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# LWR Sustainability: Assessment of Aging of Nuclear Power Plant Safety Related Concrete Structures

**Herman L. Graves, III**[1,*] and **Dan J. Naus**[2]

[1] *United States Nuclear Regulatory Commission (USNRC), Washington, DC 20555-0001, USA*
[2] *Oak Ridge National Laboratory (ORNL), Oak Ridge, Tennessee 37831-8056, USA*

**ABSTRACT**

Current regulatory testing and inspection requirements are reviewed and a summary of degradation experience is presented. Techniques commonly used to inspect NPP concrete structures to assess and quantify age-related degradation are summarized. An approach for conduct of condition assessments of structures in NPPs is presented. Criteria, based primarily on visual indications, are provided for use in classification and assessment of concrete degradation. Materials and techniques for repair of degraded structures are generally discussed.

**KEYWORDS**

*Nuclear power plants, aging management, nondestructive evaluation, in-service inspection, condition assessment, degradation, structural engineering*

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## 1. Introduction

The Atomic Energy Act and USNRC regulations limit commercial reactor power licenses in the U.S. to an initial 40-year period, but also provide the option of renewing the licenses. Currently in the U.S. 104 NPPs are licensed for commercial operation and provide about 20% of all electrical power produced. About one-quarter of these plants are under 20 years old, but more than one-third are 30 or more years old. By the year 2015 over 40% of the current plants will have reached the end of their initial operating license period. In an effort to continue furnishing a timely and cost-effective solution to electricity production requirements as well as provide an environmentally clean energy source, some utilities have applied to renew their initial operating license for their plants. In fact by May 2012, 71 of the currently operating units have been through the license renewal process.

One of the key concerns that could affect the continued operation and development of nuclear power relates to the impact of aging of the plants on plant performance. Age-related degradation may affect the engineering properties, structural resistance/capacity, failure mode, and location of failure initiation that may in turn affect the ability of a structure to withstand challenges in service. It is necessary that safety issues related to plant aging and continued service be resolved through sound scientific and engineering understanding. Furthermore, in contrast to many mechanical and electrical components, replacement of many structures is impractical.

Background information and data have been developed for improving existing and developing new methods to assist in quantifying the effects of age-related degradation on the performance of NPP safety-related structures. Factors that can lead to age-related degradation of safety-related structures are identified and their manifestations described. Current regulatory in-service inspection requirements are reviewed and a summary of degradation experience presented, including results of a utility survey addressing operating experience. Techniques commonly used to inspect NPP concrete structures to assess and quantify age-related degradation are summarized. Criteria, based primarily on visual indications, are provided for use in classification and assessment of concrete degradation.

*Corresponding author, E-mail: herman.graves@NRC.gov

Materials and techniques for repair of degraded structures are generally discussed.

## 2. Regulatory and inspection requirements

The Nuclear Management and Resources Council (NUMARC, the predecessor of the Nuclear Energy Institute [NEI]) submitted 11 industry reports (IRs) to the NRC for review in 1990. Ten of the reports discussed aging issues of components and structures in NPPs and the last report addressed a screening methodology for the proposed integrated plant assessments (IPAs). Title 10 of the Code of Federal Regulations, Part 54 (10 CFR Part 54) was originally published in 1991. This Federal Regulation established the procedures, criteria, and standards that govern NPP license renewal applications (LRAs). In 1993 the NRC Staff recommended that the technical information in the IRs be incorporated into the proposed draft standard review plan (SRP) for license renewal.

In 1997 a report was issued that reconciled the NUMARC/NEI, IRs with the newly published inservice inspection requirements of Subsections IWE and IWL of 10CFR50.55a, the Federal Regulation for license renewal consideration. The initial SRP for the review of LRAs was issued in 2001 along with the NRC Staff evaluation of existing aging management programs, which is also known as the Generic Aging Lessons Learned (GALL) Report. The NRC also issued in 2001 Regulatory Guide (RG) 1.188 that governs the standard format and content of LRAs. Public comments on RG 1.188 were resolved and on draft NUREG-1800,"Standard Review Plan for Review of License Renewal applications for Nuclear Power Plants," and NUREG-1801, GALL Report. All three documents were revised and updated in September 2005 and NEI published an industry guidance document, NEI 95-10, for implementing the requirements of 10 CFR 54 (also known as the License Renewal Rule). Reference [1] provides additional background.

The NRC's Office of Nuclear Reactor Regulation (NRR) is responsible for ensuring the public health and safety through licensing and inspection activities at all commercial nuclear power reactor facilities in the United States. Evaluation of LRAs is performed by the Division of License Renewal (DLR). DLR performs its work in accordance with the requirements of 10 CFR 54. In addition, DLR also uses the guidance provided in NUREG-1800 and NUREG-1801, and follows the precepts of NRC RG 1.188. In December 2010, Revision 2 of NUREG-1800 and -1801 was published.

## 3. Degradation Experience

Service-related degradation can affect the ability of a NPP civil structure to perform satisfactorily in the unlikely event of a severe accident by reducing its structural capacity or jeopardizing its leaktight integrity. The root cause for most degradation can generally be linked to a design or construction problem, inappropriate material application, a base-metal or weld-metal flaw, maintenance or inspection activities, or excessively severe service conditions.

Primary mechanisms that can produce premature deterioration of reinforced concrete structures include those that impact either the concrete or steel reinforcing materials (i.e., mild steel reinforcement or post-tensioning system). Degradation of concrete can be caused by adverse performance of either its cement-paste matrix or aggregate materials under chemical or physical attack. Chemical attack may occur in several forms: efflorescence or leaching; attack by sulfate, acids, or bases; salt crystallization; and alkali-aggregate reactions. Physical attack mechanisms for concrete include freeze/thaw cycling, thermal expansion/thermal cycling, abrasion/erosion/cavitation, irradiation, and fatigue or vibration. Degradation of mild steel reinforcing materials occurs as a result of corrosion. Post-tensioning systems are susceptible to corrosion plus loss of prestressing force, primarily due to tendon relaxation and concrete creep and shrinkage.

With respect to concrete structures, occurrences of degradation have been reported either early in plant life or after several years of operation. Causes were primarily related to improper material selection, construction/design deficiencies, or environmental effects. Age-related degradation occurrence examples include failure of prestressing wires (Calvert Cliffs); corrosion of steel reinforcement in water-intake structures (Turkey Point and San Onofre); leaching of tendon gallery concrete (Three Mile Island); and low prestressing forces (Ginna, Turkey Point 3, Zion, and Summer) [2].

## 4. Inspection of Nuclear Power Plant Concrete Structures

The various concrete degradation mechanisms often produce visible indications, patterns, or features on exposed surfaces during initial manifestation and propagation. These indications can be evaluated using visual inspection and condition survey techniques, enhanced or supplemented with other testing and analytical methods as needed. Internally initiated degradation requires the use of in-place nondestructive testing or invasive testing on samples removed from the structure [3].

Techniques proven to be useful in the evaluation of a concrete structure can be categorized as follows:

- Visual inspection,
- Nondestructive testing;
- Invasive testing; and
- Analytical methods.

Information from plant records will help supplement information obtained from evaluation techniques: structural drawings, calculations, design strengths, strength data for concrete cylinders from the original construction, construction testing reports, minimum cover thickness, reinforcing bar size and location, and prestressing tendon size and location [3].

Visual inspection can provide significant quantitative and qualitative data regarding structural performance and the extent of any degradation. Visual inspection includes direct and indirect inspection of exposed surfaces, crack and discontinuity mapping, physical dimensioning, collection of data pertinent to the environment that the structure is exposed.

Nondestructive examination (NDE) or testing techniques require the use of special equipment to obtain specific data. The non homogeneity of concrete, thick cross sections, and large quantities and sizes of reinforcing steel (for example, typical nuclear power plant construction), limit the effectiveness of many nondestructive testing methods. The goal of this form of testing is to provide quantitative information about a structure without removing or damaging any material. Table 1 lists some NDE measurement techniques that are currently used.

**Table 1. Some current NDE measurement techniques for concrete**

| **Non Destructive Methods** |
|---|
| Visual Inspection |
| Ground penetrating radar |
| Ultrasonic (pulse velocity and pulse echo) |
| Impact Echo |
| Acoustic Emissions |
| Half-Cell potential |

Invasive testing focuses on the removal of concrete or steel reinforcement specimens from the structure for laboratory testing to determine physical, chemical, micro structural, and mechanical properties or other information. Generally, this technique is limited to a controlled number of samples to minimize any detrimental effects on remaining structural performance.

Analytical methods involve the use of supplemental calculations or analysis techniques to evaluate the structural behavior and resistance of the structure. Examples of analytical methods include the use of finite element analysis. It may also be necessary to re-evaluate the structural capacity of the structure or structural component in question, because the original calculations may not be available or the design may have been governed by calculations for a physically similar but different structure. In general, some form of analysis will be required in the event that any potentially significant degradation is found during the inspection and testing phase [3].

## 5. Continued Assessment of Structural Degradation

Definitive aging studies require actual plant experience. To gain an understanding of what has been learned from plants worldwide and to determine effective assessment techniques USNRC staff has been involved in a number of activities internationally and nationally.

### 5.1 International Activities

The NRC routinely engages in cooperative research activities with the International Atomic Energy Agency (IAEA), the Organization for Economic Cooperation and Development (OECD) and its Nuclear Energy Agency (NEA), and other organizations to foster the international exchange of data and analysis results, which contribute to the safe worldwide operation of nuclear facilities.

#### 5.1.1 Committee on the Safety of Nuclear Installations (CSNI)

The staff participates in international technology exchanges through the IAEA Engineering Safety Section and the Seismic Subgroup of the Working Group on Integrity of Components and Structures (IAGE), under the auspices of the OECD/NEA Committee on the Safety of Nuclear Installations (CSNI). The Staff's ongoing research program, Study on Post-tensioning Methods is an OECD/CSNI program with the goal to develop a state of the art report on the use of grouted and ungrouted tendons.

#### 5.1.2 IAEA International Generic Aging Lessons Learned (IGALL)

IAEA IGALL has three interaction levels – a Steering Group (SG) that provides overall direction for the program (NRC Director of Division of License Renewal is the US member), a Clearing Group (CG) that ensures that the final products are consistent with SG direction, and three Working Groups (WGs) that are developing the final products. The three WGs (WG1 addresses Mechanical Components, WG2 addresses Electrical and I&C Components, and WG3 addresses Civil Structures and Components, Staff form USNRC Division of License Renewal are involved is this WG) have begun their work; the CG had its first meeting to ensure common approaches and goals for each of the WGs. IGALL is using the basic approach in the US GALL report (NUREG-1801), although the aging management review (AMR) line item tables have a different arrangement from GALL and the aging management program (AMP) descriptions have nine elements.

### 5.2 National Activities

#### 5.2.1 Generic Aging Lesson Learned (GALL)

In December 2010, the Standard Review Plan for License Renewal Applications for Nuclear Power Plants (SRP-LR), NUREG-1800, was revised to incorporate information from the GALL report and lessons learned from the staff review of the initial license renewal applications. The SRP-LR provides guidance to the NRC staff for reviewing applications for license renewal. The principal purpose of the SRP-LR is to assure quality and uniformity of staff reviews and to present a well-defined base from which to evaluate applicants programs and activities for the period of extended operation.

The GALL report, NUREG-1801, represents an evaluation that documents which generic existing programs should be augmented for license renewal and which generic programs adequately manage aging effects without change. NRC research and licensing staff will continue to work together in future revisions of the GALL reports to make sure research findings are referred to in the updated reports.

### 5.2.2 Aging Management Program Review

The prior update of the license renewal guidance documents generally focused on the Aging Management Review (AMR) line items. The purpose of the Aging Management Program Review (AMP) expert panels was to review and evaluate relevant information and to identify proposed revisions to the GALL Report. Sources for potential revisions included both NRC internal and external information. The primary objective was to confirm that the AMP is actually adequate at managing the aging (degradation) mechanism and to update items as necessary to: correct errors; reflect generic precedents established during License Renewal Application (LRA) reviews; incorporate approved or non-controversial Interim Staff Guidance items; and minimize LRA exceptions.

The current guidance update will include a focus on the content of the AMPs and alignment of the AMP elements with the generic AMP element descriptions in the LR-SRP Appendix A.1 (branch technical position). Information in all sections of the guidance documents will be within the update scope; however the AMP content will be examined more closely than in the prior revision. The AMP review effort is ongoing and to date NRC staff has conducted comprehensive studies at two reactor sites.

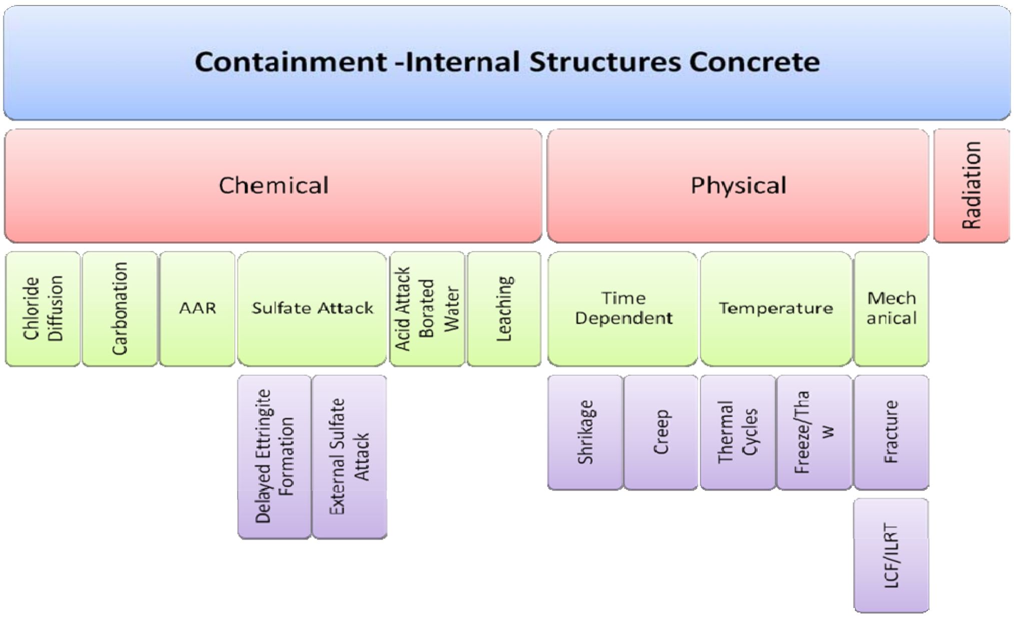


**Figure 1 – Degradation Modes in Reactor Containments (Concrete)**

### 5.2.3 Expanded Proactive Materials Degradation Analysis (EMPDA)

In collaboration with the U.S. Department of Energy's Office of Nuclear Energy's (DOE) Light Water Reactor Sustainability Program (LWRSP), the NRC has initiated expert panels to use a modified Phenomena Identification and Ranking Technique (PIRT) process to evaluate aging degradation phenomena on the Core Internals and Primary Systems; Balance of Plant Systems and Components; Reactor Pressure Vessel (RPV); Concrete Structures; and Electric Cabling. This work expands on the original NUREG 6923, Proactive Materials Degradation Analysis (PMDA), and looks forward 40 years to at least 80 years of operating life. The original PMDA work did not include a review of concrete structures. The planned EMPDA report includes a volume that summarizes the results of an expert-panel assessment of the aging and degradation of concrete civil structures. The panels of the EMPDA include a diverse body of experts representing regulatory bodies, industry (EPRI, vendors, etc.), U.S. national laboratories, academia, and international organizations. Figure 1 shows some degradation items considered by the expert concrete panel. A final report on this effort is expected late calendar year 2013.

5.2.4 Concrete Materials Database

An activity under the DOE LWRSP concrete research program is the development of a concrete materials property database. It is envisioned that the concrete material database will provide data and information to help quantify aging and environmental effects on current and future performance of concrete and concrete-related structures. A materials property database (hand copy and electronic version) developed under an earlier NRC research program on structural aging has been updated and populated with data and information available in the literature as well as results obtained from sampling and testing of concrete-related materials from nuclear power plants. Data and information developed under this activity have application for long-term structural performance assessments and trending, evaluation of environmental effects, and development of service-life models.

Potential additional applications of the concrete material sampling activity would be to: provide feedback on effectiveness of current aging management programs and input for development of improved aging management strategies, indicate the overall quality of construction, develop acceptance criteria for current and future condition assessments, assess and validate non-destructive testing methods, evaluate repair activities, and furnish information for application to new plant designs. Results developed under this task will have direct application to helping ensure that existing nuclear power plants can continue to operate safely [4].

## 6. Materials and Techniques for Repair

In July 28, 2011 a Task Group on Repair of Reinforced Concrete of Existing Nuclear Power Plants (TG) was formed. This group is part of the Nuclear Energy Standards Coordination Collaborative (NESCC), a joint initiative of the American National Standards Institute (ANSI) and the National Institute of Standards and Technology (NIST), DOE and the NRC. NESCC was created in June 2009 with the goal of identifying and responding to the current needs of the nuclear industry through the development of consensus standards. The scope of NESCC repair TG is to:

- Establish coordination and consistency for safety and non-safety concrete repairs in existing nuclear power plants: evaluate the concrete structure, assess the repair strategy, design and implement the repair and monitor the repair
- Identify repair requirements for safety related concrete components and develop a plan to incorporate these new requirements into codes and standards. Collaboration with standards developing organizations (SDOs) will be required
- Identify U. S. Nuclear Regulatory Commission regulatory documents related to concrete repair for existing nuclear power plants and identify any needs.

The effort of the TG has revealed that little information has been documented in the literature on the long-term durability of repairs. Also, when a repair is required the success is largely dependent on workmanship during installation. Therefore, experience personnel should be used to design and install repairs. Another factor that must considered is that each nuclear power plant structure is very unique. Because of the technical specifications and requirements, a repair that applied at one nuclear plant may not be usable at another similar plant.

To date the repair TG has developed a draft report which states that the report is intended to be an overall snapshot on what should be done to improve the repair of NPP concrete. This report is neither a code nor a standard, but only a set of coordinated recommendations to the SDO's involved with concrete repair of nuclear power plants in hopes of "harmonizing" commonly cited concrete codes and standards. These recommendations only identify gaps, overlaps, or conflicts in existing codes and standards (a final report on repair is scheduled to be published mid calendar year 2013).

## 7. Summary

Instances of concrete degradation have been observed in containments and other structures at nuclear plants during the initial license period. Therefore, there is reason to suspect that, during an extended license period in a number of plants, degradation will be found and conditions have to be evaluated and addressed. In cases where degradation is visible and of a type previously encountered in concrete structures consensus codes and standards should be used if available.

In addition to documented practice cited in consensus codes and standards, affected stakeholders (e.g., review agencies, plant owners) in the technical community have used a body of knowledge built upon and openly published in technical literature. The information in published literature can provide the technical basis for judgment and evaluation of degraded plant conditions.

It is not reasonable to assume that all future incidents of degradation will be resolved by documented practice or studies. In general, undegraded structures have design margins when properly designed and constructed. However, with aging the available safety margins may become uncertain if aging is not properly inspected and managed especially in inaccessible areas.

## Disclaimer

The contents of this paper are based on the authors' knowledge and their work for the USNRC. However, the paper is an independent product of the authors and does not necessarily reflect the views or regulatory position of the USNRC.

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