Evaluation of the Technical Basis for Extended Dry Storage and Transportation of Used Nuclear Fuel — *Executive Summary*

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Authors

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Introduction

The U.S. Nuclear Waste Technical Review Board (Board) is tasked by the amendments to the Nuclear Waste Policy Act of 1982 to independently evaluate U. S. Department of Energy (DOE) technical activities for managing and disposing of used nuclear fuel and high-level radioactive waste. This report was prepared to inform DOE and Congress about the current state of the technical basis for extended dry storage[1] of used fuel and its transportation following storage. The Board expects that the report also will be valuable in informing the Blue Ribbon Commission on America's Nuclear Future, and other interested parties, on these issues.

When the used nuclear fuel that is currently stored at commercial nuclear power plant sites will be transported to other locations is not known. Understanding the length of time that used fuel can be stored, without the fuel or the storage system components degrading to the extent that the ability to meet the regulatory requirements for continued storage is affected, is a primary concern. In addition, understanding how the condition of the used fuel changes with time is important to determining when this may affect the ability to transport the fuel without significant risk of damage or release of radioactive materials. Finally, being able to predict

1 U.S. nuclear utilities are operating dry-storage facilities for used fuel that are licensed for operating periods of up to 60 years. The fuel in these facilities and the used fuel that will be discharged in the foreseeable future may need to remain in storage for much longer periods. Some have suggested that this period could extend to as long as 300 years. This report evaluates the technical basis for dry storage of used fuel during such extended periods but does not encompass extended wet storage of fuel. In this report, the term "fuel" refers to both the uranium pellets and the metal cladding.

confidently how used fuel will behave when it is handled after transportation to a repository or a processing facility also is necessary.

This report presents the results of a review of publicly available literature and published information on research completed to date related to extended storage and transportation of used fuel. The Board reports these results without challenging the technical findings of researchers but believes that they form a suitable basis for the evaluation presented here. In addition, regulatory authority, National Laboratory, and industry experts have been consulted to confirm the current state of knowledge and the research and development recommendations to enhance confidence in the evaluation of extended storage included in this report.

Background

Figure 1 shows graphics of typical pressurized- and boiling-water reactor fuel assemblies consisting of fuel rods arranged in assemblies. After irradiation, these constitute the "used fuel" that is stored at reactor sites in pools and in dry-storage systems.

Following discharge from the reactor, used fuel is initially stored in racks under water in pools up to 40 feet deep (see Figure 2). During this period of wet storage, some degradation may be detectable, although it is typically minimal.

Before the pools at a nuclear power plant are filled to their licensed capacity, the operator needs to provide additional storage capacity so that the power plant can continue operating. Thus, many utilities have built dry-storage facilities (referred to as Independent Spent Fuel Storage Installations, or ISFSIs) on their sites. These installations are large parking-lot-type concrete pads with protective fencing and continuous security surveillance. The

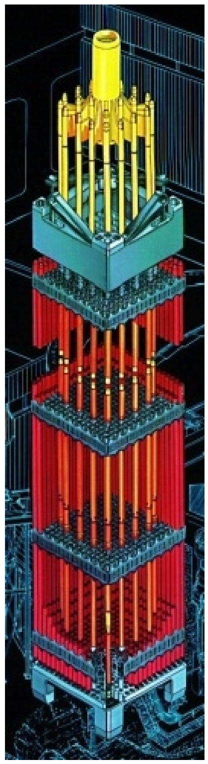


Figure 1.
Typical Pressurized-Water Reactor (left) and Boiling-Water Reactor Fuel Assemblies (right)

Courtesy Westinghouse (left) and http://gepower.com/prod_serv/products/nuclear_energy/en/downloads/gnf2_adv_poster.pdf (right)

fuel may be stored vertically in metal or concrete casks or horizontally in modular concrete storage facilities. The fuel inside concrete dry-storage casks is in bolted or welded canisters that are loaded in the spent-fuel pool and transferred to the ISFSI in an on-site transfer cask. Similar canisters are used for fuel that is stored in horizontal storage modules and may be used to contain fuel in metal storage casks, although some metal casks contain the fuel in open baskets without an inner canister.

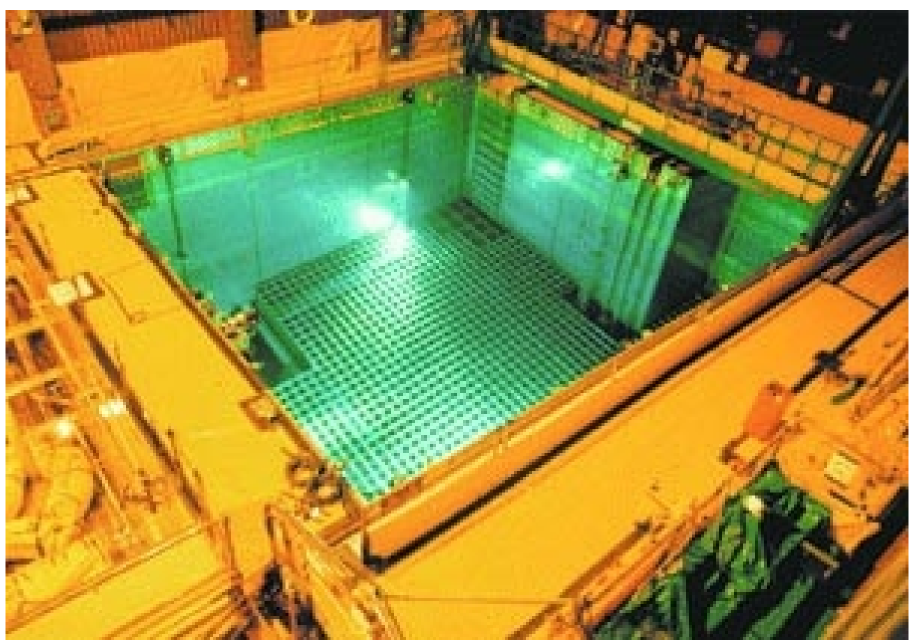


Figure 2.
Typical Used-Fuel Storage Pool

(from http://www.nrc.gov/waste/spent-fuel-storage/pools.html)

Figure 3 shows concrete casks storing used fuel at the Connecticut Yankee Nuclear Power Plant site. Figure 4 shows typical components that constitute a concrete storage-cask system, including the multipurpose canister (MPC) and the vents that provide the airflow to cool the canister. Metal casks that contain the fuel in open baskets do not have the same ventilation arrangement but typically have external heat-transfer fins to assist with the cooling.

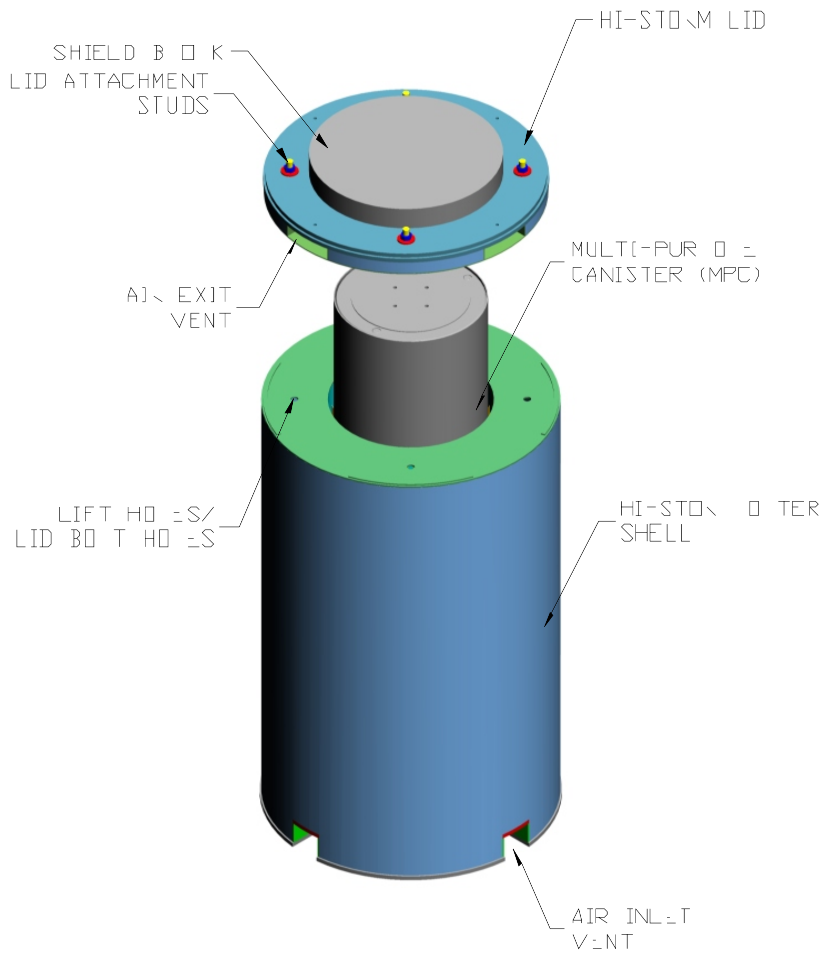
Figure 3.
Independent Spent-Fuel Storage Installation

Photo from NAC International, Inc. with permission

Before used fuel is loaded from a pool into a canister, the canister is lowered into the storage pool inside a shielded transfer cask. If the fuel is to be loaded into a metal cask with an open basket, the cask is lowered into the pool with the basked installed. Following loading of the fuel, a lid is installed and the cask is removed from the pool. The water is drained from the cask and, if a canister is

Figure 4.
Typical Vertical Dry-Cask Storage System

Graphic Courtesy of Holtec International, Inc.



being used, the water also is drained from the canister. The lid then is bolted or welded in place, and operations to dry the fuel are started.

This process typically involves several cycles of alternately applying a vacuum and backfilling the canister, or the cask, with helium. During the periods when the vacuum is applied, the fuel rods lose much of their cooling and the temperature of the fuel rises. The temperature rise enhances drying, but the temperature has to be controlled below predetermined limits to prevent thermal stresses that could result in cladding damage. Once the drying process is completed, the canister or cask is pressurized with helium, both to provide improved heat transfer and to minimize the potential for fuel degradation during subsequent storage.

Findings

This review finds that fuel rods discharged from nuclear power plants are typically in good condition with only a very small percentage of rods having cladding defects. Early references reported that less than 0.04 percent of fuel rods failed, while later plant records indicate that the failure rate has decreased to less than 0.0005 percent for more recently discharged fuel. During preparation for transfer to dry-storage facilities, failed fuel assemblies are loaded into specifically designed compartments in the canisters or metal casks, separate from intact fuel assemblies.

The most significant potential degradation mechanisms affecting the fuel cladding during extended storage are expected to be those related to hydriding, creep, and stress corrosion cracking.

The fuel-drying process is not perfect. After drying, residual water remains in unknown amounts that can affect subsequent internal degradation processes. The vacuum-drying heat cycles can change the nature of the hydrogen in the cladding and stress the fuel.

According to the literature review, the fuel, the dry-storage system components (canister, cask, etc.), and the concrete foundation pad may all degrade during dry storage. Some degradation mechanisms may be active during the early years of dry storage, while different mechanisms may be active at the lower temperatures that would be expected during extended storage.

The most significant potential degradation mechanisms affecting the fuel cladding during extended storage are expected to be those related to hydriding, creep, and stress corrosion cracking. These mechanisms and their interactions are not yet well understood. New research suggests that the effects of hydrogen absorption and migration, hydride precipitation and reorientation, and delayed hydride cracking may degrade the fuel cladding over long periods at low temperatures, affecting its ductility, strength, and fracture toughness. High-burnup fuels tend to swell and close the pellet-cladding gap, which increases the cladding stresses and can lead to creep and stress corrosion cracking of cladding in extended storage. Fuel temperatures will decrease in extended storage, and cladding can become brittle at low temperatures.

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Only limited references were found on the inspection and characterization of fuel in dry storage, and they all were performed on low-burnup fuel after 15 years or less of dry storage. Insufficient information is available yet on high-burnup fuels to allow reliable predictions of degradation processes during extended dry storage, and no information was found on inspections conducted on high-burnup fuels to confirm the predictions that have been made. The introduction of new cladding materials for use with high-burnup fuels has been studied primarily with respect to their reactor performance, and little information is available on the degradation of these materials that may occur during extended dry storage. Consequently, without any data for predicting how aging affects the fuel condition over longer storage periods, vendors model the condition of high-burnup used fuel currently in storage on the basis of the limited series of examinations of fuel that have been performed to date. These also form the basis for predicting the behavior of used fuel during extended dry storage and normal handling and transport of used fuel and in the event of transportation accidents.

...accurately predicting how the used fuel and canister temperatures will change over extended dry storage is important.

As noted above, one of the main deterrents to corrosion of the fuel cladding and the canister or metal cask internals during extended dry storage is the presence of helium. If the helium leaks and air is allowed to enter the canister or cask, this, together with the moisture in the air, can result in corrosion of the fuel cladding, the canister, and the cask. However, although provision is made to monitor the pressure of the helium during extended storage in bolted canisters, there is currently no means of confirming the presence of helium in welded containers or casks, nor is there a requirement for periodically inspecting the integrity of the closure welds for defects. If these storage systems were inspected for weld defects and/or tested for helium periodically, this would allow welded containers and casks with leaks to be repaired and refilled with helium.

During extended dry storage, degradation mechanisms also act on the outside of canisters, on storage casks (concrete or steel), and on modular concrete facilities as well as on the storage pads. The effect of these degradation mechanisms will depend on the environmental conditions at the specific location, on diurnal and seasonal temperature variations, and on the presence of corrosive agents and moisture in the air. The review identified references to general metal and concrete deterioration mechanisms and modeling, but none included the information necessary to predict the degradation of dry-storage canisters, casks, or concrete structures during extended storage.

Given the temperature dependence of many of the degradation mechanisms described above, accurately predicting how the used fuel and canister temperatures will change over extended dry storage is important. During this review, however, little information was found on detailed thermal modeling during the period of extended dry storage.

Regardless of the length of storage, used fuel eventually will have to be moved from the reactor sites, either to off-site interim storage facilities or to used-fuel processing facilities for recycling or for management of waste. Transportation regulations are largely focused on the integrity of the transportation casks, which contain the used fuel, and maintaining subcriticality of the fuel. The primary goal is to ensure that the cask does not fail in the event of a transportation accident, with the potential for release of radioactive materials. The regulations require that under both normal and accident conditions, the transportation cask and its contents are capable of meeting stringent performance specifications that include maintaining geometric configuration of the fuel to certain limits, largely for criticality control, and to address concerns about external radiation levels.

If the fuel degrades during extended storage, it could be susceptible to damage from the vibration and shocks encountered during transport operations. The consequences may include release of fission-product gases into the canister or the cask interior, which must be contained during a transportation accident.

Used-fuel transportation casks are designed to withstand a series of transportation accidents without release of radioactive materials. Figure 5 shows a full-scale crash test performed by Sandia National Laboratory in 1977 in which a locomotive traveling at approximately 80 miles per hour was crashed broadside into a used-fuel transportation cask. In this test, the cask and the dummy fuel inside it performed in accordance with the regulatory requirements.

Upon reaching the interim storage location, the repository site, or other processing facility, the used fuel may have to be handled, and the integrity of the fuel following the transportation and handling operations may not be known with confidence. If the

Figure 5.
Spent-Fuel Crash Test

http://www.sandia.gov/records mgmt/ctb1.html

fuel is to be processed instead of being placed in a repository after transportation, the casks and used-fuel canisters will need to be opened and the fuel removed. Before this is done, consideration will need to be given to the condition of the fuel, and a means will need to be available for determining whether the fuel has failed. This may require opening the cask in a hot cell as opposed to the more traditional spent-fuel pool. Following extended storage, the integrity of the used fuel after transportation cannot be ensured because some long-term degradation processes are uncertain and transportation-accident loading predictions for aged fuels have not been fully validated.

Review of the relevant technical sources used as the basis for this report has shown the following:

> Little data are publicly available on the behavior of high-burnup fuel during dry storage or on its behavior during subsequent handling and transportation. No information is

available on the behavior during dry storage of the more advanced materials now being used for fuel cladding and fabrication of fuel-assembly structural components.

The physical state of the cladding when fuel is placed into dry storage is not currently well characterized. There may be zones of physical weakness and, in some cases, the cladding may be close to failure. Normal handling of fuel assemblies, off-normal occurrences, and accident events would then be more likely to result in additional damage to fuel rods.

Cladding-degradation mechanisms, their interactions with each other, and the expected behavior of cladding after extended dry storage are not well understood. Also not well understood are some of the conditions that affect these degradation mechanisms, such as the changes in fuel temperatures that will occur over time and the amount of residual water present after drying.

At the low temperatures expected to be reached during extended dry storage, and even in the presence of air, used-fuel-pellet material oxidizes at a very slow rate. Even if a gross breach occurs and fuel-pellet material is released from the fuel cladding, it will not oxidize to powder easily or quickly. Consequently, if fuel material is released inside the canister or cask, containing and repackaging it safely once the canister or cask is opened should not present any undue problem. Fission-product gases also would be released inside the canister or the cask. If the canister or cask were to be opened, they would need to be dealt with by the ventilation system in the fuel-handling facility.

Corrosion mechanisms will cause degradation of the metal components of dry-storage systems during extended dry-storage periods: for example, the outer surfaces of fuel canisters. Consequently, establishing an effective regular inspection and maintenance program is important.

In order to develop a better understanding of how the conditions of fuel and storage systems change during extended dry-storage, it will be important to establish a program for inspecting and characterizing the physical condition of used fuel and dry-storage systems over time. This will reduce the uncertainty in predicting the future state and behavior of the used fuel and the storage-system components during subsequent operations.

Several concrete deterioration and rebar-corrosion mechanisms are known to cause degradation of reinforced concrete in dry-storage systems, including the storage pad. Consequently, establishing a regular inspection and maintenance program for these systems is important.

Some plausible off-normal and accident scenarios for the handling and transport of used-fuel casks have not been fully evaluated. Performing full-size testing of transport packages to demonstrate the behavior of both the package and the fuel may be beneficial. At a minimum, validation of computer models using scaled tests should be carried out. However, the performance of some components, such as bolts and welds, are particularly difficult to scale. Consequently, if scaled tests are performed, additional testing of full-scale components may be needed to verify that the performance of these components is being modeled correctly.

There are security risks associated with the dry storage of used fuel, and the risks will likely change with time. These risks and how they change need to be addressed using a risk-informed process that considers the probability of the risks and the potential consequences. This process then should be used as the basis for determining what action, if any, is needed to provide the necessary level of security during extended dry-storage periods.

Research and Development Recommendations

On the basis of this review, we recommend that a number of research and development programs be implemented. They are focused primarily on improving the understanding of key fuel-degradation mechanisms and increasing confidence in the projection of the behavior of the used fuel and storage systems during extended dry-storage periods and subsequent transportation of the fuel. The intention is to prevent problems that may otherwise be encountered during later fuel-handling operations following transportation of used fuel to disposal or processing facilities. The recommended research programs investigate the following issues:

Understanding the mechanical cladding behavior and fuel-cladding degradation mechanisms potentially active during extended dry storage, including those that will act on the materials introduced in the last few years for fabrication of high-burnup fuels

Understanding and modeling the time-dependent conditions that affect aging and degradation processes, such as temperature profiles, in situ material stresses, quantity of residual water, and quantity of helium gas

Modeling of age-related degradation of metal canisters, casks, and internal components during extended dry storage

Inspection and monitoring of fuel and dry-storage systems to verify the actual conditions and degradation behavior over time, including techniques for ensuring the presence of helium cover gas

Verification of the predicted mechanical performance of fuel after extended dry storage during cask and container handling, normal transportation operations, fuel removal from casks and containers, off-normal occurrences, and accident events

Design and demonstration of dry-transfer fuel systems for removing fuel from casks and canisters following extended dry storage

Conclusions

...additional information is required to demonstrate with similarly high confidence that used fuel can be stored in dry-storage facilities for extended periods without the fuel degrading...

The technical information currently available, together with the experience gained to date in the dry storage of spent fuel, demonstrates that used fuel can be safely stored in the short term and then transported for additional storage, processing, or repository disposal without concern. However, additional information is required to demonstrate with similarly high confidence that used fuel can be stored in dry-storage facilities for extended periods without the fuel degrading to the extent that it may not perform satisfactorily during continued storage and subsequent transportation.

Consequently, the Board recommends that a number of research and development programs be implemented to demonstrate that used fuel can be stored safely in dry-storage facilities for extended periods. Research alone will not be sufficient. Because the experience base for extended dry storage of used fuel is short and the credible degradation phenomena are several and not robustly

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predictable in a quantitative sense, an in-service inspection and maintenance program appears to be necessary as part of a used fuel management program that includes long-term dry storage. The technical details of such an in-service inspection program obviously will depend on the desired safety objectives of extended dry storage. Consequently, a practical engineering approach that is based on the observational method and periodic assessments will likely be required to provide an adequate safety basis in addition to what can be learned from targeted scientific investigations.

The regulations concerning dry storage of used fuel do not currently address storage for extended periods. There also is some inconsistency between the regulations that apply to dry storage and those that apply to transportation, and how to meet both sets of regulations is unclear. It would be helpful in managing extended dry storage of used fuel if the regulations were revised as an integrated set and based on a risk assessment for safety significance and consequence. In addition, the Board thinks that the regulatory requirements related to physical security and terrorist threats also should be reviewed on a risk-informed basis using potential consequence analysis and integrated with the storage and transportation regulations.

At this point, the nuclear waste management policy of the United States is unclear, and the result is that used fuel will be stored at reactor sites for longer than originally foreseen. It is thus essential that the appropriate research and development programs and monitoring and inspection programs are implemented as a matter of priority to demonstrate that used fuel can be stored safely for extended periods and then transported and handled as part of a future waste management program.

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