Interim UFD Storage and Transportation - Transportation Working Group Report

Fuel Cycle Research & Development

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

The Used Fuel Disposition (UFD) Transportation Task commenced in October 2010. As its first task, Pacific Northwest National Laboratory (PNNL) compiled a draft list of structures, systems, and components (SSCs) of transportation systems and their possible degradation mechanisms during very long term storage (VLTS). 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 (Stockman et al. 2010). 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), 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 have been summarized and are included as Appendix A of this report. The degradation mechanisms have been evaluated for influenced by very high burnup, additional data needs, importance of research and development (R&D), and the 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 the conclusions section of this report. As a follow-on task to the initial transportation FEPs development, the specific details of each FEP will be further developed to specifically address transportation issues and data gaps. This will be prepared as part of the effort to support the end of year transportation milestone.

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ACRONYMS

ANL	Argonne National Laboratory
DOE	U.S. Department of Energy
FEP	Feature, Event, or Process
GWd/MTU	Gigawatt-day per metric ton uranium
INL	Idaho National Laboratory
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
R&D	Research and Development
SNL	Sandia National Laboratories
SRNL	Savannah River National Laboratory
SSC	Structure, System, or Component
UFD	Used Fuel Disposition
VLTS	Very Long Term Storage

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 after very long term storage (VLTS) (on the order of 100 to 300 years). 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 used nuclear fuel after VLTS.

This document presents the compilation of Features, Events, and Processes (FEPs) related to the transportation of used nuclear fuel after VLTS. The initial identification utilized the efforts produced by the UFD Storage Task (Stockman et al., 2010) as a stepping off point and then identified those FEPs that may be unique to the ability to transport used nuclear fuel after VLTS.

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 post-VLTS transportation. This report is focused on UO_2-based light water reactor used nuclear fuel.

1.1 Scope

The UFD Transportation Task commenced in October 2010. As its first task, Pacific Northwest National Laboratory (PNNL) compiled a draft list of structures, systems, and components (SSCs) of transportation systems and their possible degradation mechanisms during VLTS. 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 (Stockman et al. 2010). 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), 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 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 draft 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. Appendix A is the work product from this meeting.

Appendix A also identifies whether the particular stressor and degradation would be affected by VLTS (100 to 300 years) or higher burnup used nuclear fuel (> 45,000 MWd/MTU). As with the UFD Storage Task, whether additional data were needed to characterize the phenomenon, the importance of Research and Development, and the Transportation Importance were determined. Transportation Importance was based on the ability of the stressor/degradation mechanism to cause the SSC to fail to perform its function during normal conditions of transportation (NCT), during hypothetical transportation accident conditions (HAC), or during retrieval. In the context of transportation, these functions are containment, structural integrity, heat transfer (thermal), criticality control, and shielding. This is consistent with the methodology used in the UFD Storage Task. In addition, Transportation Importance was determined based on transportation after VLTS, so that long term degradation mechanisms such as delayed hydride cracking would have an opportunity to operate prior to transportation. It is important to note that the normal conditions of transportation, hypothetical transportation accident conditions, or retrieval were not viewed as stressors, but rather as requirements that must be met by a shipping container and its contents before used nuclear fuel would be shipped.

1.2 Conclusions

In general, the Transportation Importance assigned in Appendix A mirrored the importance assigned by the UFD Storage Task (Stockman et al. 2010). However, there were a few differences:

- Delayed hydride cracking of cladding was assigned a low Transportation Importance. In Stockman et al. (2010), delayed hydride cracking was grouped with hydrogen embrittlement and assigned a high importance. This difference was more a matter of refinement because transportation also assigned hydrogen embrittlement a high ranking.

- Embrittlement of neutron poisons was assigned a medium transportation importance while in Stockman et al. (2010), it was assigned a low importance. This was because the hypothetical accident conditions associated with transportation are somewhat more severe than storage accidents, and transportation cask designs rely upon neutron poisons and flux traps to be in specific locations in specific amounts in the casks during these hypothetical accident conditions.
- Bare fuel casks were distinguished from metal canisters in this report while in Stockman et al. (2010) they were not. This was because of the presence of the elastomer seals that would be present in the bare fuel casks that would not be present in the metal canisters.
- Corrosion of metal canisters and bare fuel casks were assigned a medium transportation importance while in Stockman et al. (2010), corrosion of canisters was assigned a high importance. This was because many transportation casks do not credit the metal canister as a confinement barrier, and because bare fuel casks would be maintained during VLTS, reducing the importance of corrosion.

2. REFERENCES

EPRI 1998	EPRI (Electric Power Research Institute). 1998. Data Needs for Long-Term Dry Storage of LWR Fuel. EPRI Report No. TR-108757. April.
EPRI 2002	EPRI (Electric Power Research Institute). 2002. Technical Bases for Extended Dry Storage of Spent Nuclear Fuel. EPRI Report No. 1003416. December.
EPRI 2010a	EPRI (Electric Power Research Institute). 2010. Used Fuel and High-Level Radioactive Waste Extended Storage Collaboration Program, November 2009 Workshop Proceedings. EPRI Report No. 1020780. March
EPRI 2010b	EPRI (Electric Power Research Institute). 2010. Industry Spent Fuel Storage Handbook. EPRI Report No. 1021048. July.
EPRI 2010c	EPRI (Electric Power Research Institute). 2010. Transportation of Commercial Spent Nuclear Fuel, Regulatory Issues Resolution. EPRI Report No. 1016637. December.
NWTRB 2010	NWTRB (Nuclear Waste Technical Review Board). 2010. Evaluation of the Technical Basis for Extended Dry Storage and Transportation of Used Nuclear Fuel. December.
Stockman et al. 2010	Stockman C, B Hanson, H Alsaed, C Ottinger Farnum, JL Buelt, KB Sorenson, S Birk. 2010. Storage – Research and Development Opportunities Work Package – Year-End Report. U.S. Department of Energy, Fuel Cycle Research and Development.

Appendix A

Transportation Features, Events, and Processes (FEPs)

Appendix A

Structures, Systems, and Components and Potential Stressors and Degradation Mechanisms for Transportation of Used Nuclear Fuel After Very Long Term Storage

Stressor	Degradation Mechanism	Influenced by VLTS or Higher Burnup	Additional Data Needed	Importance of R&D	Transportation Importance	Notes
Fuel						
Thermal and Mechanical	Fuel Fragmentation	Yes	Yes	Low	Low	Importance assumes cladding remains intact. Discussed in Stockman et al. 2010, Section 3.1, NWTRB 2010, Section 4.4.1. Potential for damage to fuel during NCT and HAC. Damaged fuel could also pose retrievability issues. Fragmentation should have been addressed in SAR.
	Restructuring/Swelling (Bambooing)	Yes	Yes	Low	Low	
Radiation	None	NA	NA	NA	NA	Reduction in radiation dose rate over time would be a point of interface with the security task.
Chemical	Fuel oxidation	Yes	Yes	Low	Low	
Cladding						

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Stressor	Degradation Mechanism	Influenced by VLTS or Higher Burnup	Additional Data Needed	Importance of R&D	Transportation Importance	Notes
Thermal	Annealing of Radiation Embrittlement	No	Yes – Thermal modeling during extended dry storage	Medium	Medium	Discussed in Stockman et el. 2010, Section 3.2, NWTRB 2010, Section 4.4.2. Annealing decreases the strength and increases the ductility Fracture toughness increase helps cladding resistance to fracture under dynamic loads (accidents).
	Metal fatigue caused by temperature fluctuations	Yes	Yes	Low	Low	The amount of creep that could occur during transportation would not be significant. However, creep could be an issue for VLTS, during which creep could occur, followed by transportation. Thermal cycling requirement designed to limit damage to cladding (maximum 10

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						cycles with maximum 65C fluctuation). Creep rupture minimized with cladding temperatures below 400C (normal) and 570C (off-normal, accidents). Thermal cycling can enhance the amount of hydrogen the re-precipitates in the form of radial hydrides
	Phase change	No	No	N/A	N/A	
Radiation	Embrittlement	No	No	N/A	Medium	Radiation embrittlement important in conjunction with hydrogen embrittlement. Sensitive to temperature decrease.
Chemical	Emissivity changes from Zn or oxidation	TBD	TBD	TBD	Low	
	Attack of fission products on cladding (pellet clad interaction,	Yes	Yes	Low	Low	

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	iodine-assisted stress corrosion cracking, fission product assisted stress corrosion cracking)					
	H_2 effects (Embrittlement)	Yes	Yes	High	High	Fuel temperatures will decrease in extended storage and cause embrittlement at low temperatures. Transition between ductile and brittle behavior could be as low as 200C. Impacts ductility, strength, and fracture toughness. Higher burnup fuels may experience more hydride reorientation problems (i.e., radial hydrides). Delayed hydride cracking and embrittlement may be dominate mechanism in long term storage not creep rupture. Potential hydride reorientation during interim dry storage

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						and its effects on cladding properties have become one of the primary cladding performance concerns for used fuel transportation. (1016637). Zirconium hydrides may create points of reduced fracture toughness in the cladding, leading to cladding fracture under stress conditions such as those caused by HAC. (1016637)
	Delayed hydride cracking	Yes	Yes	Low	Low	Delayed hydride cracking and embrittlement may be dominate mechanism in long term storage not creep rupture. Slower developing.
	Oxidation	Yes	Yes	Medium	Medium	Internal monitoring systems need to be explored to assess the internal environment and

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Stressor	Degradation Mechanism	Influenced by VLTS or Higher Burnup	Additional Data Needed	Importance of R&D	Transportation Importance	Notes
						fuel cladding conditions Used fuel drying process can drive oxidation rates. Protect clad configuration. Potential for oxidation due to air ingress or inadequate drying.
	Wet Corrosion (Waterlogged Rods, Radiolysis of air and water, General Corrosion, Pitting, Stress Corrosion Cracking, Crevice Corrosion, Galvanic Corrosion, Fission Products)	No	Yes	TBD	Low	Corrosion probably more of an issue for baskets than for cladding. Waterlogged rods can be detected and replaced with dummy rods.
Mechanical	Creep	Yes	Yes	Medium	Low	Potential for damage to cladding during NCT and HAC. Damaged cladding could also pose retrievability issues. High burnup fuel can cause swelling, clad stress, creep and SCC.

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						Cladding embrittlement leading to cladding fracture during storage or transportation accident. If excessively brittle, the cladding could fracture under impact loads currently associated with HAC. Consequently, criticality safety of the reconfigured fuel assembly must be demonstrated. (ISG 19) For high burnup fuel, the thermal evaluation should consider credible or bounding fuel reconfigurations, for example, possible accumulation and relocation of damaged fuel near temperature-sensitive components such as elastomeric seals. (ISG 19)

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Stressor	Degradation Mechanism	Influenced by VLTS or Higher Burnup	Additional Data Needed	Importance of R&D	Transportation Importance	Notes
						For high burnup fuel, the containment evaluation should consider fuel fragmentation and releasable fines. (ISG 19). For high burnup fuel, the shielding analysis should identify and evaluate credible or bounding reconfigurations of fuel under HAC. (ISG 19). If the canister is never opened the spallation of CRUD should not be an issue. Also, Co-60 half life is 5.27 yrs.
	Fretting	No	TBD	TBD	TBD	Fretting during NCT could cause failure of clad.
Grid Spacers						
Thermal and Mechanical	Creep	Yes	No	N/A	N/A	Discussed in Stockman et el. 2010, Section 3.3. Potential for

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						damage to grid spacers during NCT and HAC. Under NCT cladding and baskets probably more important than grid spacers.
	Metal fatigue caused by temperature fluctuations	Yes	Yes	Low	Low	
Chemical	Wet corrosion	No	Yes	Low	Low	
Fuel Baskets						
Thermal and Mechanical	Creep	Yes	Yes	Low	Low	Discussed in Stockman et el. 2010, Section 3.4. Potential for damage to fuel baskets during NCT and HAC. Unyielding cask basket structure prevents fuel rod arrays from attaining optimum moderation conditions, thus limiting reactivity increases. (1016637)

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	Metal fatigue caused by temperature fluctuations	Yes	Yes	Low	Low	
Chemical	Wet corrosion	No	Yes	Low	Low	
Neutron Poisons (Boral – 80%)						
Thermal and Mechanical	Embrittlement and cracking	Yes	Yes	Medium	Medium	Discussed in Stockman et el. 2010, Section 3.5. Potential for damage to neutron poison during NCT and HAC. Flux traps and neutron poisons must be located in specific locations within shipping container.
	Metal fatigue caused by temperature fluctuations	Yes	No	N/A	N/A	
	Creep	Yes	No	N/A	N/A	
Radiation	Poison burnup	Yes	Yes	Low	Low	Depletion of neutron absorbers is not likely to be an issue.
	Embrittlement and Cracking	Yes	Yes	Medium	Medium	
Chemical	Wet corrosion	No	Yes	Low	Low	

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Stressor	**Degradation Mechanism**	**Influenced by VLTS or Higher Burnup**	**Additional Data Needed**	**Importance of R&D**	**Transportation Importance**	**Notes**
	(Blistering)					
Neutron Shields						
Thermal and Mechanical	Embrittlement, cracking, shrinkage, and decomposition	Yes	Yes	Low	Low	Discussed in Stockman et el. 2010, Section 3.6. Potential for damage to neutron shields during HAC. Transportation cask would likely have neutron shield so degradation would be addressed by cask maintenance program.
Radiation	Poison burnup	Yes	Yes	Low	Low	Transportation cask would likely have neutron shield so degradation would be addressed by cask maintenance program.
	Embrittlement and Cracking	Yes	Yes	Low	Low	Transportation cask would likely have neutron shield so degradation would be addressed by cask maintenance program.

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Chemical	Wet corrosion	No	Yes	Low	Low	Transportation cask would likely have neutron shield so degradation would be addressed by cask maintenance program.
Canisters						
Bare Fuel Casks (TN32, TN40, TN68)						
Thermal and Mechanical	Embrittlement of elastomer O-rings	Yes	Yes	Low	Low	Discussed in Stockman et el. 2010, Section 3.7.
	Temperature Fluctuations Relax Seals and Bolts	Yes	Yes	Medium	High	Transportation failure
Radiation	Embrittlement of Elastomer O-rings	Yes	Yes	Low	Low	Primary seal is metal, secondary is elastomer Surveillance program
Chemical	Humid Oxidation	Yes	Yes	High	Medium	
	Marine Environment	Yes	Yes	High	Medium	
	Wet Corrosion (General Corrosion, Pitting, Stress Corrosion Cracking, Crevice Corrosion, Galvanic Corrosion)	Yes	Yes	High	Medium	Corrosion of container could be important mechanism for losing the inert fill

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Stressor	Degradation Mechanism	Influenced by VLTS or Higher Burnup	Additional Data Needed	Importance of R&D	Transportation Importance	Notes
						gas.
Metal Canisters						
Thermal and Mechanical	None	N/A	N/A	N/A	N/A	Used fuel contained in welded metal canister.
Radiation	None	N/A	N/A	N/A	N/A	Used fuel contained in welded metal canister.
Chemical	Humid Oxidation	Yes	Yes	High	Medium	
	Marine Environment	Yes	Yes	High	Medium	
	Wet Corrosion (General Corrosion, Pitting, Stress Corrosion Cracking, Crevice Corrosion, Galvanic Corrosion)	Yes	Yes	High	Medium	Corrosion of container could be important mechanism for losing the inert fill gas.
Inert Fill Gas						
Thermal and Mechanical	Diffusion through canister wall	Yes	Yes	Low	Low	Welded containers do not have the means to confirm the presence of helium.
Radiation	N/A	N/A	N/A	N/A	N/A	
Chemical	N/A	N/A	N/A	N/A	N/A	