Technical Paper
https://doi.org/10.7733/jnfcwt.2023.038

Review of Aging Management for Concrete Silo Dry Storage Systems

Donghee Lee, Sunghwan Chung, Yongdeog Kim, and Taehyung Na*
Central Research Institute, Korea Hydro & Nuclear Power Co., Ltd., 70, Yuseong-daero 1312beon-gil, Yuseong-gu, Daejeon 34101, Republic of Korea

(Received August 29, 2023 / Revised September 13, 2023 / Approved September 21, 2023)

The Wolsong Nuclear Power Plant (NPP) operates an on-site spent fuel dry storage facility using concrete silo and vertical module systems. This facility must be safely maintained until the spent nuclear fuel (SNF) is transferred to an external interim or final disposal facility, aligning with national policies on spent nuclear fuel management. The concrete silo system, operational since 1992, requires an aging management review for its long-term operation and potential license renewal. This involves comparing aging management programs of different dry storage systems against the U.S. NRC's guidelines for license renewal of spent nuclear fuel dry storage facilities and the U.S. DOE's program for long-term storage. Based on this comparison, a specific aging management program for the silo system was developed. Furthermore, the facility's current practices—periodic checks of surface dose rate, contamination, weld integrity, leakage, surface and groundwater, cumulative dose, and concrete structure—were evaluated for their suitability in managing the silo system's aging. Based on this review, several improvements were proposed.

Keywords: Spent fuel, Dry storage system, Aging management, License renewal, Periodic verification

*Corresponding Author.
Taehyung Na, Central Research Institute, Korea Hydro & Nuclear Power Co., Ltd., E-mail: taehyung.na@khnp.co.kr, Tel: +82-42-870-5533

ORCID

Donghee Lee	0009-0009-8830-7632	Sunghwan Chung	0000-0001-8457-1356
Yongdeog Kim	0009-0003-3334-984X	Taehyung Na	0009-0002-2572-1229

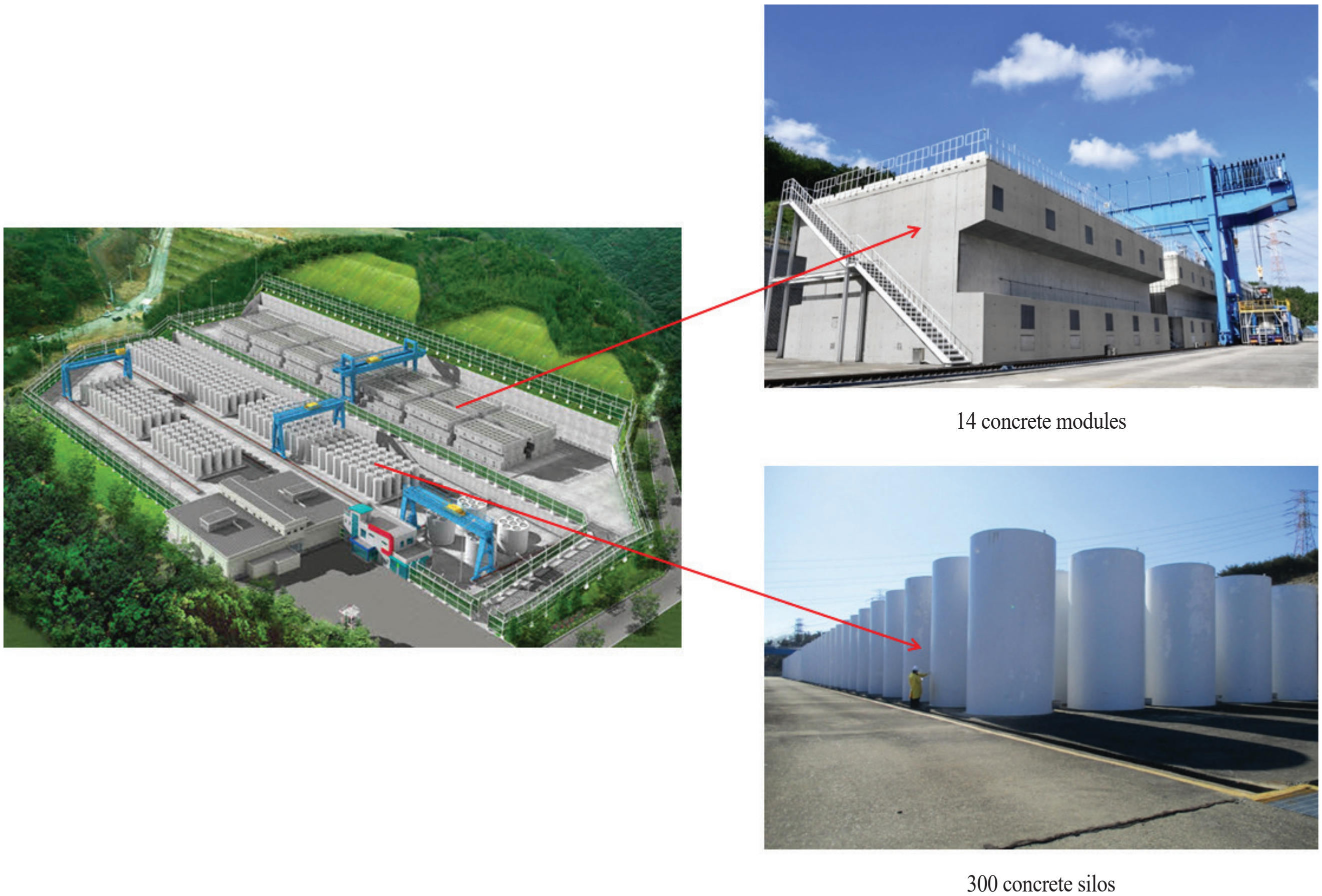


Fig. 1. SNF dry storage facility at the Wolsong NPP site.

1. Introduction

Since the 1980s, many nuclear power plants (NPPs) around the world have operated spent nuclear fuel (SNF) dry storage facilities [1]. Korea has also been operating a SNF dry storage facility using 300 concrete silo systems and 14 vertical module systems at the Wolsong NPP site since 1992 (see Fig. 1).

The SNF dry storage facility at the Wolsong NPP must be operated safely until SNF is released to an interim storage facility or a final disposal site in accordance with the national policy on SNF management, so the structural integrity of dry storage systems loaded with SNF must be maintained for a long period of time [2, 3]. In particular, the concrete silos are licensed for 50 years, but as more than 30 years of operation have passed since 1992, it is necessary to review the aging management in preparation for long-term operation and license renewal in the future.

However, as the dry storage systems are subject to time constraints for a limited lifetime, the countries operating SNF dry storage facilities are working to ensure the safe performance of facility for long-term operation. The IAEA has also recommended that the SNF dry storage facilities must be regularly assessed for long-term storage of SNF and has proposed technical standards for the aging management programs (AMPs) and integrity assessments to ensure the long-term safety of dry storage facilities [4, 5]. The United States has established AMPs and technical requirements for

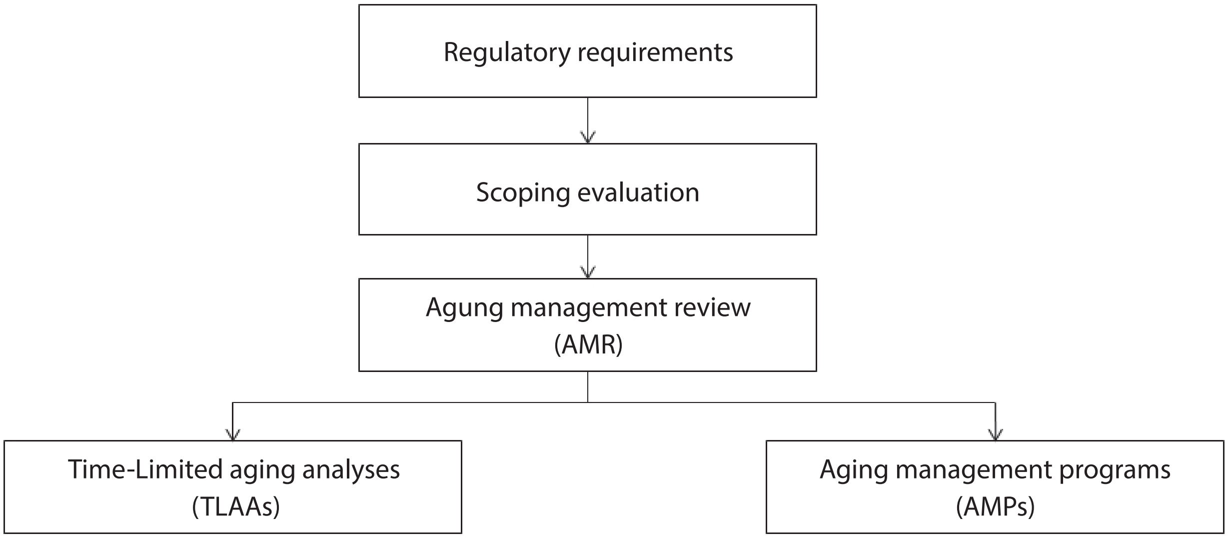


Fig. 2. License renewal process.

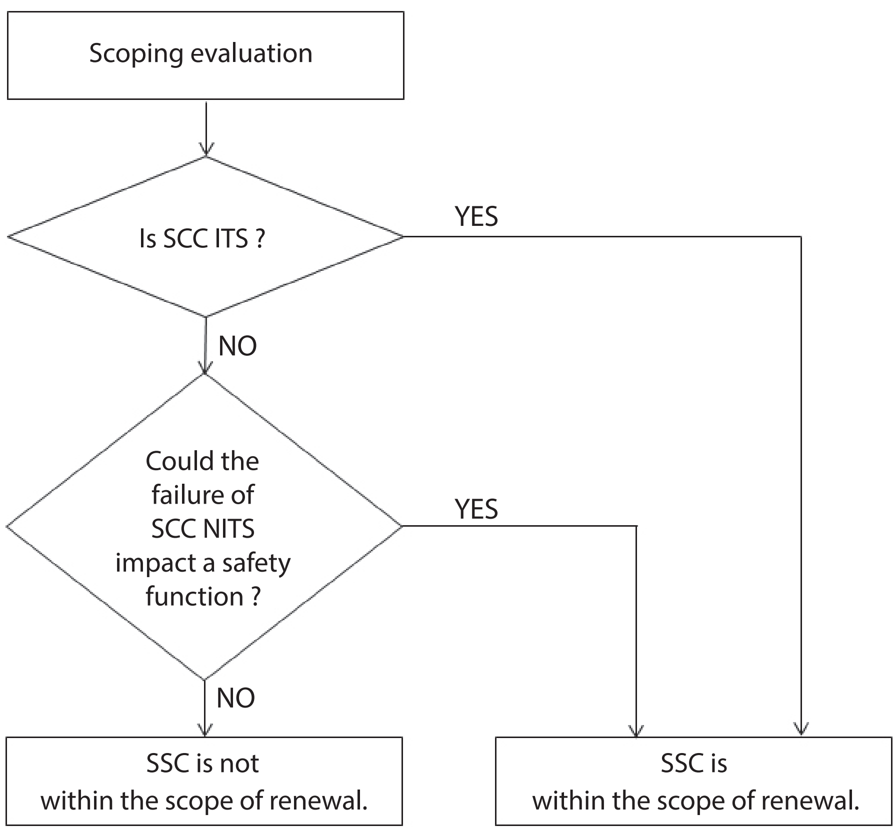


Fig. 3. Scoping evaluation process.

extending the life of SNF dry storage systems and provided technical guidelines for structures, materials, environments and aging mechanisms [6, 7].

Korea has carried out periodic assessments to prepare for the degradation of NPPs and developed assessment guidelines, but these are focused on the NPP facilities and are not directly applicable to the SNF dry storage systems. Therefore, it is desirable for Korea to develop a separate technical guideline that is suitable for the characteristics of SNF dry storage facility like the U.S. This paper identified the existing AMPs for SNF dry storage systems according to the U.S. dry storage license renewal guideline [6] and derived the AMPs for concrete silo dry storage system. And the suitability of periodic verification being currently conducted by the NPP's procedures for the aging management of silo dry storage system was reviewed, and the improvements were suggested.

2. License Renewal Guidance for Dry Storage Systems

The U.S. is renewing the licenses for dry storage systems in accordance with the NUREG-1927 of license renewal guideline [6] to ensure the continued and safe operation of SNF dry storage systems for a long time beyond their design life. The license renewal process as described in the guideline is shown in Fig. 2 [6]. A scoping evaluation is performed to identify the structures, systems and components (SSCs) subject to aging management in accordance with the regulatory requirements and an aging management review (AMR) is performed to demonstrate that the dry storage system continues to perform its intended function. AMR includes a time-limited aging analysis (TLAA) and an aging management program (AMP) for aging issues that could adversely affect the dry storage system.

The scoping evaluation analyzes whether the function of SSCs is important for safety (ITS) or not (NITS) to select the SSCs within the scope of license renewal and examine

Table 1. SSCs' safety categories

A	Critical to safe operation
B	Major impact to safety
C	Minor impact to safety

Table 2. SSCs' intended functions

CB	Containment boundary
CC	Criticality control
RS	Radiation shielding
HT	Heat transfer
SS	Structural support

the aging effect. Even if an SSC is NITS, it is included within the scope if the loss of function would affect safety. The scoping evaluation process is shown in Fig. 3. The selected SSCs are classified to determine if their functions are ITS, and the scope of renewal can be reduced by identifying which the SSCs are within the scope.

The SSCs in the dry storage systems are grouped into three safety categories, A (important for safe operation), B (significant impact on safety), and C (minor impact on safety), based on their impact on safety, referring to the NUREG/CR-6407 [7]. The functions of SSCs ITS are defined as CB (containment boundary), CC (critical control), HT (heat transfer), RS (radiation shielding) and SS (structural support). The safety categories and intended functions of SSCs are shown in Tables 2 and 3, respectively.

AMR is performed on the components and operating environment of SSCs which are within the scope of license renewal. Through this, the expected aging mechanism of each SCC is identified and appropriate aging management activities (AMA) which are divided into TLAA and AMP are applied. Fig. 4 shows AMR process. The SCCs are evaluated to determine if they are subjected to aging, and if not, no further action is taken. If the functions of SSCs are degraded, determine how to manage the aging, i.e., which AMP to take.

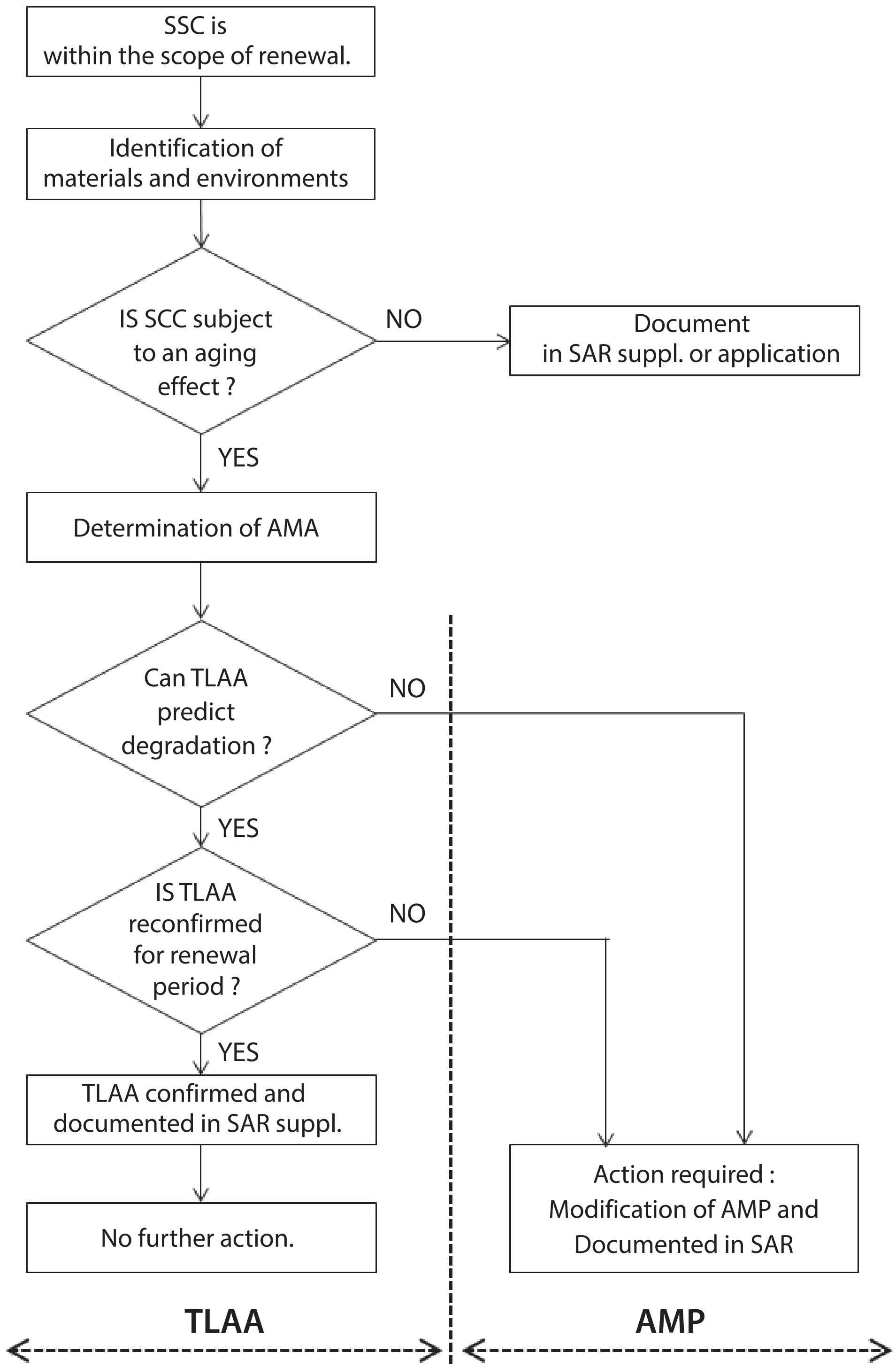


Fig. 4. Aging management review process.

Table 3. Ten AMP elements for dry storage systems

Elements	Description
Scope	To include the specific SSCs subject to AMR
Preventive actions	To mitigate or prevent the aging effects
Parameters monitored or inspected	To be linked to the aging effects on the intended functions of particular SCCs
Detection of aging effects	To occur before there is a loss of SSCs' intended function
Monitoring & tendering	To provide for prediction of the aging effects and timely corrective or mitigative actions
Acceptance criteria	To ensure that the SSCs' intended functions are maintained under the licensing basis design conditions during the extended operations
Corrective actions	To be timely
Confirmation process	To ensure that preventive actions are adequate corrective actions have been completed and are effective
Administrative controls	To provide a formal review and approval process
Operating experience	To provide objective evidence to determine that aging effects will be adequately managed and the SSCs' intended functions will be maintained during the extended operations

TLAA predicts the aging mechanism and analyzes whether the safety of SSCs is reconfirmed. If the safety is reconfirmed, no further action is required, but if the safety is not reconfirmed, TLAA must be modified or a new AMP must be developed. TLAA has many advantages over an AMP. While the AMP requires monitoring to predict current and future conditions, TLAA does not require such monitoring and can be calculated or analyzed to demonstrate the integrity of SSCs. The aging mechanisms for which TLAA is not appropriate is determined if it is included within the existing AMP. If it is, the aging mechanism is being managed appropriately and no further action is required. If not, a new AMP should be developed for the aging mechanism.

3. Aging Management Programs for Dry Storage Systems

Effective AMPs can ensure the integrity of dry storage systems for long-term operation. A report prepared by the DOE and ANL describes SSC-specific AMPs for dry storage systems currently licensed and operating in the U.S. [8]. The purpose of aging management is to ensure that the safety functions of SSCs are not compromised by aging within the scope of the original license or the scope of any license extension. As the dry storage systems are essentially structures and deterioration may not be obviously detectable, other AMPs may be required such as aging effect prevention, aging effect mitigation, aging condition monitoring, and SSC safety performance monitoring.

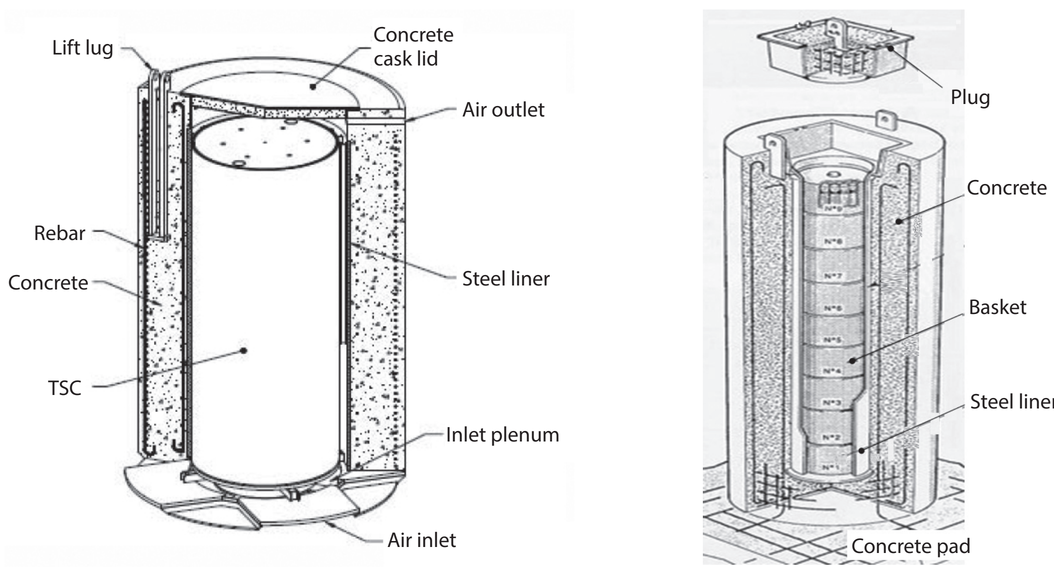
Table 4. Typical AMPs of dry storage system reviewed by DOE and ANL

S1	Monitoring of concrete structures
S2	Monitoring of protective coatings on carbon steel structures
M1	External surface monitoring of mechanical components
M2	Ventilation system monitoring
M3	Canister welds monitoring
M4	Canister bolt seals monitoring
M5	Internal structure/structure integrity monitoring

Since the types and details of AMPs may differ for the specific SSCs, the methodology and planning of aging management for long-term operation of dry storage systems uses the 10 elements of AMPs based on NUREG-1927, as shown in Table 3.

Table 5. Example of AMPs applicable to NAC MAGNASTOR system

AMP		Monitoring	Function
S1	Concrete structure surveillance	Cracking, material delamination and loss of adhesion, loss of water-tightness and strength, loss of strength, etc.	RS, SS
S2	Protective coating monitoring	Corrosion, cracking	-
M1	External surface monitoring of mechanical components	SCC, corrosion, cracking	SS, HT, RS
M3	Canister welds monitoring	SCC, corrosion, cracking	SS
M5	Internal structural and functional integrity monitoring	Impact on fuel and canister integrity, recoverability and transportability	SS



(a) MAGNASTOR system (b) Silo system

Fig. 5. Overviews of MAGNASTOR and concrete silo systems.

4. AMP Analysis Applicable to Silo Dry Storage Systems

Typical AMPs applicable to the representative metal and concrete dry storage systems analyzed by the DOE and ANL are shown in Table 4. An example of AMP applied to the NAC's MAGNASTOR concrete dry storage system similar to the concrete silo storage system is shown in Table 5. Fig. 5 shows the MAGNASTOR dry storage system and the silo dry storage system [1, 9].

By comparing the AMP items for the MAGNASTOR system analyzed by the DOE and ANL, the AMPs that can be applied to the silo system are two structural (S1, S2) and three mechanical (M1, M3, M5). Table 6 shows the applicable AMPs for each component required for the long-term monitoring of silo system.

4.1 Monitoring Concrete Structures (S1)

Concrete structures important to safety are monitored for cracking, spalling and loss of strength, etc. The S1 AMP is to inspect the concrete silo structure in accordance with

Table 6. AMPs for silo dry storage system

S1	Concrete structure	Inspection of concrete structure in according to NPP procedure
S2	Inner liner	Monitoring of liner coating condition
M1	Inner liner and basket surfaces	SCC/corrosion/crack monitoring
M3	Basket welds	SCC/corrosion/crack monitoring
M5	Structural and functional integrity of internal structure	Analytical evaluation of the integrity of fuel and basket due to radiation and temperature

the NPP's procedure. Since the concrete pad is reinforced by the silo structure and rebars, it is reasonable to be considered as a safety-related structure because it behaves together with the silo structure during external loads such as earthquake. In the case of the MAGNASOTR system, the concrete pad is included within the AMP, even though the concrete pad is separated from the system and its bottom. The NPP's procedure only mentions the silo structure, so it is necessary to supplement the inspection procedure for the concrete pad. In addition, since the non-destructive strength of concrete is a mandatory item for life management in the NPP's procedure, a reliable strength estimate is required to maintain the silo system for more than 50 years of design life. For this purpose, it is necessary to conduct additional compressive strength tests on the concrete cores along with non-destructive tests during the NPP's regular inspections.

4.2 Monitoring of Protective Coating on Carbon Steel Structures (S2)

This AMP monitors the integrity of the protective coating (radiation-resistant epoxy paint) on the carbon steel liner inside the silo system. As the structure is welded and sealed, it is not easy to inspect the interior directly. So it is considered unsuitable to include it in the periodic AMP. This is not a problem unique to the silo system, but is common to most dry storage systems. The DOE-ANL report [8] suggests that this can be addressed in an indirect way. The containment surveillance system connects circulating pumps and filters to exhaust and drain pipes and tests the silo's internal air for excessive moisture. If excessive moisture is detected, the carbon steel liner's containment may be compromised because outside air has invaded the interior. This indirect method provides an indication of the deteriorating effects on the protective coating of the carbon steel liner.

4.3 Monitoring the Outer Surface of Basket (M1) and the Leakage of Basket Welds (M3)

The integrity of outer surfaces and leakage of welds for the stainless-steel baskets stacked inside the silo system. The NPP's "Radiation Safety Management Procedure" states that no fission products must be detected in the analysis of gamma and alpha-beta radiation during the leakage test. The leakage of radioactive material from the baskets is monitored by a radiation monitoring system, and radiation dose rates are periodically monitored at the silo structure and the boundary of storage facility. In addition, surface water and groundwater samples are collected in the vicinity of the facility to check for radioactive material leakage. The DOE-ANL report [8] states that this indirect monitoring method is practical due to the difficulty of accessing the surface of basket welds.

4.4 Monitoring the Structural/Functional Integrity of Internal Structures (M5)

This AMP applies to the stainless-steel baskets inside the silo system and SNF loaded inside the baskets, and

Table 7. Periodic inspections for silo system

Inspections	Inspection items	Frequency	Relates AMPs
Dose Rate	Surface dose rate	Daily	S1, M3, M5
Contamination	Surface contamination	Weekly	S1, M3, M5
Surface water	Gamma nuclide, tritium	Weekly	S1, S2, M1, M3, M5
Groundwater	Gamma nuclide, tritium	Quarterly	S1, S2, M1, M3, M5
Cumulative dose	4-point measurement	Quarterly	S1, M3, M5
Leakage	Beta/particulate/oxo/inert-gas	Annually	S1, S2, M1, M3
Welds	PT for shielding plug welds	Semi-annually	S1, S2, M1
Structure	Degradation of concrete structures	Annually and every 5 years	S1

includes monitoring for degradation of HT (heat transfer), RS (radiation shielding) and SS (support structure) functions due to high temperature and radiation. That is, the effects of temperature and radiation for the integrity, recoverability and transportability of SNF and baskets are monitored. It is important to verify the integrity of spent nuclear fuel for long-term dry storage, so aging characterization tests are needed on the actual spent nuclear fuel in dry storage. As it is difficult to conduct a direct test, it is planned to participate in Canada CNL's characterization test of the dry-stored CANDU SNF to obtain data on the fuel aging effects due to long-term dry storage.

5. Review of Aging Management for the Silo Dry Storage System

Due to the high level of uncertainty regarding the operation of interim storage facility, it is not possible to rule out the possibility that the dry storage facility at the Wolsong NPP site will continue to operate beyond the license life of 50 years. It is necessary to proactively prepare for the license renewal of the dry storage facility, and the aging management is essential to ensure the safety of dry storage system for long-term storage and to enhance public acceptance.

The inspection items and frequency being periodically conducted by the NPP's procedure for the aging management of silo system are shown in Table 7. And the suitability of periodic verification was reviewed and the improvements were suggested.

5.1 Surface Dose Rate Measurement

Although the silo's SAR [9] requires quarterly dose rate measurements, the dose rate on the outer surface of silo system is measured daily in compliance with to the legal requirements [10], which is considered appropriate. However, it is desirable to establish a real-time dose rate monitoring system through remote monitoring to reduce the exposure and workload of workers who measure daily, to consider computerized management of measurements, and to improve the reliability of measurement data.

5.2 Measurement of Contamination

The legal requirement [10] is to measure the contamination level in the radiation control area once a week, and the inside and outside of storage facility are measured once a week according to the NPP's procedure. As the silo system is double-welded to maintain containment, there is virtually no radioactive contamination, so the weekly measurement of surface contamination is considered appropriate.

5.3 Inspection of Shielding Plug Welds

The SAR does not specifically address the inspection of welds, but it is recommended that the plug welds be inspected if excessive moisture is detected during containment inspections. Since the upper welds of silo system are inspected twice a year, it is considered adequate.

5.4 Containment Boundary Leakage Inspection

According to the NPP's procedure, leakage inspection must be performed periodically, and measurements are made once a quarter for the first year after fuel loading, once a semi-annually for the second year, and once a year thereafter. The current annual leakage inspection measurement frequency for the silo system is considered appropriate, but if excessive moisture is detected and the integrity of containment boundary is suspected, it is necessary to flexibly operate the inspection frequency to verify the integrity of containment boundary.

5.5 Surface Water and Groundwater Inspections

The SAR does not mention the inspection, but requires that the surrounding surface water be monitored for elevated levels of radionuclides. The legal requirement is to measure the three-month average concentration of radionuclides in the vents and drains, and the NPP's procedure provides for weekly measurements of surface water and quarterly measurements of groundwater, which is considered adequate.

5.6 Cumulative Dose Assessment

The SAR requires continuous gamma radiation measurements at the storage facility boundary, but the legal requirement is to measure the external radiation dose rate of the facility once a week. According to the NPP's procedure, the dose rate is measured at the facility boundary and the cumulative dose is calculated once a quarter. Currently, the frequency is judged to be fine as the cumulative dose is measured continuously and evaluated quarterly, but it is recommended to change to continuous monitoring through a remote real-time monitoring.

5.7 Concrete Integrity Inspection

The SAR requires a quarterly full inspection of the silo storage area, paying particular attention to serious cracks and delamination of the concrete, but the NPP's procedure states that the inspection frequency must be once a year for routine inspections, every five years for periodic inspections, and as needed for special inspections. The silo system is required to perform routine inspections every 5 years according to this procedure, but it is necessary to consider whether the frequency of routine inspections is increased to quarterly according to the SAR. The 5-year interval for routine inspections is considered reasonable as it is consistent with the 10-year PSR interval for nuclear power plants.

6. Conclusion

In order to prepare the aging management plan suitable for the concrete silo dry storage system, the AMPs for each dry storage system in accordance with the U.S. license renewal guidelines were compared and the AMP that can be applied to the silo system was derived. And the suitability of periodic verification being currently conducted by the NPP's procedures for the aging management of silo system was reviewed, and the improvements were suggested.

For the monitoring of concrete structures (S1), the NPP's procedure can be utilized, but additional monitoring of the concrete pad is required. The monitoring of the protective coating of carbon steel structure (S2), the monitoring of the outer surface of basket (M1), and the monitoring of the leakage of basket welds (M3) are all related to the containment of dry storage system, and the indirect monitoring of detection of excessive moisture and radioactivity during the containment inspection was analyzed. Monitoring of structural and functional soundness of internal structures (M5) requires the test analysis of actual SNF in long-term dry storage.

The periodic verification of surface dose rate inspection, surface contamination inspection, weld inspection, leakage inspection, surface water and groundwater inspection, cumulative dose assessment and concrete inspection currently in place to manage the aging of silo system was reviewed. For the surface dose rate and cumulative dose assessment, it is necessary to establish a remote real-time monitoring system for continuous monitoring to reduce worker exposure and improve efficiency and reliability. It is desirable to operate the leakage inspection flexibly. And the concrete integrity inspections may be considered for increased frequency compared to routine inspections.

The concrete silo dry storage system must be operated safely and independently at the Wolsong NPP site until the interim storage or final disposal of SNF begins, even if the NPP ends its life and is decommissioned. Therefore, since the dry storage system has different structural and physical characteristics from the NPP facility, it is desirable to establish and implement the long-term aging management program suitable for the characteristics and site conditions of dry storage system separately from the NPP's procedures.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

Acknowledgements

This work was supported by the Institute of Korea Spent Nuclear Fuel grant funded by the Korea government the Ministry of Trade, Industry and Energy (No.2021040101002C).

REFERENCES

[1] U.S. Electric Power Research Institute. Industry Spent Fuel Handbook Rev.1, EPRI Technical Report, 300 2020701 (2021).

[2] Korea Nuclear Safety Act, Republic of Korea (2023).

[3] U.S. Nuclear Regulatory Commission, U.S. 10 Code of Federal Regulations Part 72, Licensing Requirements for the Independent Storage for Spent Nuclear Fuel, High-Level Radioactive Waste and Reactor-Related Greater than Class C Wastes, 10 CRF Part 72 (2023).

[4] International Atomic Energy Agency, Storage of Spent Nuclear Fuel, IAEA Safety Standards Series No. SSG-15 (Rev.1) (2020).

[5] International Atomic Energy Agency, Understanding and Managing Ageing of Material in Spent Fuel Storage Facilities, IAEA Technical Report Series No.443 (2006).

[6] U.S. Nuclear Regulatory Commission. Standard Review Plan of Renewal of Specific Licenses and Certificates of Compliance for Dry Storage of Spent Nuclear Fuel, U.S. NRC Final Report, NUREG-1927 Rev.1 (2016).

[7] J.W. McConnell, Jr., A.L. Ayers, Jr, and M.J. Tyacke. Classification of Transportation Packaging and Dry Spent Fuel Storage System Components According to Important to Safety, U.S. Nuclear Regulatory Commission Report, NUREG/CR-6407 (1996).

[8] O.K. Chopra, D.R. Diercks, R.R. Fabian, Z.H. Han, and Y.Y. Liu, Managing Aging Effects on Dry Cask Storage Systems for Extended Long-Term Storage and Transportation of Used Fuel, U.S. Department of Energy, FCDR-UFD-2013-000294 (ANL 13/15) (2013).

[9] Korea Hydro and Nuclear Power Co., Ltd. Safety Analysis Report for the 4th Extension of Spent Nuclear Fuel Dry Storage Facility of Wolsong Nuclear Power Plant Unit 1, KHNP Repsort (2004).

[10] Enforcement Rules of the Nuclear Safety Act, Republic of Korea (2023).