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AGING MANAGEMENT OF RADIOACTIVE MATERIAL PACKAGING AND DRY CASK STORAGE SYSTEMS

Y.Y. Liu

Argonne National Laboratory
Lemont, IL 60439

J.M. Shuler

U.S. Department of Energy
Washington, D.C. 20585

ABSTRACT

Principles and practices for aging management of radioactive material packaging and dry cask storage systems for spent nuclear fuel are described, with emphasis on aging-related environmental degradation of materials, and structural health monitoring of structures, systems, and components that are important to safety. The overview is based on years of experience in conducting technical certification review of transportation packaging for the U.S. Department of Energy (DOE) and developing guidance documents for DOE and the International Atomic Energy Agency on aging management for dry cask storage systems for long-term storage and subsequent transportation of spent nuclear fuel. Challenges remain in aging management and prediction of remaining life for packaging and casks because damage of structures and components may be hidden, and their failure could be triggered by external events.

INTRODUCTION

There are four types of aging management programs (AMPs) that manage aging effects on structures, systems, and components (SSCs) in nuclear power plants and spent fuel dry cask storage systems for license renewal applications [1–4]. These four types of AMPs are: (1) Prevention programs that preclude aging effects from occurring; (2) Mitigation programs that slow the effects of aging; (3) Condition-monitoring programs that inspect/examine for the presence and extent of aging; and (4) Performance-monitoring programs that test the ability of a structure or component to perform its intended safety function for the period requested in the license renewal application. More than one type of AMP may be implemented for a component to ensure that aging effects are managed throughout the extended period of operation, which may vary from years to decades. For radioactive material (RAM) transportation packaging, the International Atomic Energy Agency (IAEA) Safety Standard [5] states, “*The design of the package shall take into account ageing mechanisms.*” For aerospace, civil, and mechanical engineering systems, the term structural health monitoring (SHM) [6] is often used to refer to the process of implementing a damage identification strategy, whereby damage is defined as changes to the material and/or geometric properties of these systems, including changes to the boundary conditions and system connectivity, that adversely affect the system’s performance. SHM, therefore, is closely related to aging management, as it is almost equivalent to a combination of condition monitoring and performance monitoring of SSCs that are important to safety (ITS). In the following sections, we begin with transportation of RAM packages after extended storage; this topic

highlights the importance of aging management because the “State of Health” of the package needs to be demonstrated before shipment, and because aging-related environmental degradation of SSCs of packaging depends on exposure conditions and time. Subsequently, we discuss inspection, monitoring, mitigation, and repair, followed by updating of AMPs.

TRANSPORTATION OF RAM PACKAGES AFTER EXTENDED STORAGE

The need for transport of spent nuclear fuel (SNF) for disposal after extended storage is recognized, and the storage method needs to comply with the transport safety regulations in effect at the time of license renewal during storage, or during subsequent shipment, which may occur in the future after decades of storage. The 2018 version of SSR-6 [7] introduced the following requirements that will be applied to “shipment after storage”:

Para 106: *“Transport comprises all operations and conditions associated with, and involved in, the movement of radioactive material; these include the design, manufacture, maintenance and repair of packaging, and the preparation, consigning, loading, carriage including in-transit storage, shipment after storage, unloading and receipt at the final destination of loads of radioactive material and packages.”*

Para 503 (e): *“For packages intended to be used for shipment after storage, it shall be ensured that all packaging components and radioactive contents have been maintained during storage in a manner such that all the requirements specified in the relevant provisions of these Regulations and in the applicable certificates of approval have been fulfilled.”*

Para 613A: *“The design of the package shall take into account ageing mechanisms.”*

Para 809 (f): *“If the package is to be used for shipment after storage, a justification of considerations to ageing mechanisms in the safety analysis and within the proposed operating and maintenance instructions [shall be included].”*

Para 809 (k): *“For packages which are to be used for shipment after storage, a gap analysis program describing a systematic procedure for a periodic evaluation of changes of regulations, changes in technical knowledge and changes of the state of the package design during storage [shall be included].”*

Concerning Para 613A, for shipment after storage, consideration of aging mechanisms is important because of the long period between loading and the start of shipment. The consideration of the impact of aging on the package should be supported by AMPs and time-limited aging analyses (TLAAs). The AMPs should address aging effects by including prevention, mitigation, condition monitoring, and performance monitoring for effective aging management. Concerning Para 809 (k), the gap analysis is a periodic assessment of whether the package design complies with the current transport regulations. This gap analysis should consider changes in the regulations, changes in technical knowledge, and changes in the state of the package due to aging during storage, resulting in the identification of gaps and research actions to fill the gaps [8].

RAM Transportation Packaging

For RAM transportation packages (i.e., packaging loaded with RAM contents) that are used for interim storage in a facility, a material surveillance program is implemented to ensure that the packages can maintain their ITS functions for the duration of storage and subsequent transportation. Good examples are the 9975 Type B RAM transportation packages transported from several DOE facilities in the early 2000s to the Savannah River Site and stored in the K-Area Material Storage (KAMS) facility. A materials surveillance program for the 9975 packages in KAMS was implemented in 2010; it included periodic inspections and aging studies of the elastomeric O-ring seals, using mockup fixtures of a 9975 containment vessel under controlled temperature conditions during extended storage, with annual reporting, most recently in September 2022 [9].

A methodology has been developed that may be used to extend the periodic leakage rate testing intervals of DOE-certified Type B transportation packages such as Models 9975, 9977, and 9978. The methodology is based on acceptable results of long-term O-ring performance tests and continuous monitoring of environmental conditions of the packages provided by the ARG-US radio frequency identification (RFID) temperature monitoring system [10]. Early results obtained from field testing and applications of the ARG-US RFID system on 9977 indicated that the system is reliable, and that the packaging ambient temperature can be monitored and recorded by the RFID tag sensors even when the packaging is located outside the range of the RFID reader [11]. Extending the intervals between the periodic leakage rate testing of the packaging not only enhances safety by reducing handling and radiation exposure of workers, but also cuts annual operating costs during the storage phase of packaging by an estimated US\$2500–3000 per package. This ARG-US RFID system methodology has been included in the Certificates of Compliance (CoC) as an option for requesting extension of the periodic leakage rate testing interval for 9975, 9977, 9978 and ES-3100 packages, and credits can be taken for RFID tag seal sensors as an electronic tamper-indicating device for enhanced security and safeguards during storage and subsequent transportation. (For information on U.S. Department of Energy [DOE]-certified packages, see <https://rampac.energy.gov/home/package-certification-information/certificates/doe>.)

Dry Cask Storage Systems

In addition to Ref. [2], additional NRC guidance on AMPs for dry cask storage systems can be found in the “Standard Review Plan for Spent Fuel Dry Storage Systems and Facilities - Final Report” [12], the “Standard Review Plan for Transportation Packages for Spent Fuel and Radioactive Material: Final Report” [13], and the IAEA report “Aging Management Programs for Spent Fuel Dry Storage Systems, Final Report” [14]. An extended summary of this IAEA report, found in Ref. [8], highlights approaches to developing AMPs for all current dry storage technologies; methodology for generating an AMP; identification and classification of SSCs for scoping evaluation; technical underpinnings with examples of specific aging mechanisms; operating experience and lessons learned; monitoring, mitigation, and repair technologies for AMPs; and updating AMPs. Because of their practical significance, two topical areas—(1) inspection, monitoring, mitigation, and repair, and (2) update of AMPs—are discussed further below.

INSPECTION, MONITORING, MITIGATION, AND REPAIR

As noted earlier, condition monitoring and performance monitoring are two types of AMPs for SSCs in dry cask storage systems and facilities. Monitoring could be continual or continuous, with periodic inspection as a key element of an AMP that specifies inspection (and evaluation) of the SSCs by using nondestructive examination (NDE) methods. Periodic inspections of SSCs identify active degradation that exceeds the AMP acceptance criteria and requires corrective action to mitigate and repair. Subsequent inspections may be conducted more frequently and on a larger sample size. For potential degradation that is below the AMP acceptance criteria, future inspection is based on monitoring and trending, whereby the inspection frequencies and sample sizes may be adjusted as necessary. The goals of periodic inspection (or continual monitoring) are to verify that part or all of the inspected SSCs are free from active degradation, to mitigate and repair if active degradation is found, and to adjust the planned inspection frequency accordingly.

Section 7 of Ref. [14] provides descriptions of the state-of-the-art technologies for inspection, monitoring, mitigation, and repair for AMPs that include subsections on bolted-cask systems and welded-canister systems, and each subsection contains three additional sub-subsections on aging-related effects, inspection challenges, and NDE operational experience. Other subsections cover concrete inspection, and monitoring systems that are, or could be, employed to help augment

inspections or potentially reduce the frequency of (or eliminate) inspections. Continuous and periodic condition and/or performance monitoring would enable timely detection of aging effects, such as pressure drop and/or leakage from the confinement boundary of bolted casks or welded canisters, thus allowing mitigation and repair to continue effective aging management of dry cask storage systems that reduces risk, ensures public safety and health, and protects the environment. Various monitoring technologies are at different stages of development and implementation. The primary monitoring systems that are in common usage today are pressure-monitoring systems for bolted-cask systems and temperature-monitoring systems for both bolted-cask and welded-canister systems. Other monitoring systems under development include acoustic emission, helium, concrete, and radiation.

As an example, Figure 1 below compares periodic inspection of a welded canister surface for indications of chloride-induced stress corrosion cracking (CISCC) with continuous monitoring of gas leakage from the canister due to CISCC [15, 16], followed by mitigation and repair for continuing storage, subsequent transportation, and disposal. Both condition monitoring by periodic inspection and leakage performance monitoring may be necessary as they are complementary in aging management.

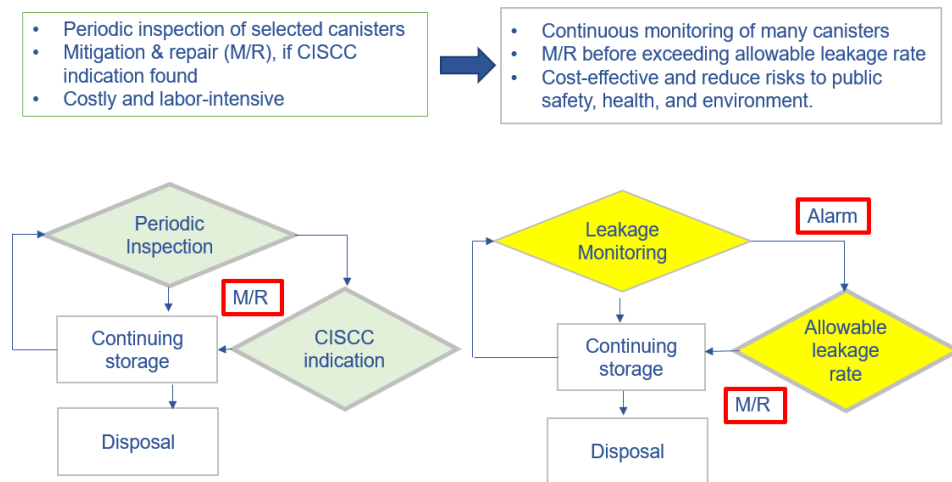


Figure 1. Comparison of periodic inspection of welded cannister surface with continuous monitoring of gas leakage

UPDATE OF AGING MANAGEMENT PROGRAMS

During extended storage of spent fuel, the state of the storage system SSCs may change, related technical knowledge may change, and related regulations may change. With those changes, the AMPs may need to be updated. To ensure continued safe storage of SNF, operating experience on age-related degradation and aging management should be used to update AMPs. Operators should review operating experience to confirm that the AMPs remain effective at managing age-related degradation, or make any necessary changes to the AMPs to ensure their continued effectiveness. In this way, the AMPs are considered learning programs that evolve to respond to operating experience and aggregated knowledge. The approach, called the “Plan/Do/Check/Act” (PDCA) cycle, was first introduced for aging management of SSCs in nuclear power plants, but is also applicable to spent-fuel dry cask storage systems. As illustrated in Figure 2 (courtesy of Dr. Toshiari Saegusa, 2023), there are also remarkable parallels between aging management for SSCs of SNF storage systems and for the human body.

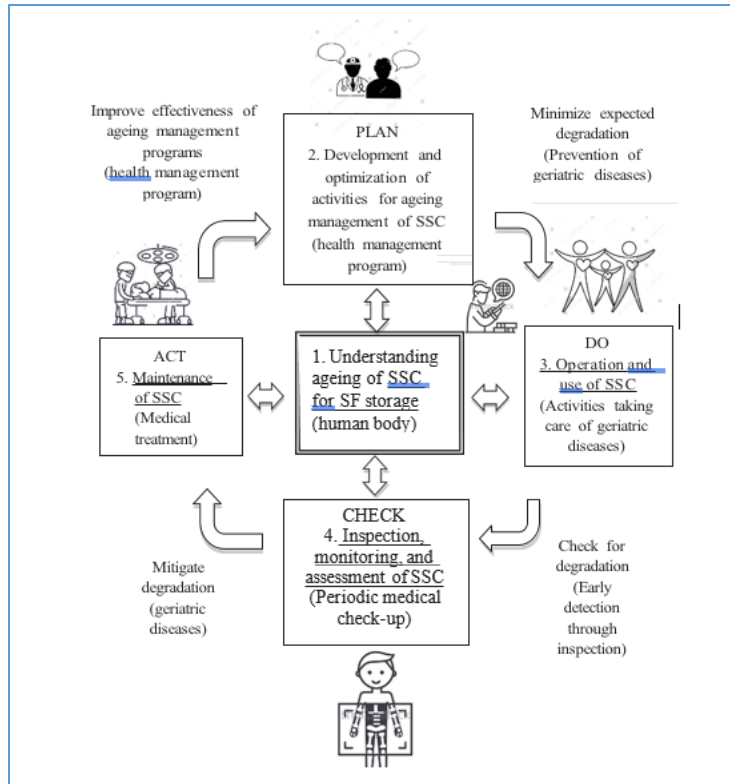


Figure 2. Plan/Do/Check/Act (PDCA) cycle for AMPs

DISCUSSION

It should be noted that some aging effects may not require an AMP if the effects can be shown, by analysis, to be incapable of adversely affecting a safety function of SSC for the licensed operating period. Such analyses, referred to as TLAAs, are usually a design-basis safety analysis with a time-dependent component. TLAAs are calculations or analyses used to demonstrate that SSCs within the scope of aging management will perform their safety function(s) throughout the operating period. TLAAs may be used to assess fatigue life, i.e., number of cycles to predicted failure, or time-limited life, i.e., operating time frame until expected loss of intended function, such as a corrosion-rate calculation. TLAAs should account for environmental effects that contribute to aging effects. Examples of TLAAs include (1) fatigue analyses of metallic structures and components to determine the number of loading cycles to failure; (2) boron depletion analysis of neutron poison plates to evaluate the potential loss of criticality control due to neutron irradiation, and (3) corrosion-rate calculations to determine if the loss of material from metallic surfaces could degrade structural and shielding functions [17]. Updating of TLAAs is required for extended periods of operation in the license renewal applications.

Development of guidance documents for IAEA on AMPs for extended storage and subsequent transportation of SNF and high-level waste continues. A new project on Performance and Assessment of Storage Systems for Extended Durations (PASSED) was launched in 2022 [18]. PASSED expands the scope of AMPs to cover many aspects related to dry and wet storage systems, including performance, monitoring and inspection, mitigation, and remedial actions.

Challenges remain in aging management of SSCs for RAM transportation packages and SNF dry cask storage systems because structural failures are intrinsically an emergent phenomenon; for example, in brittle fracture, a long period of crack initiation is followed by a short period of crack propagation after a critical flaw size is reached. In the case of high-burnup spent fuel, embrittlement of the cladding owing to hydride re-orientation during vacuum drying and early storage [19] may be hidden from periodic inspection and continuous monitoring, so that the “absence of evidence” of damage is not the same as

“evidence of absence” of damage. Emergent behavior is common in natural disasters triggered by giant earthquakes and avalanches.

SUMMARY AND CONCLUSIONS

An overview of aging-management principles and practices for RAM packaging and SNF dry cask storage systems has been provided, with emphasis on aging-related environmental degradation of materials and structural health monitoring of structures, systems and components that are important to safety. Examples based on technical certification review of RAM transportation packaging for DOE are provided, and development of guidance documents for DOE and IAEA on aging management for SNF dry cask storage systems for long-term storage and subsequent transportation is discussed. Challenges remain in aging management and prediction of remaining life for packaging and casks because damage of structures and components may be hidden, and their failure could be triggered by external events.

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REFERENCES

1. U.S. Nuclear Regulatory Commission, Generic Aging Lessons Learned (GALL) Report — Final Report (NUREG-1801, Revision 2), December 2010.
2. U.S. Nuclear Regulatory Commission, Managing Aging Processes in Storage (MAPS) Report: Final Report (NUREG-2214), July 2019.
3. Y.Y. Liu, “Aging Management for Extended Storage and Transportation of Used Nuclear Fuel,” Part IV, Ageing and Radiation, in *The Ageing of Materials and Structures, towards Scientific Based Solutions for the Ageing of Our Assets*, eds. K. van Breugel, D. Koleva, and T. van Beek, Springer, 2017.
4. Y.Y. Liu, D. Diercks, O.K. Chopra, and M. Nutt, “Managing Aging Effects on Dry Cask Storage Systems for Extended Long-Term Storage and Transportation of Used Fuel,” IAEA International Conference on Management of Spent Fuel from Nuclear Power Reactors: An Integrated Approach to the Back End of the Fuel Cycle, Vienna, Austria, June 15–19, 2015.
5. International Atomic Energy Agency Safety Standard, Storage of Spent Nuclear Fuel, Specific Safety Guide, No. SSG-15 (Rev. 1), 2020.
6. C.R. Farrar and N.A.J. Lieven, “Damage prognosis: the future of structural health monitoring,” *Phil. Trans. R. Soc. A* 365, 623–632, 2007.
7. International Atomic Energy Agency Safety Standard, Regulations for the Safe Transport of Radioactive Material, Specific Safety Requirements No. SSR-6 (Rev. 1), 2018 Edition. Para. 613A.
8. Y.Y. Liu and C. Gastl, “Ageing Management Programs for Spent Fuel Dry Storage Systems,” IHLRW-ANS Winter Meeting, Phoenix, AZ, Nov. 13–17, 2022.
9. T.T. Truong and Z. Lowe, FY2022 Status Report: Model 9975 O-Ring Fixture Long-Term Leak Performance, SRNL-STI-2022-00437, Revision 0, September 2022.
10. Y.Y. Liu, H.C. Tsai, and J. Shuler, “Extending intervals for periodic leakage rate testing of radioactive material transportation packaging,” *Packaging, Transport, Storage & Security of Radioactive Material*, 22(1), 27–34, 2011.

11. Y.Y. Liu, H. Tsai, B. Craig, J.H. Lee, and J. Shuler, "Field Testing and Applications of ARG-US Radio Frequency Identification System," 9th International Conference on Facility Operations-Safeguards Interface, Savannah, GA, September 23–28, 2012.
12. Standard Review Plan for Spent Fuel Dry Storage Systems and Facilities - Final Report (NUREG-2215), April 2020.
13. U.S. Nuclear Regulatory Commission, Standard Review Plan for Transportation Packages for Spent Fuel and Radioactive Material: Final Report (NUREG-2216), August 2020.
14. International Atomic Energy Agency, Ageing Management Programs for Spent Fuel Dry Storage Systems, Final Report of a Coordinated Research Project, IAEA TECDOC report (to be published in 2023).
15. Y.Y. Liu, B. Craig, Z. Han, K. Byrne, H. Takeda, and T. Saegusa, "RAMM-TM for detection of gas leakage from canisters containing spent nuclear fuel," *Nuclear Engineering and Design* 385, 111534, 2021.
16. T. Saegusa, H. Takeda, and Y.Y. Liu. "Monitoring of helium gas leakage from canister storing spent nuclear fuel: Radiological consequences and management," *Nuclear Engineering and Design* 382, 11139, 2021.
17. O. Chopra, D. Diercks, D. Ma, Z. Han, and Y.Y. Liu, "Role of Time-Limited Aging Analysis in Managing Aging Effects on Used Fuel Dry Storage Systems," 55th INMM Annual Meeting, Atlanta, GA, July 20–24, 2014.
18. A. Gonzalez-Espartero, L. McManniman, and C. Gastl, "IAEA activities to assess the performance of spent fuel and storage systems to support future transportability," SMiRT-26, Berlin/Potsdam, July 10–15, 2022.
19. M.C. Billone, T.A. Burtseva, and Y.Y. Liu, "Effects of Drying and Storage on High-Burnup Cladding Ductility," International High-Level Radioactive Waste Management Conference, Albuquerque, NM, April 28–May 2, 2013.