Current Research in Storage and Transportation of Used Nuclear Fuel and High-Level Radioactive Waste

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Abstract: Through the Department of Energy (DOE)/ Office of Nuclear Energy (NE), Used Fuel Disposition Campaign (UFDC), numerous institutions are working to address issues associated with the extended storage and transportation of used nuclear fuel. In 2012, this group published a technical analysis which identified technical gaps that could be addressed to better support the technical basis for the extended storage and transportation of used nuclear fuel. This paper summarizes some of the current work being performed to close some of those high priority gaps. The areas discussed include: 1. developing thermal profiles of waste storage packages, 2. investigating the stresses experienced by fuel cladding and how that might affect cladding integrity, 3. understanding real environmental conditions that could lead to cask stress corrosion cracking, 4. quantifying the stress and strain fuel assemblies experience during normal truck transport and 5. performing a full-scale ten-year confirmatory demonstration of dry cask storage. Data from these R&D activities will reduce important technical gaps and allow us to better assess the risks associated with extended storage and transportation of used nuclear fuel.

Keywords: Used Nuclear Fuel, Storage, Transportation, dry cask storage

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1. INTRODUCTION

The United States of America currently has 100 nuclear power reactors in 72 different nuclear power plants that supply about 19% of the country's electricity. The production of this energy creates "used nuclear fuel" which must be safely managed, contained, and disposed. These processes are often called the "back end" of the nuclear fuel cycle. Once the nuclear fuel no longer creates heat effectively in the reactor it becomes "used nuclear fuel" and is moved to a "spent fuel pool" at the nuclear power plant. As the pools near capacity, utilities move some of the older (typically 5 years) used fuel into "dry cask" storage. (U.S. NRC, 2013)

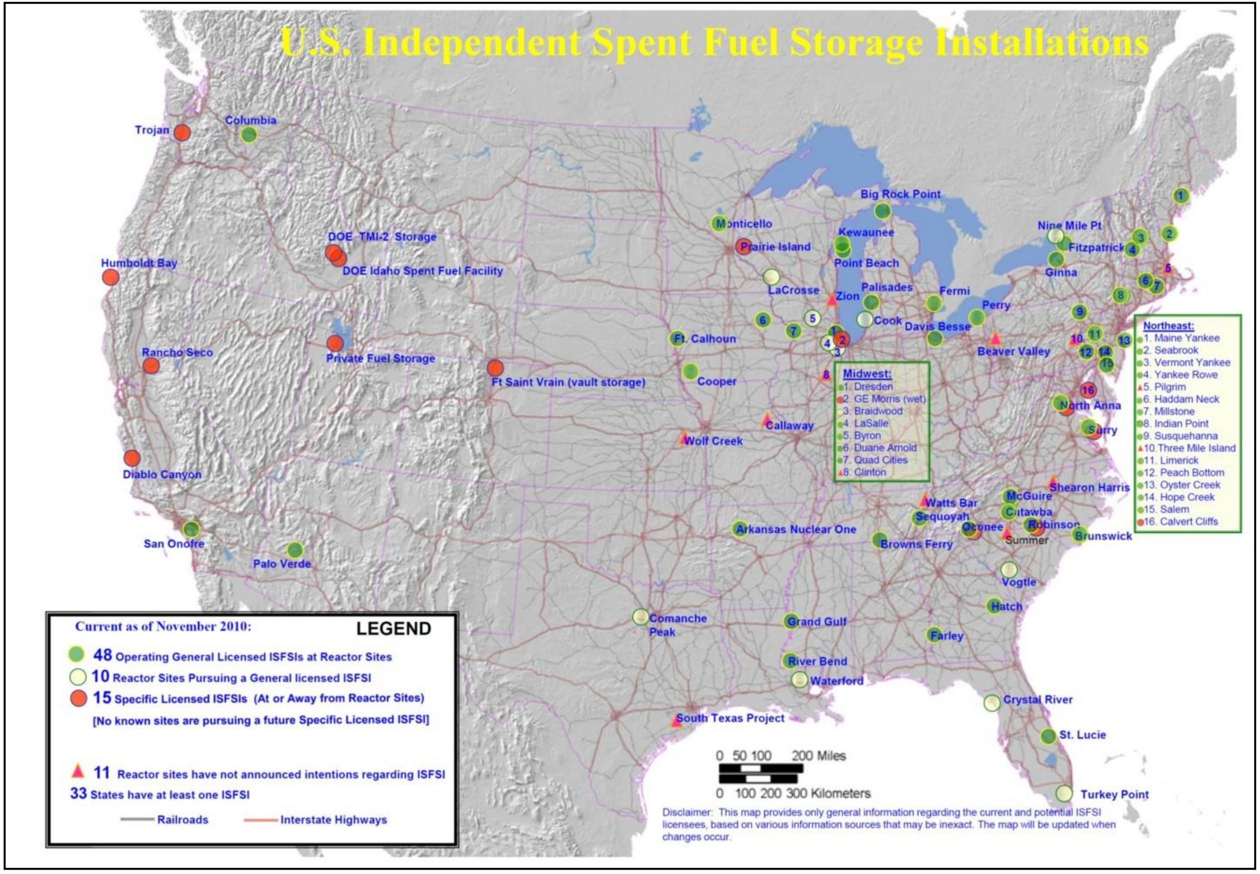
Dry cask storage allows used fuel to be surrounded by inert gas inside a container called a cask. The casks are typically steel cylinders that are either welded or bolted closed. The steel cylinder cask provides containment of the used fuel. Each cask is surrounded by additional steel, concrete, or other material to provide radiation shielding to workers and members of the public. (U.S. NRC, 2013) The casks can either be stored vertically or horizontally on the dry cask storage pad.

Figure 1: Horizontal Dry Storage (left) and Vertical Dry Storage (right)

There is currently about 70,000 metric tons of commercial used fuel accumulated in storage in the United States- about 80% of that is in used fuel pools and about 20% is stored in dry casks. This total increases by about 2000 metric tons annually. (U.S. NRC, 2013) Over time, nuclear power plants have found ways to use the fuel efficiently for a longer time in the reactor. Fuel that has been irradiated to more than 45 gigawatt-days per metric ton of uranium (GWd/MTU) is defined as high burn-up fuel. This high burnup fuel is comprising a larger percentage of the used fuel inventory. Due to the length of storage time and increased amount of high-burn-up fuel in the commercial used nuclear fuel inventory (UNF), the current infrastructure for the storage and transportation of commercial used nuclear fuel must provide both a safe and secure storage of our waste, but it must also maintain it in a condition so that the waste can withstand the stresses and strains of repackaging and transportation to a consolidated facility and permanent repository. While still believed to be safe, the R&D community does not have the same amount of data on the material characteristic of this fuel and therefore the DOE and NRC are supporting research in this area.

Current storage sites are shown below. Source: U.S. NRC website, downloaded 5/10/2012.

Figure 2. U.S. Locations where Used Fuel is currently stored.



The U.S. Department of Energy supports the development of the technical basis for storage and transportation because they are responsible for the used fuel once it leaves the reactor site for further disposition. The U.S. NRC is tasked with regulating the storage, transportation and disposal. In 2009, the Department of Energy (DOE)/ Office of Nuclear Energy (NE) established the Used Fuel Disposition Campaign (UFDC) as part of the Nuclear Energy Fuel Cycles Technologies Program that supports overall research and development focused on issues associated with the nuclear fuel cycle. Establishment of the Used Fuel Disposition Campaign was recognition that important issues associated with the backend of the fuel cycle needed to be addressed on a national scale. The Used Fuel Disposition Campaign focuses on two principal areas; 1) R&D associated with the storage and transportation of used nuclear fuel and 2) research on permanent geologic disposal. This paper focuses on the R&D associated with storage and transportation and relates directly to the issue of extended storage with an added focus on high burnup used nuclear fuel. The UFDC used fuel storage and transportation R&D campaign has three main objectives:

1. Develop the technical bases to support the continued safe and secure storage of used fuel for extended periods.
2. Develop the technical bases for retrieval of used fuel after extended storage.
3. Develop the technical bases for the transport of low and high burnup fuel after extended periods of dry storage.

One of the first products of the UFDC Storage and Transportation R&D area was to identify data gaps that could be addressed to better support the technical basis for extended storage and transportation. This work was compared with other independent gap analyses to benchmark results. This comparison showed that there was good consensus with the technical gaps. The *very high* priority gaps are listed by rank order in Table 1.

Table 1. UFDC Top Priority Gaps Sorted by Rank ((Used Fuel Disposition Campaign, 2012)**)**

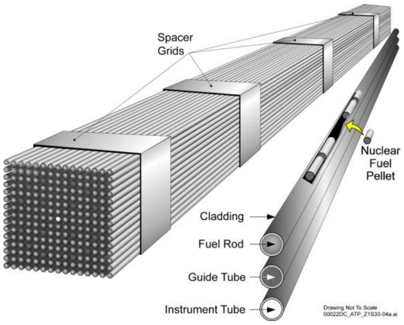
	Rank	**Priority**
Thermal profiles	1	Very High
Stress profiles	1	Very High
Monitoring – External	2	Very High
Welded canister – Atmospheric corrosion	2	Very High
Fuel Transfer Options	3	Very High
Monitoring – Internal	4	Very High
Welded canister – Aqueous corrosion	5	Very High
Bolted casks - Fatigue of seals & bolts	5	Very High
Bolted casks - Atmospheric corrosion	5	Very High
Bolted casks - Aqueous corrosion	5	Very High
Drying issues	6	Very High

Filling these gaps is a multi-year project. This report will focus on the work currently in progress to address some of those technical gaps.

2. Cladding Integrity Investigations (Gaps: Stress Profiles and Drying Issues)

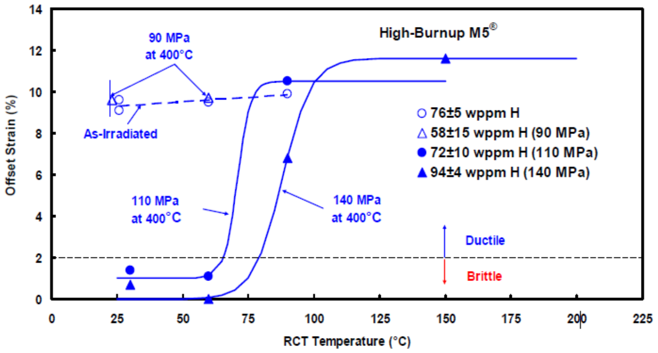
A fuel assembly is comprised of numerous fuel rods held together in a spacer grid. Each fuel rod contains many nuclear fuel pellets. See Figure 2 for a picture of the assembly, spacer grid, fuel rod, and nuclear fuel pellet. The cladding is the outer layer of the fuel rod and is usually made of zirconium alloys, which are used because of their low absorption cross-section of thermal neutrons, high hardness, ductility, and corrosion resistance. Because the cladding is the first line of defense for fuel integrity, efforts are underway to better understand and predict the strength and ductility during drying, storage, and transportation conditions. When the fuel assembly is removed from the spent fuel pool and placed in a cask for dry storage, the temperature of the fuel and cladding peaks initially and then slowly cools. This peak temperature can cause numerous effects that need to be better understood for high burnup fuel such as: ductile to brittle transition temperature, hydride precipitation and re-orientation, and fuel pellet-to-pellet and pellet-to-clad interaction. Our goal is to be able to predict what happens to high-burnup cladding in different temperature and pressure conditions so that we can determine the best ways to manage the aging of the fuel cladding, and how it will perform during transport.

Figure 2: Diagram of a nuclear fuel assembly, fuel rods with outer cladding, and fuel pellets inside the rod.



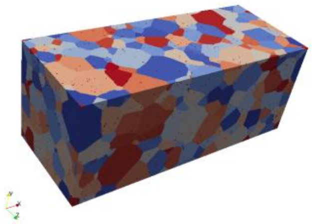
2.1 Ductile to Brittle Transition Temperature (DBTT): In order to maintain the integrity of the fuel and cladding, is important to understand where the fuel is in the ductile to brittle transition temperature curve as a function of time, burnup, and hydrogen up-take . Argonne National Lab has been working to determine the DBTT on the most common cladding types. Recent ring compression test on high burnup fuel cladding indicate that the cladding may not drop below the ductile to brittle transition temperature at pressures typically seen in high burnup fuel. See data for M5 cladding in Figure 3. (Billone, 2014) Work in this area will continue to verify these results and perform further tests at lower temperatures.

Figure 3: DBTT for High-Burnup M5 cladding. All at 400°C but at different different pressures. (Billone, 2014)



2.2 Hydride Formation: As the fuel is burned in the reactor for longer periods of time, hydrogen uptake by the cladding is also increased where it form hydrides in the circumferential direction. When the fuel is removed from the pool and begins the drying process, the fuel experiences a temperature spike and then subsequent cooling. During that time, the hydrides can dissolve and then precipitate again, but this time in the radial direction. Radial hydrides reduce ductility and can potentially lead to cracks in the cladding. Sandia National Labs is developing computer models to show how these hydrides form and be able to predict the conditions under which they form, as seen in Figure 4. This will allow us to better understand how to prevent radial hydride formation in fuel cladding.

Figure 4: Computer model showing the hydride growth in cladding. (Tikare, Hernandez, & Weck, 2013)



2.3 Fuel Pellet-To-Pellet And Pellet-To-Clad Interaction: With funding from the NRC, Oak Ridge National Labs has been using finite element analysis to develop models working on understanding the vibration integrity and flexural rigidity of the cladding of high burnup fuel. A surrogate used fuel rodlet containing surrogate fuel pellets was continually vibrated back and forth in ta U-frame bending fatigue testing system (see diagram in Figure 5). Results show that pellet-to-pellet and pellet-to-clad contact is very important to the strength of the fuel rod. When there is good pellet-to-pellet contact and pellet-to-cladding contact, the stresses are absorbed by the pellet, and much less stress is absorbed by the cladding. When there is poor cohesion at the pellet-to-pellet and pellet-to-clad interface, the embedded pellets can no longer provide effective structural support which can cause the rod to loose flexural rigidity, especially at the pellet-to-pellet interfaces. (Jiang & Wang, 2014) An example of the stress distribution with poor pellet-to-pellet cohesion is shown in Figure 6. The red color indicates areas of higher stress, the blue color show areas of lower stress.

Figure 5: U-frame Tool used to repeatedly flex the fuel rodlet to obtain data on rod vibration integrity and flexural rigidity. (Jiang & Wang, 2014)

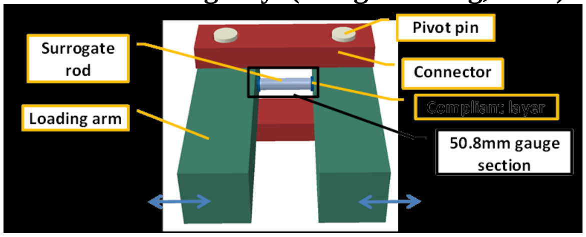
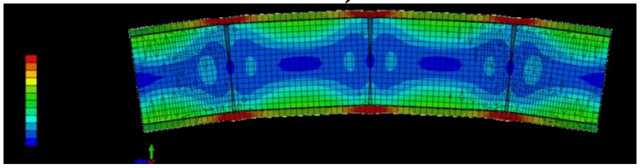


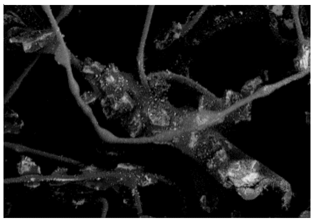
Figure 6: Example of FEA showing stress distribution with poor Pellet-to-Pellet contact (Jiang & Wang, 2014)



3.0 DEGRADATION OF THE METAL CANISTERS AND CASKS (Gaps: Atmospheric and Aqueous Corrosion): Additional work is being performed by DOE and its partners to understand environmental degradation of the metal casks. This research area is focused on the potential for stress corrosion cracking resulting from exposure of the cask to different inland and marine environments in combination with the residual stresses from the canister welds.

Figure 7: Dust accumulation on the surface of a horizontally stored cask. (Enos, Bryan, & Norman, 2013)

Figure 8: Dust particles collected from the outer surface of an in-use SNF storage container. (Enos, Bryan, & Norman, 2013)



Dust samples from dry storage casks collected in both east and west coast marine environments are being analyzed to better understand when and if conditions exist for initiation and growth of stress corrosion cracking. See Figure 7 and Figure 8 for sources of the dust samples and an enlarged picture of a dust sample. Initial results indicate that the salts do not appear to have much sodium or chlorine, but are high in calcium and $SO_{4.}$ The remainder of the sediment appears to be mostly comprised of pollens. (Enos, Bryan, & Norman, 2013) The initial analysis of this dust composition does not appear to be very corrosive to stainless steel.

Our goal in this research area is to determine what conditions could lead to canister corrosion and potential cracking, if those conditions exist where casks are stored, and how to potentially mitigate those conditions.

4.0 UNDERSTANDING THE TEMPERATURE GRADIENTS AND AIR FLOW DUIRNG STORAGE (Gap: Thermal Profiles): Dry canisters are typically stored on a concrete pad adjacent to the nuclear power plant. They can be stored horizontally or vertically in storage overpacks and are cooled by natural convection through vent openings in the concrete overpack. The Pacific Northwest National Laboratory is currently working to develop models that predict the thermal profiles of the canisters as they cool. Data to validate this modeling comes from canister temperature measurements and fuel radioactive decay calculations. Being able to predict the temperatures and thermal conditions provides needed data for understanding the ductility of the fuel and cladding, the rate of chemical reactions on the cask surface, and the pressures within the fuel. These data and tools will allow us to predict when fuel temperatures may drop below the Ductile to Brittle Transition Temperature, and when salts may deliquesce onto a cask surface. Knowing this information may affect how the fuel is handled during storage and transportation.

Figure 9: PNNL Analysis of temperature on cask surface. (Adkins)

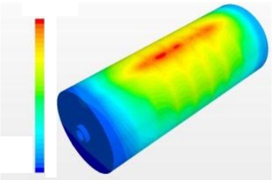
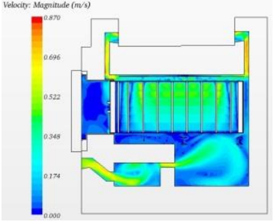


Figure 10: PNNL Analysis of airflow through a horizontal storage module. (Adkins)



5.0 FORCES EXPERIENCED DURING NORMAL TRANSPORT (Gap: Stress Profiles): While we have a good understanding of the ability for a waste package to withstand numerous accident scenarios. We do not have a complete understanding of the loadings that fuel within a waste package would experience during normal road or rail transport. Currently, investigations are underway using a surrogate fuel assembly (Figure 11) and subjecting it to shock and vibration on a shaker table (Figure 12) similar to the shocks and vibrations obtained from routine truck transport. Results indicate that the stresses and strains experienced by the assembly during normal truck transportation conditions are much less than the levels thought to create damage to used fuel cladding --200 microstrain during the test vs. 9400 microstrain for high burnup used fuel. (Figure 14). Due to limitations of the shaker table testing, further analysis incorporating low frequencies and more degrees of freedom are needed. (McConnell, et al., 2013) On February 25, 2014, Sandia National Labs tested the same surrogate assembly on a truck over a 38 mile distance in Albuquerque, New Mexico. (Figure 15)This test was designed to incorporate the low frequencies and numerous degrees of freedom that the shaker table could not incorporate. The truck driving route consisted of dirt road, interstate highway, and city roads. Initial data indicate that stresses and strains are again much lower than the levels thought to create damage to used fuel (~400 microstrain vs 9400 microstrain for high burnup fuel). These results suggest that failure of the rods is unlikely during normal conditions of transport due to stress or strain. In addition, data from these tests is used to validate fuel assembly models (Figure 13).

Data for rail transport have recently been obtained, and testing using this data is planned within the next year. The data indicates that truck transport subjects the fuel to greater stresses and strains than rail, but because it is estimated that the majority of shipments will be over rail, it is still important to obtain and analyze this rail data. The goal of this work is to determine if high burnup used fuel can safely withstand truck and rail transport and to validate models being developed to better understand the structural performance of fuel under normal conditions of transport.

Figure 11: The surrogate fuel assembly instrumented with accelerometers and strain gauges. (McConnell, et al., 2013)

Figure 12: Surrogate Assembly on Shaker Table to be subjected to the vibrations seen on a 700 mile Truck Transport. (McConnell, et al., 2013)

Figure 13: Fuel Assembly Submodel (Adkins, et al., 2013)

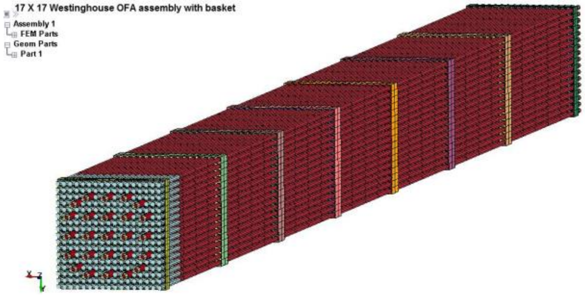


Figure 14: Elastic portion of stress—Shaker test shows that stresses and strains during normal conditions of transport are well below levels believed to create damage. (Klymyshyn, Sanborn, Adkins, & Hanson, 2013)

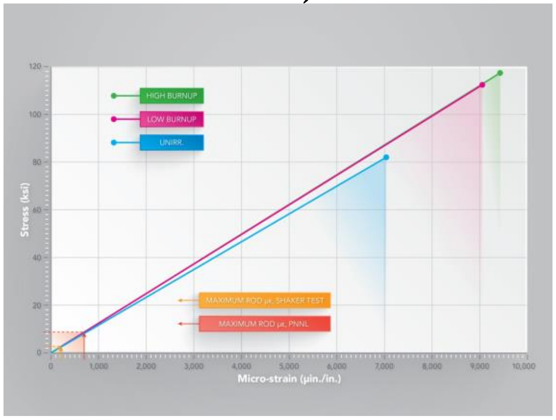


Figure 15: Surrogate assembly on 38 mile Truck transport. The assembly is bolted and strapped to concrete blocks to simulate the weight of a transport canister. (photo: Saltzstein)

6.0 FULL-SCALE DEMONSTRATION (Gaps: Internal and External Monitoring and Drying Issues). In order to obtain confirmatory information on drying and long-term storage conditions of high burnup fuel, DOE, EPRI, and Dominion Power are starting a ten-year project to obtain data from a cask of high burnup fuel as it goes through the typical drying process and then cools for many years. Analysis if similar rods with similar pedigrees and burnup history (sister rods) will be tested before cooling to obtain time-zero data. Data from periodic inspection of rods in the cask will provide information on how the high burnup fuel degrades over time. Thesedata can be compared to the data from the sister rods. Environmental data collected from the cask, such as temperature and fission gas, will provide information on the environment around the rods and potentially detect any failures. This data will be used to assist in the extension of storage and transportation licenses, validate our current predictive models, and better recommend the best conditions to for safe storage and aging.

7.0 CONCLUSION

In the United States, two unrelated factors have focused attention on the integrity of high burnup spent fuel (i.e., > 45 GWD/MTU) during storage and transportation operations: the need for longer-term storage at the independent fuel storage sites and the higher fuel burnups related to efficiencies in US reactor operations. A strong technical basis is being developed to demonstrate our understanding of high burnup fuel response during storage and transport. This requires validation of the integrity of high burnup spent fuel through a combination of testing and analysis to demonstrate actual performance in the areas of loads, applied strains, material properties, and pellet-clad interaction. Through the national labs and universities, the US DOE Storage and Transportation R&D Program is developing this technical basis.

8.0 ACKNOWLEDGEMENTS

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