Aging Management Program for Reinforced Concrete Structures

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The U.S. Nuclear Regulatory Commission has developed an aging management program (AMP) for reinforced concrete structures as guidance for complying with requirements for renewal of licenses for independent dry storage installations and certificates of compliance for dry storage systems for spent nuclear fuel. The AMP consists of condition monitoring, performance monitoring, mitigation and prevention activities. The program includes periodic visual inspections by personnel qualified to monitor reinforced concrete for applicable aging effects, such as those described in industry codes and standards. Identified aging effects are evaluated against acceptance criteria derived from the approved design bases or industry codes and standards.

The program also includes periodic sampling and testing of ground water and the need to assess the impact of any changes in its chemistry on below-grade concrete structures. Additional activities include radiation surveys to ensure the shielding functions of the concrete structure are maintained, and daily inspections to ensure the air convection vents are not blocked. The AMP includes provisions where modifications may be required depending on the design bases of the site or system.

I. INTRODUCTION

In December 2013, the U.S. Nuclear Regulatory Commission (NRC) created a task force to expand guidance for the review of renewal applications for Special Nuclear Material Licenses (specific licenses) and Certificates of Compliance (CoCs) for dry storage systems of spent nuclear fuel. The task force developed example aging management programs (AMPs) for structures, systems and components (SSCs) within the scope of renewal, i.e. SSCs defined as important to safety (ITS) and SSCs that support safety functions. The AMPs will be included in revision 1 of NUREG-1927 (Ref. 1), "Standard Review Plan for Renewal of Spent Fuel Dry Cask Storage System Licenses and Certificates of Compliance" and made available for public comment in the spring of 2015. This paper provides an example AMP for reinforced concrete structures to be included in the revised guidance, which may be used by specific licensees and CoC holders when preparing renewal applications.

IA. REGULATORY REQUIREMENTS

Pursuant to Title 10 of the Code of Federal Regulations (10 CFR), Part 72 (Ref. 2), the NRC may issue a specific license for the operation of an independent spent fuel storage installation (ISFSI) or a CoC for the design of a dry storage system. The NRC may further renew a license or CoC upon application by the licensee or CoC holder for a period not to exceed 40 years.

10 CFR 72.42(a) and 72.240(b) provide the requirements for renewal applications for specific licenses and CoCs, respectively. The renewal application must include time-limited aging analysis (TLAAs) that demonstrate SSCs ITS will continue to perform their intended function for the requested period of extended operation; and a description of aging management programs (AMPs) for management of issues associated with aging that could adversely affect SSCs ITS.

I.B. TLAAs

TLAAs are calculations or analyses used to demonstrate that SSCs within the scope of renewal will maintain their intended function throughout an explicitly stated renewal period (e.g., 40 years).[1] These calculations or analyses are used to assess fatigue life (number of cycles to predicted failure), or time-limited life (operating timeframe until expected loss of intended function). TLAAs should account for environmental effects and must be contained or incorporated by reference in the design bases. TLAAs are those calculations and analyses that meet all six criteria in 10 CFR 72.3. The AMP for reinforced concrete structures described in this paper includes provisions for exclusion of aging effects from the AMP through the use of TLAAs.

I.C. AMPs

AMPs monitor and control the degradation of SSCs within the scope renewal so that aging effects will not result in a loss of intended functions during the renewal period.[1] An AMP includes all activities that are credited for managing aging mechanisms or effects for specific SSCs. An effective AMP mitigates or detects the aging effects and provides for the prediction of the extent of the effects of aging and timely corrective actions before there is a loss of intended function.

NUREG-1927[1] defines AMPs to contain 10 elements, namely:

1. Scope of the program,
2. Preventive actions,
3. Parameters monitored or inspected,
4. Detection of aging effects,
5. Monitoring and trending,
6. Acceptance criteria,
7. Corrective actions,
8. Confirmation process,
9. Administrative controls, and
10. Operating experience.

The AMP for reinforced concrete structures provided in this paper has been structured in the format described in NUREG-1927.

II. AGING MANAGEMENT PROGRAM FOR REINFORCED CONCRETE STRUCTURES

II.A. SCOPE OF THE PROGRAM

The scope of the program includes the following aging management activities:

- Visual inspection of all above-grade (accessible, inaccessible) and below-grade (underground) concrete areas;
- A groundwater chemistry program to manage below-grade (underground) aging mechanisms of (i) corrosion of embedded steel and (ii) chemical attack due to chlorides and sulfates;
- Radiation surveys to (i) ensure compliance with 10 CFR 72.104; (ii) monitor performance of the concrete as a neutron shield at near system locations (i.e. determine dose uptrends), and (iii) validate modeling analysis and calculations described in the design bases; and
- Daily inspections to ensure the air inlet/outlet vents are not blocked and design temperature limits are not exceeded.

The AMP provides means to address the following aging effects and mechanisms, as described in ACI 349.3R-02 (Ref. 3) and SEI/ASCE 11-99 (Ref. 4):

- Cracking or loss of material (spalling, scaling) due to freeze-thaw degradation;
- Cracking or loss of material (spalling, scaling) due to chemical attack (chloride, sulfate induced);
- Cracking and loss of strength due to cement aggregate reactions;
- Cracking, loss of material, and loss of bond due to corrosion of embedded steel;
- Increase in porosity/permeability and loss of strength due to leaching of $Ca(OH)_2$;
- Cracking and distortion due to long-term settlement;
- Cracking and reduction in strength due to high temperature dehydration; and
- Cracking and reduction in strength due to gamma and neutron irradiation.

Calculations or analyses (TLAAs when appropriate) may be used to demonstrate that aging effects due to irradiation and high temperature dehydration do not require an AMP. More specifically, the renewal application may demonstrate that no part of the concrete exceeds:

- Critical cummulative fluences per ACI 349.3R-02, i.e. 10^{17} neutrons/m^2 and 10^{10} rad for gamma dose.
- Temperature limits per ACI 349-02, i.e. 150°C for general areas and 200°C for localized areas.

Additional site-specific AMPs may be required for the following scenarios:

- A dewatering system is used to prevent long-term settlement;
- The design bases includes embedded aluminum subcomponents without a protective insulating coating; and
- Protective coatings are relied upon to manage the effects of aging for a subcomponent.

II.B. PREVENTIVE ACTIONS

The aging management activities described in the scope are categorized as:

- Conditions monitoring: visual inspection
- Mitigation: groundwater chemistry program
- Performance monitoring: radiation surveys
- Prevention: daily inspections of air inlets/outlets

Preventative actions are not required for structures designed and fabricated in accordance to ACI 318 (Ref. 5) or ACI 349 (Ref. 6), as specified in the design bases. Otherwise, the design bases demonstrate that:

- For ISFSI locations in moderate (100-500 day-inch/yr) and severe (>500 day-inch/yr)

weathering conditions, the concrete mix design was verified to meet air content & water-to-cement ratio requirements of ASTM C260 (Ref 7) or equivalent. This condition applies to all CoC renewals, since the system location is not site-specific; and
- A petrographic examination [ASTM C295 (Ref. 8) or equivalent] was performed to demonstrate reactive aggregates would not lead to loss of intended function.

A site-specific AMP may be required if the above two conditions are not satisfied in the design bases.

II.C. PARAMETERS MONITORED OR INSPECTED

For visual inspections, the parameters monitored or inspected quantify the following aging effects:
- Cracking,
- Material loss (spalling, scaling),
- Loss of bond, and
- Increased porosity and permeability.

The AMP references the following parameters, as appropriate:
- Affected surface area,
- Geometry/depth of defect,
- Cracking, crazing, delaminations,
- Curling, settlements or deflections,
- Honeycombing, bug holes,
- Popouts and voids,
- Exposure of embedded steel,
- Staining/ evidence of corrosion, and
- Heavy dusting, efflorescence of any color.

The parameters evaluated are adequate for surface geometries that may support water ponding.

For the groundwater chemistry program, the parameters monitored/inspected include:
- Water pH; and
- Concentration of chlorides and sulfates in the water.

For radiation surveys, the parameters monitored or inspected include gamma dose and/or neutron fluence. For inspections of the air inlet/outlet vents, the parameters monitored/inspected include any identification of blockage that may lead to the design temperature limits being exceeded.

II.D. DETECTION OF AGING EFFECTS

II.D.1. Method/Technique

The method or technique used for inspection/monitoring achieves the acceptance criteria, as defined in element II.F of this AMP. Pursuant to the requirements in 10 CFR 72.158 and 72.164, an engineering justification or technical bases is provided, which references applicable consensus codes and standards, and/or adequate calibration procedures to ensure the method or technique will provide reliable data.

For visual inspections, the method/technique is defined as:
- Visual method for above-grade (accessible) areas (e.g., feeler gauges, crack comparators).
- Visual method for above-grade (inaccessible) and below-grade (underground) areas. More specifically, the proposed method is a site-qualified system with valid sensitivity/resolution (e.g., video/ fiber optic camera).

For the groundwater chemistry program, the method/technique is defined as an adequate chemical analysis method. For radiation surveys, the method/technique is defined as a calibrated detector with a valid energy range. For inspections of the air inlet/outlet vents, the method/technique is defined as visual.

II.D.2. Frequency of Inspections

The proposed inspection schedule is commensurate with ACI 349.3R-02 (Ref. 3). Alternative inspection frequencies provide a valid technical basis (engineering justification, operational experience data) for any deviation from ACI 349.3R-02.

For visual inspections, the frequency of inspection is defined as:
- For above-grade (accessible and inaccessible) areas: $\leq$ 5 years
- For below-grade (underground) areas: $\leq$ 10 years, and when excavated for any reason
- The use of opportunistic inspections in lieu of planned inspections includes a valid technical basis (engineering justification, operational experience data).

For the groundwater chemistry program, the frequency of monitoring is justified (e.g. quarterly, semiannual). For radiation surveys, the frequency of monitoring is justified (e.g. quarterly). For inspections of the air inlet/outlet vents, the frequency of inspection is daily or as allowed per technical specifications.

II.D.3. Sample Size

For visual inspections, the sample size includes all surface areas, or a justified sample size. For visual inspections, the groundwater chemistry program, and radiation surveys, the sample size clearly identifies and justifies specific locations. The AMP properly defines accessible and inaccessible areas, and defines their respective sample size. For inspections of the air inlet/outlet vents, the sample size includes all air inlets and outlet vents.

II.D.4. Data Collection

Data collection for visual inspections is commensurate with applicable consensus codes/standards/reports, e.g. ACI 224.1R (Ref. 9) for quantitative analysis (crack width, depth, extent), ACI 562 (Ref. 10), ACI 364.1R (Ref. 11). The AMP references the process by which inspection/monitoring operating experience is shared with the industry.

II.D.5. Timing

The timing of the inspections includes the lead system inspection, performed per the guidance in NUREG-1927 (Ref. 1), and at the frequency justified by the AMP.

II.E. MONITORING AND TRENDING

Monitoring and trending methods are commensurate with defect evaluation standards, e.g. ACI 201.1R (Ref. 12), ACI 207.3R (Ref. 13), ACI 364.1R (Ref. 11), ACI 562 (Ref. 10), or ACI 224.1R (Ref. 9)for crack evaluation.

Monitoring and trending methods reference plans/procedures used to (i) establish a baseline prior to or at the beginning of the renewal period, and (ii) track trending of parameters or effects not corrected in a previous inspection (e.g. crack growth rates, corrosion rates, pore density/ affected areas, or dose rates).

II.F. ACCEPTANCE CRITERIA

For visual inspections, the acceptance criteria are commensurate with the 3-tier quantitative criteria in ACI 349.3R-02 (Ref. 3):

- Acceptance without further evaluation,
- Acceptance after review, and
- Acceptance requiring further evaluation.

The acceptance criteria clearly identify when a finding is to be entered in the Corrective Action Program (e.g, when Tier 2 acceptance per ACI 349.3R-02 is exceeded).

For visual inspections, the acceptance criteria are commensurate with ASME Code Section XI, Subsection IWL (Ref. 14), which states that an aggressive below-grade environment is defined as a water pH < 5.5 and concentrations of chlorides and sulfates exceeding 500 ppm and 1500 ppm, respectively.

For radiation surveys, the acceptance criteria are justified and sufficient to identify a statistically significant uptrend in neutron dose rate at near overpack locations. The adequacy of the acceptance criteria considers design bases calculations documented in the FSAR. NUREG-1536 (Ref. 15) and NUREG-1567 (Ref. 16) provide further guidance for the selection of cask or overpack locations at which dose rates are calculated per the initial specific license or dry storage system design review. For inspections of the air inlet/outlet vents, the acceptance criterion is the absence of any blockage that may lead to the design temperature limits being exceeded.

Alternative acceptance criteria may be provided. For such cases, the acceptance criteria:

- Include a quantitative basis (justifiable by operating experience, engineering analysis, consensus codes/standards),
- Avoid use of non-quantifiable phrases (e.g. significant, moderate, minor, little, slight, few, etc.), and
- Are achievable and clearly actionable, i.e method/technique is qualified to meet the stated quantitative criteria (e.g., sufficient resolution/sensitivity).

II.G. CORRECTIVE ACTIONS

The Corrective Actions are in accordance with the specific or general licensee Quality Assurance (QA) Program and consistent with 10 CFR Part 72 Subpart G, or 10 CFR Part 50 Appendix B (Ref. 2). The QA Program ensures that corrective actions are completed within the specific or general licensee's CAP, and include provisions to:

- Perform functionality assessments,
- Perform apparent cause evaluations, and root cause evaluations,
- Address the extent of condition,
- Determine actions to prevent recurrence; ensure justifications for non-repairs,
- Trend conditions,
- Identify operating experience actions, including modification to the existing AMP (e.g. increased frequency), and

- Determine if the condition is reportable to the NRC (e.g., results in the loss of intended function).

The AMP references applicable concrete rehabilitation standards, e.g.:

- Cracking: ACI 224.1R (Ref. 9), ACI 562 (Ref. 10), ACI 364.1R (Ref. 11), and ACI Repair Application Procedures (RAP) Bulletins, or
- Spalling/scaling: ACI 562, ACI 364.1R, ACI 506R (Ref. 17), and ACI RAP Bulletins.

II.H. CONFIRMATION PROCESS

The confirmation process is in accordance with the specific or general licensee QA Program and consistent with 10 CFR Part 72 Subpart G, or 10 CFR Part 50 Appendix B. The QA Program ensures that the confirmation process includes provisions to:

- Determine follow-up actions to verify effective implementation of corrective actions,
- Preclude repetition of significant conditions adverse to quality, and
- Monitor for adverse trends due to recurring or repetitive findings.

II.I. ADMINISTRATIVE CONTROLS

The administrative controls are in accordance with the specific or general licensee QA Program and consistent with 10 CFR Part 72 Subpart G, or 10 CFR Part 50 Appendix B. The QA Program ensures that the administrative controls include provisions that define:

- Inspector requirements,
- Record retention requirements,
- Examination review process,
- Frequency/methods for reporting inspection results to NRC, and
- Frequency for updating the AMP based on industry-wide operational experience.

II.J. OPERATING EXPERIENCE

The AMP references and evaluates applicable operating experience, including:

- Internal and industry-wide condition reports,
- Internal and industry-wide corrective action reports,
- Vendor-issued safety bulletins,
- NRC Information Notices, and
- Applicable industry and DOE initiatives (e.g., EPRI or DOE sponsored inspections).

The AMP clearly identifies any degradation in the referenced operating experience as either age-related or event-driven, with proper justification for that assessment. Past operating experience supports the adequacy of the proposed AMP, including the method/technique, acceptance criteria, and frequency of inspection.

The AMP references the methods for capturing operating experience from other ISFSIs with similar in-scope SSCs.

III. CONCLUSIONS

The U.S. Nuclear Regulatory Commission has developed example aging management programs (AMPs) for structures, systems and components (SSCs) defined to be within the scope of renewal of specific licenses and certificates of compliance per the criteria in NUREG-1927. These example AMPs, including the one discussed in this paper for reinforced concrete structures, have been developed to ensure a consistent and technically comprehensive review of the effects of aging for dry storage system designs and independent spent fuel storage installations. It further provides an acceptable approach for licensees and CoC holders to ensure aging mechanisms and effects will not result in a loss of intended function, and comply with the requirements in 10 CFR Part 72. The specific AMP presented in this paper should not be considered a regulatory requirement on itself. The applicant may propose an alternate AMP, which the NRC will review to ensure requirements in 10 CFR Part 72 are met. The AMP in this paper will be made available for public comment in Spring 2015, and may be modified as a result of those comments.

REFERENCES

1. NUREG–1927, *Standard Review Plan for Renewal of Spent Fuel Dry Cask Storage System Licenses and Certificates of Compliance*, U.S. Nuclear Regulatory Commission, Washington, DC (2011).
2. Title 10, *Code of Federal Regulations*, Part 72, "Licensing Requirements for the Independent Storage oof Spent Nuclear Fuel, High-Level Radioactive Waste, and Reactor-Related Greater Than Class C Waste, United States Government, Washington, DC (2014).
3. ACI 349.3R-02, *Evaluation of Existing Nuclear Safety-Related Concrete Structures*, American Concrete Institute, Farmington Hills, MI (2010).
4. SEI/ASCE 11-99, *Guideline for Structural Condition Assessment of Existing Buildings*, American Society of Civil Engineers, Reston, VA (2000).
5. ACI 318-11, *Building Code Requirements for Structural Concrete*, American Concrete Institute, Farmington Hills, MI (2011).

6. ACI 349-06, *Code Requirements for Nuclear Safety-Related Concrete Structures*, American Concrete Institute, Farmington Hills, MI (2007).
7. ASTM C260/C260M-10a, *Standard Specification for Air-Entraining Admixtures for Concrete*, American Society for Testing and Materials, West Conshohocken, PA (2010).
8. ASTM C295/C295-M-12, *Standard Guide for Petrographic Examination of Aggregates for Concrete*, American Society for Testing and Materials, West Conshohocken, PA (2012).
9. ACI 224.1R-07, *Causes, Evaluation, and Repair of Cracks in Concrete Structures*, American Concrete Institute, Farmington Hills, MI (2007).
10. ACI 562-13, *Code Requirements for Evaluation, Repair, and Rehabilitation of Concrete Buildings*, American Concrete Institute, Farmington Hills, MI (2013).
11. ACI 364.1R-07, *Guide for Evaluation of Concrete Structures before Rehabilitation*, American Concrete Institute, Farmington Hills, MI (2007).
12. ACI 201.1R-08, *Guide for Conducting a Visual Inspection of Concrete in Service*, American Concrete Institute, Farmington Hills, MI (2008).
13. ACI 207.3R-94, *Practices for Evaluation of Concrete in Existing Massive Structures for Service Conditions*, American Concrete Institute, Farmington Hills, MI (2008).
14. ASME Boiler and Pressure Vessel Code, Section XI, Subsection IWL, *Requirements for Class CC Concrete Components of Light-Water-Cooled Plants*, American Society of Mechanical Engineers, New York, NY (2013).
15. NUREG–1536, *Standard Review Plan for Spent Fuel Dry Storage Systems at a General License Facility*, U.S. Nuclear Regulatory Commission, Washington, DC (2010).
16. NUREG–1567, *Standard Review Plan for Spent Fuel Dry Storage Facilities*, U.S. Nuclear Regulatory Commission, Washington, DC (2000).
17. ACI 506R-05, *Guide to Shotcrete*, American Concrete Institute, Farmington Hills, MI (2005).