NRC Technical Research Program to Evaluate Extended Storage and Transportation of Spent Nuclear Fuel – 12547

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ABSTRACT

Any new direction proposed for the back-end of spent nuclear fuel (SNF) cycle will require storage of SNF beyond the current licensing periods. The Nuclear Regulatory Commission (NRC) has established a technical research program to determine if any changes in the 10 CFR part 71, and 72 requirements, and associated guidance might be necessary to regulate the safety of anticipated extended storage, and subsequent transport of SNF. This three part program of: 1) analysis of knowledge gaps in the potential degradation of materials, 2) short-term research and modeling, and 3) long-term demonstration of systems, will allow the NRC to make informed regulatory changes, and determine when and if additional monitoring and inspection of the systems is necessary.

INTRODUCTION

The existing regulatory framework for SNF transport, specified in Title 10 of the Code of Federal Regulations (10 CFR) Part 71, "Packaging and Transportation of Radioactive Material," [1] has been effectively demonstrated through significant operational experience over a period of more than 40 years. Similarly, the existing regulatory framework for SNF storage, specified in 10 CFR Part 72, "Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High-Level Radioactive Waste, and Reactor-Related Greater than Class C Waste," [2] has been effectively demonstrated for almost 20 years, with over 1,200 casks loaded at 60 independent spent fuel storage installations (ISFSIs) in the United States. Under 10 CFR, Part 72, licensees may apply for an initial 40-year license for dry cask storage, followed by a 40-year license renewal provided that aging management programs are put in place for structures, systems, and components important to safety. The 80-year safety basis with aging management is supported by research and analytical studies such as the U.S. Department of Energy (DOE) Cask Demonstration Program that examined a cask loaded with lower burnup spent nuclear fuel (approximately 30 GWd/MTU) [3]. The data from this study can be extrapolated to maintain a licensing safety finding that low-burnup SNF can be safely stored in a dry storage mode for at least 80 years with an appropriate aging management program that considers the effects of aging on systems, structures, and components (SSCs). The regulatory frameworks for both storage and transportation under current time frames are also supported by voluntary domestic and international consensus standards; and processes for implementing licensing reviews, inspection programs, and enforcement oversight.

The current administration has decided that Yucca Mountain is not a viable option. In the absence of a disposal facility for SNF, any new direction proposed for the back-end of the SNF cycle will require storage of SNF beyond the currently anticipated licensing periods. Evidence from the DOE test also suggests that dry storage of SNF can likely be maintained up to 100 years; however, licensees have not developed a safety basis and the NRC has not reviewed such a request for extended periods of storage. The long-term safe storage and subsequent transportation of SNF beyond the current license period or for higher burnup fuel will require the development of technical bases for effective aging management programs (AMPs) over several license renewal periods

The study described in this paper identifies, evaluates, and prioritizes the need for additional technical data on the behavior and aging of SSCs so that the NRC can effectively license and regulate extended periods of spent SNF management (up to 300 years) through multiple dry cask license renewals. These data will be used by the NRC to provide guidance on: 1) systems that must be monitored and inspected, 2) frequency of the monitoring and inspection, and time frames in which replacement or repair of systems might be expected, and 3) whether current guidance to the applicants must be revised for longer term storage. In addition they will provide the basis for the NRC to determine if the applicants AMPs required for a license inspection are adequate to ensure that the dry storage of SNF can be safely and securely maintained, with the additional ability to transport the SNF, without repackaging, after the storage is completed.

METHODOLOGY

In order to avoid evaluating degradation phenomena that might occur over an indefinite and possibly infinite period of time, the NRC staff chose to arbitrarily assume that dry storage would be required for no more than 300 years at which time a path forward for the final disposition of the SNF will have been established. This time duration was arbitrary, and does not imply that SNF will be stored for 300 years, that the NRC will license storage for 300 years or that NRC endorses storage for 300 years. During the course of this study a technical basis might be found to indicate that degradation will dictate the duration of storage.

Three pronged study

A three-pronged approach was taken to develop and confirm the necessary data. The first prong was to identify and assess the operable degradation mechanisms that would affect the systems necessary for safety and operation of the dry cask storage systems (DCSS). The questions of concern were criticality, containment, shielding, structural stability, and retrievability. Those mechanisms that could degrade the DCSS but of which little were known were given the highest priority. The second phase is to do short-term laboratory research, and modeling on those high priority mechanisms. The third phase is to conduct a demonstration to benchmark the results of the short-term research over a longer term, and to look for additional mechanisms that may not have been identified as a lead indicator.

Assumptions in the Study

To meet the goals stated above a number of assumptions were made in developing the plan to support extended storage and transportation (EST):

1- Only oxide based SNF (UOX) fuel, mixed oxide (MOX) fuel, and gas-cooled reactor graphite fuel (i.e. Fort St Vrain (FSV)) are initially considered. The UOX SNF comprises the bulk of the commercial SNF currently in storage and SNF that will be placed in storage in the near future. The characteristics of MOX SNF are very similar to UOX fuel.

FSV SNF is currently in storage under an NRC license and will eventually have to be transported.
2- Only current modes of storage (concrete or metal overpacks) and transportation (above and below ground) are being considered.
3- The current licensed fuel burnup limits will not be increased beyond the current limit of 62.5 GWd/MTU without confirming that it can be safely handled and considers the impact of raising the burnup limit on the back-end of the fuel cycle.
4- Lack of institutional controls will not be evaluated.
5- Maintain retrievability of SNF so no options are closed. Maintain cladding integrity but indicate where this assumption drives the conclusion concerning data needs.
6- Dry storage at-reactor, away-from reactor, and decommissioned reactor sites, will be considered. Wet storage at-reactor or away-from reactor (Morris) will not be considered in this study.

GAP ANALYSIS

During the first phase of the safety review, NRC contracted with the Savannah River National Laboratory (SRNL) to perform the initial gap assessments to identify technical issues that require research and analyses for EST. The SRNL reevaluated the conclusions of the 1997 and 2003 EPRI gap assessments [4, 5] that along with a cask demonstration [3] provided a technical basis for the current licensable storage duration of SNF.

In addition to reevaluating issues in the original documents [4, 5], the current SRNL evaluation addressed:

- Aging management and long-term monitoring requirements
- Influence of very long-term storage on transportability; and transportation issues caused by lower SNF temperature
- New cladding types, fuel compositions, assembly designs, and MOX have been and will continue to be put into use
- High burnup (62.5 GWd/MTU) SNF
- Increasing heat loads in dry storage casks systems change the temperature profile of the cask components
- Underground and coastal environments
- Degradation of concrete and other non-fuel system components
- Condition of SNF and basket in an inaccessible sealed canister
- Repackaging at sites where reactor decommissioning has taken place resulting in the loss of wet pools, and requiring dry transfer. Degradation conditions that could require repackaging; what are they and when could they be expected to occur

Similar studies were being conducted by DOE, the Nuclear Waste Technical Review Board (NWTRB), and the Electric Power Research Institute (EPRI) through their International Extended Storage Cooperative Program (ESCP) subcommittee of which NRC is a participant. The NRC staff is evaluating all these gap analyses along with the SRNL analyses to identify the degradation caused by key mechanisms, and rank the knowledge of how each degradation mechanism operates. The extent to which the degradation of each component affects its ability to perform its safety or operational functions was also evaluated. Further research will be carried out on those degradation mechanisms that have the most influence on safety but of which the least is known for the dry storage configurations.

RESEACH ACTIVITIES

Based on the preliminary results of the gap analysis stress corrosion cracking (SCC) of the canister in a coastal environment, better definition of the maximum and minimum temperature distribution within the cask, the potential effects of incomplete drying of the cask, and the need for a full scale demonstration of the behavior of the systems have emerged as the technical areas that need further investigation. Since both the degradation of the fuel and the cladding in storage, and behavior during transportation depend on the moisture in the canister and the temperature, analytical work to better define the high and low temperature distributions, and the effects of incomplete drying on the system has been started.

A demonstration project is contemplated in phase three. A study has been completed to determine the types of information that would be yielded from each type of demonstration. In addition aging management plans developed for reactors in the GALL report [6] are being evaluated to determine if any of them are adaptable to dry storage materials and components.

Stress Corrosion Cracking of Canisters

Most dry casks and all canisters are fabricated from type 304, 304L, 316, or 316L stainless steels. These casks are not annealed to relieve the welding stress. Some dry cask storage facilities in the United States are located near coastal areas where the atmosphere tends to be chloride rich. Studies by EPRI [7] and Southwest Research Institute (SwRI) [8] indicated that chloride may enhance the susceptibility of the welds and base material of austenitic stainless steel casks to SCC. The conclusions in the NUREG/CR-7030 report acknowledge that the test conditions used in the investigation may be conservative with respect to actual dry casks. As such, there are knowledge gaps concerning the initiation and progression of SCC for in-service conditions.

A deterioration of the weld or base material could significantly affect the ability of the canister to maintain its containment, criticality control, and retrievability functions. Exposure of the SNF in the canister due to a leak in the weld may result in severe fuel degradation with additional release of fission products or other radionuclides. The severity of the issue is strongly dependent on the atmospheric conditions in the gap between the canister and the overpack, in particular the salt content, particle size, humidity level, temperature, air movement speed etc. In order for NRC staff to determine whether regulatory action is required on this issue, a plan is being developed to determine if salt corrosion of stainless steel canister materials and welds can occur under the environmental conditions that exist at potentially vulnerable licensee sites, and for the specific cask geometries and SNF conditions (e.g., burnup) that exist at those sites.

One area of uncertainty is the minimum surface chloride concentration for the onset of SCC. In the SwRI tests, a relatively high concentration of salt was periodically deposited on the stainless steel specimens. In service, the deposition of atmospheric salts on a cask is likely to occur in a more irregular manner, dependent on the atmospheric conditions such as temperature and the relative humidity (RH) on the canister surface, salt concentration in air, and the configuration of the canister. It would be useful to know the minimum surface chloride concentration and susceptible windows of temperature, RH, and salt concentration on the canister surface for the onset of SCC in order to identify the casks most susceptible to SCC. This information is necessary to form the technical bases for appropriate inspection frequency and evaluate proposed mitigation actions. A project has been started at the Center for Nuclear Waste Regulatory Analyses (CNWRA) to:

(a) Determine the minimum chloride concentration for the onset of SCC in austenitic stainless steel alloys used for dry cask storage systems.
(b) Evaluate the effects of canister temperatures between 43 and 85ºC under realistic atmospheric conditions (e.g., salt fog environments).

Tests described in NUREG/CR-7030 [8] focused on the deleterious effects of sea salt. Little work has been done to date to identify other non-coastal dusts or atmospheric species that could affect the cask integrity. For example, industrial activities in the vicinity of dry cask storage facilities could result in a locally high atmospheric concentration of sulfur and nitrate containing species along with various organics. In addition to investigating SCC in coastal environments, the project will also determine which non-coastal dusts or atmospheric species may contribute to degradation of dry cask alloys.

Research on these other atmospheric species will be helpful to identify which casks, beyond those at coastal sites, could be vulnerable to long-term degradation such that inspection and mitigation activities are appropriate.

Temperature distributions

The reorientation of hydride is a function of drying temperature, hydrogen content, cool down history and alloy type. Furthermore, the minimum cladding temperature during transportation appears to be key in determining if hydride reorientation will lead to the reconfiguration of the cladding during both normal and accident conditions. To evaluate the extent of hydride reorientation in the cladding of fuel stored in a cask and potential vulnerabilities during transport, realistic temperature distributions are needed.

Applicants have stated that their current temperature models were designed to over predict the expected temperature of the cladding. This has been acceptable in estimating maximum temperatures because predictions are conservative. For example, ignoring the contact between the cladding/spacers and the basket lowers thermal conductivity and, therefore, overestimates cladding temperature. However, biasing the temperatures high is undesirable when seeking the lowest temperatures during transportation after extended storage. In that case, over predicting the minimum temperature is unacceptable. Also, over predicting will not be acceptable if the canister temperature is affected, considering SCC of canisters. To properly calculate the minimum temperatures during transportation, the models will have to be adjusted to eliminate the deliberate high temperature biases. The adjustments may require acquiring additional experimental data to adequately modify code models, e.g., developing a model to account for the heat transfer between the cladding/spacers and the basket.

Models are being developed to eliminate the biases that over predict cladding temperatures and, thus, produce a computational tool that is suitable for calculating realistic and bounding upper temperatures expected in storage and the lowest cladding temperatures expected during transportation. Since the SNF temperatures have an axial and radial distribution within the cask, and also depend on the storage duration, the models will be used to generate time-dependent, three-dimensional temperature maps for various loadings of pressurized water reactor (PWR) and boiling water reactor (BWR) SNF. The models will explicitly address uncertainties that can bias temperature history predictions. In the course of developing these models, thermal parameters such as assembly basket contact area may be required. These models will guide the NRC when requesting thermal parameter input from the applicant.

Drying

After the SNF is placed in a cask or canister, the water is drained and the system further dried either by pulling a vacuum or flowing dry heated gas through the system. Current US criteria on adequacy of drying is that a residue water content in a canister of ≈ 0.25 mole, while in Japan the criteria is 10% water content in the atmosphere (≈100 grams of water). There have been cases where a canister thought to be dry has been opened after transport and found to contain water. It is not known whether this is due to the criteria for dryness being incorrect or improper drying techniques. Incomplete drying has the potential to result in a number of deleterious effects inside the canister or cask such as:

- Cladding oxidation
- Hydrogen absorption in the cladding
- Fuel oxidation and hydration when cladding breaches are present
- Risk of exceeding flammability limits
- Heat transfer degradation (degradation of the thermal conductivity of the gas)
- Hydrogen absorption on canister/cask structural materials
- Corrosion due to radiolysis of fission products
- Canister/cask pressurization
- Galvanic corrosion of the SNF rods
- Galvanic corrosion of internal cask component materials (e.g., coatings, aluminum basket, neutron absorbers, steel, and cladding)

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While drying issues are usually thought of as a short-term issue, the duration during which incomplete drying may have an effect on the materials is strongly dependent on the initial temperature of the canister and the radiation field. This task does not evaluate when drying ceases to be an issue but rather the potential effects if the canister is incompletely dried. For the purposes of analysis, it is assumed that anywhere from one mole to one liter of water is remaining in the canisters/casks of sizes currently used to store both PWR and BWR SNF. The analysis covers the time period from finish of drying to 300 years or when the water is completely removed from the cask by interactive processes. Simultaneous interactions were evaluated.

Preliminary conclusions of the evaluation are:

1. The amount of residual water will decrease with time, primarily with oxidation/hydration of cladding and the SNF matrix (i.e., UO_2). The cladding and the SNF matrix with defective cladding will have a large surface area for the reaction compared with other internal components.
2. Radiolysis in an important mechanism for the reaction. 80% of the canister will be subject to high temperature and low RH (less than 20%). Below a threshold value of RH (metal: 20 - 40 %; SNF: 40%), aqueous degradation will not occur. Therefore, oxygen (or other oxidizers such as H_2O_2) mainly reacts with cladding and the SNF matrix under these conditions.
3. Water may be consumed in a relatively short-time (few decades). This time will depend largely on radiolysis kinetics.

4. Cladding unzipping appears to be an issue only for the upper bounds of the amount of initial residual water, and faster radiolysis kinetics. Unless the recombination of atoms to molecules is very slow, hydrogen generated by radiolysis will not be absorbed in the metal because the molecular size is large. Only hydrogen generated during the aqueous corrosion will be absorbed.
5. In the presence of the hydrogen generated, there could be oxygen present because the consumption rate by corrosion is slower than the production rate by radiolysis. Therefore, there could be a potential issue of hydrogen flammability for the upper bounds in 4.
6. There are important uncertainties, especially associated with the amount of residue water and radiolysis kinetics. The extent of other component corrosion appears to be insignificant, but the uncertainties need to be evaluated further.

Demonstration project

Examination of a cask system and low burnup SNF after 15 years provided confidence in interim storage of low burnup SNF in current technologies. Data for longer storage periods and high burnup SNF have not been developed. The third phase of the EST program is to benchmark the models and empirical conclusions developed in the research Phase II over a long-time frame under realistic conditions. The goals for such a demonstration would likely include obtaining verification of predictive models for aging of dry storage cask system components and building confidence in the performance of these systems over extended time periods. The DOE is evaluating the availability of resources within the USA and issues that must be overcome to conduct a demonstration. This evaluation, conducted by CNWRA for the NRC, examined the potential types of demonstration that could be conducted and the data that can and cannot be obtained from each.

A number of technical issues are emerging from recent gap assessment described above. As part of Phase III for a high burnup demonstration project, various configurations of dry storage casks systems and experiments may be used. At present, no specific cask demonstration program has been developed (e.g., no specific selection of casks, SNF types, and test configurations). Because no specific program has been developed, the intent of this evaluation was to develop and evaluate several examples of potential cask demonstration program options that consider various types of casks, SNF types, and other parameters.

To develop the cask demonstration options, a number of potential demonstration cask configurations, environments, and additional parameters have been considered. In this evaluation, these parameters are referred to as “elements and factors” and include aspects like the SNF assembly type (PWR and BWR), SNF cladding materials (Zircaloy-4, lined Zircaloy-2, Zirlo™, M5®), cask system components, and environments (highly industrial, coastal/marine). Combinations of these parameters were used to develop the cask demonstration options. In the development process for the demonstration options, the following considerations were viewed as the most important for selection of parameters:

1. Obtaining maximum collection of data for technical issues
2. Timeframe or urgency for collecting data
3. Obtaining measurable data for selected high burnup fuel types and cladding materials

4. Obtaining data from major dry cask system design variations (directly loaded metal cask system, canister-based system in concrete overpack or module in vertical or horizontal configurations)
5. Costs, feasibility of opening the system, and regulatory and operational requirements

Potential testing configurations were generalized into three classes based upon the assumption that a cask demonstration program may either: 1) use dry cask storage systems that are new, or 2) utilize systems that are already in use at a utility site. Because the usage of new dry casks may be prohibitively complex and costly, it is possible that a cask demonstration program may consider separating assessment of the SNF and the cask system components. Therefore, an additional class is included as a hot cell demonstration program that would replicate a cask confinement environment and is considered the most feasible approach for assessing the SNF if it is assessed separately from a dry cask storage system. The three general classes of demonstration testing configurations were considered:

Class 1—Use of new cask storage system(s) including

- Installation of new modified cask(s) for enhanced at-storage monitoring (would require licensing approval)
- Selection of SNF assemblies from spent fuel pool
- Pre-demonstration and post-demonstration NDE, DE SNF examination
- Possible periodic removal of SNF and examination for directly loaded metal cask(s)
- SNF access for canister-based systems would only be done at termination of demonstration program

Class 2—in-use casks at ISFSI site(s)

a. Monitoring of selected cask(s)
    - At-storage monitoring
    - Possibly obtaining an exemption to add penetrations to monitor cask interior; however, monitoring options may be less than those for Class 1
    - Possible periodic removal of SNF and examination for directly loaded metal cask(s)
    - For canister-based cask, SNF would not be removed until program termination
b. Accessing a cask system to assess cask system component conditions.
    - Only considering the cask system non-fuel components (post-demonstration examination of SNF may be optional)
    - Monitoring of appropriate parameters related to cask system components if necessary (e.g., monitoring a cask at a lower temperature with stainless steel canister in coastal environment to assess SCC)

Class 3—hot cell demonstration –

a. Full SNF assemblies and potentially other materials exposed to the same normal environments inside the dry storage system

A series of cask demonstration options that incorporate these three general classes have been developed by permuting the key elements and factors identified above, including

Option A—Multiple new casks with multiple SNFs and other conditions
Option B—Limited number of new casks with multiple SNFs and other conditions
Option C—Single new cask with limited SNF and other conditions
Option D—Assess multiple, already-in-use casks with multiple SNF types
Option E—Assess single, already-in-use cask with one SNF type

Option F—Assess multiple, already-in-use casks and a hot cell demonstration
Option G—Assess a single, already-in-use cask and a hot cell demonstration

These cask demonstration options were evaluated against one another to illustrate differences between potential data relevant to the overall goals of the cask demonstration stated above and other program requirements, including activities that would be necessary for each option (e.g., transportation of SNF, opening cask to access SNF, timing, costs, availability of SNF, availability of casks, regulatory paperwork, among others) that will be obtained for each demonstration of extended storage of high burnup SNF. Progressively less complicated demonstrations were sequentially evaluated to determine what information can be garnered from each. The pros and cons were evaluated for each prototype cask demonstration program.

GALL Study

There are safety class and other components in an aging nuclear power plant (NPP) (e.g. concrete structures, bolted closures, coatings, neutron absorbing materials) that are subject to aging degradation that are similar to materials and aging modes in components of a DCSS. The SRNL is performing a detailed evaluation of the applicability and sufficiency of the AMPs as contained in Chapter XI of the NUREG-1801, Rev. 2 to materials and components identified in the aging issues report [6] for management of degradation under EST. The following topics will serve as the template for the AMP for a DCSS component that will be considered in the evaluation:

- Scope
- Preventive Actions
- Parameters Monitored/Inspected
- Detection of Aging Effects
- Monitoring and Trending
- Acceptance Criteria
- Corrective Actions

The periodic inspections in Chapter XI mostly follow those of Section XI of the ASME Boiler & Pressure Vessel Code. The methods, frequencies, and acceptance criteria listed in the referenced subsections of the ASME code will also be evaluated for applicability and sufficiency.

The lack of accessibility of the internals to the canister, including the SNF in a DCSS would exclude them from the existing AMP covered in the scope of NUREG-1801, Rev. 2. All other components, including the dual-purpose canisters, of the DCSS will be explicitly addressed in this task.

SUMMARY

The NRC has started a research program to obtain data necessary to determine if the current regulatory guidance is sufficient if interim dry storage has to be extended beyond the currently approved licensing periods. The three-phased approach consists of:

- the identification and prioritization of potential degradation of the components related to the safe operation of a dry cask storage system,
- short-term research to determine if the initial analysis was correct, and
- a long-term prototypic demonstration project to confirm the models and results obtained in the short-term research.

The gap analysis has identified issues with the SCC of the stainless steel canisters, and SNF behavior. Issues impacting the SNF and canister internal performance such as high and low temperature distributions, and drying have also been identified. Research to evaluate these issues is underway. Evaluations have been conducted to determine the relative values that various types of long-term demonstration projects might provide. These projects or follow-on work is expected to continue over the next five years.

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