UFD Storage and Transportation - Transportation Working Group Report

Fuel Cycle Research & Development

Prepared for
U.S. Department of Energy
Used Fuel Disposition Campaign

Steven J. Maheras
Steven B. Ross
Pacific Northwest National Laboratory

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PNNL Project Manager	See attached Information Release Form.	08/31/2011
	Brady Hanson	Date

SUMMARY

The Used Fuel Disposition (UFD) Transportation Task commenced in October 2010. As its first task, Pacific Northwest National Laboratory (PNNL) compiled a list of structures, systems, and components (SSCs) of transportation systems and their possible degradation mechanisms during extended storage. The list of SSCs and the associated degradation mechanisms [known as features, events, and processes (FEPs)] were based on the list of used nuclear fuel (UNF) storage system SSCs and degradation mechanisms developed by the UFD Storage Task (Hanson et al. 2011). Other sources of information surveyed to develop the list of SSCs and their degradation mechanisms included references such as *Evaluation of the Technical Basis for Extended Dry Storage and Transportation of Used Nuclear Fuel* (NWTRB 2010), *Transportation, Aging and Disposal Canister System Performance Specification, Revision 1* (OCRWM 2008), *Data Needs for Long-Term Storage of LWR Fuel* (EPRI 1998), *Technical Bases for Extended Dry Storage of Spent Nuclear Fuel* (EPRI 2002), *Used Fuel and High-Level Radioactive Waste Extended Storage Collaboration Program* (EPRI 2010a), *Industry Spent Fuel Storage Handbook* (EPRI 2010b), and *Transportation of Commercial Spent Nuclear Fuel, Issues Resolution* (EPRI 2010c). SSCs include items such as the fuel, cladding, fuel baskets, neutron poisons, metal canisters, etc. Potential degradation mechanisms (FEPs) included mechanical, thermal, radiation and chemical stressors, such as fuel fragmentation, embrittlement of cladding by hydrogen, oxidation of cladding, metal fatigue, corrosion, etc. These degradation mechanisms are discussed in Section 2 of this report. The degradation mechanisms have been evaluated to determine if they would be influenced by extended storage or high burnup, the need for additional data, and their importance to transportation. These categories were used to identify the most significant transportation degradation mechanisms. As expected, for the most part, the transportation importance was mirrored by the importance assigned by the UFD Storage Task. A few of the more significant differences are described in Section 3 of this report.

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TABLES

ACRONYMS

ANL	Argonne National Laboratory
DOE	U.S. Department of Energy
FEP	Feature, Event, or Process
GWd/MTU	Gigawatt-day per metric ton uranium
HAC	Hypothetical accident conditions
INL	Idaho National Laboratory
ITS	Important to Safety
NCT	Normal conditions of transport
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
Psig	Gauge pressure (in pounds force per square inch)
R&D	Research and Development
SNL	Sandia National Laboratories
SRNL	Savannah River National Laboratory
SSC	Structure, System, or Component
UNF	Used Nuclear Fuel
UFD	Used Fuel Disposition

DEFINITIONS

Basket	A chemically non-reactive cruciform or egg-crate-like structure inside a storage canister or cask or transportation canister or cask that establishes the physical boundaries of positions for and provides structural support and protection for used nuclear fuel assemblies, provides neutron poison media between fuel assembly locations, provides neutron flux traps between fuel assembly locations, and provides mechanisms and channels for transferring heat away from fuel assemblies.
Burnup	A measure of the total thermal power produced by a specified quantity and type of nuclear fuel material irradiated in a nuclear reactor, e.g., megawatt-days per metric ton of initial uranium fuel.
Canister	A container, along with an internal basket, used as a component of a system for the storage or transportation of used nuclear fuel.
Container	As used herein, a canister.
High Burnup	Burnup exceeding 45,000 megawatt-days per metric ton of initial uranium nuclear fuel.
Hypothetical Accident Conditions	Test conditions for hypothetical transportation accidents used to evaluate the ability of transportation casks to satisfy performance requirements for certification specified in 10 CFR 71.
Low Burnup	Burnup less than 45,000 megawatt-days per metric ton of initial uranium nuclear fuel.
Neutron Poison	A material that has a high neutron absorption cross-section and that is used in a storage or transportation cask/canister basket to reduce the number of neutrons available in order to prevent a sustained nuclear chain reaction.
Normal Conditions of Transport	Test conditions for incident-free, normal transportation used to evaluate the ability of transportation casks to satisfy performance requirements for certification specified in 10 CFR 71.
Retrieval	Removal of UNF from a storage or transportation canister or cask.
Shipping Container	As used herein, a shipping cask, or a transportation package used for the safe transportation of used nuclear fuel.
Stressor	Any environmental factor that has the potential to cause degradation, modification, or failure of one or more important to safety functions of a storage or transportation canister or cask.

Very High Burnup	Synonymous with high burnup.

USED FUEL DISPOSITION - TRANSPORTATION

1. INTRODUCTION

The primary objective of the Used Fuel Disposition (UFD) Transportation program is to evaluate the issues and technical gaps associated with transportation of used nuclear fuel (UNF) after extended storage. This effort needs to evaluate both low burnup fuel and high burnup fuel (exceeding 45 GWd/MTU) and the unique issues it may present. The outcome of this work will help to form the technical basis for transportation of UNF after extended storage and of high burnup UNF for nearer term transportation.

This document presents the compilation of Features, Events, and Processes (FEPs) related to the transportation of UNF after extended storage and higher burnup UNF for nearer term transportation. The initial compilation used the efforts produced by the UFD Storage Task in *Gap Analysis to Support Extended Storage of Used Nuclear Fuel* (Hanson et al. 2011) as a stepping off point and then identified those FEPs that may be unique to the ability to transport high burnup UNF and all UNF after extended storage.

The potential degradation mechanisms identified include those developed as part of the UFD Storage Task and include potential degradation mechanisms that may be unique to transportation or present a challenge for demonstrating and verifying the safety and compliance with regulatory requirements of post-extended storage transportation. This report is focused on UO_2-based light water reactor UNF.

1.1 Approach

The UFD Transportation Task commenced in October 2010. As its first task, Pacific Northwest National Laboratory (PNNL) compiled a list of structures, systems, and components (SSCs) of transportation systems and their possible degradation mechanisms during extended storage. The list of SSCs and the associated degradation mechanisms [known as features, events, and processes (FEPs)] were based on the list of SSCs and degradation mechanisms developed by the UFD Storage Task (Hanson et al. 2011). Other sources of information surveyed to develop the list of SSCs and their degradation mechanisms included references such as:

- *Evaluation of the Technical Basis for Extended Dry Storage and Transportation of Used Nuclear Fuel* (NWTRB 2010)
- *Data Needs for Long-Term Storage of LWR Fuel* (EPRI 1998)
- *Technical Bases for Extended Dry Storage of Spent Nuclear Fuel* (EPRI 2002)

- *Used Fuel and High-Level Radioactive Waste Extended Storage Collaboration Program* (EPRI 2010a)
- *Industry Spent Fuel Storage Handbook* (EPRI 2010b)
- *Transportation of Commercial Spent Nuclear Fuel, Issues Resolution* (EPRI 2010c).
- *Transportation, Aging and Disposal Canister System Performance Specification, Revision 1* (OCRWM 2008)

SSCs include items such as the fuel, cladding, fuel baskets, neutron poisons, metal canisters, etc. Potential degradation mechanisms (FEPs) included fuel fragmentation, creep, fatigue, annealing, embrittlement, oxidation, and corrosion. Potential stressors include mechanical, thermal, radiation and chemical stressors and provide a means to categorize the FEPs for a particular SSC.

The list was presented to the UFD Transportation Working Group team members in January 2011 in a meeting held in Albuquerque, New Mexico. Based on the feedback from the meeting attendees, the list was revised and presented to the UFD Transportation Working Group team members at a second meeting in March 2011. This meeting was held in Las Vegas and was attended by representatives of the U.S. Department of Energy (DOE), Savannah River National Laboratory (SRNL), Idaho National Laboratory (INL), Argonne National Laboratory (ANL), Oak Ridge National Laboratory (ORNL), Sandia National Laboratories (SNL), and PNNL. The SSCs and associated FEPs have been further revised and updated and are discussed in Section 2.

Section 2 also identifies whether the particular stressor and degradation would be affected by extended storage or higher burnup UNF (> 45,000 MWd/MTU). As with the UFD Storage Task, whether additional data were needed to characterize the phenomenon, the importance of new research and development, to improve understanding or reduce uncertainties, and the importance to the ability to demonstrate and verify safe transportation in compliance with regulations were determined. Transportation Importance was determined based on the projected ability of a stressor/degradation mechanism to cause an SSC to fail to satisfactorily perform any of its important to safety (ITS) functions during normal conditions of transportation (NCT), during hypothetical transportation accident conditions (HAC), or during retrieval. In the context of transportation, these functions are containment, prevention of nuclear criticality, shielding, heat transfer, structural integrity, and operations support (McConnell et al. 1996). This approach is consistent with the methodology used in the UFD Storage Task. In addition, Transportation Importance was determined based on transportation occurring after extended storage when long term degradation mechanisms such as delayed hydride cracking of zirconium-alloy fuel cladding would have a greater opportunity to impact the structural and confinement performance of the nuclear fuel assembly structure and thereby have the potential to affect the ability to (or approach to) demonstrate safety and regulatory compliance for transportation. It is important to note that the normal conditions of transportation, hypothetical transportation accident conditions, and retrieval were not viewed as stressors, but rather as test conditions to which a transportation package (shipping container and its UNF contents) must be subjected to determine its ability to satisfy regulatory performance requirements for safe transportation before UNF would be shipped.

2. FEATURES, EVENTS, AND PROCESSES

Shipping containers include the necessary structures, systems, and components (SSCs) to perform the following functions (McConnell et al. 1996):

- Containment: The components and supporting materials that are incorporated into the container design for the purpose of retaining the radioactive material during normal and accident conditions.
- Criticality control: The components and supporting materials that are incorporated into the container design for the purpose of maintaining the contents in a subcritical configuration during normal and accident conditions.
- Shielding: The components and supporting materials that are incorporated into the container design for the purpose of reducing radiation emitted by the contents during normal and accident conditions.
- Heat transfer: The components and supporting materials that are incorporated into the container design for the purpose of decay heat removal under normal conditions and protecting temperature-sensitive components (e.g., lead shielding and seals) under accident conditions. These components also provide significant integrity protection of these contents.
- Structural integrity: The components and supporting materials that are incorporated into the container design for the purpose of maintaining the structure in a safe condition during normal and accident conditions.
- Operations support: The components and supporting materials that are incorporated into the container design for the purpose of routine use (e.g., loading, unloading, use maintenance, monitoring, and transporting).

Typical shipping containers for UNF include the following SSCs:

- Fuel

- Cladding
- Assembly Hardware
- Fuel Baskets
- Neutron Poisons
- Neutron Shielding
- Containers (Bolted Direct-Load Metal Casks and Welded Metal Canisters)
- Inert Fill Gas

Additional SSCs include:

- Gamma Shielding
- Handling, Loading, and Operational Testing Features
- Impact Limiters and Impact Limiter Hardware
- Pressure Relief Devices
- Vessel Inner Shell, Vessel Lid, Vessel Lid Closure Hardware, Vessel Lid Inner Seal, Vessel Shell Bottom Head, Vessel Shell Upper Head, and Vessel Outer Shell
- Lifting Lugs, Trunnions, and Attachments; Lifting/Tiedown Hardware; Tiedown Lugs; Packaging Hardware; Protective Covers; Security Lockwire and Seals; Skids/Forklift Channels
- Neutron Shielding Shell
- Corrosion Protection Systems
- Anti-Contamination and Decontamination Features
- Heat Transfer and Thermal Protection Systems/Components.

This report focuses on determining the features, events, and processes (FEPs) that could lead to failure of these SSCs during extended storage or during subsequent transportation. In this report, failure is defined as the inability to comply with the performance requirements for test conditions specified for the NCT and the HAC in 10 CFR 71.71 and 10 CFR 71.73, respectively. For NCT, these test conditions include:

- Operating temperatures ranging from -40 °C (-40 °F) to 38°C (100 °F);
- External pressures ranging from 25 to 140 kPa (3.5 to 20 psi);
- Normal vibration experienced during transportation;
- Simulated rainfall of 5 cm/hr (2 in/hr) for 1 hour;
- Free fall from 0.3 to 1.2 meters (1 to 4 feet), depending on the package weight; and
- Impact of a 6-kilogram (13-pound) steel cylinder with rounded ends dropped from 1 meter (40 in) onto the most vulnerable (regarding performance of any ITS feature) surface.

For HAC, these test conditions include:

- Free-drop test: drop package 9 m (30 ft) onto an essentially unyielding horizontal surface with the package orientation arranged so that its weakest (regarding performance of any ITS feature) point is struck,
- Puncture test: drop package 1 m (40 inches) onto a vertical, 15 cm (6 in) diameter, cylindrical mild steel bar striking the package at its most vulnerable spot,
- Thermal test: exposure of packaged, fully engulfed in a fire having a temperature of at least 800ºC (1475ºF) for a period of 30 minutes with less than the specified loss of containment effectiveness, and
- Immersion test: package placed under a head of water of at least 15 m (50 ft) or an external pressure of 150 kPa (21.7 psi).

Sections 2.1 through 2.8 discuss each SSC in more detail, including potential degradation mechanisms, whether degradation is affected by extended storage or higher burnup, whether additional data is needed to address unknowns or uncertainties regarding the degradation mechanism, and the importance of conducting research and development to improve knowledge of or reduce uncertainties regarding the degradation mechanism.

2.1 Fuel

Irradiated uranium oxide fuel could degrade through 4 primary mechanisms during extended storage: 1) fuel fragmentation, 2) restructuring/swelling, 3) fission product attack on cladding, and 4) fuel oxidation (see Table 1). These phenomena were discussed in Section 5.1 of Hanson et al. (2011) and NWTRB (2010), Section 4.4.1. For dry storage, these degradation mechanisms were assigned a low priority for additional research and development.

Degradation of fuel during extended storage could affect the six transportation safety functions as follows:

Containment: Degradation of the fuel could have an impact on containment only if a cladding breach had occurred and the fuel was considered damaged, which is defined as UNF with other than hairline cracks or pinhole leaks (NRC 2007). This damaged fuel could release fission gases and thereby increase the pressure in containment. Also, fission products would be more mobile affecting the performance assessment of containment seals for bolted containments.

Criticality Control: Degradation of the fuel would have an impact on criticality control only if the fuel did not maintain its original configuration, which would require a significant cladding breach to occur.

Shielding: Degradation of the fuel would have an impact on the radiation dose rate external to shielding only if a significant cladding breach along with a substantial failure of the integrity of the cladding and fuel assembly structure had also occurred and the fuel did not maintain its original configuration. However, substantial radioactive decay would occur during extended storage, progressively reducing the radiation dose rate from the fuel. This would reduce the importance of the radiological protection provided by shielding present in the shipping container. However, the reduced radiation dose rate may increase safeguards and security concerns.

Heat Transfer: There is no expected degradation process during extended storage that would alter the decay heat removal properties of the fuel. However, if relocation of fuel occurred because of failure of the cladding and fuel assembly structure, the distribution of the fuel heat source within the shipping container would change, which would change the heat transfer conditions and could impact on structures because of thermal stresses, etc. This would seem not to be a problem for low heat fuel, which would be the case for extended storage. However, it could present a problem for high-burnup shorter cooled UNF. Because the certificate of compliance for a shipping container specifies the maximum burnup, minimum cooling times, and maximum heat loads, as long as these criteria are met, degradation of the fuel would have no impact.

Structural Integrity: Degradation of the fuel is expected to have no impact on the structural integrity of the shipping container. However if relocation of fuel occurred because of failure of the cladding and fuel assembly structure, the distribution of the fuel heat source within the shipping container would change, which would change the heat transfer conditions and could impact on structures because of thermal stresses, etc. This would seem not to be a problem for low heat fuel, which would be the case for extended storage. However, it could present a problem for high-burnup shorter cooled UNF.

Operations Support: Degradation of the fuel in absence of degradation of the cladding would have no impact on the operations support safety function of the shipping container.

Based on the impacts of the degradation mechanisms associated with fuel on the transportation safety functions, the degradation mechanisms associated with fuel were assigned a LOW transportation importance.

Table 1. Potential Stressors and Degradation Mechanisms that Could Impact the Performance of Fuel

Stressor	Degradation Mechanism	Influenced by Extended Storage or Higher Burnup	Additional Data Needed	Transportation Importance
Thermal and Mechanical	Fuel fragmentation	Yes	Yes	Low
	Restructuring/swelling	Yes	Yes	Low
Chemical	Fission product attack on cladding	Yes	Yes	Low
	Fuel oxidation	Yes	Yes	Low

2.2 Cladding

Cladding could degrade through 9 primary mechanisms during extended storage: 1) annealing of radiation damage, 2) metal fatigue caused by temperature fluctuations, 3) phase changes, 4) emissivity changes, 5) embrittlement and reorientation, 6) delayed hydride cracking, 7) oxidation, 8) wet corrosion, and 9) creep (see Table 2). These phenomena were discussed in Section 5.2 of Hanson et al. (2011) and NWTRB (2010), Section 4.4.2. For dry storage, embrittlement and reorientation was assigned a high priority for additional research and development; annealing of radiation damage, delayed hydride cracking, oxidation, and creep were assigned a medium priority, and the other degradation mechanisms were assigned a low priority.

Degradation of cladding during extended storage could affect the six transportation safety functions as follows:

Containment: If the cladding had degraded such that the configuration of the UNF assembly and its fuel component could not be assured under NTC and HAC, then the containment function of the shipping container could be affected.

Criticality Control: If the cladding had degraded such that the configuration of the UNF assembly and its fuel component could not be assured under NTC and HAC, then the ability of the fuel to be maintained in a subcritical configuration could be affected.

Shielding: If the cladding had degraded such that the configuration of the UNF assembly and its fuel component could not be assured under NTC and HAC, then the radiation shielding function of the shipping container could be affected.

Heat Transfer: If the cladding had degraded such that the configuration of the UNF assembly and its fuel component could not be assured under NTC and HAC, then the fuel may not maintain its original configuration and the heat transfer function of the shipping container could be affected.

Structural Integrity: Degradation of the cladding would have no impact on the structural integrity of the shipping container. However, if relocation of fuel occurred because of failure of cladding and fuel assembly structure, the distribution of the fuel heat source within the shipping container would change, which would change the heat transfer conditions and could impact on structures because of thermal stresses, etc. This would seem not to be a problem for low heat fuel, which would be the case for extended storage. However, it could present a problem for high-burnup shorter cooled UNF.

Operations Support: Degradation of the cladding could allow relocation of the fuel to occur which could impact the operations support safety function of the shipping container, especially during loading and unloading.

Based on the impacts of the degradation mechanisms associated with cladding on the transportation safety functions, annealing of radiation damage and embrittlement and reorientation of hydride species were assigned a HIGH transportation importance; delayed hydride cracking, oxidation, and creep were assigned a MEDIUM transportation importance, and the other degradation mechanisms were assigned a LOW transportation importance.

Table 2. Potential Stressors and Degradation Mechanisms that Could Impact the Performance of Cladding

Stressor	Degradation Mechanism	Influenced by Extended Storage or Higher Burnup	Additional Data Needed	Transportation Importance
Thermal	Annealing of radiation damage	Yes	Yes	High
	Metal fatigue caused by temperature fluctuations	Yes	Yes	Low
	Phase change	No	Yes	Low
Chemical	Emissivity changes	No	Yes	Low
	H_2 effects: embrittlement and reorientation	Yes	Yes	High
	H_2 effects: delayed hydride cracking	Yes	Yes	Medium
	Oxidation	Yes	Yes	Medium
	Wet corrosion	No	Yes	Low
Mechanical	Creep	Yes	Yes	Medium

2.3 Assembly Hardware

Assembly hardware could degrade through 4 primary mechanisms during extended storage: 1) creep, 2) metal fatigue caused by temperature fluctuations, 3) corrosion and stress corrosion cracking, and 4) hydriding effects (see Table 3). These phenomena were discussed in Section 5.3 of Hanson et al. (2011). For dry storage, corrosion and stress corrosion cracking was assigned a medium priority for additional research and development. Creep, metal fatigue caused by temperature fluctuations, and hydriding effects were assigned a low priority.

Degradation of assembly hardware during extended storage could affect the six transportation safety functions as follows:

Containment: No impact.

Criticality Control: Degradation of assembly hardware could result in loss of control of defined fuel rod pitch and could lead to changes in mechanical stress on cladding. Loss of defined fuel rod pitch could impact criticality control. Changes in mechanical stresses on cladding could result in loss of confinement of fuel and thus subsequently have the potential to impact criticality control.

Shielding: No impact except for potential changes in stresses in cladding and consequent potential loss of fuel configuration control (see Section 2.2).

Heat Transfer: Degradation of assembly hardware could alter fuel pitch which could impact the heat transfer function. Also other possible effects (see Section 2.2).

Structural Integrity: Degradation of assembly hardware would not impact the structural integrity of the shipping container except for possible changes in thermal stresses caused if there were significant changes in the physical location of fuel.

Operations Support: Degradation of assembly hardware could impact the operations support safety function of the shipping container, especially during loading and unloading.

Based on the impacts of the degradation mechanisms associated with assembly hardware on the transportation safety functions, corrosion and stress corrosion cracking was assigned a MEDIUM transportation importance. Creep, metal fatigue caused by temperature fluctuations, and hydriding effects were assigned a LOW transportation importance.

Table 3. Potential Stressors and Degradation Mechanisms that Could Impact the Performance of Assembly Hardware

Stressor	Degradation Mechanism	Influenced by Extended Storage or Higher Burnup	Additional Data Needed	Transportation Importance
Thermal and Mechanical	Creep	Yes	Yes	Low
	Metal fatigue caused by temperature fluctuations	Yes	Yes	Low
Chemical	Corrosion and stress corrosion cracking	Yes	Yes	Medium
	Hydriding effects	Yes	Yes	Low

2.4 Fuel Baskets

Fuel baskets could degrade through 3 primary mechanisms during extended storage: 1) creep, 2) metal fatigue caused by temperature fluctuations, and 3) corrosion (see Table 4). These phenomena were discussed in Section 5.4 of Hanson et al. (2011). For dry storage, these degradation mechanisms were assigned a low priority for additional research and development.

Degradation of fuel baskets during extended storage could affect the six transportation safety functions as follows:

Containment: Degradation of fuel basket structures could lead to changes the NCT and HAC loadings on closure systems evaluated in the certified design of transportation packages. Changes in, or uncertainties in, loadings on closure systems could impact the ability to determine and verify compliance with regulatory requirements.

Criticality Control: Fuel baskets perform a criticality safety function during transportation by maintaining neutron poisons and required spacing between fuel assemblies. Therefore degradation of fuel baskets could affect the criticality control function.

Shielding: Baskets are components of the structure of a shipping cask system. Thus, shielding location and arrangement can be affected by the performance of a basket under HAC conditions, where loadings on shield walls are highest. Thus basket structural performance, if degraded, might affect the performance of shielding.

Heat Transfer: Degradation of fuel baskets could impact heat transfer within the shipping container.

Structural Integrity: Baskets are components of the structure of a shipping cask system. Thus, degradation of the baskets could affect the structural integrity of the shipping container under HAC conditions.

Operations Support: Degradation of fuel baskets could impact the operations support safety function of the shipping container, especially during loading and unloading.

Based on the impacts of the degradation mechanisms associated with fuel baskets on the transportation safety functions, the degradation mechanisms associated with fuel baskets were assigned a LOW transportation importance.

Table 4. Potential Stressors and Degradation Mechanisms that Could Impact the Performance of Fuel Baskets

Stressor	Degradation Mechanism	Influenced by Extended Storage or Higher Burnup	Additional Data Needed	Transportation Importance
Thermal and Mechanical	Creep	Yes	Yes	Low
	Metal fatigue caused by temperature fluctuations	Yes	Yes	Low
Chemical	Corrosion	Yes	Yes	Low

2.5 Neutron Poisons

Neutron poisons media could degrade through 6 primary mechanisms during extended storage: 1) thermal aging effects, 2) embrittlement and cracking, 3) stress-induced creep, 4) metal fatigue caused by temperature fluctuations, 5) poison burnup, and 6) corrosion (see Table 5). These phenomena were discussed in Section 5.5 of Hanson et al. (2011). For dry storage, thermal aging effects, embrittlement and cracking, creep, and corrosion were assigned a medium priority for additional research and development. Poison burnup and metal fatigue caused by temperature fluctuations were assigned a low priority.

Degradation of neutron poisons media could affect the six transportation safety functions as follows:

Containment: No impact.

Criticality Control: Neutron poisons are the basis for the criticality control function. Therefore, degradation of the neutron poisons could affect the criticality control function.

Shielding: No impact.

Heat Transfer: Degradation of neutron poisons media could impact heat transfer within shipping containers.

Structural Integrity: Degradation of neutron poisons media would not impact the structural integrity of the shipping container, except to the extent that the poison bearing materials are used in, or as functional components of, basket structures, which are integral to the structural performance of the shipping container.

Operations Support: Degradation of neutron poisons media could impact the operations support safety function of the shipping container, especially during loading and unloading. Here the effect would be twofold, one being criticality control and the other would be neutron radiation, which would be multiplied by the subcritical multiplier effect.

Based on the impacts of the degradation mechanisms associated with neutron poisons media on the transportation safety functions, thermal aging effects were assigned a HIGH transportation importance. Creep and corrosion were assigned a MEDIUM transportation importance. Embrittlement and cracking, metal fatigue caused by temperature fluctuations, and poison burnup were assigned a LOW transportation importance.

Table 5. Potential Stressors and Degradation Mechanisms that Could Impact the Performance of Neutron Poisons

Stressor	Degradation Mechanism	Influenced by Extended Storage or Higher Burnup	Additional Data Needed	Transportation Importance
Thermal	Thermal aging effects	Yes	Yes	High
Thermal and Radiation	Embrittlement and cracking	Yes	Yes	Low
Thermal and Mechanical	Creep	Yes	Yes	Medium
	Metal fatigue caused by temperature fluctuations	Yes	Yes	Low
Neutron Radiation	Poison burnup	Yes	Yes	Low
Chemical	Corrosion (blistering)	Yes	Yes	Medium

2.6 Neutron Shielding

Neutron shields could degrade through 4 primary mechanisms during extended storage: 1) embrittlement, cracking, shrinkage, and decomposition, 2) radiation embrittlement, 3) poison burnup, and 4) corrosion (see Table 6). These phenomena were discussed in Section 5.6 of Hanson et al. (2011). For dry storage, these phenomena were assigned a low priority for additional research and development.

Degradation of neutron shields during extended storage could affect the six transportation safety functions as follows:

Containment: No impact.

Criticality Control: No impact.

Shielding: The neutron shields in shipping containers are typically made from boron containing polymer-based materials. For transportation-only overpacks, these neutron shields would be maintained during the life of a shipping container, so any degradation would be remediated and have no impact. For transportable storage casks such as the TN-32, neutron shields are not designed to be maintained. Thus for the transportable storage casks, neutron shield degradation could impact the ability to transport UNF after extended storage.

Heat Transfer: Heat transfer components pass through neutron shielding and could be affected by degradation of the neutron shielding material.

Structural Integrity: Degradation of neutron shielding could impact the structural integrity of the shipping container if the neutron shield contributes to impact protection or the structural performance of handling features or if it interacts with impact protection components of the shipping packaging as may be the case for transportable storage casks. For transport-only shipping containers neutron shields would be maintained during the life of a shipping container, so any degradation would be remediated.

Operations Support: No impact.

Based on the impacts of the degradation mechanisms associated with neutron shields on the transportation safety functions, the degradation mechanisms associated with neutron shields for transportation-only systems were assigned a LOW transportation importance. For transportable storage casks, embrittlement, cracking, shrinkage, and decomposition were assigned a MEDIUM transportation importance. Other degradation mechanisms were assigned a LOW transportation importance.

Table 6. Potential Stressors and Degradation Mechanisms that Could Impact the Performance of Neutron Shielding

Stressor	Degradation Mechanism	Influenced by Extended Storage or Higher Burnup	Additional Data Needed	Transportation Importance
Thermal and Mechanical	Embrittlement, cracking, shrinkage, and decomposition	Yes	Yes	Low for transportation only systems, Medium for transportable storage cask systems.
Radiation	Radiation embrittlement	Yes	Yes	Low
	Poison burnup	Yes	Yes	Low
Chemical	Corrosion	Yes	Yes	Low

2.7 Containers

There are two generic types of containers used to store UNF, bolted direct-load metal casks and welded metal canisters. About 13% of the storage containers currently in use are bolted direct-load metal casks and 87% are welded metal canisters. Welded metal canisters could degrade through 2 primary mechanisms during extended storage: 1) external atmospheric corrosion, and 2) internal aqueous corrosion. Bolted direct-load metal casks could degrade through 5 primary mechanisms during extended storage: 1) thermomechanical embrittlement of elastomer seals, 2) thermomechanical fatigue of seals and bolts, 3) radiation-enhanced embrittlement of elastomer seals, 4) external atmospheric corrosion, and 5) internal aqueous corrosion (see Table 7). These phenomena were discussed in Section 5.7 of Hanson et al. (2011). For dry storage, atmospheric corrosion and aqueous corrosion were assigned a high priority for additional research and development. Thermomechanical fatigue of seals and bolts was assigned a medium priority and thermomechanical, chemical or radiation-induced embrittlement of elastomer seals was assigned a low priority.

Degradation of containers during extended storage could affect the six transportation safety functions as follows:

Containment: The degradation of the containers could impair the ability to provide containment of radioactive material. Further, any degradation of the container could impact the ability to maintain the inert cover gas which could lead to degradation of the fuel, the fuel basket, the cladding, and neutron poisons.

Criticality Control: Degradation of the container could lead to the loss of inert atmosphere and the potential acceleration of oxidation and corrosion of the clad/fuel, fuel assembly structure, basket structure, and neutron poison material. Any early corrosion could provide a mechanism for loss of confinement of fuel from its fuel assembly structure and change in the physical location of components and materials that are relied on to prevent criticality. In addition, any failure of the container could have the potential to fail the moderator exclusion control (if applicable) and introduce potential criticality issues.

Shielding: Any loss of container integrity is not expected to significantly impact the ability of the package to provide radiation shielding.

Heat Transfer: Any degradation of the container internals could impact system heat transfer.

Structural Integrity: Depending on the specific shipping container, degradation of welded metal canisters could impact the structure of the shipping container. Degradation of bolted direct-load metal casks could impact the structural integrity of the cask, i.e., the shipping container.

Operations Support: Degradation of the containment function of the shipping container, if it led to degradation of the basket structure, fuel assembly structure, neutron poison media, cladding, or fuel could impact loading/unloading operations

Based on the impacts of the degradation mechanisms associated with containers on the transportation safety functions, thermomechanical fatigue of seals and bolts was assigned a HIGH transportation importance. Atmospheric and aqueous corrosion was assigned a MEDIUM transportation importance. Embrittlement of elastomer seals was assigned a LOW transportation importance.

Table 7. Potential Stressors and Degradation Mechanisms that Could Impact the Performance of Container

Stressor	Degradation Mechanism	Influenced by Extended Storage or Higher Burnup	Additional Data Needed	Transportation Importance
Welded Metal Canisters				
Chemical	Atmospheric Corrosion (Including Marine Environment)	Yes	Yes	Medium
	Aqueous Corrosion: general, localized (pitting, crevice), stress corrosion cracking, galvanic	Yes	Yes	Medium
Bolted Direct-Load Metal Casks				
Thermal and Mechanical	Embrittlement of elastomer seals	Yes	Yes	Low
	Thermomechanical fatigue of seals and bolts	Yes	Yes	High
Radiation	Embrittlement of elastomer seals	Yes	Yes	Low
Chemical	Atmospheric Corrosion (Including Marine Environment)	Yes	Yes	Medium
	Aqueous corrosion: general, localized (pitting, crevice), stress corrosion cracking, galvanic	Yes	Yes	Medium

2.8 Inert Fill Gas

The container provides the primary physical boundary for used fuel storage. The inert fill gas, typically helium, provides a non-chemically-reactive/non-oxidizing environment that is a key basis for determining that fuel classification does not change during extended storage. The inert fill gas also performs a heat transfer function thereby minimizing thermally-induced creep and accelerated corrosion of cladding and/or fuel which could affect the ability to perform ITS functions. Thus, monitoring for out-leakage of helium (or other inert gas) and in-leakage of oxygen is likely to be an important factor in the safe long-term storage of used fuel in dry storage systems and subsequent transportation. Because the inert fill gas is typically helium, it will not degrade when exposed to radiation and does not degrade through chemical means (a possible exception includes the effects of residual moisture and associated radiolytic decontamination products). A primary degradation mechanism would be diffusion of the inert fill gas through the canister wall (see Table 8). The inert fill gas could also be lost from a failed container (see Section 2.7) or, over very long periods of time, through minute leakage pathways that would not constitute failed containment. Last the inert gas fill could be modified over time by residual moisture and associated radiolytic decontamination products and by the gradual accumulation of gases leaking through pinholes and cracks in the cladding of undamaged UNF.

Loss of, atmospheric contamination, residual moisture modification, and/or fuel gas modifications of inert fill gas during extended storage could affect the six transportation safety functions as follows:

Containment: The degradation of inert fill gas (caused by failure of the containment boundary of containers or by modification resulting from residual moisture) could impair the ability to protect the physical integrity and functional performance of canister and UNF SSCs because of either corrosion, higher temperatures resulting from loss of heat transfer media, or both. Further, degradation of the containment boundary could further impact the ability to maintain the inert cover gas.

Criticality Control: Degradation of the containment boundary of the container could lead to the loss of inert atmosphere and the potential acceleration of oxidation and corrosion of the clad/fuel, fuel assembly structure, basket structure, and neutron poison material. Any early corrosion could provide a mechanism for loss of confinement of fuel from its fuel assembly structure and for change in the physical location of components and materials that are relied on to prevent criticality.

Shielding: Except for conditions where corrosion arising from in-leakage of atmospheric contaminants resulted in degradation of one or more SSCs contributing to significant displacement of fuel from its normal location, degradation or loss of inert gas fill is not expected to significantly impact the ability of the package radiation shielding to satisfy regulatory requirements for safe transportation.

Heat Transfer: Degradation of inert gas fill would impact the heat transfer characteristics of the shipping container system. Conditions wherein corrosion arising from in-leakage of atmospheric contaminants resulted in degradation of one or more SSCs contributing to significant displacement of fuel from its normal location, could also impact system heat transfer.

Structural Integrity: Except for conditions wherein corrosion arising from in-leakage of atmospheric contaminants or from residual moisture contaminants resulted in degradation of one or more SSCs contributing to significant degradation of ITS structures, degradation of the inert fill gas would not impact the structural integrity of the shipping container.

Operations Support: Loss of inert gas backfill could lead to higher than normal temperatures among SSCs inside a loaded container. A need to unload UNF that is thermally hot could lead to operations impacts. Except for conditions wherein corrosion arising from in-leakage of atmospheric contaminants or from residual moisture contaminants resulted in degradation of one or more SSCs contributing to significant degradation of ITS structures, loss or modification of inert fill gas would have no other impact on operations.

Based on the impacts of the degradation mechanisms associated with containers on the transportation safety functions, the degradation mechanisms associated with inert fill gas were assigned a HIGH transportation importance.

Table 8. Potential Stressors and Degradation Mechanisms that Could Impact the Performance of Inert Fill Gas

Stressor	Degradation Mechanism	Influenced by Extended Storage or Higher Burnup	Additional Data Needed	Transportation Importance
Thermal and Mechanical	Diffusion through canister wall	Yes	Yes	High
Radiation	N/A	N/A	N/A	N/A
Chemical	N/A	N/A	N/A	N/A

2.9 Other Structures, Systems, and Components

In McConnell et al. (1996), there are additional SSCs identified that were not identified in Hanson et al. (2011). These SSCs tend to be limited to shipping containers as opposed to dry storage containers, and not all SSCs would be found in all shipping container designs. These SSCs include items such as:

- Gamma Shielding
- Handling, Loading, and Operational Testing Features such as drain port plugs; vent and drain port plugs and pressure relief device inner seals; vent port plugs; leak check port plugs and seals; vent

and drain port plug and pressure relief device outer seals; vent, drain, and leak check port cover plates; etc.

- Impact Limiters and Impact Limiter Hardware
- Pressure Relief Devices
- Vessel Inner Shell, Vessel Lid, Vessel Lid Closure Hardware, Vessel Lid Inner Seal, Vessel Shell Bottom Head, Vessel Shell Upper Head, and Vessel Outer Shell
- Lifting Lugs, Trunnions, and Attachments; Lifting/Tiedown Hardware; Tiedown Lugs; Packaging Hardware; Protective Covers; Security Lockwire and Seals; Skids/Forklift Channels
- Neutron Shielding Shell
- Corrosion Protection Systems
- Anti-Contamination and Decontamination Features
- Heat Transfer and Thermal Protection Systems/Components.

These SSCs would be verified to be functional before shipping and would be remediated if found to be degraded. Therefore, these features were assigned a LOW transportation importance.

3. CONCLUSIONS

In general, the Transportation Importance assigned in Section 2 mirrored the importance assigned by the UFD Storage Task (Hanson et al. 2011). However, there were a few differences:

- Thermomechanical fatigue of seals and bolts for bolted direct-load metal casks was assigned a high transportation importance while in Hanson et al. (2011); it was assigned a medium importance. This was because failure of seals and bolts during transportation accidents could lead to releases from the shipping container.
- Corrosion of welded metal canisters and bolted direct-load metal casks were assigned a medium transportation importance while in Hanson et al. (2011), corrosion of canisters was assigned a high importance. This was because many shipping containers do not credit the welded metal canister as a confinement barrier, and because bolted direct-load metal casks would be maintained during extended storage, reducing the importance of corrosion.
- Contamination and loss of fill gas during extended storage was assigned a high transportation importance. The reasons include the effects of radiolytic decontamination products of residual moisture, the effects of leakages of gasses from fuel for undamaged UNF, and the very long-term

loss of light gas through very small leakage paths in metal seals, through diffusion through elastomer seals, and through very small leakage paths that may exist through canister weld porosity.

- Cladding annealing should be given a High priority. The reason is that this mechanism could reduce stresses in cladding and thus has the potential to mitigate some of the impacts of hydride precipitates. This needs to be better understood. On a related subject, cladding creep could also reduce stresses in cladding and may be localized, vs. general. If so, cladding creep could also reduce the impacts, and uncertainties associated with, of hydride formations.
- Neutron shields are a potential problem for transportable storage casks where the neutron shielding is not subject to inspection and replacement/maintenance. Over long periods of time, these organic materials could degrade, in particular if exposed to atmospheric contaminants and also if they have molecular instability that leads to long term degradation. Because the shields can be augmented for transport there is only a limited shielding issue. However, if the neutron shielding material interacts with ITS structures of a transport cask, there could be other issues that need to be addressed.

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