Hanson, et al. (2011) indicate that during extended storage, thermal annealing could decrease the hardness, increase ductility, and decrease the possibility of breakage from mechanical shock during movement or transport. However, annealing may facilitate creep, and could release hydrogen trapped in dislocation loops, and may ultimately affect the hydrogen-related phenomena. Cladding composition is also believed to affect annealing. Hanson, et al. (2011) state that limited available data suggest that adding niobium affects the thermal recovery by increasing the onset temperature relative to Zircaloy-2.

Sindelar, et al. (2011) state that annealing may occur during drying and may affect hydride reorientation and delayed hydride cracking. NWTRB (2010) indicates that annealing has not been observed in testing over thousands of hours at 323 °C [613 °F] and annealing is only expected at temperatures above 400 °C [752 °F].

NRC Staff Evaluation

High-temperature annealing of irradiation damage, and the resulting gradual return of material properties to their initial pre-irradiated state, is well understood for a number of materials, particularly steels used in nuclear construction. The annealing of irradiation hardening in zirconium alloys used for cladding has been studied for high temperatures and short times, but not extensively. It is not known whether every zirconium-based alloy used for cladding displays the same annealing characteristics nor the degree to which annealing of irradiation hardening occurs at low temperatures for very long times. In addition, it is not known whether annealing of radiation hardening would result in partial or full recovery of the initial properties of the material prior to irradiation. Finally, the impact of annealing irradiation defects on other spent fuel degradation mechanisms, such as hydrogen redistribution, is not known.

The NRC staff characterizes the level of knowledge of annealing of irradiation hardening, as medium for initiation time, because although this phenomenon is relatively well understood from a physical standpoint, there are not many studies at temperatures relevant to extended dry storage. Conclusions from the 15-year storage demonstration project suggest that at 350 °C [662 °F] and below, hardly any annealing takes place. Little, if any, annealing occurred during the prestorage operation or during storage in the 15-year demonstration. This is supported by the uniformity of the hardness values calculated for three different locations where temperatures were above 350 °C [662 °F], and by comparison of the hardness data from Surry with that from Turkey Point (NRC, 2003b). The NRC staff characterizes the level of knowledge as medium for propagation rate because the phenomenon is relatively well understood at higher temperatures, but it is not clear whether the data can be extrapolated to the temperature and time spans considered for very long-term storage. The level of knowledge was characterized as low for degradation or failure because the extent of annealing and the impact on strength are not well known for extended storage and transportation. In fact, failure is highly dependent on temperature and cladding loading conditions (including rod internal pressure) and more work is needed that focuses on annealing at temperatures expected during extended storage and transportation.

A1.6 Irradiation Growth

Description of Degradation Phenomenon

During normal operation in the reactor, irradiation growth is most apparent in the zirconium alloy that constitutes the fuel cladding. This is because the cladding material is bombarded with fast neutrons that cause atomic displacement cascades that result in the formation of point defects. Because this phenomenon is associated with fast neutron bombardment of the cladding matrix, it is unlikely to continue in long-term storage and transportation conditions.

In general, irradiation growth can result in very minor wall thinning of the cladding and the associated degradation of the maximum load that the cladding can withstand, leaving the cladding vulnerable to failure under loading or impact.

Synopsis of Previous Gap Assessments

NWTRB (2010) discusses the effects of ionizing radiation on the crystal structure of the spent fuel, both during in-reactor operation and during storage. It details the known mechanisms of matter-radiation interactions, and concludes that the effects of in-reactor radiation likely dwarf any further cumulative effects during storage and that no additional research is necessary for this degradation mechanism. It also states that β and γ–radiation are the predominant sources of radiation damage over the first 500 years of spent fuel storage, with β-decay as the primary source of radiation damage over the EST period of interest.

NRC Staff Evaluation

The NRC staff determined that the phenomenon of cladding irradiation growth has been studied extensively, and the microstructural damage mechanisms that lead to cladding growth are known. In addition, many fuel behavior codes already have the ability to predict growth for known cladding alloys and under known reactor conditions, largely based on previous operational experience. The NRC staff concludes that fast neutron fluence in EST is negligible compared to that received in reactor, such that the growth mechanism is not applicable to storage and transportation of spent fuel.

A1.7 Propagation of Existing Flaws

Description of Degradation Phenomenon

Existing flaws in spent fuel cladding are likely to consist of any of the following: surface cracks on the inner or outer wall, through-wall cracks, wall thinning due to oxide spallation on the outer surface, or wall thinning due to fretting wear on the outer surface. Propagation of these existing flaws require a certain level of stress, strain, temperature, or combination thereof. Areas of the cladding where wall thinning has occurred will tend to concentrate stresses, which could result in accelerated creep in dry storage conditions. Existing surface or through-wall cracks will act as more severe stress concentrators and can be responsible for other phenomena, such as delayed hydride cracking, or fatigue crack growth during the drying cycles.

In general, flaw propagation has the potential to lead to partial and through-wall cracking of the cladding, resulting in the release of fission gases into the cask environment. Flaw propagation phenomena are degradation phenomena that are operative both in the short- (i.e., 40 years) and long-term (i.e., >40 years) storage timeframes.

Synopsis of Previous Gap Assessments

Sindelar, et al. (2011) include an analysis of the flaw stability in Zircaloy tubing. The results of this analysis suggest that internal pressure on the cladding is not sufficient to drive subcritical cracking; however, residual stresses and stresses generated by hydride precipitation may be sufficient to cause DHC. If a subcritical flaw forms during the dry storage period, the internal pressure on the cladding would not cause a gross rupture (e.g., axial split) of the cladding. These conclusions are based on the cited published data for threshold stress intensities for DHC and room temperature fracture toughness value for a heavily hydride microstructure. Sindelar, et al. (2011) note that the analysis does not consider the development of a clustered, axially oriented hydride distribution. Sindelar, et al. (2011) advocate the development of a fracture methodology for flaw stability in Zircaloy fuel tubes. The methodology should consider subcritical growth leading to mechanical instability, multiple flaws, hydride effects, flaw orientation, loading rates, and the ductile-brittle transition temperature for cladding.

NRC Staff Evaluation

The propagation of existing flaws as described previously has been studied extensively for most known flaw propagation mechanisms. NRC staff determined that in general, the stresses resulting from an existing flaw can be calculated using widely accepted methods, and flaw propagation can be predicted using fracture mechanics or stress analysis, both of which are very well understood topics. However, what is difficult to predict is the existence of precursors to cracks, as well as localized wall thinning. If a through-wall crack already exists, it may be detected by measuring coolant activity in the spent fuel pool, but if only precursors exist (such as localized excessive corrosion, a hydride blister, or wear from fretting during operation in the reactor), they are likely to go undetected. Current codes and models do not predict localized phenomena or flaws, especially for high burnup SNF. Regarding extended storage and transportation, the initial distribution of flaws and the exact stress and temperature conditions that can assist flaw propagation are not known.

The NRC staff characterized the level of knowledge of existing flaw propagation as low for initiation time, because it is not possible to predict the existence flaws or flaw precursors with existing tools, and only flaws that are detectable via poolside inspections can be taken into account. The level of knowledge was characterized as high for propagation rate because there is a substantial amount of research on stress distribution around a crack, delayed hydride cracking, fracture mechanics, and most other potential mechanisms that can lead to flaw propagation. In addition, flaw propagation mechanisms have been studied for very broad ranges of temperatures and stresses The NRC staff characterized the level of knowledge as medium for degradation or failure because, although flaw propagation can be predicted with reasonable accuracy if the exact stress and temperature conditions are known, the exact conditions in storage and transportation may not be well known. Furthermore, the potential microstructural changes (particularly with regard to hydride distribution) are not well known under extended storage and transportation conditions.

A1.8 Fatigue Due to Drying Cycles

Description of Degradation Phenomenon

An important step in the process of moving spent fuel from the spent fuel pool to a dry storage canister is drying the spent fuel assemblies. This is typically done by pumping down the internal pressure of the canister and allowing the fuel assemblies inside to heat up as a result of decay heat, which results in the evaporation of the remaining water in the canister. Once a target low pressure is attained, the canister is sealed off from the vacuum pump and the pressure is monitored for a predetermined amount of time. If the pressure remains below the target value, the process is complete, but if the pressure increases, the vacuum drying process is repeated. The vacuum drying process heats and cools the fuel assemblies. This process causes thermally induced cyclic stresses in the cladding and thus can result in thermal fatigue of the cladding. NRC staff guidance (NRC, 2003a) recommends limiting temperature cycling to less than 10 cycles with a maximum amplitude of 65 °C [149 °F] per cycle, but there is no regulatory limit on the number and amplitude of the drying cycles.

In general, fatigue due to drying cycles has the potential to lead to the degradation of mechanical properties of the cladding, as well as initiate cracks in the cladding, leaving the cladding vulnerable to failure under loading or impact. Phenomena related to fatigue due to drying cycles have the potential to lead to partial and through-wall cracking of the cladding, resulting in the release of fission gases into the cask environment. Fatigue due to drying cycles may be operative in the short (i.e., 40 years) storage timeframe, but the NRC staff does not expect this to be an active degradation mechanism, because drying procedures used during cask loading commonly limit the number of drying cycles that are allowed.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) have a limited treatment of thermal fatigue during drying and long-term storage, and this analysis indicates that fatigue due to thermal cycles in both drying and temperature fluctuations in long-term storage is unlikely. However, Hanson, et al. (2011) follow the guidance by NRC (2003a) for the number of temperature cycles that are allowed. Analyses of axial and radial temperature profiles of low and high burnup fuels over the entire period of dry storage, taking into account normal and off-normal environmental conditions, are needed to determine the extent of metal fatigue caused by temperature fluctuations.

Sindelar, et al. (2011) do not directly address fatigue from drying cycles but do indicate that changes to the fuel initial condition during dryout can occur. These changes are dependent on the thermal cycle process used and may include some recovery of radiation damage, creep, and hydride microstructure reconfiguration.

NRC Staff Evaluation

Metal fatigue due to thermal cycling is a relatively well-known and well-understood phenomenon. In general, the NRC staff does not expect that metal fatigue due to drying cycles will occur for the conditions prescribed in NRC (2003a). If more cycles than recommended in NRC (2003a) are used, then the effects of the cycling must be analyzed by the applicant to be nondegrading before a license is issued. The NRC staff does not expect metal fatigue due to drying cycles to be an issue for short- or long-term storage, because of the restrictions on thermal cycling during drying.

A2 FUEL

Degradation mechanisms for fuel include oxidation and physical changes, such as swelling and fragmentation. The level of knowledge regarding the degradation mechanisms and the status of monitoring and inspection techniques are summarized in Table A2–1.

Once a storage canister is sealed, there are no known monitoring and inspection capabilities for the degradation phenomena listed in Table A2–1. Many of these phenomena that take place during storage also take place during reactor irradiation, although the operational conditions are substantially different. Many of the degradation phenomena important for fuel and cladding are correlated to the condition of the material prior to loading into dry storage (i.e., degradation during storage is related to prior degradation that occurred during irradiation under reactor conditions). A number of cladding degradation phenomena lead to through-wall cracking, and these phenomena cannot be monitored in a sealed canister. However, radiation monitoring and inspection of spent fuel storage systems for leaks may reveal whether degradation has proceeded to cladding breach, which results in fission product release. Although it would then be too late to prevent the breach, detection of cladding breaches provides information to characterize the state of the fuel and cladding system for future handling.

A2.1 Atmospheric Air Ingress and Fuel Oxidation

Description of Degradation Phenomenon

The oxidation of UO_2 in air for relative humidity below 40 percent may lead to the formation of U_3O_8, which is a compound up to 36 percent less dense than UO_2, based on theoretical density. If the relative humidity is above 40 percent at lower temperatures, fuel hydration will occur. The

Table A2–1. Level of Knowledge and Monitoring Techniques—Fuel

Component	Degradation Phenomena	Level of Knowledge			Monitoring or Inspection Capability
		Initiation Time	Propagation Rate	Degradation or Failure Complete	
Fuel	Air oxidation (off-normal condition)	H*	H*	M*	No
	Fission gas release during accident	H	H	L	No
	Helium release during an accident	H	L	L	No
	Pellet swelling due to helium generation	L	L	L	No
	Additional fuel fragmentation	H	H	L	No

H=High
M=Medium
L=Low
*See discussion of these degradation phenomena. The inert atmosphere of a properly sealed canister will be such that this degradation mechanism will likely not be operable.

oxide form is also more porous and fragile and results in volumetric changes, or bulking of the fuel. The rate of oxidation is thermally activated and decreases with temperature. The rate decreases as the burnup increases (Hanson, et al., 2008). Extensive fuel oxidation can lead to the initiation and propagation of axial cladding splits and the release of the fine grained U_3O_8. Additional fission gas will be released as a result of the oxidation.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) describe several scenarios under which fuel oxidation can occur as an off-normal or accident condition. Air oxidation can occur due to accidental canister backfill with air (instead of helium), in which case the reaction will stop as the oxygen in the canister is consumed. It can also occur due to breach of canister or seals accompanied by clad breach. Either scenario is considered unlikely, but either may hinder the ability to retrieve fuel assemblies through normal handling, with a potential impact on radiation protection, confinement, and subcriticality. DOE determined that sufficient data exist to model this mechanism for EST, although Hanson, et al. (2011) state that minimal data are available for HBU fuel and there is a need for additional data to show that the finer grain sizes will not accelerate oxidation rates.

NWTRB (2010) analyzed the behavior of irradiated fuel under oxidizing conditions, which is known to occur at much more rapid rates than under non-irradiated conditions. The ultimate effect is a full destruction of the initial UO_2 ceramic structure and transformation of most of the structure into a very fine powder U_3O_8. This powder has an orthorhombic crystal structure with a volumetric increase of 31–36 percent. If the relative humidity of air is greater than 40 percent, hydration may occur, producing a volume change larger than for U_3O_8, and additional fuel fines. NWTRB (2010) presents the actual case of a transportation accident of damaged fuel rods in an air-filled canister that occurred in 1980 and led to severe poolside contamination upon unloading. This event led to a regulation change mandating the canisters to be filled with helium gas instead of air. This highlights the need for maintaining the helium cover at all times and establishing monitoring systems that ensure these types of accidents are prevented. NWTRB (2010) also states that the potential for low-temperature oxidation of the fuel needs to be better understood.

Sindelar, et al. (2011) state that during storage, the fuel should be in a helium atmosphere, which would prevent oxidation even in the event of fuel cladding failure. However, exposure to air/oxygen at elevated temperatures will generally cause the UO_2 pellets to first form U_4O_9. This transformation occurs first along the grain boundaries, likely leading to fission gas releases. The fuel ultimately converts to U_3O_8, which is 36 percent less dense than UO_2 and tends to form a fine powder. Fuel swelling due to U_3O_8 formation has been shown to be able to cause cladding splitting. High burnup fuel has been reported to be more resistant to oxidation than low burnup fuel making it less of a concern for this degradation mechanism. The lower temperatures of extended storage will slow the fuel oxidation rate and allow sufficient time to detect and mitigate the off-normal condition. MOX fuels may be more susceptible to this degradation mechanism due to a flatter temperature profile, leaving the fuel, cladding, and cask at elevated temperature for longer time. There are numerous variables, including potential air oxidation rates, air ingress rates, and temperature of the fuel at time of off-normal conditions, which require data to evaluate the safety impact. Sindelar, et al. (2011)recommend monitoring for cover gas and containment efficacy during extended storage to avoid air oxidation.

NRC Staff Evaluation

The mechanisms and kinetics of UO_2 oxidation are well known. However, the effects of burnup on fuel oxidation under abnormal conditions have yet to be comprehensively studied. To fully assess the possibility and extent of high-burnup fuel oxidation over long periods of time at relatively low temperatures, the competing influences of (i) grain size reduction in the rim region and porosity increase and (ii) the presence of fission products stabilizing the matrix should be studied. In addition, the likelihood of introducing an oxidizing environment into the fuel rods must be determined.

The NRC staff characterized the level of knowledge of fuel oxidation as high for initiation time, because this phenomenon is only expected to occur in some cases where fuel cladding breaches have occurred in the reactor. Such failures can generally be detected by sipping of the fuel assemblies prior to loading in a canister; thus the initiation time can be well established. The level of knowledge was also characterized as high for propagation rate in EST because the temperature of the fuel will be low enough to allow sufficient time after a cask breach to provide any necessary remedial action. The level of knowledge was also characterized as medium for degradation or failure because volume expansion of fuel due to oxidation is well characterized. However, failure is highly dependent on temperature and burnup effects in the fuel that are poorly understood. The NRC staff expects that axial splitting of the cladding, which is the endpoint of this degradation phenomenon, would occur gradually at a relatively slow rate at the lower temperatures of EST.

A2.2 Rod Internal Pressurization

Description of Degradation Phenomenon

The production and accumulation of fission gases within the fuel material are expected outcomes of their use in the reactor. Many of the produced fission gases are soluble within the fuel matrix, while some others are not, like xenon and krypton. The matrix-insoluble gases tend to diffuse out into grain boundaries, cracks, and surfaces, and a small amount that increases with burnup, called fission gas release (FGR), gets released from the fuel matrix and accumulates in the gap regions between pellet and cladding. HBU fuels tend to also form a hard and porous rim that traps some of these gases and slows their release (Lassman, 1995). The overall effect of these gas releases from the matrix into the void space during irradiation in the reactor is that of increased internal rod pressure and, consequently, increased stress levels on the clad walls. Fission gas production and release during in-reactor irradiation have been extensively studied, and thus the initial state of spent fuel can be predicted with reasonable accuracy upon discharge from the reactor. After discharge from the reactor, fission gas production is negligible as long as the fuel remains in a subcritical condition, as is expected in dry storage conditions. Therefore, the fission gas inventory at the beginning of spent fuel storage is known.

After discharge from the reactor, spent fuel is a dynamic environment in which the compounds/elements present in the matrix continuously undergo transformations through various decay mechanisms. One of these mechanisms involves the generation of helium (α decay), usually from actinide fission products, which decay by emitting helium nuclei. The emitted α-particles then recombine with free electrons, forming helium atoms. The produced helium segregates and precipitates into helium bubbles at grain boundaries. The grain boundaries then have greater localized stresses as the bubbles grow, and this increases the likelihood for boundary decohesion, and eventual fuel fragmentation. Fuel fragmentation is likely to release fission gas and helium trapped in bubbles on the grain boundaries, thus increasing the rod internal pressure.

In general rod internal pressurization during storage (due to helium generation and subsequent release of fission gases once the accumulation of helium on grain boundaries causes further fragmentation) can lead to failure due to excessive cladding stresses and strains. Rod internal pressurization can lead to flaw initiation and propagation and has the potential to lead to partial and through-wall cracking of the cladding, resulting in the release of fission gases into the cask environment. Rod pressurization in itself is not a degradation mechanism but a condition that stresses the cladding and enables other mechanisms to operate.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) consider the combined effect of this mechanism with that of helium gas release. Of concern, however, is the pressurization of the rods under accident conditions due to fuel fragmentation and thus higher gas fractions released from the matrix. A data gap is assessed in terms of the release fractions for HBU fuels and the corresponding fuel particle size distribution that could impact the nature of the releases should the clad fail.

The NWTRB (2010) analysis of the fission gas releases from the fuel includes details on the current understanding of the diffusive, thermally activated process by which the gas release occurs, migration, coalescence, microcracks formation, transport to grain boundaries/cracked surfaces, and release into the clad-gap space. NWTRB (2010) states that during storage, the dominant fission-gas release mechanism is diffusion, which is expected to continue during long-term storage, albeit at slower rates due to decreasing thermal inventories. However, the NWTRB also states that some experts feel the expected small amount of gas diffusion in stored fuels needs to be verified. The possibility of an overpressurized rod failure alongside containment breach would allow the most abundant of the fission gases, xenon/krypton, to be released and carry some of the other more volatile fission products, like iodine, cesium, and chlorine. This type of release should be easily detectable, and NWTRB (2010) suggests recanistering in such an event.

NWTRB (2010) considers helium gas microcracking as part of the rod-pressurization issues. It concluded that the fuel self-irradiation will continue during the storage period. It also notes there is a gradient in the gas distribution within the pellets, with the higher concentrations of trapped gas near the center. NWTRB (2010) states that more research is needed to determine whether helium accumulation during long-term storage will lead to further microcracking, grain boundary decohesion, and subsequent fuel fracturing. Microcracking may be more prevalent with MOX fuel; thus further studies are recommended, especially for MOX and HBU fuels, in which microstructure changes can play a role.

Sindelar, et al. (2011) consider helium in part of their assessment of fission gas release from the fuel. It identifies the need for greater knowledge of fission gas release and its impact on clad stress during storage. Fission product gas production will essentially be complete after reactor operation, and most gas releases from the fuel pellet to rod interior occur prior to dry storage, but gas releases during dry storage could increase internal pressure. Most fission product gas (nominally >90 percent) is contained in the fuel pellet during and after normal operation, and more data are needed to assess fission gas release during long-term storage. Higher burnup fuels will contain greater amounts of fission product gases, potentially leading to greater internal rod pressures.

NRC Staff Evaluation

Fission gas production during irradiation in a commercial reactor is relatively well understood, and current NRC-approved vendor fuel behavior codes take this phenomenon into account to calculate rod-internal pressures upon discharge from the reactor. This phenomenon has not been studied to the same extent for SNF during extended storage. Little information exists for storage and transportation regarding helium generation leading to additional fission gas release and potential pellet fragmentation, under either normal or accident conditions. The impact on rod internal pressure for these conditions is similarly poorly known. Another phenomenon that should be studied is the athermal diffusion of fission gases and helium through the fuel over very long periods of time at storage temperatures.

Knowledge of initial rod pressurization was characterized as high for initiation time, because reasonably reliable modeling tools exist to predict fission gas release and actinide decay. Because the fuel temperature in storage is too low for thermal diffusion, the only mechanism for further pressurization is the athermal release of helium produced from alpha decay. Rondinella, et al. (2010) predict that this may not occur until 100 or more years have elapsed. The second mechanism for fission gas release and resulting increased rod internal pressurization is further fracture of the fuel fragments. Little or no information is available on this phenomenon. The NRC staff expects that such fracturing would occur only during an accident, and gas release would be rapid. Thus, the NRC staff characterizes knowledge of the initiating condition for this phenomenon as high. In contrast, the amount of gas released during fuel fracture is unknown; thus the NRC staff characterizes the level of knowledge as low.

A2.3 Pellet Swelling

Description of Degradation Phenomenon

Fuel pellet swelling during storage is the result of helium gas production/release. As the pellets expand, the helium-filled gap with the clad wall is narrowed; eventually the pellet impinges upon the clad wall at different spots, creating points of concentrated thermal stresses and chemical interactions with corrosion-aggressive volatile fission products, such as iodine and cesium [pellet clad interactions (PCI)].

In general, pellet swelling can increase stresses on the cladding and can potentially lead to cladding splitting (rupture) due to pellet cladding mechanical interaction. These phenomena have the potential to lead to partial and through-wall cracking of the cladding, resulting in the release of fission gases into the cask environment. Pellet swelling is a degradation phenomena that is operative in a long-term (i.e., >100 years) storage timeframe, due to increased accumulation of helium.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) analyze this phenomenon. The resultant hour glassing and bambooing deformation effects of fuel pellets are of concern for pellet-clad bonding and localized thermal stresses. The main cause of failure due to fuel swelling will be pellet-cladding mechanical interaction (PCMI). Hanson, et al. (2011) conclude that no additional fuel restructuring or swelling will take place under long-term storage conditions, but it also identifies data gaps in this area and recommends “modeling and simulation to calculate local hoop stress from pellet-clad bonding and thermal expansion/contraction at the temperatures of interest…to determine if the stresses are large enough to cause localized creep or SCC.” DOE also recommends additional data gathering on the effects of HBU on fuel properties (thermal properties, fracture toughness, hardness). The overall degradation mechanism is not deemed a limiting mechanism in the long-term DOE storage strategy.

NRC Staff Evaluation

The only mechanism for fuel pellet swelling in storage is the helium product of the alpha decay. Models predict significant buildup of helium at times >100 years, The NRC staff recommends that this be confirmed by experiment. Because the internal rod pressure is insufficient to cause delayed hydride cracking (DHC), PCMI would be the only source of cladding stress for DHC to cause cladding breach and crack propagation. The level of knowledge of fuel swelling due to helium generation is considered low until the magnitude of the stress on the cladding due to the swelling can be experimentally confirmed.

A2.4 Additional Fuel Fragmentation

Description of Degradation Phenomenon

Further fuel fragmentation, above that which occurs in a reactor, has the potential to result in increased fission gas release, rod internal pressure, and increased pellet-cladding mechanical interaction. These phenomena have the potential to lead to increased cladding stresses and increased creep. PCMI has the potential to lead to partial and through-wall cracking of the cladding, resulting in the release of fission gases into the cask environment.

Synopsis of Pervious Gap Assessments

NWTRB (2010) assesses the expected state of the fuel after reactor operation, and fully describes the cracking, fragmentation, and geometric changes it undergoes, as well as the underlying reactions and material properties involved. As stated in NWTRB (2010, Section 4.1.1, p. 46), “Normal reactor operation…leads to pellet fracturing into 10 to 30 pieces with some additional powder creation.”

Hanson, et al. (2011) consider the combined effect of this mechanism with that of helium gas release, concluding that no additional fuel fracturing is expected under normal extended storage conditions beyond the 300-year period of interest for EST. Of concern, however, is the pressurization of the rods under accident conditions due to fuel fragmentation and thus higher gas fractions released from the matrix. A data gap is assessed in terms of the release fractions for HBU fuels and the corresponding fuel particle size distribution that could impact the nature of the releases should the clad fail. Hanson, et al. (2011) recommend cask-drop testing for fracturing response under off-normal and accident conditions, as well as studies of particle distributions in fractured HBU fuels, for which the fine-grained and more fragile rim could result in a higher level of respirable-sized particles and further complicate retrievability options.

NRC Staff Evaluation

Fragmentation in the reactor is caused by the significant radial thermal gradient across the pellet. The size and number (10–30) of pellet fragments can vary greatly depending on operating parameters such as power levels, ramp rates, and burnup. Generally, pellet fragment size decreases with increasing burnup, and fragmentation in the outer diameter of the pellet is often greater at high burnups due to the development of a high burnup rim structure. The thermal gradients in storage are orders of magnitude less than in the reactor, and no further fragmentation is expected under normal storage conditions. Further pellet fragmentation beyond that which occurs during irradiation is unlikely in normal dry storage until after 100 years. Beyond 100 years, helium accumulation due to alpha decay of actinides and transuranics leads to the accumulation of helium gas bubbles on the fuel grain boundaries. Once the stresses at the grain boundaries reach a certain level, grain boundary decohesion can occur and lead to fuel fragmentation. The NRC staff expects this mechanism for fuel fragmentation to occur under normal conditions of storage and transportation and result in the release of some fission gases trapped on the fuel grain boundaries.

Under abnormal conditions, fuel fragmentation may occur if the canister is breached, allowing for an air atmosphere to contact an already breached rod. If air oxidation occurs, the fuel will dissociate into a powder of U_3O_8, which adds to the source term. In addition, gases trapped on the grain boundaries would become free to be released. The extent of this release is rarely measured in oxidation experiments. The NRC staff does not expect fission gas trapped inside the grains to be released, because the temperature for diffusion is too low.

Under an accident scenario, if energy is imparted to the pellet due to an impact, the NRC staff expects additional fragmentation to occur. The extent of fragmentation will depend on the accident type and the energy delivered to the pellet. Little is known about the fracture behavior of the fine grained rim region formed at high burnup. Anecdotal evidence from the preparation of ceramographic mounts indicates that the region is rather friable. On the other hand, microhardness measurements on the rim have led Spino, et al. (2003) to conclude that compared with normal fuel microstructure, the rim has a greater resistance to fracture. Particulates in the respirable range may form from fracture of either the rim or nonrim portion of the fuel.

The NRC staff characterized the level of knowledge of additional fission gas release and fuel fracturing as high because these will not occur in normal storage until well after 100 years or will initiate only if and when an accident occurs, in which case the fracture and release will occur rapidly. The knowledge of the extent of fuel fragmentation and the resultant fission gas release is low because the extent of fragmentation and fission gas released during an impact accident is not well known.

A3 FUEL ASSEMBLY HARDWARE (GRID SPACERS, GUIDE TUBES, AND ASSEMBLY CHANNELS)

Fuel assembly hardware consists primarily of grid spacers (including springs), guide tubes (in Pressurized-water Reactors; PWRs), and assembly channels (in Boiling-water Reactors; BWRs). Grid spacers are used to maintain spacing between the fuel rods, control fuel rod vibration, and provide lateral support. They are generally composed of a zirconium alloy similar to the cladding, Inconel®, or both. Inconel spacer springs have a lower stress relaxation rate with irradiation than zirconium alloys. PWR guide and instrumentation tubes and BWR assembly channels are composed of a zirconium alloy similar to the fuel cladding and provide structural support to the assemblies. Fuel assembly hardware contributes to retrievability, thermal, and criticality functions. During normal operation, changes to the condition of fuel assembly hardware are expected; however, these changes are not accounted for in evaluating the performance of the hardware during extended storage. The level of knowledge regarding the degradation mechanisms and the status of monitoring and inspection techniques are summarized in Table A3–1.

A3.1 Creep of Fuel Assembly Hardware

Description of Degradation Phenomenon

Creep involves the slow strain of fuel assembly hardware, which may occur as a result of extended time under applied stress at elevated temperature. The creep process may be exacerbated by neutron irradiation. Temperature and stress can influence creep behavior over long time periods. Significant creep of fuel assembly hardware could lead to changes in fuel rod pitch, potentially affecting retrieveability, or lead to a more reactive configuration particularly upon flooding during retrieval or transportation accident scenarios. Creep of fuel assembly hardware would likely be operative only in the short-term (<40 years) due to decreasing temperatures over extended storage times.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) indicate that creep is not expected to be a degradation mechanism for fuel assembly hardware. Hanson, et al. (2011) acknowledge that while fuel assembly hardware materials could be subject to creep at dry storage temperatures, the components are not load

Table A3–1. Level of Knowledge and Monitoring Techniques—Fuel Assembly Hardware

Component	Degradation Phenomena	Level of Knowledge			Monitoring or Inspection Capability Available
		Initiation Time	Propagation Rate	Expected Effects	
Fuel assembly hardware	Creep	H	H	M	No
	Metal fatigue caused by temperature fluctuations	M	M	M	No
	Wet corrosion and stress corrosion cracking	M	M	L	No
	Hydriding effects	H	H	H	No

H=High
M=Medium
L=Low

bearing, except for the distributed weight of the fuel pins on the grid spacers and guide tubes, and that the hardware is not subjected to gas pressure. Hanson, et al. (2011) also observe that temperature will decrease as the fuel ages over time, further reducing creep rate. Load-bearing guide tubes and grid spacer springs could experience creep and relaxation from the weight of the assembly during extended storage, which would allow greater lateral movement of the fuel rods, but the amount of creep would be limited by the space between the pins and bottom nozzles and tie plates. Creep of fuel assembly hardware would also be bounded by cladding creep due to lower temperatures and stress levels experienced by fuel assembly hardware compared to fuel cladding.

Additional Information

EPRI (2011) states that if creep of fuel assembly hardware occurs, it may affect retrievability and have minor effects on thermal, radiological, and criticality functions. The mechanical properties of irradiated fuel assembly hardware, such as grid spacers, are being tested in some international programs. Creep behavior on irradiated materials may be included in these investigations.

NRC Staff Evaluation

Creep of fuel assembly hardware should be bounded by creep of fuel cladding, which will experience greater stresses from gas pressure within the tubes and higher temperatures because it is closer to the fuel than the fuel assembly hardware. Fuel assembly hardware is composed of similar (zirconium alloys) or more creep-resistant (Inconel) materials than zirconium fuel cladding.

The level of knowledge of initiation time is high because creep is known to be a temperature-dependent degradation process. The level of knowledge of propagation rate is high due to available knowledge of cladding creep, which bounds creep of fuel assembly hardware. Cladding will be at either the same or at a slightly higher temperature and significantly higher stress. The level of knowledge of the expected effects of fuel hardware creep is medium, because while the creep displacement is expected to be limited, there is some uncertainty regarding the amount of creep necessary to affect retrievability and fuel pin pitch.

There is currently no inspection or monitoring method for creep of fuel assembly hardware.

A3.2 Metal Fatigue Caused by Temperature Fluctuations of Fuel Assembly Hardware

Description of Degradation Phenomenon

Metal fatigue may occur as a result of temperature fluctuations, which lead to stress fluctuations experienced by the material. Cumulative stress cycles of sufficient magnitude can lead to a change in material properties, metal fatigue, and failure below yield strength. Metal fatigue due to temperature fluctuations of fuel assembly hardware would likely be more operative during extended storage beyond 40 years due to an increasingly accumulated number of stress/temperature cycles over time.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) conclude metal fatigue of fuel assembly hardware would not lead to failure during storage, but may result in unacceptable performance during storage design basis and hypothetical transportation accidents, particularly with respect to subcriticality and fuel retrievability. Hanson, et al. (2011) consider that extended storage times would result in additional seasonal temperature variations as well as an increased probability of extreme weather conditions; however, the fuel assembly hardware's proximity to the heat-producing fuel would reduce the effect of the external temperature changes on the assembly hardware material. Failure from fatigue during storage is not expected, but fatigue could affect the hardware structural integrity in accident scenarios and lead to unacceptable changes in fuel pin pitch.

EPRI (2011) indicates that if metal fatigue of fuel assembly hardware occurs, it may affect retrievability and have minor effects on thermal, radiological, and criticality functions. The report also observes that fatigue caused by temperature fluctuations during extended storage would be trivial when compared to the fatigue conditions the components experience during in-reactor operation.

NRC Staff Evaluation

Hanson, et al. (2011) indicate that analyses of temperature profiles (axial and radial) of low and high burnup fuels over the entire period of dry storage, taking into account normal and off-normal environment conditions, are needed to determine the extent of metal fatigue caused by temperature fluctuations. EPRI (2011) suggests that additional analyses are not necessary. Neither Hanson, et al. (2011) nor EPRI (2011) address the effect of temperature change during the drying cycle on fatigue considerations. The NRC staff believes the effects of temperature fluctuations on fuel hardware should be much less significant than its effects on cladding.

The NRC staff characterizes the level of knowledge of initiation time, propagation rate, and effects of metal fatigue of fuel assembly hardware caused by temperature fluctuations is medium. Temperature fluctuations are expected to be minimized by the proximity of the fuel hardware to the heat-generating fuel. Additional information on temperature profiles during the storage period is necessary to improve estimates of the magnitude of temperature changes and fatigue on the fuel assembly hardware.

There is currently no inspection or monitoring method for metal fatigue of fuel assembly hardware.

A3.3 Corrosion and Stress Corrosion Cracking of Fuel Assembly Hardware

Description of Degradation Phenomenon

Corrosion and stress corrosion cracking (SCC) of the fuel assembly hardware may occur if moisture is present in the canister. The amount of moisture present will greatly affect the degree of corrosion and SCC. Corrosion and SCC of fuel assembly hardware may be operative both in the short term and over extended storage periods depending on the amount of moisture remaining after drying, the integrity of the stainless steel canisters, and the effectiveness of the cask seals at preventing moisture ingress.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) indicate corrosion of assembly hardware may occur because of inadequate drying, but the rate and extent of corrosion would be limited to the initial period of storage and cease once the water is consumed in the corrosion reactions. Hanson, et al. (2011) is limited to the initial storage period, when moisture inside the cask from inadequate drying is present, and does not consider corrosion during extended storage due to lower temperatures and a lack of moisture. Operating experience has shown SCC of top nozzles leading to failure and dropping in 1980s-era Westinghouse fuel assemblies. Based on this experience, Hanson, et al. (2011) conclude that corrosion and stress corrosion cracking of fuel assembly hardware would not lead to failure during storage conditions, but may result in complicating retrieval by necessitating the use of special handling tools.

NRC Staff Evaluation

Hanson, et al. (2011) indicate that the key factor in understanding the potential consequences of corrosion and SCC of fuel assembly hardware is the amount of moisture present in the sealed canister or cask after drying. The NRC staff agrees that understanding of maximum possible moisture content after drying and the initial state of fuel assembly hardware degradation following reactor operation, including preexisting cracks, is necessary to evaluate the extent of corrosion and stress corrosion cracking. Most of the moisture present after drying would likely be consumed during corrosion of cladding and the SNF matrix with defective cladding, which have a much greater surface area compared to fuel assembly hardware. Also corrosion is only possible at relative humidity above 20–40 percent, which may not be present as a consequence of the limited residual water and disassociation of water as a result of radiolysis. To assess the possibility of corrosion and stress corrosion during extended storage, additional information on the integrity of cask seals and stainless steel canisters is needed.

The level of knowledge of initiation time and propagation rates for corrosion and stress corrosion cracking of fuel assembly hardware is medium because the stresses on the hardware during storage and the initiating crack size are not well determined. Some residual water is expected in canisters and dry casks that will promote corrosion of the internal structures including fuel assembly hardware. Information is available to evaluate the corrosion propagation rates. Limited water available during the initial storage period will limit hardware corrosion processes. Additional information on the expected amount of water in the cask and canisters, the initial condition of the hardware, and expected performance of stainless steel canisters and cask seals over extended periods is necessary to evaluate the effects of corrosion and stress corrosion cracking of fuel assembly hardware. Knowledge of the effects of corrosion and stress corrosion cracking of fuel assembly hardware is low because no one has looked into it in any detail

There is currently no inspection or monitoring method for corrosion and SCC of fuel assembly hardware.

A3.4 Hydriding Effects on Fuel Assembly Hardware

Description of Degradation Phenomenon

Hydriding effects on fuel assembly hardware may occur in zirconium alloys that experience hydrogen pickup at high temperatures followed by cooling. As temperature decreases, zirconium hydride precipitates as a result of decreasing solid solubility in the zirconium matrix. The hydrides are brittle and reduce ductility and fracture toughness of the zirconium alloys. Lack of hoop stress in fuel assembly hardware tubes makes hydride reorientation much less likely compared to cladding. Hydride reorientation would be operative in the short term following the drying process, while embrittlement would be operative over extended storage as temperatures decrease.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) state that hydriding effects on fuel assembly hardware could lead to failure only during storage design basis and hypothetical transportation accidents, not during normal storage. This assessment considers that the fuel assembly hardware should see less serious effects from hydriding than fuel cladding due to a lack of hoop stress required to cause hydride reorientation. Hydriding is unlikely to cause sufficient fuel assembly hardware failure to impact safety functions, but could cause significant material property changes that may impact analyses of the storage design basis and hypothetical transportation accidents.

EPRI (2011) notes that hydride reorientation is unlikely due to a lack of stress to cause reorientation during drying. Therefore, any significant hydriding effects would have been experienced already in the reactor. Generally, residual water will be dissociated into oxygen (or other oxidizers) and hydrogen by radiolysis. Molecular hydrogen from the radiolysis will not be readily absorbed into the fuel assembly hardware alloys. Hydrogen is absorbed in atomic form, which is produced in reduction reactions during aqueous corrosion. The limited volume of water and the dissociation of residual water may result in a relative humidity that is insufficient to support aqueous corrosion reactions.

NRC Staff Evaluation

Hanson, et al. (2011) and EPRI (2011) agree that hydride reorientation requires stresses that are not present in fuel assembly hardware during drying. Hydriding effects on fuel assembly hardware should be bounded by the more severe case of fuel cladding, which experiences significant hoop stresses from interior gas pressure. Additional data are needed on the ductility and fracture toughness of zirconium alloys at the lower temperatures expected during extended storage.

The level of knowledge of initiation time and propagation rate is high due to available knowledge of hydriding effects in cladding, which conservatively bounds hydriding effects in fuel assembly hardware. The level of knowledge of the effects of fuel assemble hardware hydriding is high and will be bounded by the behavior of the fuel rods, where the stresses are much higher.

There is currently no method for inspection or monitoring of hydriding effects on fuel assembly hardware.

A4 FUEL BASKETS

Fuel baskets consist of a grid structure designed to support fuel assemblies and maintain them in a subcritical geometrical arrangement. Fuel baskets may be composed of carbon steel, stainless steel, aluminum alloys, and Inconel along with the associated weld metals. Fuel baskets are designed to ensure retrievability, subcriticality, and thermal performance functions are fulfilled (Hanson, et al., 2011). The level of knowledge regarding the degradation mechanisms and the status of monitoring and inspection techniques are summarized in Table A4–1.

A4.1 Creep of Fuel Baskets

Description of Degradation Phenomenon

Creep involves the slow strain of fuel basket material, which may occur as a result of extended time under applied stress at elevated temperature. The creep process may be exacerbated by neutron irradiation. Temperature and stress can strongly influence creep behavior over long time periods. Creep of fuel baskets would likely be operative only in the short term (<40 years) as temperatures decrease over extended storage time. Note that creep of fuel baskets is addressed in initial licensing of dry storage casks for 40 years. Creep of fuel baskets may lead to lack of control of geometry, which would affect retrievability and thermal performance and may have implications for maintaining subcriticality. The effects of fuel basket creep will be dependent on the amount of creep, which is a function of actual temperatures, loads, and materials.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) address the possibility of creep of fuel baskets. Sindelar, et al. (2011) briefly describe creep of fuel baskets in a more general discussion of degradation phenomena. EPRI (2011) discusses the potential for creep of aluminum components in fuel baskets, but indicates that the amount of creep would be relatively low.

Hanson, et al. (2011) indicate that load-bearing aluminum basket components may be subject to creep at temperatures greater than 93 °C [200 °F]. Carbon and stainless steel components are

Table A4–1. Level of Knowledge and Monitoring Techniques—Fuel Baskets

Component	Degradation Phenomena	Level of Knowledge			Monitoring or Inspection Capability Available
		Initiation Time	Propagation Rate	Expected Effects	
Fuel baskets	Creep	H	H	M	No
	Weld embrittlement	L	L	L	No
	Metal fatigue caused by temperature fluctuations	M	M	M	No
	Corrosion	M	M	L	No

H=High
M=Medium
L=Low

not subject to creep at dry storage temperatures. As the fuel ages, temperature may decrease to below the aluminum creep threshold. Sindelar, et al. (2011) note that creep is generally only significant at temperatures greater than 40 percent of the material's absolute melting temperature. Carbon steel and stainless steel would not be subject to creep at dry cask storage temperatures, but aluminum may be susceptible to creep in the early stages of dry storage. With time, the possibility of creep decreases as the temperatures decrease.

NRC Staff Evaluation

Hanson, et al. (2011), Sindelar, et al. (2011), and EPRI (2011) agree that creep of carbon steel and stainless steel basket materials should not be significant but creep of the aluminum basket materials will be temperature and load dependent. Cask modeling may be able to provide information about the temperature and loads fuel basket materials experience. There are limited data on Metamic HT creep that can be extrapolated for 300 years, and composite modeling for creep is weak. Fortunately the stresses on Metamic HT are so low that creep would not be significant.

The level of knowledge of initiation time is high, because creep of these materials at elevated temperatures has been extensively studied, and the phenomenon is expected to be most significant at elevated temperatures that will occur early in storage The level of knowledge of propagation rate is high due to available knowledge of creep of engineered materials and the assessment of creep revaluated in initial licensing. The level of knowledge of the effects of fuel basket creep is medium due to uncertainty regarding the deformation expected for aluminum basket materials.

There is currently no inspection or monitoring method for creep of fuel baskets.

A4.2 Embrittlement of Fuel Basket Welds

Description of Degradation Phenomenon

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.

Synopsis of Previous Gap Assessments

Although the degradation mechanism in the material is understood, there are no gap assessment studies for the potential embrittlement of fuel basket welds caused by long-term thermal aging.

NRC Staff Evaluation

Low-temperature weld embrittlement of austenitic stainless steel welds is dependent on the quantity of ferrite in the austenitic stainless steel welds, the operating temperature, and the exposure time of the welds. The level of knowledge of the initiation time and propagation rate of fuel basket weld embrittlement is low. Data on low-temperature weld embrittlement are restricted to a relatively small list of literature references. The NRC staff expects the potential for weld embrittlement is expected to decrease as the decay heat of the spent fuel declines. Fuel loadings of high burnup and MOX fuel may create the mostly likely potential for embrittlement of the basket welds. Although a clear transition from ductile to brittle behavior has been observed (Alexander and Nanstad, 1995), it is unclear whether this would affect the final transportation of spent nuclear fuel. Due to the limited data on the subject, the NRC staff characterizes the level of knowledge of the effects of basket weld embrittlement as low.

There is currently no inspection or monitoring method for weld embrittlement.

A4.3 Metal Fatigue Caused by Temperature Fluctuations of Fuel Baskets

Description of Degradation Phenomenon

Metal fatigue of fuel baskets may occur as a result of temperature fluctuations, which lead to stress fluctuations experienced by the material. Cumulative stress cycles of sufficient magnitude can lead to a change in material properties, metal fatigue, and failure below yield strength. Metal fatigue failure of fuel baskets could impact criticality, thermal, and retrievability functions. Metal fatigue due to temperature fluctuations of fuel baskets would likely be more operative during extended storage beyond 40 years due to the increasing accumulated number of stress/temperature cycles over time.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) state that metal fatigue of fuel baskets is unlikely with the low temperatures expected during extended storage. Longer storage times mean more summer-winter transitions as well as increased probability of extreme weather conditions. However, the anticipated temperature fluctuations for the fuel baskets are expected to be low due to the proximity of the baskets to the heat-generating fuel and the large thermal capacity of storage casks. The report acknowledges operating experience has involved cracking of nonstructural welds due to thermal expansion stresses that did not impact the safety function.

EPRI (2011) indicates that metal fatigue of fuel baskets may affect retrievability and have minor effects on thermal, radiological, and criticality functions. The report also observes that fatigue over a 60-year lifetime has been analyzed and approved by the NRC for CASTOR bolted lid casks at Surry.

NRC Staff Evaluation

Hanson, et al. (2011) and EPRI (2011) agree that metal fatigue as a result of thermal fluctuation has been evaluated based on the magnitude of temperature changes that fuel baskets will experience during dry storage. Long-term performance during extended storage may be evaluated and bounded using thermal models. Neither Hanson, et al. (2011) nor EPRI (2011) addresses the effect of temperature change during the drying cycle on fatigue considerations. Operating experience involving thermal-stress-related cracking of fuel basket welds (albeit nonstructural) indicates the potential for degradation by metal fatigue, which is strongly dependent on material properties of thermal expansion coefficient and fatigue resistance.

The level of knowledge of initiation time, propagation rate, and the effects of metal fatigue caused by temperature fluctuations is medium, because significant information is available to evaluate long-term performance of the basket materials during extended storage. Additional data on temperature fluctuations during drying and extended storage would enhance the ability to model the magnitude of temperature changes and assess fatigue.

There is currently no inspection or monitoring method for metal fatigue of fuel baskets.

A4.4 Corrosion of Fuel Baskets

Description of Degradation Phenomenon

Corrosion of fuel baskets may occur if moisture and oxygen are present in the canister. The amount of moisture present will greatly affect the degree of corrosion. Corrosion of fuel baskets could lead to component failure affecting retrievability, altered thermal performance, and fuel bundle configurations necessary to maintain subcriticality. Corrosion and SCC of fuel baskets may be operative both in the short term and over extended storage periods depending on the amount of moisture remaining after drying and the effectiveness of the cask seals at preventing moisture ingress.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) indicate that corrosion of fuel baskets is not likely due to the limited moisture expected to remain after drying. In addition, Hanson, et al. (2011) state that the exhaustion of the small amount of expected residual water during the initial stage of storage and decreasing temperatures minimizes the likely impact of corrosion during extended storage. Baskets composed of carbon steel and aluminum would be expected to be more susceptible to corrosion than stainless steel.

Sindelar, et al. (2011) state that corrosion of fuel baskets would be limited to the early storage period and should have no additional impact during extended storage due to lack of moisture. While limited corrosion may occur due to residual moisture after drying, this water will be consumed by corrosion early in storage and not allow for more extensive corrosion over extended time. Corrosion would be expected to be higher for aluminum and carbon steel baskets than stainless steel baskets.

EPRI (2011) observes that water left in the canister or cask after drying may affect drying time, but it is not an extended storage issue. In a previous assessment, EPRI (1998) indicated there was a potential for galvanic corrosion of aluminum fuel baskets in the presence of water.

NRC Staff Evaluation

Hanson, et al. (2011) and Sindelar, et al. (2011) agree that the key factor in understanding the potential consequences of corrosion and SCC of fuel baskets is the environment including the amount of moisture present in the sealed canister or cask after drying. Corrosion is not expected in a dry canister environment. Understanding the maximum amount of moisture after drying would allow conservative estimations for the extent of corrosion. Greater knowledge is needed of the integrity of cask seals over extended storage to prevent the ingress of moisture and oxygen that could promote corrosion. To assess the possibility of corrosion during extended storage, additional information on the integrity of cask seals and stainless steel canisters is needed.

The level of knowledge of initiation time and propagation rate of fuel basket corrosion is medium, because some residual water may remain in canisters and casks after normal drying that can promote corrosion of the internal structures including fuel baskets, and significant information is available to evaluate the corrosion propagation rates of the basket materials. Knowledge of the effects of basket corrosion is low. Additional information on the volume of water remaining after normal drying, including the effects of waterlogged rods as well as the expected performance of stainless steel canisters and cask seals over extended periods, is necessary to evaluate fuel basket corrosion.

There is currently no inspection or monitoring method for corrosion of fuel baskets.

A5 NEUTRON ABSORBERS

Neutron absorbers are boron-containing materials used to prevent criticality of the high-density fuel assembly arrangement during transportation, loading, and retrieval, particularly in the event of flooding or moderator introduction. Neutron absorbers may or may not be load bearing components depending on the design of the basket and how the absorbers are integrated into the fuel basket structure as panels between assemblies. This evaluation is limited to materials that are presently used in dry cask storage systems. Neutron poison materials in use include borated aluminum alloys (BorAluminum), metal-matrix composites (Metamic and Bortec), borated stainless steel (NeutroSorb and Neutronit), and aluminum boron carbide laminate composites (Boral®) (Sindelar, et al., 2011). Boral consists of a porous matrix of aluminum and boron carbide hot rolled between a cladding of fully dense aluminum. However, the edges of the porous matrix are not covered by cladding, allowing for water ingress when submerged. Borated aluminum alloys, metal-matrix composites, and borated stainless steels have essentially no porosity due to the nature of their processing. Neutron absorbers are designed to ensure subcriticality in conditions of loss of moderator exclusion, but their degradation may also affect retrievability and thermal performance functions of the system. The level of knowledge regarding the degradation mechanisms and the status of monitoring and inspection techniques are summarized in Table A5–1.

A5.1 Creep of Neutron Absorbers

Description of Degradation Phenomenon

Creep involves the slow strain of neutron absorbers, which may occur as a result over extended time under applied stress at elevated temperature. The creep process may be exacerbated by neutron irradiation. Temperature and stress can strongly influence creep behavior over long time periods. Significant creep of neutron absorbers could affect criticality considerations, particularly upon flooding during retrieval or transportation accident scenarios. Creep may also affect thermal performance and retrievability if dimensional changes are significant. Creep of neutron absorbers is likely to be operative only in the short term (<40 years) due to decreasing temperatures over extended storage times.

Table A5–1. Level of Knowledge and Monitoring Techniques—Neutron Absorbers

		Level of Knowledge			
Component	**Degradation Phenomena**	**Initiation Time**	**Propagation Rate**	**Expected Effects**	Monitoring or Inspection Capability Available
Neutron absorbers	Creep	H	H (L*)	H	No
	Metal fatigue caused by temperature fluctuations	M	M	M	No
	Wet corrosion and blistering†	M	M	L	No
	Thermal aging effects	L	L (H*)	L	No
	Absorber depletion	H	H	H	No
	Embrittlement and cracking	H	H	M	No

H=High
M=Medium
L=Low
*Structural aluminum neutron absorbers.
†Short-term issue as a result of residual water remaining after drying.

Synopsis of Previous Gap Assessments

Only Hanson, et al. (2011) formally address the possibility of creep of neutron absorbers. Sindelar, et al. (2011) briefly mention creep of neutron absorbers.

Hanson, et al. (2011) indicate that creep is a concern for load-bearing neutron absorbers, which include metal-matrix composites and alloy materials. Creep is not anticipated to be a degradation mechanism for non-load-bearing materials, such as cermet neutron absorbers. Hanson, et al. (2011) observe that neutron absorbers hold only their own weight in vertical storage systems and that loads are spread over large areas in horizontal systems. Hanson, et al. (2011) also note that a 2-year creep test of Metamic at temperatures and loads bounding expected conditions for dry storage showed cumulative creep strain as high as 0.24 percent, which led to adoption of a limiting creep strain of 0.40 percent over the 5-year service life. More significant creep can be expected over longer storage times, but creep rates are expected to decrease as temperatures decrease.

Sindelar, et al. (2011) observe that creep of aluminum-based materials used as neutron absorbers is viable given the anticipated temperature greater than 100 °C [212 °F].

NRC Staff Evaluation

Hanson, et al. (2011) and Sindelar, et al. (2011) agree that creep of neutron absorbers is possible. Both Hanson, et al. (2011) and Sindelar, et al. (2011) state that additional information on expected temperatures, creep properties (particularly of borated aluminum neutron absorber materials), and loads on the neutron absorbers during extended storage is needed to assess the potential for creep. Several factors will limit the creep of neutron absorbers. With the exception of Metamic, which also serves as a basket material, neutron absorbers are not under applied loads other than supporting their own weight. For absorbers contained within a stainless steel structure, the creep will be limited by available volume inside this outer structure. The creep rate will decrease as temperature decreases with increasing storage times. Note that the mechanical properties of irradiated internal structures, such as grid baskets, are being tested in some international programs. Creep behavior on neutron absorbers may be included in these investigations.

The level of knowledge of initiation time is high because creep of the neutron absorbers is known to be a function of temperature and stress. The level of knowledge of propagation rate and the effects of creep of the neutron absorbers is overall medium due to the availability of some creep data for most neutron absorber materials. Some uncertainty exists on the amount of creep that will occur and the amount of creep necessary to impact safety functions; however, creep will be limited by decreasing temperatures over the extended storage period.

There is currently no inspection or monitoring method for creep of neutron absorbers.

A5.2 Metal Fatigue Caused by Temperature Fluctuations of Neutron Absorbers

Description of Degradation Phenomenon

Metal fatigue may occur as a result of temperature fluctuations, which lead to stress fluctuations experienced by the material. Cumulative stress cycles of sufficient magnitude can lead to metal fatigue and failure. Metal fatigue and failure of neutron absorbers could impact criticality, thermal, and retrievability functions. Metal fatigue due to temperature fluctuations of neutron absorbers would likely be more operative during extended storage beyond 40 years due to an increasing accumulated number of stress/temperature cycles over time.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) state that metal fatigue of neutron absorber materials would only potentially affect load-bearing neutron absorbers (metal-matrix composites and alloy materials) under accident loading conditions. The report observes that longer storage times mean more summer-winter transitions as well as increased probability of extreme weather conditions. However, the proximity of the neutron absorbers to the heat-producing fuel would reduce the effect of the external temperature changes on the absorber material. Failure from fatigue during storage is not expected, but fatigue could cause material property changes leading to unacceptable performance in accident scenarios.

NRC Staff Evaluation

Hanson, et al. (2011) conclude that metal fatigue-caused temperature fluctuations are unlikely for load-bearing metal-matrix composite and alloy-type neutron absorber materials and do not impact non-load-bearing encased cermet materials. Additional data are desirable to evaluate the effect of metal fatigue on load-bearing neutron absorber materials and evaluate performance during design basis accidents. Hanson, et al. (2011) do not address the effect of temperature change during the drying cycle on fatigue considerations. Note that the mechanical properties of irradiated internal structures, such as grid baskets, are being tested in some international programs. Fatigue behavior on neutron absorbers may be included in these investigations.

The level of knowledge of initiation time, propagation rate, and the expected effects of metal fatigue of the neutron absorbers are medium because temperature fluctuations are expected to be minimized by the proximity of the neutron absorbers to the heat-generating fuel. Additional data on temperature fluctuations during drying and extended storage would enhance the ability to model the magnitude of temperature changes and assess fatigue.

There is currently no inspection or monitoring method for metal fatigue by temperature fluctuations of neutron absorbers.

A5.3 Wet Corrosion and Blistering of Neutron Absorbers

Description of Degradation Phenomenon

Wet corrosion and blistering may occur in cermets, such as Boral, that possess porosity. Observed blisters are believed to be a result of water entering pores in the material during loading, leading to internal corrosion. The greater volume of the corrosion product (Al_2O_3) will seal off the pores, creating isolated regions that contain hydrogen (a byproduct from the corrosion process), Al_2O_3, and water. Heating during drying and/or increasing hydrogen produced from continued corrosion over time can cause internal pressure in sealed pores to increase. This pressure can lead to blistering where the aluminum cladding plastically deforms and separates from the inner absorber material. Wet corrosion and blistering may cause dimensional changes affecting criticality considerations due to moderator displacement as well as retrievability function. Wet corrosion and blistering of neutron absorbers is likely to be possible only in the short term. Wet corrosion and blistering of neutron absorbers during extended storage would only occur if undetected loss of seal or confinement failure of the casks or canisters occurred and sufficient water is available.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) state that wet corrosion and blistering is a degradation mechanism for aluminum boron carbide cermets (Boral) with open porosity, but not for metal-matrix composite and alloy neutron absorber materials without significant porosity. There have been two recorded instances of Boral blistering in dry storage systems: one in Canada in the 1980s and another in Spain in 2003. In the Spanish case, for example, high heating rates were used, which caused expansion of trapped water before sufficient drying could occur.

Sindelar, et al. (2011) discuss the issue of blistering in cermet neutron absorber materials, while observing that metal-matrix composite and borated aluminum and stainless steel absorber material have essentially no porosity and are not subject to the blistering degradation mechanism observed for Boral. Blisters may develop as a result of water remaining in the porous matrix due to vaporizing water during vacuum drying or from corrosion during long-term storage at temperatures near 260 °C [500 °F].

NWTRB (2010) mentions that blistering and bulging of Boral is linked to the pool environment and therefore is not applicable to dry storage systems.

NRC Staff Evaluation

NWTRB (2010) and EPRI (2011) indicate that neutron absorber degradation is not an issue in dry storage conditions, but these reports do not address water remaining in Boral pores, as Hanson, et al. (2011) and Sindelar, et al. (2011) discussed. Hanson, et al. (2011) and Sindelar, et al. (2011) agree that Boral blistering is related to water entering the material during wet loading, but these reports do not clearly describe the exact mechanism of blister formation. Blisters are known to form during the heating of the vacuum drying process, but may also occur from trapped hydrogen production from corrosion during long-term storage. Some analyses and possibly selected validation tests would provide needed information on the expected amount of residual water that could be trapped, mainly in Boral. Unlike cladding or the SNF matrix, neutron absorbers will be under aqueous conditions for short periods of time during canister or cask loading. Information is needed to determine whether blistering can occur during extended storage simply as a result of corrosion-related hydrogen production by residual water in the pores.

The level of knowledge of initiation time and propagation rate is medium due to the incomplete, understanding of the mechanism of blistering of neutron absorber materials. Information is available to understand the effects of manufacturing processes and their variations of pore size, the density of porosity, and the susceptibility to blister formation. Small pores (as opposed to large pores or no pores) are of most concern, because they can trap water and lead to blister formation. The level of knowledge for the effects of corrosion and blistering of the neutron absorbers is low.

There is currently no inspection or monitoring method for wet corrosion and blistering of neutron absorbers.

A5.4 Thermal Aging Effects on Neutron Absorbers

Description of Degradation Phenomenon

Thermal aging effects, including decreases in tensile and yield strength, may occur as a result of extended time at elevated temperature. Thermal aging effects of neutron absorbers could impact criticality functions during transportation accident scenarios. Thermal aging effects on neutron absorbers are operative in the short term (<40 years), but the rate of aging would decrease significantly over extended storage periods as temperature decreases.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) state that thermal aging effects may be likely for load-bearing, heat-treated, aluminum-based materials. Aluminum-based materials generally experience a decline in properties above 93 °C [200 °F]. Accelerated aging testing of Metamic using higher temperatures for a shorter time to simulate lower temperature for a longer time showed a minor decrease in tensile and yield strength with virtually no change in fracture toughness. This Metamic material is not heat treated, raising concerns about heat-treated, aluminum-based materials that may show more dramatic effects.

NRC Staff Evaluation

Hanson, et al. (2011) indicate that additional data are needed to evaluate the effects of thermal aging on the mechanical properties of the various load-bearing neutron absorber materials, particularly heat-treated materials and load-bearing, aluminum-based materials. It is important to note that thermal aging effects on non-load-bearing materials are inconsequential. In order to evaluate their stability, additional information on the degree of reduction in mechanical properties and the possibility of phase instability of neutron absorber materials at dry storage temperatures is needed to assess the effect of thermal aging on these safety functions. The level of knowledge of initiation time, propagation rate, and the effects of thermal aging on neutron absorbers is low. An assessment of the long-term thermal aging effects for borated stainless steels, considering phase stability and mechanical property changes at elevated temperatures, is needed to confirm that borated stainless steels will not experience significant thermal aging effects at dry storage temperatures. Aluminum-based and especially heat-treated alloys may be significantly affected by thermal aging over extended times at dry storage temperatures. These temperatures will decrease over extended times, but knowledge is needed of the thermal aging effects on phase stability and mechanical properties as a function of time and temperatures, particularly for the heat-treated aluminum alloys, to assess their significance during extended storage.

There is currently no inspection or monitoring method for thermal aging of neutron absorbers.

A5.5 Depletion of Neutron Absorbers

Description of Degradation Phenomenon

Absorber depletion may occur if the absorber is exposed to sufficient neutron fluence to result in a significant consumption of Boron-10 atoms. Depletion of neutron absorbers could impact criticality functions. Absorber depletion is more likely to be operative in the short term (<40 years), due to the rapid decrease of neutron flux levels over time.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) state that extended storage will likely have an insignificant effect on the available neutron absorber (EPRI, 2002). Neutron radiation causes an insignificant number of Boron-10 atoms to be consumed during the first 20–40 years of storage and the neutron flux decreases significantly with time. Sindelar, et al. (2011) state that the total neutron flux after extended storage is insignificant compared to the number of absorber atoms in absorber material. NWTRB (2010) states that boron consumption by neutron absorption is insignificant.

NRC Staff Evaluation

Hanson, et al. (2011), Sindelar, et al. (2011), and NWTRB (2010) agree that the neutron flux during extended storage is likely to be insignificant relative to the available Boron-10 present in the neutron absorber material. Analyses have been made for shorter storage times showing an insignificant effect and decreasing neutron flux over time. Evaluation of the neutron source term over extended time for high burnup fuels and MOX fuels is needed to confirm intuitive extrapolations from shorter timeframe analyses and ensure no significant depletion is possible.

The level of knowledge of initiation time is high because absorber depletion begins immediately upon exposure to radiation. The level of knowledge of propagation rate and effects of depletion of neutron absorbers is high because simple extrapolation of NRC staff analyses conducted for shorter storage periods indicates that insignificant depletion is expected.

There is currently no inspection or monitoring method for depletion of neutron absorbers.

A5.6 Radiation Embrittlement of Neutron Absorbers

Description of Degradation Phenomenon

Embrittlement of neutron absorber materials due to radiation exposure may occur depending on the material of construction of the absorber. Failure of neutron absorbers due to embrittlement and cracking could impact criticality, thermal, and retrievability functions. Radiation embrittlement and cracking are operative in the short term (<40 years) when radiation levels are highest, but are not likely to be as significant during extended storage as radiation levels decrease.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) note that cracking of neutron absorber material could reduce absorber effectiveness by allowing neutron streaming. Neutron and gamma irradiation testing of various absorbers have shown that properties do not change under levels far exceeding those expected for 20–60 years of storage. Both thermal and radiation effects are not expected to increase with extended storage times due to significant decreases in temperature and neutron flux over time. Boral may be of greater concern due to inherently low ductility.

Sindelar, et al. (2011) observe that extending storage times should not affect radiation-induced embrittlement or cracking due to reducing flux over time.

NRC Staff Evaluation

Hanson, et al. (2011) and Sindelar, et al. (2011) agree that decreases in radiation flux with time will limit the effects of radiation embrittlement. Evaluation of the neutron fluence for high burnup and MOX fuels expected during extended storage is necessary to confirm the performance of the neutron absorber materials. The NRC staff expects that current data for radiation-induced damage may already bound the total expected exposure.

The level of knowledge for initiation and propagation rate is high because neutron and gamma radiation testing has been conducted on neutron absorber materials, and radiation levels during storage will decrease with time as shorter-lived radionuclides decay. The level of knowledge on the effects of radiation damage of neutron absorbers is medium because additional data are needed to evaluate effect of radiation embrittlement and cracking of cermet absorber materials.

There is currently no inspection or monitoring method for embrittlement and cracking of neutron absorbers.

A6 STEEL/CAST IRON CASKS AND STAINLESS STEEL CANISTERS, BOLTS, AND SEALS

Degradation mechanisms considered for components of the steel and cast iron casks and stainless steel canisters include uniform corrosion, localized corrosion, thermal-mechanical degradation, and irradiation damage. The level of knowledge regarding the degradation mechanisms and the status of monitoring and inspection techniques is summarized in Table A6–1.

A6.1 Atmospheric Stress Corrosion Cracking of Stainless Steel Canisters

Description of Degradation Phenomenon

Atmospheric SCC of stainless steel canisters may occur if aggressive species in solution contact the canister surfaces. Aggressive compounds could include chlorides in marine atmospheres and pollutants such as oxidized sulfur species. Deliquescence of deposits on the canister surfaces and the formation of an aqueous phase may promote SCC if sufficient concentrations of aggressive species are present. Residual stresses in the canister as a result of fabrication processes and welding of stainless steels are known to be sufficient to promote SCC. For this degradation phenomenon to occur, a significant change in the environmental

Table A6–1. Level of Knowledge and Monitoring Techniques—Steel/Cast Iron Casks and Stainless Steel Canisters, Bolts, and Seals

Component	Degradation Phenomena	Level of Knowledge			Monitoring or Inspection Capability Available
		Initiation Time	Propagation Rate	Expected Effects	
Stainless steel (SS) canister body and weld	Atmospheric stress corrosion cracking (SSC)	L	M	M	No
	Pitting and crevice corrosion	L	H	H	No
SS canisters, steel and cast iron casks and seals	Microbiologically influenced corrosion	L	M	M	No
	Irradiation damage	H	H	H	No
Steel and cast iron cask body and lid	Atmospheric corrosion (rusting)	H	H	H	Yes
Metallic seals	Corrosion	H	H	H	Yes
	Thermal-mechanical degradation	H	M	H	Yes
Polymer seals	Thermal-mechanical or radiation-induced degradation	H	H	M	No
Bolts	Corrosion, SCC, and embrittlement	M	M	L	No
	Thermal-mechanical degradation	M	M	M	Yes

H=High
M=Medium
L=Low

conditions on the cask surface is necessary. These changes (e.g., the deposition of critical surface concentrations of atmospheric deposits that promote corrosion or SCC, and a decrease in cask temperature necessary for an aqueous phase to form by condensation or deliquescence) are more likely to occur during extended storage (i.e., periods >40 years).

Synopsis of Previous Gap Assessments and Other Available Information

Hanson, et al. (2011) indicate that there are sufficient data to evaluate the potential for atmospheric corrosion and the likelihood for atmosphere SCC is significant. In the case of marine environments, key variables that must be understood include the deposition rate of salt particulates on a relevant material surface and the typical chemistry of those aerosols. The assessment by Hanson, et al. (2011) is based on the knowledge gained from atmospheric corrosion testing in environments with a combination of high moisture content and aggressive species, such as industrial areas and marine environments. Hanson, et al. (2011) cite studies that show 300-series stainless steels, including 304/304L and 316/316L grades, are susceptible to SCC in marine environments (Caseres and Mintz, 2010; Shirai, et al., 2011; Kain, 1990). The composition of the stainless steel has been shown to affect the SCC susceptibility.

Sindelar, et al. (2011) conclude that the conditions for SCC of the stainless steel canisters are likely to be present during extended storage and transportation; however, the time to initiate SCC may be highly variable. Sindelar, et al. (2011) emphasize the need for monitoring (including temperature, relative humidity, and characterization of deposits on canister surfaces) and the development of inspection methods and disposition criteria for cracks and flaws. This assessment recognizes that chlorides, which are known to promote SCC in stainless steels, may be introduced from a variety of sources including marine environments. In addition, Sindelar, et al. (2011) cite case histories that have shown SCC can also occur from the deposition of industrial pollutants, such as fly ash and associated chlorides. Low temperatures that allow condensation are expected to increase the possibility for SCC; however, Sindelar, et al. (2011) also note that the formation of mixed salts can yield solutions with high boiling points and low deliquescence relative humidity values. Sindelar, et al. (2011) suggests that the formation of an aqueous solution may be present at temperatures above 100 °C [212 °F] and at relative humidity values as low as 20 percent. Sindelar, et al. (2011) cite an SCC propagation rate of 10 mm/yr [0.039 in/yr] that was reported by CRIEPI and included in a previously published EPRI report (Gordon, et al., 2005).

NWTRB (2010) indicates that a review of the available information was insufficient to predict the degradation of dry storage canisters; however, corrosion mechanisms are expected to lead to degradation of metal components during extended storage. NWTRB states that better understanding of the threshold conditions for SCC would be beneficial to material selection and storage system design to prevent corrosion-related degradation processes. NWTRB (2010) supports this assessment with the cited results of laboratory and field tests, including the findings of Japanese studies that show SCC of austenitic stainless steels can occur in marine environments. NWTRB (2010) cites the results of Kosaki (2008), which specifically measured SCC initiation times on types 304 and 316 stainless steels ranging from 1.6 to 3 years under natural exposure conditions, and SCC growth rates of 0.04 to 0.6 mm/yr [0.0016 to 0.024 in/yr] over a range of residual tensile stresses. They further cite laboratory test results published by Mayuzumi, et al. (2008) which indicate SCC initiation of 304 stainless steel with deposited sea salt at above a minimum RH of 15 percent at 80 °C [176 °F].

Gordon, et al. (2005) and Kain (1990) summarized SCC testing with stainless steels under natural exposure conditions. Results of testing conducted at Kure Beach, North Carolina showed that stainless steel composition, materials condition, and the magnitude of applied or residual stresses affected SCC susceptibility. Gnanamoorthy (1990) reviewed three case histories of SCC of types 304 and 304L stainless steel components in marine atmospheres. Gnanamoorthy (1990) found that common causative factors included iron contamination that was likely introduced by machining operations, the presence of chloride from coastal environments, and stresses arising from fabrication or assembly. The results reported by Mayuzumi, et al. (2008) do not agree with those of Caseres and Mintz (2010). This may be due to differences in experimental conditions. For example, the SCC initiation results by Mayuzumi, et al. (2008) may have been affected by $CaCl_2$ controlling low RH or by variations in specimen temperature. Note that the test conditions reported by CRIEPI (Gordon, et al., 2005) and cited in Sindelar, et al. (2011) are described as severe with a temperature of 80 °C [176 °F] and a relative humidity of 35 percent. Temperature and humidity conditions in the actual service environment may not be as harsh as those of the CRIEPI tests.

Crack growth rates in chloride solutions at elevated temperatures have been reported (Speidel, 1981; Tamaki, et al., 1990; Newman and Mehta, 1990). The crack growth rates for stainless steels in aqueous chloride solutions are known to be dependent on temperature, solution composition, and material condition. Tamaki, et al. (1990) reported crack growth rates of more than 190 mm/yr [7.5 in/yr] in NaCl solutions at 80 °C [176 °F]. Higher crack growth rates were reported in concentrated chloride solutions at temperatures above 100 °C [212 °F].

NRC Staff Evaluation

NWTRB (2010), Hanson, et al. (2011), and Sindelar, et al. (2011) generally agree that the composition of the deposits on the canister surfaces and the environmental conditions during storage are key parameters that may determine whether SCC occurs. While coastal atmospheres are emphasized, all three reports indicate that dusts and atmospheric deposits in noncoastal environments may affect canister corrosion processes during extended storage. For SCC in coastal atmospheres, all of the reports reference similar supporting information, including work by Caseres and Mintz (2010), and the recent testing conducted in Japan. However, significant differences in the cited SCC propagation rates are noted in NWTRB (2010) and Sindelar, et al. (2011). Recommendations in NWTRB (2010) and Sindelar, et al. (2011) emphasize monitoring; inspection; characterization to evaluate changes in canister conditions; and the evaluation of mitigation measures, including improved designs and material selection (NWTRB, 2010) or cleaning to prevent the accumulation of a critical concentration of corrosive species (Sindelar, et al., 2011). Hanson, et al. (2011) indicate that dry cask system design may obscure monitoring of susceptible areas such as welds and that additional research and development on environmentally induced degradation is necessary; however, specific details are not provided.

The level of knowledge of the initiation time for SCC on stainless steel dry cask storage system canisters is ranked low. Sufficient information exists to evaluate the effects of stresses, alloy composition, and microstructures on SCC initiation of stainless steel canisters. Insufficient information is available to quantify the evolution of the conditions on the surfaces of the stainless steel canisters in dry cask storage systems. Specifically, the deposition rate for marine salts, dusts, and atmospheric deposits on the canister surfaces has not been measured and the influence of dry storage system designs and ISFSI locations has not been evaluated. This level of knowledge could be increased if environmental factors that influence SCC initiation, including canister surface temperatures and relative humidity, can be quantified with information on specific ISFSI locations, dry cask storage system design, and fuel loading parameters. These could be confirmed with field measurements.

Knowledge of the SCC propagation rates is ranked medium. The SCC growth rates in stainless steels have been measured in a variety of environments and are strongly temperature dependent. Deliquescence of marine salts, dusts, or other atmospheric deposits at elevated temperatures may lead to faster crack propagation rates than those reported by Kosaki (2008) under natural exposure conditions, but sufficient data exist to estimate crack growth rates over the range of temperatures expected during the extended storage period. Based on data available to date, a lower bound estimate for crack growth rates may range from 0.01 to 0.04 mm/yr [.0016 in/yr], based on natural exposure conditions (Sindelar, et al., 2011). The rate of 10 mm/yr [0.39 in] reported by CRIEPI (Gordon, et al., 2005) at a temperature of 80 °C [176 °F], a relative humidity of 35 percent, and $MgCl_2$ salt, may be a conservative upper bound for expected crack growth rates, because such conditions are not expected in the actual service environment.

Knowledge of the effects of SCC on stainless steel canisters is medium. SCC cracks may lead to either partial or through-wall cracks depending on the residual stress profiles in the fabrication and closure welds. Information on the fabrication processes and welding parameters and the resultant residual stress profiles, along with the range of expected crack growth rates, is necessary to determine the consequences of SCC of the stainless steel canisters.

Inspection methods for SCC of stainless alloys are well established and are regularly applied in the nuclear power industry for primary containment systems and reactor internals where high radiation fields are encountered. These methods have not been routinely applied to dry storage systems. Corrosion monitoring systems to detect environments that may promote SCC also exist but have not been routinely applied in dry cask storage systems. How readily such monitoring systems can be applied to dry cask storage is uncertain and is open to further evaluation.

A6.2 Localized Corrosion of Stainless Steel Canisters

Description of Degradation Phenomenon

Localized corrosion of stainless steel canisters may occur if aggressive species in solution come in contact with the canister surfaces. Aggressive compounds could include chlorides in marine atmospheres and pollutants such as oxidized sulfur species. Deliquescence of deposits on the canister surfaces and the formation of an aqueous phase may promote localized corrosion if sufficient concentrations of aggressive species are present. For this degradation phenomenon to occur, the environmental conditions on the cask surface must change significantly. These changes (e.g., the deposition of critical surface concentrations of atmospheric deposits that promote corrosion or SCC, and a decrease in cask temperature necessary for an aqueous phase to form by condensation or deliquescence) are more likely to occur during extended storage (i.e., periods >40 years).

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) indicate that there are sufficient data to evaluate aqueous corrosion and container performance. However, the likelihood of aqueous corrosion is currently unknown. The pitting corrosion rate in Kosaki (2008), as referenced in NWTRB (2010), predicts failure of a 13-mm [0.5 in]-thick canister may occur, at the earliest, 400 years after the canister temperature decreases to values where an aqueous phase may be present. This assessment is based on the understanding that with time, container temperatures will decrease and water may condense on the inside of the overpack and on the container surface. In addition, aqueous solutions may come in contact with the containers as a result of inadequate drying or failure of the overpack to protect the container from rainwater. The uncertainty in the chemical composition of the aqueous phase will be influenced by the local environmental conditions. The mode and rate of aqueous corrosion will be dependent on container materials, the composition of the aqueous phase, and the time in which the aqueous phase is in contact with the container materials.

Sindelar, et al. (2011) consider localized corrosion with stress corrosion cracking. Sindelar, et al. (2011) indicates that the conditions for pitting and crevice corrosion of the stainless steel canisters are likely to be present during the extended storage period. Pitting and crevice corrosion are identified as processes that may lead to through-wall breach of the container. This assessment is based on the observation that environments necessary to support corrosion reactions may contact the canister as a result of precipitation or condensation; an electrolyte may also form as a result of deliquescence of deposited dust, pollutants, or salts on the canister surfaces.

NWTRB (2010) indicates that pitting and crevice corrosion may occur on stainless steel welded canisters steel containers; however, this report concludes that the risk of pitting corrosion is insignificant based on pitting corrosion rates obtained with stainless steels in marine environments. The results of Kosaki (2008), which showed a maximum pitting corrosion rate of 20 to 30 μm/yr, supports this conclusion. Using this rate, penetration of a thin-walled {approximately 13 mm [0.5 in]} stainless steel canister would not occur until after more than 400 years.

Additional Information

Stainless steels are known to be susceptible to localized attack in welded regions. Standard austenitic stainless steel grades, such as 304 and 316 (i.e., not low carbon grades such as 304L and 316L), have been used in dry storage system canisters. These stainless steel grades may be sensitized by welding processes. Sensitization occurs as a result of chromium carbide formation at grain boundaries and the formation of chromium-depleted regions. Because of the reduced chromium concentration at the grain boundaries, sensitized stainless steels are susceptible to both SCC and intergranular attack in oxidizing chloride-containing solutions (Streicher, 2000). From available information, it is unclear whether the deposition of chloride-containing salts and the formation of oxidizing chloride-containing solutions by deliquescence could promote intergranular attack. In a marine atmosphere, chloride salts may be deposited on the dry casks over time. Below about 120 °C [248 °F]decomposition of these salts will be limited, so the chloride that is deposited will remain on the surface. At lower temperatures, possibly in the range of 80 °C [176 °F] to 60 °C [140 °F], and at appropriate humidity, deliquescence of the chloride salts can form an aqueous chloride solution on the cask surface. Oxygen transport through this thin aqueous phase can form an oxidizing chloride solution. It is unknown, however, whether the conditions that develop are sufficiently oxidizing for intergranular corrosion to occur.

Giridharan and Murugan (2007) showed welding parameters can affect pitting susceptibility of 304L stainless steel. Electrochemical measurements by Garcia, et al. (2008) have shown differences in corrosion susceptibility of 304 stainless steel welded using 308 filler metal. The heat-affected zone, fusion line, and weld metal were more susceptible to localized corrosion compared to the base metal.

NRC Staff Evaluation

NWTRB (2010), Hanson, et al. (2011), and Sindelar, et al. (2011) address the corrosion of the stainless steel casks. These assessments generally agree that the mode of localized attack is dependent on the composition of the environment and the canister materials. The assessment in Hanson, et al. (2011) is based on information included in the earlier NWTRB report. Sindelar, et al. (2011) do not provide an assessment of localized corrosion rate or predicted failure times. Both the NWTRB (2010) and Sindelar, et al. (2011) advocate development of inspection capability to assess canister condition during extended storage. Hanson, et al. (2011) indicate that additional data needs, including a thermal analysis of the container surface for a variety of systems, are necessary to determine whether the localized corrosion may occur.

Knowledge of the initiation time for localized corrosion is ranked low. Environmental conditions required for localized corrosion initiation on stainless steels are well known; however, insufficient information is available to predict the evolution of the environmental conditions on the canister surfaces. The environment on the canister surfaces will be dependent on numerous parameters including system design and location. Information needed includes deposition rate for marine salts, dusts, and atmospheric deposits on the canister. Other environmental factors that influence localized corrosion initiation, including canister surface temperatures and relative humidity, can be quantified with information on specific ISFSI locations, dry cask storage system design, and fuel loading parameters and could be confirmed with field measurements.

Knowledge of the propagation rate for localized corrosion is ranked high. The rate of localized attack, such as pitting corrosion, is dependent on the depth of the localized corrosion. Transport limitations tend to slow the rate of pitting attack, so penetration of stainless steel canisters by chloride-induced pitting or crevice corrosion would take many years. Pit growth versus time relationship has been shown to follow $d = At^{-n}$ where d is depth, A is an experientially derived constant, and n varies from 0.33 to 0.5. Field investigations have been conducted, and localized corrosion penetration rate data for stainless steels are available in a variety of environments. The NRC staff determined that the evaluation using the maximum pitting rates reported by Kosaki (2008) is conservative compared to field experience. The maximum pit penetration depth measured in 304 stainless steel was 0.028 mm [0.0011 in] after 15 years of exposure at Kure Beach, North Carolina, with the test samples located 250 m [800 ft] from the shore (Davison, et al., 1987).

Knowledge of expected degradation of localized corrosion is ranked high. Although uncertainty exists with regard to whether the environment necessary for localized corrosion initiation will be present during extended storage. The NRC staff determined that localized corrosion penetration rates in stainless steels are well characterized and through-wall penetration of the stainless steel canisters by localized corrosion is not likely during extended storage.

Inspection methods for localized corrosion of stainless alloys are well established and are regularly applied in the nuclear power industry for primary containment systems and reactor internals where high radiation fields are encountered. These methods have not been routinely applied to dry storage systems. Corrosion monitoring systems to detect environments that may promote localized corrosion also exist but have not been routinely applied in dry cask storage systems.

A6.3 Microbiologically Influenced Corrosion of Stainless Steel, Steel, and Cast Iron Casks

Description of Degradation Phenomenon

Microbiologically influenced corrosion (MIC) of stainless steels is well documented. MIC typically occurs as localized attack of stainless steel welds, and many instances of failures have been reported involving stainless steel piping systems exposed to a variety of water chemistries (Korbin, 1985). Failures are often unexpected because the exposure environment assessments prior to material selection did not consider corrosive metabolic byproducts that accompany microbial activity. For this degradation phenomenon to occur, the environmental conditions on the cask surface must change significantly, including the deposition of sufficient nutrient-bearing material from the atmosphere, and availability of sufficient water to support microbial activity. The presence of water on the canister surfaces would only be likely with a decrease in cask temperature and either condensation or deliquescence of deposited salts. Both the necessary accumulation of nutrients by atmospheric deposition and the formation of an aqueous phase are more likely to occur during extended storage (i.e., periods >40 years).

Synopsis of Previous Gap Assessments

NWTRB (2010) references the work of Bruhn, et al. (2009) demonstrating formation of biofilm on stainless steel cladding under irradiation. In addition, NWTRB (2010) states that deposits on the spent fuel container surfaces may include salts that contain chloride in marine environments, and dusts which may contain chloride, nitrates, and organics.

Additional Information

MIC propagation rates in stainless steel welds are remarkably fast and have resulted in many unexpected failures within months to a few years (Korbin, 1985). Penetration of 10 mm [0.39 in] of pipe section in less than a year are commonly reported, and Jack (2002) has reported penetration rates of up to 17 mm/yr [0.67 in/yr] for stainless steel welds. These rates are much faster than typical pitting corrosion rates. Under aggressive conditions promoted by sulfate-reducing bacteria, the penetration rates for cast iron materials can exceed 1 mm/yr [0.039 in] (King, et al., 1985).

NRC Staff Evaluation

Although the general phenomenon is well documented, knowledge of the initiation time for MIC specifically on welded stainless steel canisters and steel or cast iron bolted casks is ranked low. The potential for MIC initiation on stainless steel canisters and bolted casks depends on the evolution of the environment, material composition, and microstructure. Environmental conditions that may promote MIC are well known, but it is unclear whether such conditions will occur on the dry storage system. Insufficient information exists on evolution of the surface conditions of the stainless steel canisters and bolted casks in dry cask storage systems including the deposition rate for marine salts, dusts, and atmospheric deposits on the canister surfaces and the influence of dry cask storage system design or location. Several factors limit microbial activity including the availability of water and nutrients from deposited organics. Elevated temperatures and high radiation fields may also inhibit microbial activity and thus prevent MIC on thin-walled stainless steel canisters (Bruhn, et al., 2009). The thick-walled steel or cast iron casks would benefit less from the potentially sterilizing effects of elevated temperatures and gamma radiation, but these materials may be protected with coatings to prevent general corrosion. Silver, which is used in some cask seals, may also inhibit microbial activity.

Knowledge of the propagation rate for MIC is ranked medium. Localized attack from MIC of stainless steels and carbon steels has led to rapid through-wall penetration in numerous cases; however, it is unclear whether such rates can be sustained on stainless steel canisters, steel, and cast iron casks or bolted cask seals if the conditions necessary for MIC are discontinuous (Korbin, 1985; King, et al., 1985; Jack, 2002). Work by Bruhn, et al. (2009) has shown that bacteria that have been implicated in MIC of stainless steels can survive high doses of ionizing radiation. The limiting factor for MIC may be the availability of water and nutrients necessary for sustained microbial activity.

Knowledge of the expected degradation from MIC is ranked medium. Additional information on the evolution of the environment on steel and cast iron casks and stainless steel canisters is necessary to assess the potential consequences for MIC. If conditions for MIC, including the availability of sufficient nutrients and water occur, degradation could include either partial or through-wall corrosion of stainless steel canisters or seal corrosion.

Inspection methods for localized corrosion damage caused by MIC are similar to the methods used for crevice corrosion and pitting corrosion. Additional environmental assessments are often performed to determine whether microbial activity is involved in the failure. The inspection methods are well established and are regularly applied in the nuclear power industry for primary containment systems and reactor internals where high radiation fields are encountered. These methods have not been routinely applied to dry storage systems. Monitoring systems to detect MIC also exist. Such systems have been used in a number of industrial systems including service water systems at nuclear power plants. Available monitoring systems have not been routinely applied in dry cask storage systems. It is unclear whether the available monitoring systems could be adapted for use in dry cask storage systems.

A6.4 Irradiation Damage of Stainless Steels Canisters and Steel/Cast Iron Casks

Description of Degradation Phenomenon

Irradiation damage to metals results from neutron damage and can cause microstructural changes that depend on the material and exposure. Enhanced diffusion rates and the formation of precipitates can occur. Exposure can also increase the formation of dislocation loops that alter mechanical properties such as decreased fracture toughness, increased hardness, and increased susceptibility to stress corrosion cracking. The change in mechanical properties in some cases is similar to the effects of cold work. For the stainless steel canisters, these effects would be the result of neutron fluence from the contained spent fuel. The cumulative effects of irradiation damage are expected to increase rapidly after dry storage canisters or casks are initially loaded. With increasing time, the rate of additional damage decreases as the fuel ages.

Synopsis of Previous Gap Assessments and Other Information

Sindelar, et al. (2011) cite studies to evaluate the effects of neutron fluence on SCC susceptibility of stainless steels. Constant extension rate tests (CERT) were conducted on both irradiated (up to 2×10^{21} n/cm^2) and un-irradiated Type 304 stainless steel in both furnace-sensitized and annealed conditions. The irradiated specimens were not shown to have enhanced SCC susceptibility.

Substantial knowledge exists on the effects of irradiation on stainless steel and alloy steel materials. Damage to stainless steel materials occurs at fluence levels of $>10^{20}$ n/cm^2. For stainless steels, the effects of increasing irradiation on changes in mechanical properties are also well characterized (Gamble, 2006). For alloy steels, a neutron fluence of 10^{17} n/cm^2 is necessary to observe measurable changes to mechanical properties (U.S. Code of Federal Regulations, 2011).

NRC Staff Evaluation

Knowledge of the initiation, propagation, and expected degradation from irradiation damage on dry cask storage system materials is ranked high. The threshold values for irradiation damage for stainless steels and alloy steels have been well studied and documented. Published information is available on the fluence necessary to induce measurable changes in material properties, including hardness and fracture toughness. Fluence calculations suggest that the threshold for diminished mechanical properties is unlikely to be reached even with extended storage periods.

Detection of radiation damage is typically conducted using sample coupon specimens that are placed in the system, then subsequently removed for mechanical testing. Nondestructive analyses to assess radiation damage of in-service systems are not typically performed. Neither of these methods is routinely used for dry cask storage systems. Neutron monitoring systems exist and are actively used at operating commercial nuclear power reactors, but such systems have not been used to monitor dry cask storage systems.

A6.5 Atmospheric Corrosion of Steel and Cast Iron Casks

Description of Degradation Phenomenon

Steel and cast iron casks and the closure bolts are protected from the environment with coatings and seals. Atmospheric or aqueous corrosion may occur if the coating systems are damaged or degrade over time and expose the underlying steel or cast iron casks. The corrosion process is likely to be intermittent and would only proceed during periods where there is sufficient water film thickness to support electrochemical corrosion reactions. In most cases corrosion would result in the formation of corrosion products on the casks surfaces. Atmospheric corrosion of steel and cast iron casks requires degradation of the protective coatings, seals, or weather covers. While this degradation phenomenon could occur during the initial license period, the degradation of the protective coating seals and weather covers is expected to increase with time. In addition, the accumulation of atmospheric deposits that promote corrosion in the presence of a stable aqueous phase on the cask surface is more likely to occur during extended storage (i.e., periods >40 years).

Synopsis of Previous Gap Assessments and Other Available Information

Hanson, et al. (2011) note that the existing designs contain many materials, such as carbon and low-alloy steels, which can readily undergo atmospheric corrosion. Hanson, et al. (2011) state that the likelihood of significant atmospheric corrosion is low presumably as a result of periodic maintenance and because significant time would be required to damage the thick-walled structure. Maintenance of protective coatings and seals is necessary to protect against atmospheric corrosion during extended storage.

Sindelar, et al. (2011) indicate that carbon steel, cast irons, and low allow steels used in bolted casks are protected from corrosion with coatings. Damage to these coatings may result in corrosion of the iron base alloys during extended storage. Perforation of the thick-walled iron base alloy casks is unlikely; however, periodic maintenance of the coatings is necessary to prevent this degradation. Sindelar, et al. (2011) suggest such degradation is easy to detect during inspection.

Extended storage of spent fuel in steel and cast iron bolted casks will likely result in some of the casks being exposed to conditions where atmospheric corrosion could occur if protective coatings are not properly maintained. Atmospheric corrosion will be expected to proceed at a relatively slow rate even in aggressive industrial or marine-type environments (McCuen and Albrecht, 1994).

NRC Staff Evaluation

Both Sindelar, et al. (2011) and Hanson, et al. (2011) suggest that maintenance of the coatings on the steel and cast iron casks are necessary to mitigate atmospheric corrosion. While Hanson, et al. (2011) indicate that significant atmospheric attack is unlikely, they indicate a need for additional research. However, Hanson, et al. (2011) have neither specific details on the type of research nor a description of the additional data that are needed.

Knowledge of the initiation, propagation, and expected degradation from atmospheric corrosion of steel and cast iron casks is ranked high. The conditions necessary for the initiation of atmospheric corrosion of steels and cast irons are well known. For the active degradation mode that would affect steel and cast iron storage casks, degradation or damage to protective coatings and the presence of water on the cask surfaces are necessary conditions. Propagation rates for atmospheric corrosion of steels and cast iron materials are well characterized. The expected degradation from atmospheric corrosion of the casks will be dependent on the location where corrosion is initiated and the timing of inspection and mitigation actions, such as the repair of damaged coatings, weather covers, and seals.

Inspection methods for atmospheric corrosion on exposed surfaces of the cast iron or steel casks are well established. Visual inspection is the principal method for exposed surfaces.

A6.6 Corrosion of Metallic Seals

Description of Degradation Phenomenon

The metallic seals may corrode if the protective barriers, including secondary polymer seals, fail and allow moisture to contact the seal material. The seal material and the composition of the aqueous environment will influence the corrosion rate and mode of degradation. While this degradation phenomenon has been observed during the initial licensing period, the degradation of the protective seals is expected to increase with time. In addition, the accumulation of atmospheric deposits that promote corrosion, the presence of a stable aqueous phase and corrosion of the metallic seals are more likely to occur during extended storage (i.e., periods >40 years).

Synopsis of Previous Gap Assessment

Hanson, et al. (2011) indicate that there are sufficient data to evaluate aqueous corrosion of the bolted casks. This assessment is based on the understanding that if installed seals and weather covers fail, moisture may accumulate through either condensation or precipitation events, leading to crevice corrosion and galvanic corrosion. Hanson, et al. (2011) also cite several examples of corrosion-related failures of storage casks from EPRI (2002). These include a CASTOR-X cask with galvanic corrosion of the secondary metallic seal due to the presence of chloride probably from residual cleaning fluid, and five TN-32 casks that experienced galvanic corrosion of the secondary metallic seal due to water leakage through the protective cover. The possibility of corrosion is greater in marine environment installations. Maintenance of protective coatings and seals are necessary to protect against corrosion of the seals during extended storage.

Sindelar, et al. (2011) indicate that the seal is positioned between the cask body and the cask lid and could be susceptible to crevice corrosion. Condensation may produce the moisture necessary for the corrosion reaction. The corrosion rate of the seal and how this will affect system performance are not easily predicted. Sindelar, et al. (2011) conclude that replacement of the metallic seals may be necessary at some point during extended storage.

NWTRB (2010) has a limited discussion of seal corrosion but states that there is a moderate risk for a failure of the seal and cites two reported cases of failure of secondary (outermost) gaskets due to corrosion. Although these incidents are not fully described, it is apparent that they are the CASTOR-X and TN-32 cases cited in Hanson, et al. (2011).

NRC Staff Evaluation

All three reports address the corrosion-related degradation of metallic seals and generally agree that this could be a significant degradation process that must be considered for bolted casks. Nevertheless, there are some notable differences in the recommendations in these reports. Hanson, et al. (2011) indicate that this degradation mode can be addressed by ensuring that the weather protection covers and seals are functioning correctly, which could be covered in aging management programs. Sindelar, et al. (2011) recommend testing to evaluate the combined effects of mechanical degradation and crevice corrosion, along with periodic surveillance and acceptance criteria for leak rate detection.

Knowledge of the initiation, propagation, and expected degradation from seal corrosion is ranked high. It is well understood that corrosion of the metallic seals will only occur if they are exposed to water, either from humid air or other aqueous solutions, such as residual water from cask loading operations trapped between the seal and the machined surface of the cask body. Tests with borated water (2500 ppm; as used in PWR spent fuel pools) with chloride contamination did not show evidence of corrosion on either stainless steel or silver used in the double jacket seals (Schubert, et al., 2007). If the secondary seals fail to function or degrade during storage, humid air can wet the metallic seal and potentially promote corrosion. The NRC staff expects that the extent of degradation of the protective secondary seals will increase with time. Mitigation actions, such as the periodic replacement of secondary seals, may be effective in preventing seal degradation. Factors that influence the corrosion rate are temperature, seal materials, galvanic effects, and the composition of the aqueous phase in contact with the seal material.

Direct inspection of metallic seals for evidence of corrosion is not routinely conducted by the licensees. However, monitoring of seal integrity is required. The general approach to seal monitoring is to pressurize the region between the redundant seals, with a nonreactive gas, to a pressure greater than that of the cask cavity and the atmosphere. A monitoring system is then used to measure this inter-seal pressure. A decrease in pressure between the seals indicates that the nonreactive gas is leaking, either into the cask cavity or out to the atmosphere (NRC, 2010). Corrosion that leads to a loss of seal performance is detected by the monitoring system as a decrease in pressure.

A6.7 Creep of Metallic Seals

Description of Degradation Phenomenon

The metallic seals are exposed to compressive loads and may also be exposed to elevated temperatures. Over long periods of time at elevated temperatures, the metallic seals on bolted casks may undergo creep. The creep of the metallic seals may, in turn, lead to a loss of sealing force between the cask body and the cask lid. Creep of the metallic seals will increase with time, but the rate of creep will decrease as the cask temperatures decrease. Consequently, the most significant creep degradation is expected to occur during the initial licensing period.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) indicate there are insufficient data to evaluate the creep of seals. This assessment was based on testing conducted in France, Germany, and Japan and suggests that the maximum operating temperature for metallic seals is dependent on seal materials. While the available data suggest that the metallic seals may perform adequately for decades, thermal excursions can promote creep of the metallic seal and the bolts. Creep of the metallic seal will result in loss of sealing force and could result in a breach of the confinement boundary. No specific recommendations are provided for inspection, data analyses, or additional testing.

Sindelar, et al. (2011) state that the performance of metallic seals is known to be a function of temperature and seal material. This assessment is based on research conducted in France (Sassoulas, et al., 2006) at the Federal Institute for Materials Research and Testing (BAM) in Berlin, Germany (Völzke and Wolff, 2010). Sindelar, et al. (2011) point out the difficulty in extrapolating short-term data over 100 years or more. Extrapolation of short-term data indicates that predicted seal performance is dependent on both temperature and seal materials. Silver jacketed seals retained a higher fraction of sealing force compared to seals with an aluminum jacket. Sindelar, et al. (2011) recommend periodic surveillance of dry casks for seal leakage and continuation of seal performance testing is recommended.

NRC Staff Evaluation

Sindelar, et al. (2011) and Hanson, et al. (2011) identify important ongoing testing and analyses conducted in France and Germany. Hanson, et al. (2011) also cite testing conducted in Japan from 1990 to 2010. Both Hanson, et al. (2011) and Sindelar, et al. (2011) conclude that additional data are needed to evaluate the creep degradation of metallic seals, although Sindelar, et al. (2011) did not explicitly consider the Japanese testing.

The level of knowledge on the initiation of creep degradation of metallic seals is ranked high because creep data from short-term testing at elevated temperatures can be used to assess thermal-mechanical degradation during the earlier, higher-temperature part of the storage period.

The level of knowledge of the propagation of creep damage to metallic seal materials is ranked medium. Long-term testing, which is in progress (Sassoulas, et al., 2006), will provide additional data to enable better predictions of long-term creep of metallic seals.

The level of knowledge for the expected effects of creep degradation of metallic seals is ranked high. Sufficient data exist to make initial long-term predictions of seal performance and degradation by creep. Additional long-term creep testing data, which are expected to be available as ongoing tests are completed, may be used to refine these predictions.

As with corrosion, direct inspection of metallic seals for evidence of creep is not routinely conducted by licensees. However, the monitoring system described in the previous section (using the overpressure of nonreactive gas between the two seals) would also detect any creep sufficient to cause the loss of overpressure between the seals.

A6.8 Degradation of Elastomeric Seals

Description of Degradation Phenomenon

Polymeric or elastomeric seals are used in bolted casks as secondary seals. These seals are designed to protect the primary metallic seals from a corrosive environment. Exposure to elevated temperatures and radiation will degrade polymeric materials. Both thermal-mechanical and radiation-induced degradation of elastomeric seals will increase with time, but the rate of degradation will decrease as the cask temperatures and radiation decrease. Consequently, the most significant degradation is expected to occur during the initial licensing period.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) indicate that there are sufficient data to evaluate the thermal-mechanical or radiation-induced degradation of elastomeric secondary seals. This assessment is based on the known performance of elastomeric materials under radiation and thermal exposures. Hanson, et al. (2011) indicate some studies conclude that thermal damage is far more significant than radiation damage. Hanson, et al. (2011) cite the previous NWTRB (2010) assessment and indicate that elastomer breakdown may also generate potentially corrosive decomposition products. Hanson, et al. (2011) do not recommend additional research or testing, but rather indicate remediation by replacement if elastometer degradation is detected.

Sindelar, et al. (2011) indicate elastomers used as seals have finite lifetimes and periodic replacement would likely be required for extended storage or prior to post-storage transportation. This assessment is based on multiple studies including degradation of o-ring seals in spent fuel transportation packages. The primary degradation mechanism for polymeric (elastomeric) seals exposed to an oxygen-bearing environment is oxidation, with oxidation enhanced by elevated temperature and radiation dose. While they identify no specific research or data needs, Sindelar, et al. (2011) suggest that characterization of degraded seals as methods become available may provide useful information to predict seal performance.

NWTRB (2010) states that radiation can cause degradation of elastomer seals and lead to embrittlement and that radiation and heat also can cause chemical breakdown, releasing corrosive decomposition products such as fluorine gas. No literature or previous studies are cited to support this assessment. NWTRB (2010) suggests that replacement schedules for elastomeric seals should be identified in the dry cask storage system Safety Analysis Report (SAR).

NRC Staff Evaluation

Hanson, et al. (2011), Sindelar, et al. (2011), and NWTRB (2010) do not consider the same information in assessing the degradation of elastomeric secondary seals but reach the same conclusion that these seals can be expected to degrade and will need to be replaced.
The level of knowledge for the initiation and propagation of elastomeric seal degradation is ranked high. Information on the factors that induce degradation of polymeric seal materials, including the effects of temperatures and radiation, is available. The immediate effects of polymeric seal degradation are limited because these are secondary seals. Knowledge of the expected effects of elastomeric seal degradation is ranked low. The scatter in available short-term data limit their use in predicting the expected degradation over long periods. Long-term consequences of secondary elastomer seal failure could include exposure of the primary seal to a corrosive environment.

Direct inspection of secondary elastomeric seals for evidence of degradation is not routinely conducted. However, performance of the primary metallic seals is monitored using the system described in the previous section (using the overpressure of nonreactive gas between the two seals). The monitoring system would detect degradation of the secondary elastomeric seals to the extent that it impacts performance of the outer primary metallic seal. Because redundant metallic seals are used, degradation of the outer primary metallic seal as a result of secondary elastomeric seal damage would be detected before the inner primary metallic seal degrades.

A6.9 Corrosion, Stress Corrosion Cracking, and Embrittlement of Bolts

Description of Degradation Phenomenon

Carbon steel and cast iron casks have numerous bolts that are installed with a torque sufficient to cause the metallic seal to contact and deform in a controlled manner against the cask body and the closure lid. The bolt materials vary and may include stainless steels, low alloy steels, and nickel alloys. The bolts are protected from the environment with covers and seals. The degradation or failure of these seals or covers will expose the bolts to the environment. Subsequent degradation processes will depend on the bolt material and the environment but may include stress corrosion cracking (SCC), galvanic corrosion, or embrittlement. For this degradation phenomenon to occur, the environmental conditions on the cask surface must change significantly. These changes include the deposition of critical surface concentrations of atmospheric deposits that promote corrosion or SCC; a decrease in cask temperature necessary for an aqueous phase to form by condensation or deliquescence; and degradation of protective covers and seals, which are more likely to occur during extended storage (i.e., periods >40 years).

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) briefly address SCC of bolts as part of the assessment of the aqueous corrosion of bolted casks, and conclude that there are sufficient data to evaluate aqueous corrosion of bolted casks, including the cask bolts. This assessment is based on the knowledge that bolted casks have occluded geometries around the bolts and seals, which can collect moisture as a result of condensation and result in crevice corrosion. Hanson, et al. (2011) state/conclude that the possibility of corrosion is greatest in marine environment installations.

Sindelar, et al. (2011) also indicate that the stainless steel bolts may be susceptible to stress corrosion cracking. Sindelar, et al. (2011) recommend periodic surveillance, additional analysis of sequential bolt failures, and periodic replacement of the bolts to assure confinement.

NRC Staff Evaluation

Hanson, et al. (2011) and Sindelar, et al. (2011) have limited information on SCC and embrittlement of cask bolts. Both reports agree that SCC of stainless steel bolts may be a plausible degradation mode.

Knowledge of the initiation, propagation of corrosion, SCC, or embrittlement of bolts is ranked medium. The corrosion mode will be dependent on the bolt material and the composition of the environment in contact with the cask. Initiation of these degradation modes requires degradation of the protective covers that protect the bolts. The rate of the degradation process is also dependent on many of the same factors, including materials, material interactions, evolution of the environment, and temperature, but could be bound with available information. These degradation processes may include corrosion or cracking of the bolts. The extent of degradation will be dependent on time and the active degradation process, cask designs, and materials and environmental conditions. Because of these uncertainties, knowledge of the expected degradation rate from SCC and embrittlement of cask bolts is ranked low.

Visual inspection of the seals and protective covers on the bolt is possible, but is not routinely conducted. Determination of the extent of bolt degradation varies with the degradation mode and the bolt material. Corrosion of low alloy steel bolts can be identified with simple visual inspection if protective covers are removed. Hydrogen uptake leading to embrittlement can also occur, but is not detected by simple visual inspection. SCC of stainless steel bolts may occur in marine environments. SCC degradation may be difficult to detect without more advanced inspection methods.

Significant degradation of the bolts, sufficient to cause increased seal leakage rates, can be detected by monitoring the pressure in the region between the redundant metallic seals, using the system described in the previous section.

A6.10 Creep and Thermal Fatigue of Bolts

Description of Degradation Phenomenon

The bolts used to seal the casks are exposed to tensile stresses and elevated temperatures. Over time at elevated temperatures, the bolts may undergo creep leading to a change in the bolt dimension and a decrease in the sealing force applied to the seal between the lid and the cask body. Daily and seasonal temperature variations may also lead to thermal fatigue of the bolts. Creep and thermal fatigue of cask bolts will increase with time, but the rate of degradation will decrease as the cask temperatures decrease. Consequently, the most significant degradation is expected to occur during the initial licensing period.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) indicate that there are insufficient data to evaluate the creep and thermal fatigue of bolts. Elevated temperature exposures and fluctuations in temperature can result in thermo-mechanical fatigue of the fasteners that may, in turn, promote crack initiation and failure of the fastener. Failure of the fasteners, which provide the sealing force necessary to maintain confinement, may lead to a loss of seal between the cask body and the cask closure lid. Evaluation of the possibility of creep and thermal fatigue requires analyses of the temperature profiles expected during extended storage including the drying operations.

Sindelar, et al. (2011) provide a very limited treatment of degradation of bolts and only consider creep degradation. No references or other supporting technical bases are provided. Sindelar, et al. (2011) recommend periodic surveillance, additional analysis of sequential bolt failures, and periodic replacement of the bolts to assure confinement.

NRC Staff Evaluation

The level of knowledge of initiation, propagation, and the expected effects of creep and thermal fatigue of bolts is ranked medium. To determine the susceptibility and degradation rate of bolts requires detailed information on material temperature variations and mechanical loading is needed. Because creep is a thermal process, the rate of creep degradation will decrease with time as the cask temperatures decrease. The expected effects for creep and thermal fatigue degradation, which may include changes in bolt dimensions, may be able to be determined given the bolt installation specifications and time-temperature history of the system.

Significant degradation of the bolts, sufficient to cause increased seal leakage rates, can be detected by monitoring the pressure in the region between the redundant metallic seals, using the system described in the previous section.

A7 NEUTRON SHIELDING

For most storage systems, the concrete overpack fulfills the neutron shielding function. Many dual-purpose systems also use borated polymers or resins, which combine hydrogen and oxygen as moderators with boron as an absorber, to achieve effective shielding. Borated polymers and resins are generally integrated within the cask body in a casing, protected from the external environment. A variety of polymers and resins are used, including polyethylene, polypropylene, and borated polymers. Each of these has its own unique properties, degradation mechanisms, and degradation rate under stressors. Neutron shielding is primarily designed to assist the radiological protection function by minimizing dose exposure outside the cask. The level of knowledge regarding the degradation mechanisms and the status of monitoring and inspection techniques is summarized in Table A7–1.

A7.1 Thermal Degradation of Neutron Shielding

Description of Degradation Phenomenon

Extended exposure to elevated temperatures may have various effects on material properties, including embrittlement, shrinkage, decomposition, and changes in physical configuration, such as chain scission, cross linking, and gas evolution. Embrittlement may lead to cracking, while shrinkage or decomposition could allow for local reduction in shielding performance. This type of degradation may compromise radiological protection functions. Thermal degradation of neutron shielding is operative in the short term (<40 years) when temperature is highest, but is not likely to be significant during extended storage as temperature decreases.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) indicate that thermal degradation of neutron shielding is highly material specific. Polyethylene rods may experience shrinkage, while other shielding materials experience loss of hydrogen at elevated temperatures. Lower degradation rates are expected during extended storage due to decreasing temperatures. Hanson, et al. (2011) call for additional data through accelerated thermal aging of various neutron shielding materials, but also notes that a decreasing neutron source term over time reduces the consequences of reduced shielding performance.

Table A7–1. Level of Knowledge and Monitoring Techniques—Neutron Shielding

Component	Degradation Phenomena	Level of Knowledge			Monitoring or Inspection Capability Available
		Initiation Time	Propagation Rate	Expected Effects	
Neutron shielding	Thermal degradation	M	M	M	No
	Poison depletion	H	H	H	No
	Radiation embrittlement	H	M	M	No
	Wet corrosion	M	M	M	No

H=High
M=Medium
L=Low

Sindelar, et al. (2011) indicate that periodic radiation surveying and monitoring could be used to detect gross loss of shielding. Gradual degradation may be difficult to detect. EPRI (2011) mentions embrittlement as a potential degradation issue, saying it may lead to minor loss of neutron shielding.

NRC Staff Evaluation

Hanson, et al. (2011) indicate that additional data on accelerated thermal aging of the various types of neutron shields would aid in evaluating their long-term behavior and that thermal embrittlement, cracking, shrinkage, and decomposition of neutron shields are likely during extended storage. Sindelar, et al. (2011) only briefly discuss thermal degradation of neutron shielding; this is limited to detection of the loss of shielding that can be performed using periodic surveys.

The level of knowledge of initiation time, propagation rate, and the effects of thermal degradation of neutron shielding is medium. Shrinkage and loss of hydrogen at elevated temperature is known to occur for polymeric shielding materials. Additional data may also be necessary to evaluate neutron shielding degradation of polymer materials in systems with high burnup and MOX fuels during extended storage to assess the effects of neutron shielding degradation on radiological protection functions.

Monitoring for gross loss of shielding can be performed by surveying radiation levels outside the dry cask system. The ability to monitor for gross loss of shielding mitigates to some extent the need for additional knowledge of the degradation of the shielding material.

A7.2 Poison Depletion of Neutron Shielding

Description of Degradation Phenomenon

Poison depletion may occur if the poison material is exposed to sufficient neutron fluence to result in a significant consumption of B-10 atoms. Depletion of neutron shielding could impact radiological protection functions. Such depletion, if it occurs, is more likely to be operative in the short term (<40 years), due to rapidly decreasing neutron flux levels over time. Note, however, that even early in storage, the neutron source in the stored fuel is low compared to in-reactor conditions (on the order of 10^8-10^9 n/s/MTU for high burnup SNF after 5 years out of the reactor, and several orders of magnitude less for low burnup SNF). Self-shielding by the fuel itself and the inner cask structures further reduces the neutron flux to the outer neutron shielding.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011), following EPRI (2002), state that extended storage will likely have an insignificant effect on the available neutron poison. Hanson also states that neutron radiation causes a negligible amount of neutron poison to be consumed during the first 20 years of storage, and the neutron flux decreases significantly with time.

NRC Staff Evaluation

Hanson, et al. (2011) state that an analysis of neutron source term as a function of extended storage demonstrates that poison depletion is insignificant. Information on the performance of the neutron shielding materials with high burnup and MOX fuels over extended periods is needed to confirm extrapolations from shorter timeframe analyses to ensure no significant poison depletion is possible.

The level of knowledge of initiation time, propagation rate, and expected effects of poison depletion of neutron shielding is high. Previous assessments have shown the amount of poison depletion over 20 years to be negligible (Dominion, 2002). With time, the neutron flux decreases and the rate of poison depletion will also decrease.

Monitoring for gross loss of shielding can be performed by surveying radiation levels outside the dry cask system. The ability to monitor for gross loss of shielding mitigates to some extent the need for additional knowledge of the degradation of the shielding material.

A7.3 Radiation Embrittlement of Neutron Shielding

Description of Degradation Phenomenon

Embrittlement of neutron shielding materials may occur under exposure to neutron radiation. Embrittlement reduces ductility, fracture toughness, and resistance to cracking. Radiation embrittlement leading to cracking may affect radiological protection functions of the neutron shielding. Radiation embrittlement of neutron shielding could occur throughout the period of spent fuel storage. The rate of damage will be greatest in the short term (<40 years), when radiation levels are highest, and decrease during extended storage as radiation levels decrease.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) indicate that embrittlement of polymeric neutron shields is expected during extended storage. The threshold for radiation embrittlement is 10^6 rad for polyethylene and even less for polytetrafluoroethylene (PTFE) (EPRI, 2002). These thresholds can be reached within 10 to 100 years of storage depending on the initial fuel condition (EPRI, 2002). Neutron radiation levels during extended storage require further analysis to determine expected radiation exposure. Hanson, et al. (2011) also note that decreasing neutron source term over time reduces the consequences of reduced shielding performance during extended storage.

Sindelar, et al. (2011) observe that radiation effects are very sensitive to dose rate and the presence of reactive species, making polymer performance very application specific. Radiation may cause polymer chain scission, reducing molecular weight and resistance to creep. Polymer crosslinking may also occur, which increases molecular weight, hardness, and resistance to creep.

EPRI (2011) states that embrittlement is a potential degradation issue that may lead to minor loss of neutron shielding.

NRC Staff Evaluation

Hanson, et al. (2011), Sindelar, et al. (2011), and EPRI (2011) provide a limited assessment of the effects of radiation embrittlement on polymeric neutron shielding materials. Since the radiation levels encountered during extended storage may exceed the threshold dose (EPRI, 1998, 2002), radiation embrittlement is a likely phenomenon. Embrittlement of polymeric neutron shielding material needs to be assessed as a function of radiation exposure (including gamma ray effects) and temperature in order to predict performance of the shielding materials during extended storage. This assessment should also include the expected neutron source term for high burnup and MOX fuels to assess the significance of potential cracking or loss of shielding during extended storage.

The level of knowledge of initiation time is high because threshold data on radiation embrittlement are available for polymeric neutron shielding materials. The level of knowledge of propagation rate and the effects of embrittlement on neutron shields are medium. Additional information on the neutron source term, as well as data at radiation fluence values beyond initiation of embrittlement, is needed to determine whether radiation embrittlement will diminish the function of the neutron shield materials.

Monitoring for gross loss of shielding can be performed by surveying radiation levels outside the dry cask system. The ability to monitor for gross loss of shielding mitigates to some extent the need for additional knowledge of the degradation of the shielding material.

A7.4 Wet Corrosion of Neutron Shielding

Description of Degradation Phenomenon

Wet corrosion would only occur if moisture and oxygen are present in the environment of the neutron-shielding material. Such a condition is not expected in the normal assembly and production of dry cask storage systems. If the cask is damaged by undetected defects in assembly or degradation in service, the rate and amount of corrosion that can occur would be dependent on the amount of moisture and oxygen present. Significant corrosion of the neutron shielding may affect radiological protection functions. Wet corrosion of neutron shielding may be operative in the short term and during extended storage.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) indicate that the amount of oxygen present in the neutron-shielding environment is the key parameter for corrosion of neutron shielding. Lack of oxygen is anticipated to reduce corrosion rate during long-term storage, but leaks in the neutron shield casing could provide additional oxygen. Corrosion rate of neutron shields as a function of oxygen presence and temperature must be analyzed, but decreasing neutron source term over time reduces the significance of reduced shielding performance during extended storage.

Sindelar, et al. (2011) indicated that periodic radiation surveying and monitoring should be used to detect loss of shielding. EPRI (2011) mentions oxidation as a potential degradation issue, saying it may lead to local degradation of neutron shielding.

NRC Staff Evaluation

Hanson, et al. (2011) and EPRI (2011) generally agree and indicate that corrosion of neutron shields is a function of oxygen presence and temperature. Hanson, et al. (2011) describe additional analysis necessary to evaluate neutron shield corrosion, whereas Sindelar, et al. (2011) describe only surveying to assess degradation. While corrosion of the neutron shields is possible during extended storage, the expected decrease in the neutron source term over time decreases the significance of neutron shield degradation.

The level of knowledge of initiation time, propagation rate, and the expected effects of corrosion of neutron shielding is medium. Available information indicates that oxygen and moisture are the most important parameters for corrosion of the neutron shields. Systems that use polymeric shielding material are designed so that these materials are not exposed to environmental moisture. A more complete assessment of wet corrosion of neutron shielding over extended storage periods would require consideration of the likelihood of leaks through the shield casing, as well as additional knowledge of the corrosion rate as a function of temperature, oxygen, and moisture content (including the effects of moisture radiolysis).

Monitoring for gross loss of shielding can be performed by surveying radiation levels outside the dry cask system. The ability to monitor for gross loss of shielding mitigates to some extent the need for additional knowledge of the degradation of the shielding material.

A8 CONCRETE OVERPACKS, VAULTS, AND PADS

Degradation mechanisms considered for concrete components include cracking, spallation, rebar corrosion, chemical degradation, and radiation damage. The level of knowledge regarding the degradation mechanisms and the status of monitoring and inspection techniques is summarized in Table A8–1. For many of the degradation mechanisms in Table A8–1, the level of knowledge for the expected effects is ranked as low (L). That is because there are no mathematical degradation models developed to explain the degradation process. The reports by NWTRB (2010), Hanson, et al. (2011), and Sindelar, et al. (2011) are in general agreement on the technical bases and supporting information for these concrete degradation processes. In addition, the report by EPRI (2002) generally agrees that inspection and maintenance programs are necessary to maintain concrete components.

Many of the degradation mechanisms listed in Table A8–1 result in visible cracking or spalling of the concrete. Although more advanced methods such as petrographic examination are often necessary to determine the operative degradation mechanism(s), visual examination of

Table A8–1. Level of Knowledge and Monitoring Techniques—Concrete Overpacks, Vaults, and Pads

Component	Degradation Phenomena	Level of Knowledge			Monitoring or Inspection Capability Available
		Initiation Time	Propagation Rate	Expected Degradation	
Concrete overpacks, vaults, and pads	Shrinkage cracking	H	H	H	Visual observation
	Creep	H	H	H	Visual observation
	Fatigue	H	H	H	Visual observation
	Rebar corrosion	M	M	L	Visual observation Electrochemical monitoring
	Carbonation	M	M	L	Visual observation Core sample testing
	Leaching	H	H	M	Visual observation
	Sulfate attack	H	H	M	Visual observation Petrographic examination
	Alkali-silica reaction	H	L	L	Visual observation Petrographic examination
	Radiation damage	H	M	M	Visual observation Shield testing and radiation measurements
	Freeze-thaw	H	M	M	Visual observation Petrographic examination
	Thermal dryout	M	M	M	Testing required to assess degradation
	Thermal degradation of mechanical properties	M	M	L	Testing required to assess degradation
	Coupled mechanisms	M	L	L	Visual observation Petrographic examination

H=High
M=Medium
L=Low

concrete is an effective non-destructive evaluation (NDE) method to assess the condition of the concrete and to detect evidence of aging and degradation. Visual inspection is applicable for many concrete structures, systems, and components used for dry cask storage. However, some concrete components such as steel-encased concrete overpacks, sub-grade concrete structures, and the interior concrete surfaces in storage vaults are not amenable to simple visual inspection.

A8.1 Shrinkage Cracking

Description of Degradation Phenomenon

Autogeneous volume changes are associates with cement hydration alone and do not include environmental effects due to variation in moisture and temperature. This autogeneous volume change is usually small, generally less than 100 microstrain expansion or shrinkage. Drying shrinkage occurs when normal weight hardened concrete is dried from a saturated condition to a state of equilibrium with air at 50 percent relative humidity. The shrinkage associated with moisture loss is in the range of 400 to 800 microstrain. Among the more important factors influencing the drying shrinkage of concrete are the content of the cement paste, the water-cement ratio, the degree of hydration, the elastic modulus of aggregate, the amount and characteristics of the admixtures used, the time and relative humidity of the exposure, the size and shape of the concrete mass, and the amount and distribution of internal reinforcement.

Synopsis of Previous Gap Assessments

NWTRB (2010), Hanson, et al. (2011), and Sindelar, et al. (2011) agree that shrinkage cracking happens early after concrete placement and can be controlled through concrete formulation and placement practices. All of these reports indicate that shrinkage is not expected to be a significant issue for extended storage.

NRC Staff Evaluation

NWTRB (2010), Hanson, et al. (2011),and Sindelar, et al. (2011) all agree that shrinkage cracking is not expected to be a degradation issue over extended storage times.

Knowledge of the initiation time, propagation rate, and the expected effects of damage from shrinkage cracking is high, from extensive experience with concrete in many similar applications. Minor cracking can occur early after concrete placement. Shrinkage happens mainly in the first few years after concrete is placed. Once the majority of shrinkage has occurred, additional shrinkage cracking does not occur.

A8.2 Creep

Description of Degradation Phenomenon

Creep is the time-dependent increase in strain resulting from force. Creep in concrete is a property of the paste. The cement paste exhibits creep due to its porous structure and a large internal surface area that is sensitive to water movements. The aging of concrete in which the cement pastes continue hydration means that the cement paste continues hydration (i.e., the pore structure and elastic properties are changing over time or with age). Although creep is a paste property, aggregates substantially reduce the creep in concrete. Because creep is a long-term phenomenon, the degradation is also operative for the long term.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) indicate that creep is time-dependent deformation of the concrete and is significant when new concrete is subjected to load. The creep rate decreases exponentially with time. Creep degradation, if it occurs, will result in small cracks at the aggregate-cement interface.

NWTRB (2010) includes an assessment of concrete creep as a result of elevated temperature exposure. Creep is identified as a possible degradation mechanism for concrete in close proximity to fuel, particularly if natural cooling systems are plugged and fail to function properly.

NRC Staff Evaluation

Knowledge on the initiation time, propagation rate, and the expected effects of creep are high, from extensive experience with concrete in many similar applications. A properly designed concrete structure will have limited creep early in its lifetime, and the creep rate will decrease with time. Degradation of concrete from creep will be limited to superficial cracks in the concrete that will not compromise structural integrity of concrete function.

A8.3 Fatigue Behavior of Concrete

Description of Degradation Phenomenon

Fatigue strength is the greatest stress that the concrete can sustain without failure for a given number of stress cycles. In structural applications such as bridge decks and pavements, concrete members are subjected to repeated applications of loads at a level below the ultimate strength of concrete. In dry cask storage, repeated thermal cycles and differential temperatures are the applicable stressor, rather than repeated loading. The relatively reduced magnitude of thermal changes compared to cyclic loads suggest that effects of this degradation mechanism for concrete casks and pads are likely to be minor and operative only in the long term, if they occur at all.

Synopsis of Previous Gap Assessments

Fatigue behavior of concrete is not addressed in NWTRB (2010), Hanson, et al. (2011), or Sindelar, et al. (2011).

NRC Staff Evaluation

The NRC staff considers that fatigue of the concrete structures in spent fuel storage installations is unlikely. The concrete pads are designed for significant loads and are adequately reinforced for those loads. Concrete structures that provide shielding are either very thick and reinforced or encased in steel.

The level of knowledge for the initiation time, propagation rate, and the expected effects of fatigue on concrete is high, from extensive experience with concrete in many similar applications. The concrete structures in spent fuel storage are not subjected to the same loading that results in fatigue in other civil engineering structures.

A8.4 Corrosion of Reinforcing Steel

Description of Degradation Phenomenon

Corrosion of steel embedded within cement-based materials is an electrochemical process that leads to the formation of corrosion products with larger volumes than the parent metal. The volumetric expansion can cause extensive degradation and, possibly, cracking of the cement-based material. Corrosion of the steel can arise from (i) a general breakdown of the passive oxide film protecting the metal surface resulting from a reduction in the pH of the cement pore solution, predominantly through carbonation, or (ii) a localized breakdown of the passive film by accumulation of chloride ions at the metal surface. As corrosion progresses and iron reacts to form ferrous and ferric oxides, the significant increase in volume (by a factor of two to six) can result in pressure buildup at the cement–metal interface, which ultimately could exceed the tensile strength of the cement-based material and cause cracking, spalling, and delaminating of the material.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) indicate that corrosion of reinforcing steel has been extensively studied and that construction practices can minimize the risk of reinforcement corrosion. Corrosion of reinforcement is inevitable in environments where aggressive ion exposure occurs; however, the induction time for initiation can be significant. Consequently, Hanson et al. (2011) recommend corrosion of reinforcement should be addressed though inspection and aging management.

Sindelar, et al. (2011) indicate that the time for the initiation of rebar corrosion may be greater than 100 years using recommended construction practices. Sindelar, et al. (2011) indicate that models to predict degradation are not available and not practical. As such, Sindelar, et al. (2011) recommend development of visual assessment methods.

NWTRB (2010) indicates that corrosion of reinforcement is influenced by the quality of concrete, depth of concrete cover over steel, and the permeability of concrete. No mitigation strategies are discussed.

NRC Staff Evaluation

NWTRB (2010), Hanson, et al. (2011), and Sindelar, et al. (2011) generally agree on the causes of rebar corrosion and the factors that influence the corrosion process. Both Sindelar, et al. (2011) and Hanson, et al. (2011) recommend inspection to identify corrosion-related issues and presumably initiate appropriate mitigation actions.

The level of knowledge of the initiation time and propagation rate of rebar corrosion is medium because concrete quality, concrete cover thickness and environmental parameters are known factors for the initiation of rebar corrosion. The level of knowledge of the expected effects of rebar corrosion is low. Predicting damage from rebar corrosion is difficult because the corrosion process degrades the structure in an inconsistent manner. Cracks formed in the concrete can also act as fast diffusion paths for aggressive chemical species. Depending on the conditions mentioned earlier, rebar corrosion may occur at any time during the working lifetime of the concrete.

A8.5 Carbonation

Description of Degradation Phenomenon

Carbonation involves the reaction of dissolved carbonate species, originating mainly from atmospheric CO_2 with the cement. Carbonation is classified into two types according to mechanism (i) carbonation through the gas phase and (ii) carbonation through the aqueous phase. Both types of carbonation involve the interaction of the cement-based material with an aqueous phase. Carbonation through the gas phase involves the reaction of CO_2 with the calcium component of the cement, resulting in the precipitation of calcium carbonate. Moisture is an important factor in carbonation. Studies have indicated that carbonation does not occur in dry cement or cement at 100 percent relative humidity. At 100 percent relative humidity, the moisture blocks carbon dioxide from passing through the pores. The optimum conditions for carbonation appear to be about 50 percent relative humidity. Carbonation reaction consumes calcium hydroxide in the concrete, destroys the passivation effect of calcium hydroxide in preventing the corrosion of reinforcing steel, and lowers the pH to a point where corrosion readily occurs. Carbonation also causes shrinkage of the cement paste that may produce cracking or surface crazing of concrete. Carbonation often acts in concert with other degradation mechanisms, such as chemical attack or freeze-thaw action. Carbonation through the aqueous phase is characterized by rapid dissolution of the cement matrix, often with comparatively little accumulation of solid calcium carbonate, and is discussed in Section A8.6.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) indicate that the significance of carbonation, as well as the chemical degradation processes for concrete, requires an understanding of the dry cask storage systems environment. They conclude that unless the overpack is exposed to potentially aggressive species, degradation of concrete strength due to chemical attack is insignificant. When such conditions are discovered, an enhanced monitoring program is necessary to manage the degradation mechanism. Sindelar, et al. (2011) state that carbonation is expected to occur in concrete and penetrate to depths of the reinforcement steel well within the exposure time of 300 years, although carbonation rates depend strongly on concrete quality and environmental conditions. Sindelar, et al. (2011) recommend monitoring and inspection as well as development of NDE methods to detect carbonation. NWTRB (2010) describes carbonation along with other chemical attack mechanisms, but does not assess the significance of this degradation mode for concrete components used in spent fuel storage.

NRC Staff Evaluation

Hanson, et al. (2011) and Sindelar, et al. (2011) generally agree that carbonation is a potential degradation mode for concrete structure and must be addressed though monitoring.

The level of knowledge on the initiation time and propagation rate of carbonation is medium. The factors that affect carbonation in concrete are known, and the depth of carbonation in aged concrete structures has been characterized. Knowledge of the expected effects of carbonation is low, because modeling of carbonation and some other concrete degradation modes is straightforward only until that degradation results in the formation of significant cracks. Predictions thereafter are difficult, as the system becomes more complex. Cracks act as fast pathways for further carbonation within the damaged structure, which can then accelerate further degradation of concrete and supporting rebar. The uncertainty in the distribution of cracks leads to uncertainty in where and how uniformly degradation will proceed in a given structure. Depending on the extent of the conditions that promote carbonation, concrete carbonation may occur at any time during the working lifetime of the concrete. Inspection and monitoring are the best methods to address potential degradation from carbonation.

A8.6 Leaching

Description of Degradation Phenomenon

Concrete exposed to water is subject to leaching and the deposition of mineral deposits. Leaching and deposition are related effects produced by the dissolution and precipitation of minerals in water from any source, including groundwater, surface water, or water contained in or transported by concrete structures. The deposition of mineral deposits includes both scaling and the formation of encrustation and efflorescence. Scale deposits are generally hard, layered precipitates of calcium sulfate, calcium carbonate, or magnesium salts. Efflorescence occurs when water containing dissolved minerals migrates through concrete and subsequently evaporates on exposed surfaces leaving behind a white powdery deposit of calcium salts. Leaching may erode concrete if water migrates through porous pastes, cracks, or joints in the concrete structure. The principal constituent of concrete that is present with leaching or mineral deposition is $Ca(OH)_2$ (calcium hydroxide). $Ca(OH)_2$ is soluble to a certain extent in water and is the main cement hydration product susceptible to leaching. The degradation is operative for both the short and long term as long as the conditions for it occurring, as discussed previously, are in play.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) indicate that leaching is a well-characterized degradation mechanism. Leaching occurs only if water passes through the concrete, and that leaching may be minimized by using low permeability concrete and by preventing flowing or ponded water. Because calcium hydroxide leaching occurs on the surface of the concrete, it may be easily monitored. Sindelar, et al. (2011) indicate calcium leaching is a slow process compared to carbonation and is insignificant for the concrete in the pad or cask of dry cask storage systems. Models for the several coupled processes involved in calcium leaching from cement hydrates have been developed. NWTRB (2010) indicates concrete that is exposed to groundwater also may be susceptible to calcium hydroxide leaching, but this damage may not be discoverable unless soil is removed for inspection. The significance of this degradation mode for concrete components used in spent fuel storage was not assessed.

NRC Staff Evaluation

Hanson, et al. (2011) and Sindelar, et al. (2011) generally agree that calcium leaching from concrete is expected to be insignificant.

The level of knowledge of the initiation time, propagation rate, and expected effects of calcium leaching is high. This degradation mechanism is well characterized. Concrete components in spent fuel storage are not exposed to running water. The rate of leaching is slow compared to other degradation mechanisms, and the effects of leaching, if it occurs, are visibly apparent.

A8.7 Sulfate Attack

Description of Degradation Phenomenon

Sulfate attack is a process whereby sulfate ions in solution chemically react with compounds present in hydrated cement. This process can lead to disruptive expansion, strength loss, and/or disintegration, depending on the circumstances. For cement-based materials buried in soils, sulfate attack can be a common form of degradation because sulfates of sodium, potassium, calcium, and magnesium occur in groundwater and soil pore waters naturally or from anthropogenic sources. The attack is particularly prevalent in arid regions where naturally occurring sulfate minerals are present in the water and in the ground contacting the structures. The severity of the attack can be affected by the presence of other dissolved substances in the water, but generally increases as the concentration of sulfates in the water increases and becomes even more severe if the concrete is subjected to frequently alternating periods of wetting and drying. Concrete exposed to dry sulfate-bearing soils will not be attacked. Sometimes the source of sulfate attack on concrete may come from minerals in the aggregates, sulfates dissolved in the mix water, admixtures or additives, and possibly sulfates in the Portland cement. One form of sulfate attack is delayed ettringite formation (DEF), an internal sulfate degradation. DEF is believed to be a result of improper heat curing of the concrete where the normal ettringite formation is suppressed. It occurs in concrete that has been cured at elevated temperatures (e.g., where steam curing has been used). It can also occur in large concrete pours where the heat of hydration has resulted in high temperatures within the concrete. The sulfate concentration in the pore liquid is high for an unusually long period of time in the hardened concrete. Eventually, the sulfate reacts with calcium- and aluminium-containing phases of the cement paste and the cement paste expands. Due to this expansion, empty cracks (gaps) are formed around aggregates. The cracks may remain empty or later be partly or even completely filled with ettringite. The degradation is operative for both the short and long term as long as the conditions for it occurring, as discussed previously, are in play.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) indicate that significance of sulfate attack, as well as chemical degradation processes for concrete, requires an understanding of the dry cask storage system environment. Unless the overpack is exposed to potentially aggressive species, degradation of concrete strength due to chemical attack is insignificant. When such conditions are discovered, an enhanced monitoring program is necessary to manage the degradation mechanism.

Sindelar, et al. (2011) indicate acid rain and industrial environments may increase the sulfate concentration and promote sulfate ingress; however, even in industrial environments, sulfate ingress is slow relative to carbonation and therefore it is not considered to be the primary degradation mechanism to concrete degradation during extended storage. Sindelar, et al. (2011) suggest that tests to evaluate carbonation should include evaluation of sulfate ingress.

NWTRB (2010) indicates that sulfate attack increases the porosity and permeability of concrete and decreases density and compressive strength. Sulfate attack produces expansive reaction products that can lead to spalling, cracking, and loss of strength. For concrete that is obscured from view, soil sulfate attack may not be noticeable until damage is significant. The significance of this degradation mode for concrete components used in spent fuel storage was not assessed.

NRC Staff Evaluation

Hanson, et al. (2011) and Sindelar, et al. (2011) agree that sulfate attack is not likely to cause significant degradation during extended storage and that this degradation mode can be managed through inspection and remediation or mitigation.

The level of knowledge of the initiation time and propagation rate of sulfate attack is high. The conditions under which sulfate attack can occur are well known, and the rate of degradation is known to be less than other chemical degradation processes. The level of knowledge of the expected effects of sulfate attack is medium. The extent of damage will depend on the design of the structure, the concrete quality, and the source of sulfate.

A8.8 Alkali-Silica Reactions

Description of Degradation Phenomenon

Alkali-silica reaction (ASR) can cause serious expansion and cracking in concrete, resulting in major structural problems. ASR is the most common form of alkali-aggregate reaction (AAR) in concrete; the other, much less common, form is alkali-carbonate reaction (ACR). ASR and ACR are therefore both subsets of AAR. ASR is caused by a reaction between the hydroxyl ions in the alkaline cement pore solution in the concrete and reactive forms of silica in the aggregate (e.g., chert, quartzite, opal, strained quartz crystals). The chemical reaction produces a gel which increases in volume by taking up water. This volume increase exerts an expansive pressure, resulting in concrete failure. In unrestrained concrete (that is, without any reinforcement), ASR causes characteristic map cracking. The conditions required for ASR to occur are (i) a sufficiently high alkali content of the cement (or alkali from other sources); (ii) a reactive aggregate, such as chert; and (iii) water. ASR will not occur if there is no available water in the concrete, because alkali-silica gel formation requires water. The degradation is operative for both the short and long term as long as the conditions for it occurring, as discussed previously, are in play. Over time, reactivity decreases and the process ceases, but the time scale is uncertain. The challenge is to determine the state of the reactivity (whether continuing and at what rate, or ceased), model the process, and predict the remaining service life of the structure.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) indicate that the characteristics of aggregates that are vulnerable to detrimental reactions with alkali species within the concrete are fairly well defined and that standards currently exist to identify and select aggregate materials resistant to this class of reactions. In addition, Hanson, et al. (2011) indicate that the risk of alkali-aggregate reactions is largely based on site-specific aggregate used in the cement formulation and on the external environment. Assessment of the risk of this degradation mechanism requires that all of these factors be appropriately evaluated. If alkali-silica reactions occur, the resulting degradation is often cracking that can be identified with visual inspection.

Sindelar, et al. (2011) indicate that alkali-silica reactions are not anticipated to be significant concrete degradation mechanisms during extended storage. Nondestructive field testing to demonstrate the lack of alkali-silica reactions in concrete structures can be performed. NWTRB (2010) indicates that most reactive aggregates have been identified in the construction industry and should be avoided.

NRC Staff Evaluation

Hanson, et al. (2011), Sindelar, et al. (2011), and NWTRB (2010) agree that alkali-silica reactions are well known and can be avoided by testing of aggregates prior to their use in concrete. These assessments are based on significant civil engineering experience. Recent operating experience has revealed, unexpected degradation of the concrete in the Seabrook reactor containment as a result of alkali-silica reactions (NRC, 2011a). This case points out that proper selection of the aggregate, using the most current and restrictive industry standards, is necessary to avoid detrimental alkali-silica reactions.

The level of knowledge of the initiation time for alkali-silica reactions is high. Factors that affect alkali-silica reaction susceptibility are known, and standards exist for testing to avoiding the use of reactive aggregates. The level of knowledge for the propagation rate of alkali-silica reactions is medium. Once degradation by alkali-silica reaction has been identified, structural damage has typically already occurred. Analysis of the concrete in these cases can provide information on the future extent of propagation or determine whether the reaction is complete. The level of knowledge for the expected effects of alkali-silica reactions is low. While some assessment can be made in cases where alkali-silica reactions have been identified, this reaction results in the formation of destructive cracks that can also provide pathways for other chemical degradation processes. As with other concrete degradation processes, inspection and monitoring are important for early detection.

A8.9 Radiation Effects on Concrete

Description of Degradation Phenomenon

Irradiation of concrete causes dissociation of water into its hydrogen and oxygen components. Compressive and rupture strengths decrease somewhat due to radiation exposure and high temperatures, although the effect is tolerable under normal reactor conditions. Generally, concrete is considered stable under compressive loads until 10^{20} neutrons/cm^2 or 10^{10} rad of gamma, but the tensile properties begin to degrade after about 10^{19} neutrons/cm^2. However, all effects on concrete due to radiation are too slight to reliably measure because of the gross effects of the increased temperature during exposure.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) indicate that the effects of radiation exposure on the chemical and physical properties of concrete have been extensively studied. While no additional assessments appear to be required, Hanson, et al. (2011) state that radiation exposures associated with high burnup fuel and longer licensing periods must be assessed to validate the conclusion that irradiation remains an insignificant aging mechanism. Sindelar, et al. (2011) indicate that concrete is considered stable until 10^{20} neutrons/cm^2 or 10^{10} rad of gamma. Tensile properties may begin to degrade after about 10^{19} neutrons/cm^2. The total exposure anticipated for concrete shielding structures containing high burnup MOX fuel is less than 10^{20} neutrons/cm^2. NWTRB (2010) indicates that under typical dry storage conditions, the energy flux is negligible and decreases with time, making this radiation damage insignificant.

NRC Staff Evaluation

NWTRB (2010), Hanson, et al. (2011), and Sindelar, et al. (2011) agree that radiation damage to concrete is insignificant for extended storage.

The level of knowledge of the initiation of radiation damage to concrete is high. The neutron and gamma fluence necessary to initiate damage are well characterized. The level of knowledge of the propagation rate and the expected effects of radiation damage are medium. Some data at fluence values greater than the initiation threshold are available along with assessment of the effects of increased exposure.

A8.10 Freeze-Thaw Degradation

Description of Degradation Phenomenon

A severe exposure condition of Portland cement concrete is exposure to freezing and thawing cycles. The typical deterioration of concrete exposed to freeze-thaw conditions is random cracking and surface scaling (due to lack of adequately entrained air), or joint deterioration (due to cracking, primarily related to nondurable aggregate). Since the 1930s, air entrainment has been used to enhance the freeze-thaw resistance of Portland cement concrete exposed to an external environment. The general mechanism by which air entrainment improves concrete durability in freezing and thawing exposures is as follows: when water in the concrete freezes, it expands; this water movement generates pressures that, when they exceed the tensile strength of concrete or mortar layer at a surface, can cause cracking and scaling. Concrete has to be critically saturated (>91 percent), which is generally true for concrete surfaces. Entrained air bubbles are microscopic in size, evenly distributed in the paste fraction, and take on water during the freezing cycle to relieve pressure buildup. Generally, an air entrainment of 4 to 8 percent and, more importantly, an air bubble spacing factor of less than 0.25 mm [0.01 in] provides satisfactory freeze-thaw performance under most conditions. The degradation is operative for both the short and long term as long as the conditions for it occurring, as discussed previously, are in play.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011), and Sindelar, et al. (2011), indicate that freeze-thaw is a well-studied degradation mechanism and is of concern only under environmental conditions that result in significant freeze-thaw cycling combined with a high availability of water. NWTRB (2010) indicates that primary parameters that affect the occurrence of such degradation in concrete include the air content of concrete and the number, size, and distribution of the pores in the concrete aggregate. The location of dry cask storage systems is a major deciding factor as to whether this degradation mode is significant. Based on the information currently available, recent concrete damage at the TMI-2 fuel ISFSI at Idaho National Laboratory appears to be a result of water collecting in unprotected roof bolt holes (NRC, 2011b). Hanson, et al. (2011) also point out that proper design and construction practices identified by the American Concrete Institute (ACI), including 301 (ACI, 2010), 318 (ACI 2011), and 349 (ACI, 2006), effectively eliminate this degradation mode. Proper material selection, following ASTM standard C33 (ASTM, 2011), can also help eliminate freeze-thaw damage

NRC Staff Evaluation

Hanson, et al. (2011) and Sindelar, et al. (2011) agree that freeze-thaw can be addressed through proper concrete structure design and material selection. Both Hanson, et al. (2011) and Sindelar, et al. (2011) recommend a program of inspection for evidence of freeze thaw damage and replacement. Sindelar, et al. (2011) also advocate investigating new NDE methods that may be used to detect freeze-thaw damage. NWTRB (2010) reaches a much different conclusion, which indicates freeze-thaw may be a significant issue for concrete storage casks stored when the SNF heat load has dissipated. NWTRB (2010) contains no recommended actions for preventing or addressing freeze-thaw damage.

The level of knowledge of the initiation of freeze-thaw damage is high. Freeze-thaw damage only occurs in climates with freezing temperatures and high water availability. Concrete parameters that must be controlled to prevent freeze-thaw damage are well known. The level of knowledge on the expected extent of degradation from freeze-thaw damage is medium. Concrete structures that are susceptible have either design or material deficiencies. Freeze-thaw degradation is also weather dependent, so not all sites are equally susceptible.

A8.11 Temperature Effects on Concrete

Description of Degradation Phenomenon

Concrete structures are not typically used in elevated temperature applications. Exposure to elevated temperatures can degrade concrete strength. The ASME boiler and pressure vessel code (ASME, 2011, Section III, Division II), as well as ACI–349 (ACI, 2006), give an upper temperature limit for concrete of 65 °C [149 °F]. At elevated temperatures, concrete dryout can occur by diffusive transport of water. The rate of dryout increases significantly above 100 °C [212 °F]. Concrete dryout reduces concrete strength, making the structure susceptible to cracking and potentially other chemical degradation processes. At temperatures above 200 °C [392 °F], the increased pore pressure caused by vaporization of pore water can lead to spalling of the concrete.

Concrete subjected to heat undergoes a number of transformations and reactions, even if there is only a moderate increase in temperature. As aggregate materials normally occupy 65 to 75 percent of the concrete volume, aggregate type strongly influences the behavior of concrete at elevated temperature. Commonly used aggregate materials are thermally stable up to 300–350 °C [572–662 °F]. Aggregate characteristics of importance to concrete behavior at elevated temperature include physical properties (e.g., thermal conductivity and thermal expansion), chemical properties (e.g., chemical stability at temperature), and thermal stability/integrity. Some aggregate materials may undergo crystal transformations, significantly increasing volume between 500 and 650 °C [932 and 1202 °F]. Some siliceous or calcareous aggregates with some water of constitution exhibit moderate dehydration with increasing temperature that is accompanied by shrinkage. Most nonsiliceous aggregates are stable up to 600 °C [1,112 °F]. Apart from the crystalline transformations occurring mainly in the aggregate materials during heating, a number of degradation reactions occur, primarily in the cement paste, that result in a progressive breakdown in the concrete structure. A temperature increase produces significant changes in the chemical composition and microstructure of the hardened Portland cement paste. At low temperatures these reactions mainly take the form of dehydration and water expulsion reactions. Changes in the chemical composition and microstructure of the hardened Portland cement paste occur gradually and continuously over a temperature range from room temperature to 1,000 °C [1,832 °F]. Any degradation due to temperature effects, if possible, would be operative only in the short term.

In dry cask storage, spent fuel assemblies are typically placed in steel canisters that are surrounded by a heavy shielding shell of reinforced concrete. Vents in the shell allow air to flow through to the wall of the canister and remove heat. If the vents become blocked, the temperatures at the concrete surface will rise. Concrete will then be subject to these higher temperature effects as noted in the previous discussion on temperature effects on concrete. The effects of degradation will be manifest, if at all, only in the short term until air circulation is restored.

Synopsis of Previous Gap Assessments

Hanson, et al. (2011) indicate that concrete in dry cask storage systems is anticipated to be less than 93 °C [200 °F]. Under these conditions, elevated temperature exposure is expected to be limited to dryout, which is a well-studied mechanism. Hanson, et al. (2011) conclude that significant dryout is not expected, but actual concrete temperatures need to be confirmed, especially with high burnup fuel. Sindelar, et al. (2011) indicate that the loss of pore water from dryout may result in the formation of cracks that could act as pathways for chemical degradation processes, but no significant effect on the bulk properties of concrete is expected. Nevertheless, long-term exposure data are not available and Sindelar, et al. (2011) recommend periodic monitoring of the physical condition of the concrete during extended storage. NWTRB (2010) indicates that exposure to elevated temperature could be a significant age-related degradation mechanism for the concrete enclosures, particularly if air vents are plugged because of some off-normal scenario.

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Hanson, et al. (2011) and Sindelar, et al. (2011) agree that thermal degradation of concrete, including dehydration, is not expected given the range of expected operating temperatures and the expected decrease in temperature with time. The NRC staff expects that the assessment in NWTRB (2010) on the possibility of thermal degradation of concrete from blocked vents would only be applicable in the near term, when higher heat generation from spent fuel can lead to elevated concrete temperatures. Note that blocked vents are a limiting condition of operation for dry cask storage systems at NRC-licensed ISFSIs.

The level of knowledge on the initiation and propagation of thermal effects on concrete is medium. Significant knowledge exists based on short-term exposures over a wide range of temperatures. The expected temperature for concrete components is well established and will decrease with time. The level of knowledge for the expected effects of thermal exposure is low. The effects of temperature on the properties of concrete have significant variability and are known to be dependent on concrete chemistry and construction practices. Thermal degradation may also lead to the formation of cracks that can accelerate chemical degradation processes.

A8.12 Coupled Concrete Degradation Mechanisms

Description of Degradation Phenomenon

Coupled degradation mechanisms in concrete refer to interactions among the concrete degradation processes of temperature (T), ingress of ionic fluids into the concrete (H), stress/deformation/cracking (M), chemicals (C) and the effects of radiation (R). The term “coupled processes” implies that one process affects the initiation and progress of the others. Therefore, to predict with confidence the response of the dry cask concrete to THMCR processes, it may be useful to consider the degradation processes coupled processes in two- , three- , four- , or even five-way interactions (i.e., THMCR). Such degradation is operative for both the short and long-term as long as the conditions for coupled processes occurring are present.

Synopsis of Previous Gap Assessments

NWTRB (2010), Hanson, et al. (2011), and Sindelar, et al. (2011) do not specifically address coupled processes, although these reports note that several concrete deterioration and rebar corrosion mechanisms are known to degrade reinforced concrete. The formation of cracks as a result of thermal exposures may act as fast pathways for chemical degradation processes, such as chloride ingress and carbonation. The additional influence of heat and radiation damage can compound environmental damage.

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Degradation of concrete structures as a result of multiple degradation processes is known to occur. The identification and assessment of the relative importance of degradation processes are complex but could be accomplished with detailed petrographic analyses of degraded material. Predicting or modeling the rate of degradation of coupled processes is very challenging. The relative rates of each of these degradation mechanisms are often unknown and may be affected by other processes occurring at the same time. For example, carbonation proceeds relatively uniformly through the concrete from the surface in uncracked concrete. Cracks act as pathway for CO_2 ingress leading to a non uniform carbonation front. Cracks from another degradation process (e.g., freeze-thaw) occurring simultaneously can lead to cracks that allow uneven carbonation degradation. This can allow the carbonation front to reach rebar much sooner than predicted by carbonation ingress alone. Because of these complex process interactions, current modeling capabilities are inadequate to determine rates of the combined degradation processes or estimate the expected extent to which degradation may occur.

Many degradation processes are well understood, as are the environmental factors and concrete mix chemistries that promote these degradation processes. The threshold for initiation of many of these processes (such as alkali-silica reactions, freeze-thaw, and radiation damage) is well known from experience in other applications. Therefore, the level of knowledge is ranked as high. Other processes (such as carbonation and rebar corrosion) which are more strongly dependent on design and materials as well as environment have less complete knowledge, and are ranked as medium. Coupled processes include mechanisms with both high and medium levels of knowledge. The overall level of knowledge for the initiation of these coupled degradation modes is therefore considered to be medium. The level of knowledge of the propagation rate and the expected effects of coupled processes is considered to be low, because while their effects are understood, it remains difficult to predict how fast or what parts of a given structure will be affected by the coupled processes as these processes interact.

A9 CROSSCUTTING ISSUES

As described in Section 3.2, crosscutting issues are those topical areas that can potentially affect the performance of multiple components of the system.

A9.1 Temperature Distributions

Many degradation processes for DCSS are temperature dependent. Heat generation from SNF decreases over time, and temperatures within DCSS will change significantly over extended storage periods. Both the high and low temperature distributions in the system will impact degradation. Due to a fluence spectrum within the reactor, spent fuel rods have an axial burnup distribution that produces an axial temperature distribution within the storage cask. In addition, because of the heat loads of adjacent assemblies and heat sink at the cask walls, the fuel in the cask has a radial temperature distribution, with the coldest assemblies on the outside. The radial distribution can be altered by the loading pattern within the cask. In addition to the fuel conditions, external environmental conditions affect the temperature of a cask system. On the canister surface, temperature will be lower at the air inlet area. At some sites, seasonal variation in air temperature will also affect the canister surface temperature.

Almost all the degradation mechanisms identified in this analysis have an Arrhenius-type temperature behavior, where the rate of degradation increases exponentially with increasing temperature. For example, the hydrogen solubility and internal cladding stress both increase with temperature, making the rods more susceptible to hydride reorientation at the higher temperatures. The lower temperature distribution can be more important for other processes. As heat generation decreases, the exterior of a canister can have relatively cool spots where moisture may occur, increasing susceptibility to stress corrosion cracking. Also, at lower temperatures SNF cladding can go through a ductile to brittle transition, making it more susceptible to failure during transportation. More realistic models of temperature distribution can provide better estimates of the susceptibility to degradation.

Maximum temperatures for SNF are the greatest concern during the early stages of dry storage, as heat generation is relatively high. Due to uncertainties in the input parameters to the temperature models, the cask vendors currently use bounding temperature distributions that tend to overestimate the fuel temperature. These same temperature models, if used for extended storage periods, will also overpredict the temperatures, possibly leading to erroneous conclusions about potential degradation that is more sensitive to low temperatures.

As a result, NRC staff identified a need for more realistic models of temperature distribution. This is a crosscutting issue, as degradation of many components is temperature sensitive. Thermal models can be constructed without bounding assumptions that consider only higher temperature regimes. More detailed models can also account for changes in material properties with time, such as variation in cladding emissivity. Higher cladding emissivity as a result of oxide spallation may result in temperatures cooler than predicted without considering this effect. This could be important for determining when high burnup cladding might transition to a more brittle condition.

Due to these modeling uncertainties, knowledge of the temperature distributions is considered low, especially for the lower temperatures that occur over extended storage times. NRC staff has determined that better knowledge of temperature distributions to be important because of the impact on several temperature-dependent mechanisms, and the importance of lower temperature phenomena (such as canister SCC, or possible brittle behavior of cladding) over longer storage times.

A9.2 Drying

There are many effects inside the canister (e.g., galvanic corrosion of the cladding, oxidation of the fuel, pressure buildup, and generation of flammable hydrogen gas) that depend on the potential presence of residual moisture after loading. After drying by current recommended procedures in the Standard Review Plans (e.g., NRC, 2010), dry canisters should contain no more than 0.25 mole of free water. However, this has not been experimentally confirmed.

Since the presence of residual moisture in the canister can lead to degradation of internal components by several mechanisms, this is considered a crosscutting issue. The level of knowledge of the potential effects of residual moisture is considered low, due to the multitude of effects occurring concurrently, the lack of any drying model accounting for the synergistic effects, and no method for either measuring the extent of dryness in the canisters or the resulting effects of the residual moisture.

A9.3 Monitoring

Description of Gaps

Monitoring systems are peripheral technology that allows for the surveillance of other systems and components important to safety-functions and their surrounding environment. This section considers potential technologies that can be used to assess the performance of dry cask storage systems (DCSS) over prolonged periods of time, as well as establish and validate the technical bases for materials and system performance.

Historically, monitoring methods for dry storage systems have not been a major focus of the nuclear industry in the United States. While several mature technologies are currently applied to nuclear power reactor systems and components, most are not easily transferable to dry storage application, for a variety of reasons. For example, they may not be available in portable form, or not easily deployed away from buildings in an independent spent fuel storage installation, or unable to fit in the confined geometries of the various storage system designs. These specific logistical constraints can be significant, particularly for existing dry storage systems that were not designed to accommodate monitoring.

Methods for monitoring of dry storage systems thus need to address how readily they can be applied to new or existing DCSS, as well as the particular safety function or degradation mechanism to be monitored. Different methods will likely have different sensitivities, and tradeoffs may exist between sensitivity and ease of use. Methods that can reliably detect early signs of degradation before a safety function is severely compromised are of greater value than those that only indicate gross failure. Monitoring methods can also provide data to validate predictive models and confirm performance.

Synopsis of Previous Gap Assessments and Other Reports

NWTRB (2010), Hanson, et al. (2011), and Sindelar, et al. (2011) state the importance of developing and deploying monitoring systems to insure the long-term compliance of DCSS to their safety functions.

NWTRB (2010) indicates there is insufficient technical information available to assess how long commercial spent nuclear fuel can be stored safely in dry storage systems and then safely handled and transported. While NWTRB (2010) does not detail the requirements of a monitoring system, it does mention the need to ensure the presence of helium cover gas, as well as the need for a fuel/DCSS inspection and monitoring regime that will allow for the validation of models, assumptions, and confidence level in experimental data extrapolations to improve service-life predictions.

Sindelar, et al. (2011) recommend developing and implementing a monitoring and in-service inspection program, but do not categorize the sensing/monitoring development needs, nor analyze in detail the technology gaps for specific monitoring applications. They do, however, prescribe the use of an inspection program consistent with the requirements of ASME Boiler and Pressure Vessel Code Section XI (ASME, 2011), which would include "scope, extent, non-destructive evaluation methods, frequency, acceptance criteria, and records."

Sindelar, et al. (2011) identify two specific areas where monitoring technology development is lagging with respect to inspection needs including (i) methods of performing periodic inspections of container welds and (ii) inspection of the concrete structures that may also include inspection by sonic or ultrasonic techniques, impact tests, radiography, radar, and thermal techniques.

Hanson, et al. (2011) provide a thorough review of the level of knowledge for a monitoring program. First, they define two broad categories of monitors (i) environmental (indirect) monitors and (ii) direct monitors for specific degradation. In the case of environmental monitors, degradation from stress corrosion cracking (SCC) can be pinpointed by indirect measures, symptoms, or changes in the environment around the system. In this category, Hanson, et al. (2011) identify environmental indicators, such as pH changes, relative humidity, temperature fluctuations, in-canister oxygen levels, and pressure. The report expands on this topic and gives an overview on the possible use of pressure transducers at the vent/purge port and temperature monitoring by either thermocouple, infrared, or fiber optics. Hanson, et al. (2011) also consider the current functionality of each technique.

Hanson, et al. (2011) summarize potential direct monitoring technologies sensitive to specific degradation modes, as measurable with respect to four categories: crack/spalling/pitting, dimensional changes, discoloration/staining, and changes to bulk material properties. Hanson, et al. (2011) also identify the need for development of enabling technologies that are necessary for successfully deploying sensing systems to DCSS applications, which require maintaining confinement barriers for the SNF, as well as dealing with a harsh operating environment for the sensors. The enabling technologies refer to support systems necessary to operate the sensors (actuators) and gather and transmit the data, including requirements for sensor power transmission/generation, data transmission, sensor compatibility, and data management.

The path forward recommended by Hanson, et al. (2011) with respect to monitoring gaps is summarized at the end of the chapter, as a phased approach, with state-of-the-art review, laboratory testing, and technology development phases.

NRC Staff Evaluation and Additional Information

Given the potential range of monitoring needs, many possibilities exist for future development and field deployment of monitoring technologies. Even for current mature technologies that are well proven for other applications, further research and development are likely needed to adapt the method for use with DCSS. The availability of new monitoring systems and the effort needed for practical SNF monitoring in DCSS will ultimately depend upon decisions about requirements of continuous *in-situ* monitoring compared to periodic inspection, local or remote data gathering, types of facilities and designs, and resources available for testing, validation, and deployment.

The combined international knowledge and operating experience is noteworthy and could affect the timeline to address the gaps associated with deployment and validation of monitoring and inspection systems. The international community has been using monitoring and remote technologies at different cask maintenance and storage facilities since the early 1990s. Its work has been extensively documented in IAEA TECDOC reports (IAEA, 1998, 2005), which include country- or facility-specific DCSS inspection best practices, operating experience, current technologies used, and future technologies review. Technology has continued to advance since the most recent IAEA (1998, 2005) reports, and currently more portable or flexible forms of the same technique might be available for commercial applications.

Research and facilities from other national organizations may be applicable or adaptable to EST needs. Validation of sensitivity levels to specific degradation modes for all components can be obtained from different industries. For example, inspection technologies have been developed to assess the condition of aging civil engineered structures such as bridges. Field data are available from bridge and highway inspections using an array of field-deployed portable and *in-situ* devices. The U.S. Department of Transportation (USDOT, 1999) has collected field data for concrete structures inspections/monitoring systems. The U.S. Federal Highway Administration's Nondestructive Evaluation (NDE) Laboratory evaluates the use of NDE methods such as infrared thermographic imaging, ground-penetrating radar imaging, laser-radar scanning, acoustic emission monitors, electromagnetic acoustic transducers, embedded corrosion microsensors, and laser vibrometers to collect quantitative data about bridge conditions.

One area where the use of NDE methodologies could be beneficial is in the prediction of service life of concrete structures. Relatively little is known about properties of degraded concrete (e.g., compressive strength and elastic modulus) and the effects of the degradation process on concrete transport properties. A comprehensive approach to concrete monitoring and inspection would include testing of the concrete casks and pads to identify the degradation process, modeling of the degradation process to predict remaining service life, monitoring/surveillance, and repair. Currently, most monitoring/surveillance is done by visual observations. More sophisticated non-destructive evaluation methods to quantitatively obtain data for mechanical and chemical degradation would provide more complete information.

The ability to monitor system components for degradation can be a valuable tool for ensuring continued safety of SNF storage, and for licensees and applicants to demonstrate that they can meet regulatory requirements, by informing aging management programs and confirming performance. Potential monitoring techniques should consider the safety functions of the components being monitored, as well as the specific degradation processes of interest and the level of sensitivity required to detect degradation well before the safety function is compromised.

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APPENDIX B

REGULATORY PRIORITIZATION OF COMPONENT DEGRADATION

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APPENDIX B: REGULATORY PRIORITIZATION OF COMPONENT DEGRADATION

B1 METHODOLOGY AND RESULTS FOR REGULATORY PRIORITIZATION

The goal of the regulatory prioritization evaluation was to understand how time-dependent degradation may affect the ability of the dry storage system to fulfill specific safety functions, for both storage and for subsequent transportation. Previous NRC analyses have examined methods for assigning importance to safety and provided preliminary risk insights for performance (e.g., McConnell et al., 1996; NRC, 2007). The current prioritization evaluation utilized the experience gained by NRC staff in performing technical reviews of systems for dry storage and transportation of SNF, following the standard approach for license renewal (NRC, 2011). This allowed staff to directly relate the approach taken during licensing review to conditions which may occur following storage for an extended period.

For this evaluation, the potential degradation processes identified for dry storage systems were presented for consideration in a hypothetical future licensing review, to NRC staff reviewers with experience in both the technical and the regulatory requirements for storage and transportation. The reviewers evaluated how the degradation processes, either individually or in combination, would affect the review of the hypothetical case. Reviewers considered the technical criteria for storage system performance, as given in the standard review plan, as well as potential effects on transportation following storage.

The NRC staff recognized that not all effects will be direct; some degradation may not impact performance until the condition or function of the system changes (such as moving from storage to transport). For example, non-penetrating cracks that develop in a canister during extended storage may not immediately affect storage performance or safety (there is no loss of confinement from cracks that do not penetrate the canister wall). During subsequent transportation, however, a canister with the same non-penetrating cracks may be more likely than a pristine canister to breach in an accident. The accident analysis would therefore need to consider the history of the canister and how its potentially degraded condition would affect performance.

A hypothetical case was constructed that includes a number of degradation processes that affect several system components, as follows:

> An amendment is submitted for the license extension of a dry storage system (either direct loaded and bolted, or canisterized) that has been loaded with either high or low burnup fuel and is in use in a number of scenarios. Some of the loaded casks are at the reactor ISFSI. Others have been transported to a regional storage facility. Some of the casks have already had three or four license extensions and been in storage for up to 120 years. They are used all over the country including some coastal sites. No national policy has been set yet, so the condition of the fuel needed for final disposition has not been determined. If it is a canisterized system, the canister may be depended on for moderator exclusion. The industry is creative and has developed monitoring techniques to determine the conditions of the system both inside and outside. Evidence of one or more degradation phenomena has been observed. The

location of the degradation or the number of components affected by the degradation may be multiple.

The NRC staff evaluated the hypothetical case using the Standard Review Plan, and indicated how changes in component conditions would impact the review for specific criteria. The component conditions were evaluated for impacts on confinement, criticality, shielding, structural, thermal, and retrievability functions, as defined in Section 4. Table B1–1 shows which functions are affected by the potential changes in component condition that may come from the different degradation processes. The staff evaluation considered potential effects during storage and transportation, under both normal and accident conditions. Table B1-1 is organized by system component, and the potential change in condition of that component. In several cases, the broad performance criteria captures multiple aspects of that function. The explanation of the different aspects shown in Table B1-1 is given in Section B–2. In many cases, several different degradation mechanisms can result in the same change in component condition, and these are grouped in Table B1-1. The impact areas of these changes are arranged by component and degradation mechanism in Table 4-1 of Section 4. A blank cell in Table B1-1 indicates that no significant impact on the review was identified.

Table B1–1. Prioritization of Change of Condition of Component to Safety

Component	Change in Component Condition	Normal Storage	Accident Storage	Normal Transportation	Accident Transportation
Cladding	Localized degradation in mechanical properties		SR1		SR1
	Partial or through-wall cracks	CO1 RE1	CO1	CO1	CO1 SR2
	Macroscopic degradation of the mechanical properties along the whole rod	CO1 CR1 RE1	CO1	CO1 CR1 RE1	CO1 CR1
	Reduced thermal conductivity	TH1	TH1	TH1	TH1
	Cladding swelling and rupture	CO1 CR1 RE1	CO1	CO1 CR1	CO1 CR1
	Increased emissivity changes	TH1	TH1	TH1	TH1
Fuel-cladding interactions	Fuel swelling and added cladding stress	CO1	CO1	CO1	CO1
	Pellet powderization	CO1 CR2	CO1	CO1 CR2	CO1 CR2
	Increase in rod internal pressure	CO1	CO1	CO1	CO1
	Increased pellet fragmentation	CO1	CO1	CO1	CO1
	Changes in the fuel state that result in a higher than expected fuel temperature	TH1	TH1	TH1	TH1
	Fuel oxidation and subsequent cladding crack extension	CO1 CR1 RE1	CO1	CO1 CR1	CO1 CR1
Fuel assembly hardware	Stress relaxation of springs		SR3		SR3
	Formation of fatigue cracks	RE1		RE1	CR3
	Strain of fuel assembly skeleton (guide tubes and grid spacers)				SR4
	Cracking of fuel assembly nozzles, springs, grid spacers, and channels in boiling water reactors	CR4 RE1 SR5		CR4 RE1	CR4
	Material loss and cracking of springs, grid spacers, channels, and guide tubes	CR4 RE1 SR5		CR4 RE1	CR4
	Material embrittlement	RE1		RE1	CR3

Table B1–1. Prioritization of Change of Condition of Component to Safety (continued)

Component	Change in Component Condition	Normal Storage	Accident Storage	Normal Transportation	Accident Transportation
Fuel basket	Strain of fuel basket structure due to creep of Al basket materials at elevated temperatures				
	Cracking of fuel basket	CR4		CR4 SH1	CR4 SH1
	Material loss from carbon steel and Al basket materials	CR4 TH1	TH1	CR4 TH1	CR4 TH1
Austenitic stainless steel (SS) canister body and welds	Partial or through-wall cracks	CO1 RE2 SH2 TH1	CO1 CR5 SH2 TH1	CO1 TH1	CO1 TH1
	Partial or through-weld corrosion and cracks	CO1 RE2 SH2 TH1	CO1 CR5 SH2 TH1	CO1 TH1	CO1 TH1
SS canister body, and steel and cast iron cask and seals	Material embrittlement and reduced fracture toughness	CO1 RE2 SH2 TH1	CO1 CR5 SH2 TH1	CO1 TH1	CO1 TH1
	Partial or through-wall corrosion	CO1 RE2 SH2 TH1	CO1 CR5 SH2 TH1	CO1 TH1	CO1 TH1
Steel and cast iron cask body and lid	Partial or through-wall corrosion	CO1 SH2 TH1	CO1 CR5 SH2 TH1	CO1 TH1	CO1 TH1 SR6
Metallic seals	Corrosion and loss of seal material	CO1 RE2 SH2 TH1	CO1 CR5 SH2 TH1	CO1 TH1	CO1 TH1
	Deformation of the seal	CO1 SH2	CO1 CR5 SH2	CO1	CO1

Table B1–1. Prioritization of Change of Condition of Component to Safety (continued)

Component	Change in Component Condition	Normal Storage	Accident Storage	Normal Transportation	Accident Transportation
Polymer seals	Deformation or cracking of the polymer seal	CR5	CR5	CO1 TH1	CO1 TH1
Closure bolts	Corrosion of bolts	CO1 RE2 SH2 SR7	CO1 CR5 SH2 SR7	CO1 SR7	CO1 SR7
	Change in bolt dimensions	CO1 SH2 SR7	CO1 CR5 SH2	CO1 SR7	CO1 SR71
Neutron absorbers	Strain of neutron poison material				
	Cracking of neutron poisons	CR6		CR6	CR6
	Material loss due to blistering, deformation, and cracking	CR6		CR6	CR6
	Material property changes in material mechanical properties				CR7
	Depletion of B–10 atoms				
	Material embrittlement				CR7
Neutron shielding	Shrinkage at elevated temperature				
	Depletion of B–10 atoms				
	Cracking	SH3	SH3	SH3	SH3
	Mechanical property changes				
	Loss of material	SH3	SH3	SH3	SH3
Concrete overpack or Vault	Cracking and shrinkage of concrete	SH4 SR8	SH4	SH4	SH4
Concrete pad	Cracking and shrinkage of concrete	SR8			

CO=Confinement
CR=Criticality
RE=Retrievability
SH=Shielding
SR=Structural
TH= Thermal
Numerical suffix refers to the justification given in Section B2.

B2 EXPLANATION OF FUNCTIONAL IMPACTS OF DEGRADATION ON DRY STORAGE SYSTEM COMPONENTS

B2.1 Confinement

CO1: Regulations (10 CFR 72.236, Specific requirements for spent fuel storage cask approval and fabrication) specify that spent fuel storage casks must maintain confinement. Likewise, transportation of spent fuel that has been stored for extended periods must satisfy requirements to prevent loss or escape of radioactive material, such as those found in 10 CFR 71.51 (Additional requirements for Type B packages). For example, if pellet powderization coupled with cladding swelling were to occur, along with canister through-weld corrosion and cracks, there could be potential effects on the confinement performance of a storage or transportation cask.

B2.2 Thermal

TH1: Significant, direct thermal issues are unlikely after a long storage period because of the reduction in spent fuel decay heat. Calculations conducted to study the thermal behavior of fuel in long-term storage indicate that cladding temperatures can drop 250 to 300 °F [121 to 149 °C] within 100 years, depending on boundary and initial conditions; the temperatures of surrounding canister/cask components (shell, baskets, etc.) would also drop over time. A materials reviewer should assess how material properties change with these temperature reductions and the resulting implications. For example, relatively low cladding temperatures could result in material/property changes that can potentially compromise cladding integrity. Likewise, the irradiation, hot storage, and long cool-down periods could potentially change the mechanical properties of spent fuel. If the spent fuel should become more brittle, there could be a potential effect on the degree of dispersal should the fuel fragment during an accident where confinement is also breached.

B2.3 Shielding

In evaluating the potential significance for the shielding and radiation protection safety functions, the reviewers made the following assumptions:

- Loss of fuel basket material does not mean gross loss of material.
- For transportation, credit was taken for maintenance programs and testing and pre-shipment checks performed in accord with 10 CFR 71.87 (Routine determinations).
- Preshipment checks for transport, performed in accord with 10 CFR 71.87, would detect any significant radiation streaming paths that developed during storage from degradation of canister or cask body, welds, and seals. A package with streaming paths causing the package dose rates to exceed the limits given in 10 CFR 71.47 (External radiation standards for all packages) would not be shipped.
- Changes in cladding and fuel geometry can cause the content of the fuel compartments of the fuel baskets to become homogenized, for both storage and transportation casks. Additional failure of the fuel compartments to homogenize the contents on the scale of the entire canister is not assumed to occur.

SH1: Fuel basket cracking will impact the ability of the system shielding to meet regulations for external dose rate of 10 CFR 71.47 (External radiation standards for all packages) and 10 CFR 71.51 (Additional requirements for Type B packages), for the following reasons:

- Normal transportation—Fuel basket cracking may lead to basket failure, which in turn may cause source relocation due to vibration and other impacts during normal conditions of transport. Source relocation results in a concentration of radioactive isotopes that may impact the cask's ability to meet dose rate requirements in 10 CFR 71.47

- Accident transportation—Fuel basket cracking may lead to basket failure, which in turn may cause source relocation due to drop impacts under a hypothetical accident. Source relocation results in a concentration of radioactive isotopes that may impact the cask's ability to meet dose rate requirements 10 CFR 71.51

SH2: The partial or through-wall cracks of the austenitic stainless steel canister body and welds will impact the ability of the system shielding to meet regulations for direct radiation and release in 10 CFR 72.104, (Criteria for radioactive materials in effluents and direct radiation from an ISFSI or MRS), 10 CFR 72.106 (Controlled area of an ISFSI or MRS), 10 CFR 72.126 (Criteria for radiological protection), and 10 CFR 72.236 (Specific requirements for spent fuel storage cask approval and fabrication) for the following reasons:

- Normal Storage (including off-normal conditions, or anticipated occurrences)—Partial or through-wall cracks of the austenitic stainless steel canister body and welds will cause the cask to lose confinement boundary and potentially increase the effluents, which will impact the ability to meet the dose limits prescribed by 10 CFR 72.104, and the exposure and effluent control requirements of 10 CFR 72.126.

- Accident Storage—Partial or through-wall cracks of the austenitic stainless steel canister body and welds will cause the cask to lose confinement boundary and potentially increase the effluents, which will impact the ability to meet the dose limits prescribed by 10 CFR 72.104 and 10 CFR 72.106, and the exposure and effluent control requirements of 10 CFR 72.126.

SH3: Degradation due to loss of material or cracking will change the shielding effectiveness of the neutron shield (e.g., the neutron attenuation capability), and thus the ability of the system to meet the regulatory dose rate requirements for transportation (10 CFR 71.47 and 71.51) or the ability of the system (or the facility) to meet the regulatory dose limits and other radiation protection requirements for storage (10 CFR 72.104, 72.106, 72.126, and 72.236). Under accident conditions for both storage and transportation, degradation of neutron shielding materials is a concern only for those systems or components for which the current accident evaluations do not already assume a complete loss of neutron shielding material.

SH4: The concrete cask or overpack provides the primary gamma and neutron shielding. Significant loss of material or cracking will change the shielding effectiveness of the concrete cask or overpack or vault, and thus the ability of the cask/overpack/vault to meet the regulatory dose rate requirements for transportation for those systems that use the concrete cask/overpack to transport the spent nuclear fuel (10 CFR 71.47 and 71.51) and the ability of the system (or the facility) to meet the regulatory dose limits and other radiation protection requirements for storage (10 CFR 72.104, 72.106, 72.126, and 72.236).

B2.4 Criticality

CR1: The noted change in component condition could result in an unanalyzed condition with reconfigured fuel in the presence of borated or fresh water during unloading conditions for normal storage, under 10 CFR 71.55(b) for normal transportation, or for transportation accidents.

CR2: The noted change in component condition potentially results in an unanalyzed condition with fuel material relocating into the plenum region, possibly above or below the neutron absorber panels, in the presence of borated or fresh water during unloading conditions for normal storage, under 10 CFR 71.55(b) for normal transportation, or for transportation accidents.

CR3: Criticality evaluation for spent fuel transportation accidents depends on the geometry control provided by the grid spacers and other assembly hardware. Loss of fuel geometry in an accident would result in an unanalyzed condition with reconfigured fuel in the presence of fresh water.

CR4: Criticality evaluation for spent fuel depends on the geometry control provided by the grid spacers and other assembly and cask basket hardware. The noted change in component condition indicates an immediate loss of geometry control, which could result in an unanalyzed condition with reconfigured fuel in the presence of borated or fresh water during unloading conditions for normal storage, under 10 CFR 71.55(b) for normal transportation, or for transportation accident conditions.

CR5: Criticality evaluations for accident conditions during dry storage for 10 CFR 72.124 licensing actions do not assume fresh water in leakage. The noted conditions would indicate the potential for fresh water intrusion under accident conditions (e.g., flood and tsunami), leading to an unanalyzed condition.

CR6: Criticality evaluation for spent fuel depends on the presence and uniformity of solid neutron absorber plates. The noted conditions would result in an unanalyzed condition with loss of neutron absorber in the presence of borated or fresh water under normal storage, in the presence of fresh water under 10 CFR 71.55(b) under normal transportation, or in the presence of fresh water under transportation accident conditions.

CR7: Criticality evaluation for spent fuel for transportation accidents depends on the presence and uniformity of solid neutron absorber plates. Reduced mechanical properties of these materials, from accident impacts, may lead to loss of absorber material under the conditions in 10 CFR 71.73 (Hypothetical accident conditions), leading to an unanalyzed condition in the presence of fresh water.

B2.5 Structural

SR1: Localized generic cladding degradation effects may be postulated to occur only at the grid spacer locations. For the side-drop accidents, maximum, governing bending stresses occur at grid spacer locations, which are local and are about 40 percent higher than those at mid-span locations. Due to localized restraints provided by leaf spring-like supports, numerical simulation can be used in a sensitivity analysis to establish bounding characterization of fuel cladding stress states at those locations. A shake table vibration testing of a fuel assembly subject to transverse inertia load will further demonstrate that stress and strain states can be accurately calculated. This will lead to a benchmarked analysis technique for assessing effects of cask side drop on potential fuel pin localized damages.

SR2: This type of initial or boundary condition for fuel cladding analysis is addressed only for each specific cases. Detailed evaluation of fuel cladding structural integrity (using, e.g., fracture mechanics approaches) has not been considered necessary for any dry storage licensing action to date. For fuel cladding fracture toughness performance, dynamic stress intensity factors, such as $K_{ID,}$ may need to be developed for both regular and high burnup fuel for extended storage and transportation conditions.

SR3: For the grid spacer leaf spring configuration, other than the fuel pin plenum spring of individual rods, relaxation of spring force transverse to the fuel rod may result in a semi-rigid, pin-supported, lateral constraint to the fuel rod. This may or may not be more beneficial than that associated with fuel rods without leaf spring relaxation. Generally, effects of this degradation scenario are of secondary importance. If deemed necessary, however, numerical simulation sensitivity analysis can be used to quantify bounding structural effects on fuel clad stress performance.

SR4: Currently, conservative analysis of the fuel rod structural evaluation does not credit the beneficial effects of the identified hardware on fuel rod performance. However, due to potential degradation of structural strength of fuel rods after extended storage, contribution by the fuel assembly skeleton to the load carrying capability, other than that of fuel pins alone, may also need to be considered for demonstrating acceptable fuel rod performance. In order to perform this more detailed evaluation, an integral fuel assembly structural analysis model, which includes key subcomponents, would be needed to systematically examine fuel pin performance. Any detrimental material degradation effects can be quantified in a sensitivity structural analysis.

SR5: These scenarios are related to retrievability of undamaged fuel, defined as the ability to handle individual fuel assemblies by normal means (NRC, 2010).

SR6: For stress corrosion cracking of the heat-affected zone (HAZ), including that of the closure lid to shell weld, a finite element numerical simulation technique should be developed for estimating weld/HAZ residual stress for welds of different geometries and welding processes. This includes benchmarking computer modeling techniques with testing data. The stress driver provides a necessary basis for determining structural integrity of canister welds associated with harsh environments such as marine atmospheric conditions at an ISFSI site.

SR7: Change in the bolt condition should be evaluated and verified, as part of the aging management program, during the cask or ISFSFI licensing renewal.

SR8: Potential loss of load-carrying and shielding capability of the degraded concrete, reinforcing steels, and tie rod accessories beyond maintenance and repair is part of the evaluation by licensees in applying for renewal of a license for an ISFSI or cask (NRC, 2011).

B2.6 Retrievability

RE1: This degradation may impact the ability to retrieve the fuel by handling individual assemblies by normal means (NRC, 2010).

RE2: This degradation may affect the ability to retrieve the fuel by retrieving the canister, irrespective of the ability to handle individual fuel assemblies.

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