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Overview of the U.S. Department of Energy Research and Development Efforts Associated with the Storage and Transportation of Used Nuclear Fuel

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ABSTRACT

The United States is anticipating the need to store commercial used nuclear fuel in dry storage systems beyond the existing regulatory licensing timeframe. This is due, in part, to the delay of deployment of a repository to dispose of the commercial used nuclear fuel. Although long term storage of used nuclear fuel is deemed safe and secure, a better understanding of material degradation mechanisms and rates for dry storage system safety components is necessary to demonstrate safe performance of these systems for extended periods of time. This is especially true for high burnup used nuclear fuel (i.e., > 45 GWd/MTU) where there is limited data to ascertain long term performance.

The U.S. Department of Energy (DOE) is currently funding substantial R&D work to address issues identified as necessary to make the technical defense for extended storage and subsequent transportation of used nuclear fuel. This work covers all aspects of the dry storage systems currently licensed in the U.S.; the used nuclear fuel cladding, internal basket and structures, fuel canisters, storage and transportation overpacks, and concrete systems for shielding and support. The DOE work is closely coupled with efforts by the U.S. industry, as well as work being conducted internationally by other technical organizations.

This paper is an extension of a previous publication [1] and will review the scope and status of the current R&D work for storage and transportation of used nuclear fuel.

1.0 Background

As nuclear fuel reaches the end of its operational life, it is removed from the reactor to pool storage as a safe intermediate step to await further disposition pathways. There are three general pathways for used nuclear fuel: reprocessing, interim dry storage, and disposal. Within these three general pathways, there is a myriad of options that could define a particular fuel cycle. In general, however, existing global reprocessing capability is limited and only two repository sites are currently being licensed or are under construction for the disposal of used nuclear fuel, one each in Sweden and Finland, respectively. There is no current high level waste repository that accepts used nuclear fuel for disposal.

In the U.S., delay in repository design, licensing, and construction has created a situation where used nuclear fuel storage at utility sites will need to remain in place much longer than originally expected and longer than current regulatory storage time limits allow.

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As of May 2012, there was over 67,000 metric tons of uranium (MTU) of used nuclear fuel in storage in the U.S.; 49,000 MTU in pool storage and 18,000 MTU in dry storage in the U.S. [2] Current reactor operations in the U.S. will result in an additional 2000 MTU being off-loaded to pool storage every year. Site management will require used nuclear fuel to be transferred from pool storage to on-site dry storage as a means to manage pool availability for routine operations such as reactor refueling and off-loading and cooling of fresh nuclear fuel.

As repository programs continue to experience delays, the safe and secure storage of used nuclear fuel becomes more important. Interim storage sites must expand their sizes to accommodate new used nuclear fuel, plans for centralized interim storage sites are being considered, and extension of storage licenses for existing storage systems will be necessary pending a disposition resolution. While it is expected that used nuclear fuel can be stored safely and securely, a technical bases needs to be developed that demonstrates safe storage beyond the current licensing timeframe.

An important component in these issues deals with evolving reactor operations. In particular, nuclear fuel is being discharged with increasingly higher burnups. Given the high burnups, material property conditions of the fuel cladding may be significantly different from cladding subjected to the average burnups of even ten years ago. Higher burnup fuel is usually considered as fuel that has been irradiated to > 45 GWd/MTU. There is limited data associated with high burnup used nuclear fuel. This affects the technical bases that need to be addressed when considering extension of dry storage licenses.

This paper will discuss a path forward for development of the technical bases that will address technical gaps that need to be resolved for understanding materials degradation issues over extended periods of time. Although all safety components of a storage system need to be considered, this paper will focus on the status of the development of the technical bases associated with used nuclear fuel specifically that is in dry storage. The focus will be on the U.S. situation and the Department of Energy program that is sponsoring much of this work.

2.0 U.S. Department of Energy Used Fuel Disposition R&D Program

2.1 Technical Data Gaps

In 2009, the Department of Energy (DOE)/ Office of Nuclear Energy (NE) established the Used Fuel Disposition Campaign (UFDC) as part of the Fuel Cycles Technologies Program that supports overall R&D focused on issues associated with the nuclear fuel cycle. Establishment of the UFDC was recognition that important issues associated with the backend of the fuel cycle needed to be addressed on a national scale. The UFDC focuses on two principal areas: disposal research and R&D associated with the storage and transportation of used nuclear fuel. The storage and transportation R&D relates directly to the issue of extended storage for used nuclear fuel.

The UFDC storage and transportation R&D has three main objectives:

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

Initial efforts in this program centered on a technical data gap assessment to identify the data gaps that need to be addressed in order to develop the technical bases for extended storage. This assessment was done for all safety components of dry storage systems including the fuel, baskets, containment boundary, neutron poisons and shields, closure lids and seals, overpacks, gamma shielding, and the concrete pad. Having identified the gaps, the next step was to prioritize the gaps relative to their importance to making the safety case for extended storage.

The result of this work is a comprehensive assessment [3] of the R&D that needs to be conducted to develop the technical bases for extended storage. Table 1 lists the high priority technical gaps that need to be addressed in order to develop the technical bases for extended long-term storage. In addition to the prioritized gaps identified in Table 1, cross-cutting gaps such as monitoring, thermal and stress profiles, drying issues, subcriticality and burnup credit, and fuel transfer options were also identified.

Table 1. Summary of High- and Medium-Priority Degradation Mechanisms that Could Impact the Performance of Structures, Systems, and Components during Extended Storage [3]

SSC	Degradation Mechanism	Importance of R&D	Approach to Closing Gaps
Cladding	Annealing of radiation damage	Medium	Long-term, low-temperature annealing will be analyzed through advanced modeling and simulation with some experimental work to support the model.
	H_2 effects: embrittlement and reorientation	High	A comprehensive experimental and modeling program to examine the factors that influence hydride reorientation will be performed, with a focus on new cladding materials and high burnup fuels. Additional experimentation and modeling to provide the link between unirradiated and irradiated cladding performance will be initiated.
	H_2 effects: delayed hydride cracking	High	Experimental work combined with modeling will be initiated.
	Oxidation	Medium	Experimental work to determine the mechanisms for rapid cladding oxidation observed will be initiated.
	Creep	Medium	Long-Term, low-temperature, low-strain creep will be analyzed through advanced modeling and simulation with some experimental work to support the model.
Fuel Assembly Hardware	Corrosion (stress corrosion cracking)	Medium	Because the corrosion of fuel assembly hardware components of concern is the same or similar to cladding, the results of cladding tests and analyses will be utilized.
Neutron Poisons	Thermal aging effects	Medium	Development of an accurate source term and radiation and thermal profiles is needed. Experimental work and modeling together is collaboration with universities under the Nuclear Energy Program will be initiated.
	Creep	Medium	
	Embrittlement and cracking	Medium	
	Corrosion (blistering)	Medium	
Container (Welded Canister)	Atmospheric corrosion (including marine environment)	High	Analyses of the conditions that will exist on the cask and canister surfaces will be performed. Collaboration with the Electric Power Research Institute (EPRI)-led Extended Storage Collaboration Program (ESCP) and International Subcommittee, especially the Japanese Central Research Institute of Electric Power Industry (CRIEPI) and the German Federal Institute for Materials Research and testing (BAM), will be initiated.
	Aqueous corrosion	High	
	Thermomechanical fatigue of seals and	High	

	bolts	High	
Container (Bolted Casks)	Atmospheric corrosion (including marine environment)		
	Agueous corrosion	High	
Overpack	Freeze-thaw	Medium	Development of detailed aging management programs will be performed. Inspection tasks to provide the means for early detection will be initiated.
	Corrosion of embedded steel	Medium	

Several independent gap analyses were conducted in parallel with this study. In particular, the U.S. NRC and the International Subcommittee of the Electric Power Research Institute Extended Storage Collaboration Program (EPRI/ESCP) each conducted studies [4, 5] that are relevant to the UFDC study. While there are some differences in gaps and the order of priorities for the list of technical gaps, there is general consensus on the identified technical gaps. [6].

2.2 Experimental and Analytical Work

To address the work needed to be done that is identified in Table 1, the UFDC Storage and Transportation Research and Development program has been divided into five topical area work packages, or Control Accounts. A brief description of each Control Account provides the overview of the R&D program.

<u>Experiments</u>

For the past three years, the UFDC program has funded Argonne National Laboratory to conduct ring-compression tests on de-fueled cladding to better understand the effect that hydrides and hydride orientation in the cladding have upon degradation of the mechanical properties of the cladding. The effect that hydrogen concentration and hydride orientation has on cladding can be significant. Reduction in ductility and fracture toughness are two significant issues that need to be better understood in the storage and transportation environments for these materials. Significant progress has been made for PWR cladding materials (i.e., Zircaloy 4, ZIRLO™, M5®) [7].

Current experiments include ring compression tests (RCTs) that provide an assessment of relative ductility between cladding types, as well as estimates of the Ductile to Brittle Transition Temperature (DBTT). Estimates of these material properties associated with degraded cladding are essential to understanding the long term performance during storage as well as subsequent transportation when the fuel will need to be shipped for further disposition.

Figure 1 identifies the hydrides in the used nuclear fuel cladding. When used nuclear fuel is removed from the storage pool to a dry storage system, the fuel goes through a drying process which results in a thermal spike. As the fuel cools after drying, the hydrides may reorient from a circumferential to a radial orientation, thereby further embrittling the cladding. The degree of reorientation is a function of the increase in temperature and resultant cool down rate, as well as the internal pressure in the fuel rod. It is therefore very important to benchmark the hydride characteristics in the fuel cladding when it is placed in dry storage.

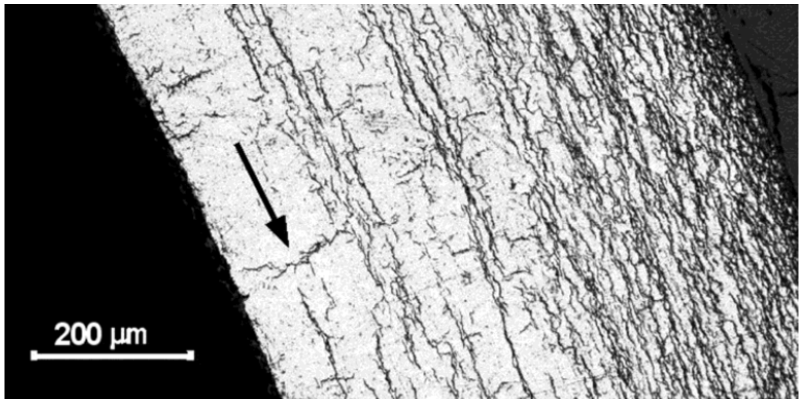

Figure 1. Circumferential and radial (note arrow) hydrides in Zircaloy-4 Cladding from 64 GWd/MTUhigh burnup fuel after drying treatment [7]

Other experimental efforts being pursued under this Control Account include; Corrosion behavior of stainless steel used nuclear fuel canisters, environmental sampling of salt concentrations for storage sites near marine environments, and hydrogen doping of new cladding materials to assess the feasibilitiy of replicating in-service conditions of used nuclear fuel cladding.

Analysis

The modeling and analysis component of this program complements the experimental work. Two main efforts are associated with this Control Account. First, models are being developed to estimate hydride development and characteristics during the transfer from pool storage to dry storage. During this operational process, a temperature spike occurs that put existing hydrides into the solidus phase. As the used nuclear fuel cladding cools, the hydrogen solidifies and may reorient from a circumferential position to a radial orientation in the cladding. The radial hydrides are particularly sensitive to stress concentrations under loading. Once the model is benchmarked to empirical data developed in the Experiments Control Account, assessments of hydride behavior for different cladding types subjected to various loadings will be possible through analysis, thereby allowing for a more efficient means of addressing the full range of cladding materials and conditions.

Given the dramatic effect that hydrides may have on cladding materials, it is important to understand the hydride mechanisms that occur during the operational life of the used nuclear fuel in order to predict how the cladding will perform under long-term storage. This understanding of the cladding properties will allow for estimations of fuel performance subjected to regulatory loading conditions. Linking the understanding of hydride effects to performance in long-term storage is essential in order to predict performance under extended storage periods and subsequent transportation. An understanding of how the used nuclear fuel cools in these environments and predicting when or if the used nuclear fuel drops below the DBTT will drive operational decisions for the management of these materials. A confirmatory storage demonstration will provide the necessary validation to confirm the long term material performance understanding that was developed from the earlier experimental and analytical work.

Second, thermal profiles of used nuclear fuel and of dry storage canistered systems are being conducted to estimate canister surface temperatures as a function of time. An understanding of the thermal profile as a function of time of the used nuclear fuel in storage will provide important information relative to when the used nuclear fuel may change from a ductile behavior to a brittle behavior. For canistered systems, the canister surface temperatures as a function of time are important to ascertain what environmental conditions will result in deliquescence of salt from the air to a brine solution on the canister surface.

Transportation

It is important to understand how high burnup used nuclear fuel will respond to the Normal Conditions of Transport (NCT) after extended storage periods. While there is much data regarding transport cask response to various mechanical and thermal loadings, there is little data relative to how the fuel inside the transport cask will respond. This work is focused on gathering mechanical loading data on fuel rods that are subjected to vibration and shock loadings that are representative of NCT. These loadings, coupled with the experimental material property data for the cladding, can then be used to assess the ability of used high burnup fuel to maintain its integrity during NCT. If the cladding can maintain its integrity, even if it is operating as a lower-shelf brittle material, the justification for transport of used high burnup fuel after extended storage becomes stronger.

Demonstration

Recently, the U.S. DOE has issued a contract to industry to initiate a long-term storage confirmatory demonstration program [8]. This program will focus on dry storage of high burnup PWR and BWR used nuclear fuels of different cladding types. In particular, this confirmatory program will monitor temperature profiles and seal performance to assure that the dry storage system is functioning as intended over the storage period. Intermittent inspections are planned to confirm fuel integrity and validate understanding of material degradation mechanisms developed from the experimental program.

Security

This program is investigating and identifying technical security issues that may arise during extended storage periods. For example, the aspect of "self-protection" changes with used nuclear fuel as it cools and the radiation danger lessens. As this self-protection aspect changes, security implications may arise with respect to the physical protection of the used nuclear fuel and the facilities that house the storage systems. This program is in the early stages of this evaluation and is addressing these aspects from a technical perspective, with monitoring of potential regulatory changes.

4.0 Conclusions

Extended long-term storage of used nuclear fuel is a reality for many nations that generate nuclear power. When regulatory frameworks were developed, current thinking at the time envisioned the ability to dispose or reprocess of the fuel within several decades. Due to many factors, repository development has not proceeded as planned and long-term dry storage of fuel in existing systems must remain the first option for managing this material. To allow confidence in the safety and integrity of these systems for periods past their original regulatory licensing timeframes, an integrated combination of near-term experimental tests and a confirmatory storage demonstration project have been implemented to demonstrate that materials used as engineering components of the storage system behave over the long term in a manner that is well understood and provide the requisite level of safety.

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