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Leading the way with Aging Management

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Abstract

Storing used fuel in licensed dry storage systems at reactor sites for long periods of time wasn't originally anticipated: interim dry storage systems were originally designed and licensed for shorter storage periods, generally 20-40 years. Beyond this interim storage period, used fuel was planned to be transported to a geological repository or recycling facilities. Due to persistent delays in implementing geological repositories or the fuel recycling facilities, there is a need to extend dry storage beyond initial time period.

The dry storage system needs to be designed and licensed to ensure that the necessary safety functions are maintained during long term period of storage and subsequent transportation after storage. Consideration needs to be given to potential aging deterioration of component materials that may occur during operation of the storage system.

In the context of extended interim dry storage, investigations are currently being carried out to demonstrate and justify the ability of the structures, systems and components associated with dry storage to maintain their intended safety functions. Further, research is also underway to determine the behaviour of used nuclear fuel and its safe and secure storage for an extended period of time.

Effective aging management programs require a technical understanding of the aging degradation mechanism, inspection and assessment techniques, prevention and mitigation measures (to retard the effects of aging) and, as needed, guidance on repairs or replacements for each component. These descriptions are part of the aging management program for the storage system which is developed for each potential degradation mechanism related to extended duration that could adversely affect structures and components important to safety.

Regulators are in the process of defining a program to monitor and maintain dry storage systems on site to ensure of same level of safety and security. In this early stage of license renewals, aging management programs include mainly periodic inspections of the used fuel dry storage systems and components to ensure potential aging effects are identified and effectively managed.

This paper provides highlights of issues related to managing effects on dry storage systems for long-term interim storage and transportation of used nuclear fuel and discuss innovative solutions being developed to monitor age-related degradation, prevent equipment failures caused by aging and develop contingency plans as needed.

1. Introduction

The management of used nuclear fuel (UNF) from nuclear power reactors is an important issue in several countries that are still evaluating and implementing sustainable UNF management solutions. Interim dry storage systems have been deployed to support continued plant operations since final disposition strategies have either not been fully developed or have not been resolved in many countries. As a result of the continued delays in the decision associated with the end of life management of the UNF, interim storage, particularly, in licensed dry storage systems, has become an increasingly prevalent method to manage UNF. Additionally, the storage duration and the inventory of UNF have been steadily increasing.

The management of used nuclear fuel using a dry storage system involves storage of UNF as well as on-site and off-site transportation before and after storage, if applicable. Further, to reduce the burden of UNF management by the reactor operator, due to extended duration of storage, it becomes necessary to develop technical solutions and services for this purpose.

2. Interim Dry Storage Systems

The Interim Dry Storage System must be designed and licensed to maintain functions important to nuclear safety including structural, thermal, radiation protection, confinement, sub-criticality control, and retrievability. The interim dry storage system must be designed to maintain these design functions under normal, off-normal and accident conditions of storage.

In a dry storage system, used nuclear fuel that has already been cooled in the fuel pool is surrounded by inert gas inside a container called a cask or a canister. The container is typically a steel cylinder that is either welded or bolted closed. The steel cylinder provides a leak-tight containment of the UNF. Each cylinder is surrounded by additional steel if needed, concrete, or other material to provide radiation shielding to workers and the public. Some of the container designs can be used for both storage and transportation.

AREVA dry storage systems

AREVA has developed different UNF dry storage solutions worldwide [1].

a- Canister solutions

The NUHOMS® system, which consists of the storage of canisters in concrete modules, was initially developed for 20-year interim storage at reactor sites. The used nuclear fuel is placed in leak-tight welded canisters or dry shielding canisters (DSC) filled with inert gas, inside a massive reinforced concrete overpack or horizontal storage module (HSM) for on-site storage. The primary barrier for the confinement for the UNF is the dry shielding canister. The HSM provides for physical protection, radiation shielding and passive decay removal of the DSC and its UNF contents. When required, in the future, the DSCs will have to be loaded into a transportation cask for transport to centralized storage, reprocessing or final disposal facilities.

NUHOMS® system is the leading technology used in the USA with more than 810 loaded systems at several reactor sites. NUHOMS® systems are licensed to accept BWR, PWR and VVER UNF and reactor related greater than class C, waste. A new generation of canister systems, the NUHOMS® EOS systems, is currently being licensed by AREVA allowing higher for a maximum decay heat of 50 kW and higher radioactive inventory resulting from UNF with burnup of up to 62 GWd/MTU, a maximum enrichment of 5 wt. % U-235 and cooling time as low as 3 years.

TN NOVA™ system is another canister system designed by AREVA. It is a system with a metal storage overpack which can be tilted vertically for storage on site.

The canister, for both the NUHOMS® and the TN NOVA ™ systems, is licensed for both storage and transportation. The advantages of these solutions are modularity, passive cooling and low up-front costs.

Figure1: NUHOMS® System at Fort Calhoun storage facility, USA

b- Dual purpose casks

Dual purpose casks are metallic casks which can be used for both storage and transportation to and from a storage facility to avoid handling the fuel assemblies twice. They are dual-certified to comply with the requirements of storage issued by national bodies and the requirements of transport regulations defined by the IAEA [2]. AREVA has designed, licensed and supplied the versatile casks constituting the TN 24 family: more than 300 metallic dual purpose casks have been loaded. These casks have been adapted to the specific needs of a variety of storage conditions and fuel assembly designs. TN 24 family metallic dual-purpose casks are operation in USA, Japan, Belgium, Switzerland, and upcoming casks in Germany, Italy. The storage capacities include up to 40 PWR fuel assemblies or up to 97 BWR fuel assemblies, and a maximum burnup of up to 70 GWd/MTU. Containment pressure and dose are monitored during the interim storage.

The advantages are modularity, passive cooling, and dual purpose storage and transport capability.

Figure2: TN24 casks at Doel storage facility, Belgium

Industrial feedback

AREVA has been developing several Used Nuclear Fuel dry storage solutions for worldwide use for more than 40 years. More than 1,100 dry storage systems designed and licensed using AREVA technologies have been loaded. A significant knowledge base associated with dry storage system operational performance is available due to knowledge sharing over the last 40 years. Further, several cask-specific inspections have been conducted periodically and the results published, as well.

Investigations have been performed in the United States to assess the performance and develop cumulative knowledge base for dry storage systems. In particular, demonstration tests were done by the Idaho National Engineering Laboratory on the TN-24P cask and the NUHOMS® system. The results were satisfactory [3]. Moreover, Post Irradiation Examinations of UNF assemblies stored 15 years in a metal cask have shown no significant degradation to the cask and, more significantly, no significant degradation to the UNF assemblies [4].

In Japan, some utilities have performed inspection campaigns related to the integrity of BWR used nuclear fuel. Additionally, integrity inspections of TN24 casks stored at Fukushima-Daiichi Storage Building (before the Fukushima earthquake) have been done after 5 and 10 years of storage of 52 BWR assemblies (~ 30 GWd/MTU). No release of fission gas (Kr-85) and no defects were observed on the used nuclear fuel assemblies (visual checking) [5].

Above all, the storage systems have demonstrated their ability to withstand severe accidents. In particular, the 9 TN24 casks stored at Fukushima-Daiichi Storage Building (with 408 BWR used nuclear fuel assemblies) withstand the tsunami in March 2011. These casks have been exposed to large amounts of sea water, sand and rubble that gushed in the building when it was hit by the tsunami [6]. Investigations on the 9 dry storage casks have been performed in 2013 and have shown no damage on the cask and on the used nuclear fuel (in particular, 3 UNF assemblies were removed from the first cask for a visual inspection) [7]. In addition, inspections of the NUHOMS® system HSM-H modules were performed following the magnitude 5.8 earthquake in August 2011, at North Anna nuclear power station ISFSI. The dry storage system installation was evaluated to be operable and withstood the consequences of the earthquake with minor cosmetic damage to the concrete.

3. Aging Management Principles

As shown by industrial feedback and operational experience, interim storage of UNF is safe and reliable. However, storage durations are constrained by limitations imposed by regulatory requirements which are based on national standards and not uniform internationally as shown in Table 1, below:

Table1: Dry Storage Licensing conditions in some countries [8]

Country	Initial license period	Renewal period
Canada	2 years	2 years
Germany	40 years	N/A
Hungary	10 years	10 years
Japan	Not limited (= reactor site license)	N/A
South Korea	Not limited (= reactor site license)	N/A
Spain	20 years	20 years
United Kingdom	Not limited (= reactor site license)	N/A
USA	20 years	40 years

These limits are typically 20 to 40 years. Until recently, a storage period of up to 40 years was considered as “long-term” and sufficient to consider decisions and implementation of a back-end fuel cycle including end-of-life used fuel and high level radioactive waste management options. Currently, it appears that storage duration may have to be extended significantly, potentially beyond 100 years, necessitating a re-evaluation of safety during the various phases: on-site interim storage, transfer, and transportation operations to the final disposal site or recycling facility. Additional safety evaluations will be needed to provide the technical and licensing basis for the justification of interim storage solutions over an extended duration and the readiness for subsequent transportation. These evaluations assess the behaviour of the fuel assemblies and the components of the dry storage systems which are potentially affected by aging mechanisms.

Used Nuclear Fuel Degradation

The aging mechanisms and consequences become more important for high burnup fuel. Higher fuel assembly burnup results in higher heat decay at discharge and increased fission gas release, generating higher stresses and higher temperatures for longer periods of time in the fuel rod cladding. In addition, the longer exposure of a fuel assembly in the reactor core to achieve a higher burnup tends to reduce the residual wall thickness through waterside corrosion further increasing the susceptibility for cladding degradation. These severe conditions have an impact on the integrity of the high burnup fuel cladding when stored. The analysis of the aging mechanisms (cladding creep, oxidation, and hydrogen effects) is important to verify the behaviour of UNF in the long term, in particular for high burnup fuel.

The knowledge gaps of the various aging mechanisms have been identified by experts worldwide, for example in reference [9].

Components Degradation

The main functions of the storage system are physical and radiation protection and confinement of the UNF and radioactive material contents. Aging management programs must ensure that all the functions of the storage systems remain intact. The integrity of the canister or the cask is particularity of importance due to maintaining the confinement design function. It could be mentioned that the atmospheric chloride-induced stress corrosion cracking (SCC) of stainless steels have been identified by the NRC as a potential degradation risk that can breach the canister shell by cracking when exposed to atmospheric chlorides like those found in marine environments.

Aging Management Plan

The storage and/or transport system needs to be designed to ensure the necessary safety functions are maintained during storage and subsequent transportation after storage. Consideration needs to be given to potential aging deterioration of component materials that may occur during operational lifetime of the storage system.

Effective aging management programs require a technical understanding of the aging degradation mechanisms, inspection and assessment techniques, mitigation measures and as needed, guidance on repairs or replacements for each component [10].

To provide information and results for understanding aging, separate effect tests or small scale effect tests may be necessary. Accelerated tests are also important. Modelling is the means by which prediction of degradation of materials or safety functions can be made. Finally, confirmatory data are provided by full scale tests, which verify the validity of the predictions.

Inspection and monitoring of dry storage systems necessitate the implementation of sensors related to aging management (cracking, surface chemistry, internal gas composition, leakage, temperature, humidity, dose rates). Some of them are already in widespread use: depending on the facility and local and/or regulatory requirements: pressure, temperature and dose are currently monitored.

The Aging Management Program should include the following features:

- Prevention program to inhibit aging effects.
- Mitigation program to decelerate the effects of aging
- Monitoring program to evaluate the condition and performance. Early detection of degradation is desired before any loss of safety function.
- Inspection program. An inspection program will ensure that the safety-related components fulfil all applicable storage and transport requirements.
- Maintenance program which keeps track of the operating history, including corrective actions and design modifications.

4. Aging Management Solutions

AREVA TN is assisting several licensees in extending their storage license periods in accordance with regulatory requirements and updated guidance consistent with the current knowledge base. AREVA TN is assisting the licensees for their on-site inspections and employing analytical tools for the developing and upgrading Aging Management Programs.

Aging management primarily requires addressing physical aging of the dry storage systems and their contents, resulting in degradation of their performance characteristics and secondly to develop solutions to monitor age-related degradation and prevent equipment / component failure.

Investigation on Fuel Behaviour

Several international initiatives regarding fuel behaviour have been launched in the past several years to generate information and close knowledge gaps on aging effects and mechanisms and on high burn-up fuel behaviour for long term storage. Thus, it can be noted that many countries like the US (EPRI, DOE), Japan (CRIEPI), Korea, Germany (BAM) and France (CEA) are conducting R&D test programs for long term storage of spent fuel. Results will assist in understanding the high burn-up fuel behaviour over time. [11]

AREVA has been involved in several R&D programs associated with fuel behaviour. In the Fuel Integrity Project (FIP) which has been developed with an UK partner, INS, the objective was to develop a methodology to evaluate, as a safety requirement for transportation, the nature and the extent of LWR used nuclear fuel assembly damage during accidental dropping of a package. Test results have led to the definition of the FIP methodology. [12] Experimental results were collected from the testing program, and the primary mechanical phenomena arising from a drop have been identified and quantified.

In parallel, AREVA is part of the team led by EPRI to develop and implement the part of a Test Plan to collect data from a used nuclear fuel dry storage system containing high burnup fuel. The principal objectives of the proposed test are to provide confirmatory data for validation of the models and methods associated with UNF dry storage cask design for high burnup fuel, and to support license renewals and new licenses for storage facilities. [13]

Investigation on Storage component

AREVA is involved in several R&D programs which some include separate effect tests or small scale effect tests in order to provide information and results to develop understanding of aging related impacts. Accelerated tests are also important, followed by simulation and modelling to allow for prediction of degradation of materials and/or impact on safety functions. Finally, confirmatory data are provided by full scale tests, which allow for the validation and verification of the predictions.

The aging-related degradation mechanisms of the materials and components that need to be evaluated for dry storage and/or transport systems include the following components:

- The canister or cask material
- The concrete
- The basket and neutron poison materials
- The sealing system
- The neutron shielding materials

The component degradation and mitigation are presented in reference [14].

Inspection and monitoring

Inspection and monitoring of dry storage need implementation of sensors related to aging management (like cracking, surface chemistry, internal gas composition, leakage, temperature, dose rate). Some of them are already in operation depending on the facility and regulatory requirements

a- Corrosion Inspection

The potential canister or cask material degradations are: Stress Corrosion Cracking (SCC), Aqueous Corrosion, and Atmospheric Corrosion.

As part of Storage Facility / License renewal activities, utilities and vendors in the United States have performed in-situ inspections of loaded canisters. Important parameters such as surface temperatures, and surface chloride concentrations were measured. Further, visual examinations were performed to determine the condition of the canister surface. AREVA has pioneered the development of tools and methods to provide full canister inspection (surface chemistry) for stress corrosion cracking in chlorine induced SCC environments. Analysis has demonstrated the effectiveness of the sampling at Calvert Cliffs NPP. The innovative measurement technology (Figure. 3) enables the operators to determine the amount of salt on the exterior of the canister.

Figure 3: SaltSmart^{TM} delivery tool on canister surface.

AREVA is studying and developing remote-weld inspection techniques that are more sensitive, simple to deploy and cost effective. This system will allow the utilities to perform Non Destructive Examinations of storage canister.

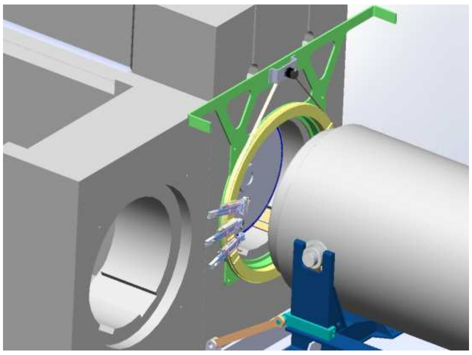

Figure4: Aging Management Tools.

b- Leak-tightness and Temperature Inspection

The confinement function of the radioactive material must be maintained in the long-term.

Pressure monitoring systems have been employed on AREVA dual purpose casks for the past several decades including the systems in the United States and Europe. This feature is also modified to be incorporated in the canister based, TN NOVA^{TM} system. This system monitors the pressure permanently - three pressure sensors continuously measure the pressure differential between inner lid and outer lid (in order to provide redundant information); and an alarm system informs the operators in case of pressure reduction or a pressure loss beyond established threshold values. The figure 5 presents the pressure monitoring system.

Figure5: Preparation of monitoring system on TN®24 casks

Temperature monitoring system could be also added on the cask in order to continuously or frequently monitor the temperatures on the surface of the cask. These temperature measurements allow for their comparison to the calculated temperatures at various intervals during the storage period and provide information of the cask component behaviour.

c- Content Monitoring

AREVA is investigating and developing innovative systems allowing the monitoring of the canister systems. One objective is the ability to monitor the cavity and the content of the storage system. For this purpose several performance parameters such as dose rates, pressure, and temperatures have been identified for measurement and assessment using sensors.

Inspection prior to transportation

Prior to any shipment, inspection of the transport system, i.e. the canister loaded inside a transport overpack or the dual purpose cask, is mandatory and should be performed in compliance with the maintenance and the operational program defined for each transport cask license.

As some inspections maybe difficult to be perform in some cases and particularly after a long storage period, alternative inspections should be considered. Nevertheless, alternative inspections must be developed to ensure that the functions important to nuclear safety of the transport system are still maintained. For example, instead of a visual inspection of the UNF, the alternative inspection may be the confirmation by operational records of the quantity and configuration of the UNF within the transport cask, and verification of the operational records for the storage conditions ensuring that there is no change to the UNF geometry or material configuration prior to transportation.

AREVA is also studying the alternate methods of inspection in order to provide assurance that the transport system can be safely transported. These methods would consider the various evaluations, assessments, monitoring and inspections performed as part of an approved aging management program, during the storage period.

Aging Management services for UNF

As part of implementing UNF management solutions, in addition to developing the technical solutions including development of inspection methods and equipment, development of services assumes an important role. Aging Management services include inspection procedures and plans, identification of systems and components for inspection, performing the actual inspections, data analysis, computer models for benchmarking and maintaining a knowledge base for a given site. These services may also include consideration for transportation, including inspection for aging effects described previously and long term monitoring at potential Interim Storage facilities, after transportation. AREVA TN is developing these services as part of a comprehensive development of Aging Management Program for the NUHOMS® system. This will also ensure that not only the best technical solutions can be implemented at the licensees' sites, but also the burden of long term UNF management is removed from the operators ensuring their renewed focus on reactor operations.

Innovative storage systems

AREVA TN is proactive and is evaluating the development of new and innovative interim dry storage systems which allow the storage for long duration and mitigate the aging effects in order to ensure that safety functions of the systems of the system or maintained or improved.

a- SCC Proof Canister

To prevent the atmospheric chloride-induced stress corrosion cracking (SCC) of canister exposed to a marine environments, AREVA has developed an alternative to its canister using Duplex SS instead of Austenitic Stainless Steel. The use of Duplex Stainless Steel has been included as a DSC confinement boundary material in the NUHOMS EOS® system which is currently under the final stages of the NRC review for storage. . The advantage of this solution is the minor design change on the original NUHOMS® license and the full compatibility with the existing storage module or transport or transfer systems.

b- Double walled Canisters

AREVA has designed several double walled canister systems providing two independent containments comprising an inner canister where the fuel is loaded and an outer canister which enclosed the inner canister. This solution has been patented in France and in US (number patent respectively FR0350775 and US 10/578 147). The fuel loading operations and the closure operations of the inner and outer canister are similar to the ones performed for classical canister (DSC) in accordance with the Technical Specifications and Requirements of the NUHOMS® license.

An alternative solution has been also designed which allow the storage of a canister inside a storage module (horizontal or vertical module) equipped with a liner. This solution has been patented in France

(FR2969362) and the patent is pending in US under number US2013261367.

When the canister, loaded with used nuclear fuel, is inserted inside the liner, the liner is then closed by a lid providing an additional and independent confinement boundary to the fuel. The annulus between the 2 shells (DSC and liner) is filled with inert gas and could be easily monitored. The advantage of this solution is the compatibility of the existing canister which involves no modification to the loading operations inside the reactor building (such as lid welding) and no modification of the transportation procedure. Indeed, the liner is used only during storage providing for an additional confinement barrier. In case of failure of the liner due to potential SCC degradation for example, the DSC with the fuel could be removed from the storage module using the transfer or the transport cask and the liner could be changed easily without damaging on the fuel placed inside the DSC. After replacing the liner, the DSC could be inserted in the same module equipped with the new liner.

Conclusion

Interim dry storage and the subsequent transportation after storage constitute the essential components of used fuel management. They are the intermediate phases prior to the final disposition of UNF – reprocessing or permanent disposal. A robust aging management program is therefore, critical to guarantee a safe and secure operability of the storage system for the initial and extended period of time as well as during transportation.

Safety and continued effectiveness of the dry storage and transportation systems will require innovative solutions to identify, monitor and mitigate any potential deterioration of the systems. Existing technical gaps need to be addressed. International exchanges on operational lessons learned will also be an important element to aging management.

Nomenclature

NUHOMS is a trademark of AREVA Inc. registered in the USA and in other countries.

TN is a trademark of TN International (AREVA Group) registered in the USA and in other countries.

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