

ACI 349.3R-18

Report on Evaluation and Repair of Existing Nuclear Safety-Related Concrete Structures

Reported by ACI Committee 349



American Concrete Institute
Always Advancing



Documents

Document Sharing Hub



Report on Evaluation and Repair of Existing Nuclear Safety-Related Concrete Structures

Copyright by the American Concrete Institute, Farmington Hills, MI. All rights reserved. This material may not be reproduced or copied, in whole or part, in any printed, mechanical, electronic, film, or other distribution and storage media, without the written consent of ACI.

The technical committees responsible for ACI committee reports and standards strive to avoid ambiguities, omissions, and errors in these documents. In spite of these efforts, the users of ACI documents occasionally find information or requirements that may be subject to more than one interpretation or may be incomplete or incorrect. Users who have suggestions for the improvement of ACI documents are requested to contact ACI via the errata website at <http://concrete.org/Publications/DocumentErrata.aspx>. Proper use of this document includes periodically checking for errata for the most up-to-date revisions.

ACI committee documents are intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. Individuals who use this publication in any way assume all risk and accept total responsibility for the application and use of this information.

All information in this publication is provided “as is” without warranty of any kind, either express or implied, including but not limited to, the implied warranties of merchantability, fitness for a particular purpose or non-infringement.

ACI and its members disclaim liability for damages of any kind, including any special, indirect, incidental, or consequential damages, including without limitation, lost revenues or lost profits, which may result from the use of this publication.

It is the responsibility of the user of this document to establish health and safety practices appropriate to the specific circumstances involved with its use. ACI does not make any representations with regard to health and safety issues and the use of this document. The user must determine the applicability of all regulatory limitations before applying the document and must comply with all applicable laws and regulations, including but not limited to, United States Occupational Safety and Health Administration (OSHA) health and safety standards.

Participation by governmental representatives in the work of the American Concrete Institute and in the development of Institute standards does not constitute governmental endorsement of ACI or the standards that it develops.

Order information: ACI documents are available in print, by download, through electronic subscription, or reprint and may be obtained by contacting ACI.

Most ACI standards and committee reports are gathered together in the annually revised the ACI Collection of Concrete Codes, Specifications, and Practices.

American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
Phone: +1.248.848.3700
Fax: +1.248.848.3701

www.concrete.org

Report on Evaluation and Repair of Existing Nuclear Safety-Related Concrete Structures

Reported by ACI Committee 349

Adeola K. Adediran*, Chair
Lisa M. Anderson*, Secretary
Branko Galunic, Vice Chair

Partha S. Ghosal*, Vice Chair
John F. Silva, Vice Chair

Omesh B. Abhat
Monzer M. Allam*
Taha D. Al-Shawaf
Carlos Cantarero-Leal
Mukti L. Das
Rolf Eligehausen
Farhad Farzam
Werner A. F. Fuchs

Stewart C. Gallocher
Herman L. Graves III*
Orhan Gurbuz
James A. Hammell
Joseph K. Harrold
Charles J. Hookham*
Thomas T. C. Hsu
Ronald J. Janowiak

Scott A. Jensen
Ola Jovall
Bernd R. Laskewitz
Nam-Ho Lee
W. Calvin McCall
Javeed Munshi*
Dan J. Naus
Nebojsa Orbovic

Madhumita Sircar*
Bozidar Stojadinovic
Amit H. Varma
Andrew S. Whittaker
Charles A. Zalesiak*

Consulting Members

Hansraj G. Ashar
Peter J. Carrato

Ronald A. Cook
Gunnar A. Harstead

Richard S. Orr
Barendra K. Talukdar

Albert Y. C. Wong

The committee thanks M. D'Ambrosia*, C. Larosche*, M. Sherman*, and D. Scott for their contributions to this report.

*Members of the subcommittee
authoring this report.

This report provides recommendations for the evaluation of existing nuclear safety-related concrete structures. The purpose of this report is to provide the owner, owner's engineering staff, consultants, and others with an appropriate procedure and background for examining concrete structural performance and taking appropriate actions based on observed conditions. Methods of examination, including visual inspection and testing techniques and their recommended applications, are cited. Guidance related to acceptance criteria for various forms of degradation and methods for repair are provided.

Keywords: corrosion; cracking; degradation; inspection; load test; nondestructive testing; nuclear plant; rehabilitation; reinforcement; repair; safety; serviceability; structural design; structural evaluation.

ACI Committee Reports, Guides, and Commentaries are intended for guidance in planning, designing, executing, and inspecting construction. This document is intended for the use of individuals who are competent to evaluate the significance and limitations of its content and recommendations and who will accept responsibility for the application of the material it contains. The American Concrete Institute disclaims any and all responsibility for the stated principles. The Institute shall not be liable for any loss or damage arising therefrom.

Reference to this document shall not be made in contract documents. If items found in this document are desired by the Architect/Engineer to be a part of the contract documents, they shall be restated in mandatory language for incorporation by the Architect/Engineer.

CONTENTS

CHAPTER 1—INTRODUCTION AND SCOPE, p. 2

- 1.1—Introduction, p. 2
- 1.2—Scope, p. 2

CHAPTER 2—DEFINITIONS, p. 3

CHAPTER 3—GENERAL METHODOLOGY AND EVALUATION PROCEDURE, p. 4

- 3.1—General methodology, p. 4
- 3.2—Scope, p. 4
- 3.3—Selective evaluation, p. 4
- 3.4—Periodic evaluation, p. 5
- 3.5—Evaluation procedure document, p. 6
- 3.6—Evaluation techniques, p. 6

CHAPTER 4—DEGRADATION MECHANISMS, p. 10

- 4.1—General, p. 10

ACI 349.3R-18 supersedes ACI 349.3R-02 and was adopted and published February 2018.

Copyright © 2018, American Concrete Institute.

All rights reserved including rights of reproduction and use in any form or by any means, including the making of copies by any photo process, or by electronic or mechanical device, printed, written, or oral, or recording, or by any information storage, reproduction or for use in any knowledge or retrieval system or device, unless permission in writing is obtained from the copyright proprietor.

- 4.2—Concrete degradation, p. 10
- 4.3—Steel reinforcement and structural steel degradation, p. 15
- 4.4—Prestressing steel degradation, p. 16

CHAPTER 5—EVALUATION CRITERIA, p. 17

- 5.1—Acceptance without further evaluation, p. 17
- 5.2—Acceptance after review, p. 19
- 5.3—Acceptance after enhanced evaluation, p. 20

CHAPTER 6—EVALUATION FREQUENCY, p. 20

CHAPTER 7—QUALIFICATIONS OF EVALUATION TEAM, p. 21

CHAPTER 8—REPAIR, p. 22

- 8.1—General, p. 22
- 8.2—Design basis and compliance, p. 22
- 8.3—Repair considerations, p. 23
- 8.4—Design of structural repairs, p. 24
- 8.5—Durability, p. 25
- 8.6—Construction, p. 27
- 8.7—Quality assurance, p. 27

CHAPTER 9—REFERENCES, p. 28

Authored documents, p. 29

CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Recent structural challenges encountered from events such as the observed alkali-aggregate reactions (AARs)/cracking at Seabrook (U.S. Nuclear Regulatory Commission (U.S. NRC) 2011), cracking and chemical attack at Zion (Gregor and Hookham 1993), and the publicized reports of concrete degradation in domestic plants (Gregor and Hookham 1993; Electric Power Research Institute (EPRI) 1990; Ashar and Bagchi 1995) have highlighted the need for guidance on acceptable structural evaluation and repair methods from a code and regulatory viewpoint. These recommendations can be used to evaluate the condition of concrete structures at any point during their service life and following any imposed damage, aging, or loading event. For post-earthquake evaluations, supplemental guidelines and evaluation criteria, such as those discussed in EPRI TR 3002005284 (EPRI 2015a) and International Atomic Energy Agency (IAEA) Safety Reports Series No. 66 (IAEA 2011), should also be considered.

The evaluation process and techniques used in this report have been revised and updated to cover possible scenarios that could be encountered in nuclear safety-related concrete structures, with insights from the state-of-the-practice in the construction industry included as well. This report provides the user with relevant and more up-to-date information on evaluation and repair of nuclear structures with a focus on those that have been deemed nuclear safety-related. Note that this report provides recommendations for performing an evaluation. The responsible engineer and evaluation team should

use engineering judgment in applying these recommendations. Visual inspection is the recommended primary evaluation tool for identification of degradation. A more exhaustive evaluation, using nondestructive examination (NDE) and invasive tests, could be warranted by observations subject to the responsible engineer's evaluation perspective.

1.2—Scope

Chapters 1 and 3 provide the introductory material and general methodology used, respectively. Chapters 4 through 7 and Chapter 9 include new information, expanded coverage, and relevant references for continued research. Chapter 8 provides guidance on the need for repair; use of proven methods, including those recently implemented in specific nuclear plants; and relevant industry references (ACI/ICRI 2013). To ensure that evaluations and any follow-up repairs are properly implemented, it is recommended that the responsible engineer remains in charge throughout the completion of all the tasks up to documentation, including evaluation reports and repair programs as defined herein.

This report supplements the ACI 349 code by presenting a framework for conducting an evaluation and developing any associated repair procedures for nuclear safety-related concrete structures. Before initiating this report, the scope of ACI 349 was self-limited to the design and inspection of newly constructed concrete nuclear structures. As the nuclear power plants in the United States grow older and become susceptible to the adverse effects of aging, their periodic inspection, proper evaluation, and repair have become more important issues. Recent U.S. NRC regulations 10 CFR50.65 and 10 CFR54 (U.S. NRC 2015a,b) require licensees to inspect and evaluate the condition of concrete nuclear structures that may have experienced age-related degradation. Also, following the accident at the Fukushima Daiichi nuclear power plant resulting from the March 11, 2011, Great Tohoku Earthquake and subsequent tsunami in Japan, the NRC established the Near Term Task Force (NTTF) to conduct a review of the NRC processes and regulations, and provide recommendations to the NRC regulatory process to enhance reactor safety. Subsequent to the NTTF findings, the NRC issued a letter under 10 CFR50.54 (U.S. NRC 2015a) on March 12, 2012, requiring owners of every U.S. nuclear power plant to perform seismic (Sezen et al. 2011) walkdowns to identify and address degraded, nonconforming, or unanalyzed conditions, and to verify the current plant configuration with respect to the current design basis and state of knowledge gained since such was prepared on seismic and flood hazards. The evaluation scope herein was tailored to support structural evaluations required by periodic regulatory requests and in support of hazard analyses. Documents including EPRI TR 3002005284 (EPRI 2015a) and NUREG/CR-5042 Supplement 2 (U.S. NRC 1989) should also be considered.

Effective maintenance, modification, and repair of any concrete structure begins with a comprehensive program of inspection and evaluation. This evaluation can include a visual review of previously accomplished repairs, maintenance, and performing condition surveys, testing, maintenance,

nance, and structural analysis. The term “concrete nuclear structure” denotes concrete structures used in a nuclear application, while the term “nuclear safety-related concrete structure” refers to a specific quality classification and a subset of concrete nuclear structures. Although this report was written to provide guidelines for completing an evaluation of nuclear safety-related structures, such guidance can also be used for other similar concrete structures in U.S. Department of Energy (DOE) nuclear facilities/laboratories, Independent Spent Fuel Storage Installations (ISFSIs) licensed under 10 CFR72 (U.S. NRC 2000), or any other applicable structures. The term “plant” is used interchangeably for “nuclear power plants,” and “facilities” is used for DOE facilities and ISFSIs, which comply with the ACI 349 code (for example, Performance Category PC-3 or PC-4 and others defined per DOE Guide 420.1.2 [U.S. DOE 2000]) in the balance of this report.

Nuclear safety-related concrete structures are designed to resist the loads associated with plant operating conditions, postulated accidents, and severe environmental conditions. These structures provide protection for nuclear safety-related components from hazards internal and external to the structure, such as postulated missile impacts, impulsive loads, flooding, fire, earthquakes, and other severe environmental conditions. Additionally, the design for some of these structures can be controlled by the required thickness of concrete intended for shielding against radiation produced during the nuclear fission process. All nuclear safety-related structures share a common function: they are integrally designed with the various systems, equipment, and components they support, and protect to restrict the spread of radiation and radioactive contamination to the general public. An effective evaluation procedure provides a rational methodology to maintain the serviceability of nuclear safety-related structures. Each evaluation should make reference to and preserve the design basis, as defined by the updated final safety analysis report (UFSAR), technical specifications, codes and standards, calculations, drawings, and test records for the affected structure(s) in the disposition of findings and results. This includes qualification of any damage or degradation found, or necessity and suitability of various repair options.

Concrete nuclear structures, while unique in application, share many physical characteristics with other concrete structures. The four basic constituents of a concrete mixture are the same for nuclear or nonnuclear concrete structures: cement, fine aggregate, coarse aggregate, and water. Admixtures that enhance the constructability and durability of concrete are also permitted in nuclear structures, with certain limitations as defined in ACI 349. Nuclear safety-related structures can be similarly reinforced with normal reinforcing steel or prestressing steel, and can contain various structural steel embedments. Over time, operational and environmental conditions and loads can result in degradation of these steel elements and could affect the expected behavior of the structure. Whether the structure is considered nuclear safety-related or not, prudent engineering practices during material (concrete mixture) design

and specification, structural design, and construction should be taken to minimize the potential for degradation during service. The success of such practices, however, is not ensured, given exposure to various events. Sound inspection programs in which the performance and condition of structures are periodically evaluated and monitored can be used to ensure that the structures continue to serve their intended function. Because of the many similarities between nuclear and nonnuclear concrete structures, practices and procedures used for their inspection and maintenance can be commonly used as defined herein.

The purpose and final scope of an evaluation procedure is defined by the owner, utility, holding company, governmental agency, or other organization. Development and implementation of an evaluation procedure for nuclear safety-related structures can serve many purposes, such as:

- a) Provide documented evidence of continued performance and function by periodic evaluation
- b) Identify and mitigate age-related degradation at early stages
- c) Provide guidance for the development of an effective maintenance program
- d) Support the application for an extended operating license
- e) Provide baseline condition data for comparison following an earthquake, a short-term environmental load, or an accident condition
- f) Provide baseline information regarding ongoing deterioration mechanisms so that any change can be identified and monitored
- g) Provide guidance for walkdowns following an earthquake, flood, tsunami, or any other external event
- h) Provide configuration and material property information for structural reanalysis, physical modification, or similar activity

This report identifies a procedure for the determination of critical structures, defines and characterizes the primary degradation mechanisms, provides insight on inspection techniques and frequencies, and provides guidance on the evaluation of inspection results and necessary repair. Herein, the word “repair” is intended to signify a goal to maintain the design basis and extend the service life of an affected structure in a nuclear plant, and encompasses rehabilitation, alteration, and repair actions. The design basis could have been changed since original design and construction in response to specific regulatory compliance requirements, so the most current design basis applies to evaluation and repair.

CHAPTER 2—DEFINITIONS

ACI provides a comprehensive list of definitions through an online resource, “ACI Concrete Terminology.” Definitions provided herein complement that resource.

BWR—boiling water reactor (BWR) is a type of light water nuclear reactor used for the generation of electrical power. In a BWR, the reactor core heats water, which turns to steam and then drives a steam turbine.

degradation—effects resulting from internal material reactions, the external environment, and normal plant operations.

design basis—current licensing commitment for the safety-related concrete structure in question that is comprised of original design calculations, drawings, codes and standards, technical specification, safety analysis report requirements, and as-built construction documents.

drummy area—area where there is a hollow sound beneath a layer of concrete due to a delamination, poor consolidation, or void.

evaluation—an engineering review of an existing concrete nuclear structure with the purpose of determining physical condition and functionality of the structure.

function—the special purpose or activity for which a structure exists or is used.

passive cracks—cracks having an absence of recent growth and an absence of other degradation mechanisms at the crack.

PWR—pressurized water reactor (PWR) is a type of light water nuclear reactor used for the generation of electrical power. In a PWR, the reactor core heats water, which does not boil. This hot water then exchanges heat with a lower-pressure water system that turns to steam and drives the turbine.

rattle space gap—“seismic gaps,” which are commonly referred to as “shake space,” “rattle space,” “construction joint systems,” or “building joint systems,” are part of the overall seismic design of the structure; their principal function is to allow different parts of the nuclear power plant to move independently during an operating-basis earthquake (OBE) or a design-basis earthquake (DBE).

repair—the reconstruction or renewal of concrete parts of an existing structure for the purpose of its maintenance or to correct deterioration, damage, or faulty construction of members or systems of a structure.

visual inspection—assessing the current condition of an accessible existing structure by observation.

CHAPTER 3—GENERAL METHODOLOGY AND EVALUATION PROCEDURE

3.1—General methodology

This report focuses on industry-accepted evaluation practices and recommends the application of those practices to the unique situations typically encountered in nuclear safety-related concrete structures. The objective is to develop a program of inspection and evaluation that recommends the most effective practices for inspection and evaluation of such structures. Through proper inspection and evaluation, the most likely locations for degradation and its causes within the nuclear safety-related structures can be identified. A thorough survey of these critical locations provides data to describe the current physical condition of the concrete, evaluate past structural performance, and form a basis for comparison during future inspections. The responsible engineer, who is the individual responsible for administering the evaluation procedure, can then review the information to

evaluate the severity of the condition. The condition could be acceptable as-is or could require further in-depth examination and evaluation. The owner may opt to monitor the condition over a period of time to obtain more data. In more severe cases, the observed condition could require repair, rehabilitation, or replacement of the affected structure. In each case, the evaluation and ultimate corrective actions are based on interpretation of both qualitative and quantitative information regarding the structure in question.

Recommendations in this report use several established ACI reports on evaluation and repair that are developed for general concrete structures (**Chapter 9**). By implementing established recommendations in typical nuclear plant applications, an effective evaluation procedure can be developed for nuclear safety-related concrete structures. Use of general condition survey (visual inspection), supplemented by additional testing or analysis as required, is a recommended approach for most evaluations.

3.2—Scope

The evaluation of existing nuclear safety-related concrete structures could be required as a result of identified degradation or abnormal performance, in support of physical modifications, or for periodic validation of structural integrity. Comprehensive evaluation of all nuclear safety-related structures at periodic intervals is also desirable to monitor operational effects and possible degradation due to environmental conditions. This chapter describes the procedural steps that can be used to effectively monitor and maintain the nuclear safety-related concrete structures via prioritized evaluation.

An evaluation procedure document should be developed by the owner (3.5). The evaluation procedure should be comprehensive and include provisions for addressing the variety of potential uses, such as those cited in Chapter 1. The two procedural methods of evaluation that can be performed are selective (3.3) and periodic evaluations (3.4). These two methods use similar evaluation tools, such as visual inspections, but are different in terms of scope. The primary components of an evaluation procedure and guidelines for preparing the evaluation procedure document are further discussed in 3.5.

3.3—Selective evaluation

The selective evaluation method is used when an evaluation of a specific structure or structural component is required due to identified issues. The purpose of a selective evaluation is to provide information on a specific structure to serve as input for structural evaluation or subsequent design modification or repair of that structure. When the selective evaluation method is used, the structure in question and the acceptance criteria of the evaluation, such as the required in-place compressive strength and other properties, should be defined based on the design basis. The appropriate evaluation techniques, such as visual inspection and testing, that are used to support the selective evaluation should be defined in the evaluation procedure document. Selective evaluations are typically performed once for a specific purpose and are

generally not repeated unless the initial evaluation indicates a need to monitor certain degradation mechanisms or structural performance over a defined period of operation.

3.4—Periodic evaluation

The periodic evaluation method can be used to demonstrate satisfactory performance of nuclear safety-related concrete structures, to identify the presence and activity of age-related degradation, or for other reasons as noted in [Chapter 1](#). In contrast to selective evaluations, periodic evaluations are not intended to address a specific issue, but rather are employed to determine physical condition and functionality of nuclear safety-related structures with respect to the design basis. Periodic evaluations should be repeated at a certain frequency using a standardized procedure. Evaluation frequency is defined by the owner according to the licensing requirements and design basis in Table 6 of this report. This form of evaluation should provide an effective method for addressing the U.S. Nuclear Regulatory Commission (NRC)-mandated maintenance rule, or for technical justification in a license renewal application for the nuclear plant as a whole. The frequency of periodic evaluations should be established by considering the factors such as accessibility, physical condition, environmental exposure, and tolerance to anticipated degradation ([Hookham 1991](#)). This section discusses the basic criteria for prioritizing and selecting structures for periodic evaluation.

The intent of the prioritization process is to inspect a representative sample of the areas that are most likely to experience some form of degradation, as well as those areas where degradation can be critical to the structural integrity of nuclear safety-related structures. To verify that the selected sample areas are, in fact, representative of worst-case conditions, complementary sample area inspections should be made in areas where little or no degradation is expected. For example, structures primarily located below grade might not be readily accessible for evaluation, but could be exposed to an aggressive environment. Measures can be implemented that establish the condition of these structures through determination of soil and groundwater chemistry and local inspection during opportune soil excavations, such as during new equipment installation. While such efforts are indirect and not comprehensive, they can be used to characterize environmental exposure conditions and their effects to assist in prioritizing further evaluation efforts. Similarly, structures located underwater will not be accessible for evaluation with the same level of visual acuity as structures above water. Measures can be implemented that establish the condition of these structures using divers, dewatering, or remote underwater cameras. The condition of these structures through the inspection of exposed portions of the structures at the waterline and above can serve as a leading indicator of conditions underwater. While such efforts are indirect and not comprehensive, the results can be used to characterize environmental exposure conditions and their effects. The results can also be used to determine whether additional inspections are warranted and to prioritize any further inspection or evaluation efforts. For guidance on investigation and evaluation of

underwater components, refer to [ACI 546.2R](#) and the *ASCE Manual of Practice (MOP 101)*.

Three primary factors pertinent to each structure are common to the prioritization process in periodic evaluation: safety significance, accessibility, and exposure conditions. Safety significance is regulated by the requirements of 10 CFR50 (U.S. Nuclear Regulatory Commission ([U.S. NRC 2015a](#))) and 10 CFR100 ([U.S. NRC 2015c](#))), from which the basic structural function and performance requirements are determined. Certain structures can provide multiple nuclear safety-related functions and are more important to the overall safety. Accessibility considerations dictate the degree to which the structure can be inspected under varying operating conditions and the need for special access requirements, such as excavation, divers and dewatering, and radiation protection. Exposure conditions are related to vulnerability of the structure to chemical, physical, and mechanical attacks due to natural and operating environments, and the microclimate to which each structure and structural component thereof is exposed. Prioritization decisions should be sensitive to any significant changes in these three factors, especially when variations such as multiple environmental exposures occur within the same structure. The following process can be used to prioritize the nuclear safety-related concrete structures for inspection ([Hookham 1991](#)):

- a) List all primary nuclear safety-related structures
- b) Categorize structures by location and accessibility; for example, exposed to external atmospheric conditions or indoors subjected to controlled environment, underwater, and subterranean, provided the surfaces of the structure can be accessed
- c) Identify and list each structural component of each structure by function, such as wall, column, and slab
- d) Identify and evaluate the safety significance of each structure and structural components within each structure and specify the extent of their boundaries, interfaces, and connectivity
- e) Examine the aggressiveness of the operating and environmental exposure(s) and local conditions according to their propensity to promote various degradation mechanisms
- f) Develop a prioritized listing of structures and their structural components for inspection; those most critical to the structural integrity and safety of the plant and those most likely to be exposed to severe degradation conditions should be given the highest priority
- g) Assemble the design basis, including as-built drawings, specifications, design calculations, and other information addressing each structure on the prioritized listing

The number of structures included in a specific evaluation is dictated by the purpose of the evaluation. As an example, it might be necessary to consider the complete listing of structures to support a license-renewal application. For periodic evaluations, all nuclear safety-related structures should be considered in the selection process of the structural components list. Following prioritization and determination of an implementation schedule, the evaluation procedure is applied to the selected structures by the evaluation team. [Chapter 7](#) addresses qualification of the evaluation team.

Activities involved in the evaluation process, including assembling records, confirming design basis, completing a visual inspection, other testing, and preparing the evaluation, should be determined by taking into consideration the degradation mechanisms to which the structure might be exposed. Typically, the initial evaluation activity involves a visual condition survey of exposed surfaces. If subsequently deemed necessary, this survey can be supplemented with other testing or analytical methods with the consideration of factors such as accessibility, radiation exposure, and susceptibility to degradation.

3.5—Evaluation procedure document

The evaluation procedure document should be prepared in accordance with the format for procedure writing, enumeration, and approval process of the plant. As a minimum, the document should identify the following:

- a) Scope and applicability
- b) Description of applicable degradation mechanisms at the plant for periodic evaluations
- c) Evaluation-team qualifications and responsibilities (Chapter 7)
- d) Structures selected for periodic evaluation and reasons for selection (Chapter 3)
- e) Documentation and archival requirements
- f) Approved evaluation methods that will be used, including uses and limitations (3.5) for selective and periodic evaluations
- g) Acceptance criteria (Chapter 5)
- h) Evaluation equipment use and calibration
- i) Frequency of periodic evaluation (Chapter 6)

Detailed information and recommendations for addressing these subjects are found in this report. Plant-specific uses for the procedure should be predefined, and acceptance criteria predetermined and integrated into the evaluation procedure. The evaluation procedure document should also accurately define procedural requirements for conducting either a selective or a periodic evaluation.

One prerequisite activity during the implementation process is ensuring that a qualified evaluation team of engineers and inspectors is assembled. A responsible engineer should be assigned to lead the evaluation team. Qualifications of the responsible engineer should meet the requirements listed in Chapter 7. Each evaluation team member should be familiar with the evaluation procedure document and their responsibilities before conducting an evaluation.

3.6—Evaluation techniques

The various concrete degradation mechanisms (Chapter 4) often produce visible indications, patterns, or features on exposed surfaces during initial manifestation and propagation. Note that experience has indicated that some degradation mechanisms, such as internal cracking due to overstress, can remain internal without showing any signs on the surface of the structure. However, unless there is a compelling basis to evaluate a structure for internal degradation without any external conditions cited in Chapter 5, additional examination and testing might be unnecessary. Overstress can be

caused by various mechanisms such as freezing and thawing or changes in prestress loads. Visible 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 and examination or invasive/destructive testing on samples removed from the structure. The evaluation of suspected low-strength concrete also requires supplemental testing using the methods and process defined in Chapter 20 of **ACI 349-13**. This chapter summarizes the available evaluation techniques, which are also discussed in **ACI 437R**.

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

- a) Visual inspection
- b) Nondestructive examination (NDE) and testing
- c) Invasive testing
- d) Analytical methods

The following as-built design basis information can be requested from plant records to supplement information required for the evaluation:

- a) Structural drawings
- b) Calculations
- c) Design strengths
- d) Mechanical property and strength data from the original construction
- e) Construction testing reports
- f) Minimum cover thickness
- g) Reinforcing bar size and location
- h) Prestressing tendon size and location, and prestress force

The assembly of available information should be completed by the evaluation team; if additional data are required to support the evaluation, these data should also be acquired by the team through testing. Involvement of contractors, as well as the use of NDE or invasive test methods, might only be necessary or appropriate if warranted for certain selective evaluations or investigation of an area of more significant structural degradation. The capabilities and qualifications of the evaluation team and any specialized laboratories or consultants should be in accordance with Chapter 7.

3.6.1 Visual inspection—Visual inspection can provide 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 to which the structure is exposed, and protective coatings review. Visual inspection can be used to define the current condition of an accessible concrete structure in terms of the following:

- a) Extent and cause of degradation
- b) Material deficiencies
- c) Performance of coatings
- d) Condition of concrete cover
- e) Damage from past service loads
- f) Current response to applied loads, as evidenced by vibration, deflection, settlement, cracking, and spalling

Typically, visual inspection is both the initial and primary technique used for any evaluation, supplemented as needed by NDE and other methods. For structures that are primarily inaccessible without the removal of soil or neighboring structures, other preliminary efforts should be considered to characterize the local condition of the structure or its environmental exposure. Those efforts could include soil and groundwater sampling and testing for aggressiveness, and initial test methods such as core sampling and NDE. Selection of other evaluation techniques for further structural evaluation is made after visual inspection results and other data are gathered and evaluated. Commonly used practices and checklists for the visual inspection and condition survey of existing concrete structures are found in [ACI 201.1R](#), [ACI 207.3R](#), and [ASCE/SEI 11](#).

The scope of the visual inspection should include all exposed surfaces identified by the prioritization process; joints and joint material; interfacing structures and materials, such as abutting soil; embedments; and attached components, such as base plates and anchor bolts. These components should be directly viewed (maximum 24 in. [600 mm] focal distance) as practical based on access and radiation limitations. If possible, photographs or video images should be taken of any discontinuities, defects, and significant findings. Comprehensive direct viewing can require the installation of temporary ladders, platforms, or scaffolding. Use of binoculars, fiberscopes, and other optical aids is recommended if needed to gain better access, augment the inspection, or further examine any discontinuities. Such equipment should have suitable resolution capabilities under ambient or enhanced lighting. The condition of surrounding structures should also be observed to better assess the aggressiveness of the operating environment. Observation of possible degradation when using optical aids should be followed up with direct viewing, as noted previously.

Visual inspection also requires the use of equipment for dimensioning and measuring the size of degraded areas. This equipment should be in good working order and either properly calibrated or verified as having the required accuracy. For crack investigations, equipment such as a feeler gauge, optical crack comparator, mechanical movement indicator, and data acquisition system defined in [ACI 224.1R](#) can be used for quantifying width, depth, and extent of the cracking. For crack-length measurement and general dimensioning purposes, an ordinary retractable metal tape should provide the desired accuracy.

Use of the visual inspection technique is limited by the ability to access all surfaces of a structure, as well as the inability to detect fine or internally generated defects. The inability to access all surfaces of a structure reduces the ability to verify the physical condition and the absence of degradation. For structures that are largely inaccessible, such as foundations and lower walls, this situation represents a primary concern for performing a complete evaluation. Evaluation of inaccessible structures is further defined in [Chapter 6](#). In addition, certain degradation mechanisms, such as fatigue, can manifest and propagate within a structure before any visible signs are apparent. For structures exposed

to elevated thermal gradients or restraint, large impactive or impulsive loads, or time-varying vibratory loads, consideration supplementing any visual inspections with NDE or invasive testing (3.6.2 and 3.6.3).

Documentation of visual inspection results should include a general description of observed surface conditions, location or size of any significant discontinuities, noted effects of environmental exposure, and presence of degradation. Sketches, photographs, video recordings, and other means should be used to supplement text descriptions. A reference standard, such as a ruler or crack comparator, should be placed on any structural component before photography or recording to serve as a scaling factor for interpreting the image. If additional testing is required, note any limitations on equipment use.

3.6.2 Nondestructive examination—Nondestructive examination requires special equipment to obtain the desired data. The thick cross sections and large quantities and sizes of reinforcing steel are typical characteristics in nuclear safety-related structure construction. These characteristics limit the effectiveness of many NDE methods; some benefits have been noted through correlation of NDE results to destructively removed samples that have been laboratory-tested. Examples are compressive strength and mechanical properties. The goal of NDE is to provide quantitative information about a structure without removing or damaging any areas of the structure. [Refai and Lim \(1992\)](#) identified the following NDE methods as being potentially applicable to nuclear safety-related concrete structures:

- a) Structure performance evaluation
 - i. Load testing
 - ii. Modal analysis
 - iii. Vibration and structural motion monitoring
 - iv. Settlement monitoring
 - v. Evaluation of prestress loss
- b) Hardened concrete testing
 - i. Acoustic and ultrasonic methods
 - 1. Chain drag or hammer sounding
 - 2. Ultrasonic pulse-velocity
 - 3. Impact-echo
 - 4. Ultrasonic pulse-echo
 - ii. Ground-penetrating radar
 - iii. Infrared thermographic testing
 - iv. Resonant frequency methods such as impact-echo and impulse response
 - v. Surface hardness and strength methods
 - 1. Rebound hammer
 - 2. Penetration resistance (Windsor probe)
 - 3. Pullout
 - 4. Break-off
 - vi. Electrical resistivity
- c) Reinforcement and embedment tests
 - i. Magnetic methods
 - ii. Electrical half-cell potential and polarization resistance measurements
 - iii. Radiographic methods
 - iv. Ground-penetrating radar for reinforcement location
- d) Coating system tests

- i. Adhesion testing
- ii. Holiday testing

Descriptions for each of these methods, including equipment required and application to concrete, are found in a variety of publications (Refai and Lim 1992; Malhotra and Carino 2003; U.S. Army Corps of Engineers 1995; Malhotra 1976; ASTM D5144; ASTM International 1990). In general, performance tests are used to assess the global performance under load and, over time, these test methods have limited application to nuclear safety-related structures because of size, integrated performance of surrounding equipment and structures, and extreme design basis load magnitude. Load testing is permitted by ACI 349 to verify the structural integrity of a structure or structural component. The response of a loaded structure by measurement of its deflection, settlement, or vibratory motion can also provide valuable data regarding past and future performance.

Hardened concrete test methods are used to examine the surface and subsurface concrete condition for the presence of cracking, voids, poor consolidation, and other discontinuities that can affect performance. These test methods are also used to estimate strength (ACI 228.1R). ACI and industry publications given in Chapter 9 document the evolution of these methods into practical tools for the evaluation of a general concrete structure. Continued improvement of equipment, a better theoretical understanding of test methods, and new tools to analyze and process signals received from ultrasonic, radar, infrared, and other methods will increase the value of these techniques for the evaluation of nuclear structures.

Reinforcement and embedment test methods such as electrical half-cell potential and polarization resistance measurements have been developed to aid in the verification of steel location and examination of reinforcement and embedded structural steel for corrosive activity without concrete cover removal (Malhotra and Carino 2003). Although the accuracy of these methods is influenced by a variety of physical effects, they can provide a valuable indication of corrosion activity at an early stage. Magnetic methods also have practical application for determining the size and depth of reinforcement in uncongested areas.

Coating-system tests can be used to assess the durability and condition of protective coatings and linings installed on concrete structures for enhanced protection from the surrounding environment. Although it is not directly a measure of structural integrity, the long-term performance of a structure in an aggressive environment can be contingent on satisfactory coating system performance.

Nondestructive examination techniques for hardened concrete, reinforcement, and embedments, and coating-system tests are oriented toward providing specific information about the material constituents and their condition or the presence of voids and other internal defects, as opposed to verifying overall structural integrity. For example, ultrasonic pulse velocity and other stress wave methods and radar testing can be coupled with visual inspection to examine structures for cracking associated with internal or external degradation mechanisms. The use of multiple testing tech-

niques often increases the accuracy and confidence in the results; the cost of testing is relatively minor compared with the implementation of extensive repair without sufficient knowledge of structural conditions.

There are many limitations associated with the application of NDE techniques to nuclear safety-related concrete structures due to their massive concrete size, large size and congestion of reinforcing bars, limited accessibility due to radiological conditions, reliability of equipment, and interpretation of results. Some test methods also require a representative calibration standard composed of similar materials to conduct the work. Limited published and industry-accepted procedures exist for many of the methods. If NDE is used, significant background and experience with the testing methodology is required. The accuracy and interpretation of the obtained results also requires consideration, which is further discussed in 3.7. Despite these limitations, NDE is often a valuable tool in the evaluation of existing structures.

When NDE is used, the equipment type(s), calibration records, and complete description of application should be noted in the evaluation documentation. The referenced test method (ASTM designation and title) should also be identified, if available, along with the names of testing personnel, date, and complete description of results.

3.6.3 Invasive testing—Invasive/destructive testing techniques require the use of special equipment to obtain the desired data. Invasive testing focuses on the removal of concrete or steel reinforcement specimens from the structure for laboratory testing to determine physical, chemical, microstructural, and mechanical properties or other information from the sample. Generally, this technique is limited to a controlled number of samples to minimize any detrimental effects on the remaining structure. Included in this category are concrete core sampling and follow-on testing such as unconfined strength and petrographic analysis, concrete cover removal and steel reinforcement evaluation, and removal of coatings for laboratory testing. Invasive testing also includes the testing of soil and groundwater chemistry, and other material samples that represent the environment to which a structure is subjected. Of particular interest are the presence and concentration of aggressive chemicals in the environment such as chlorides, sulfates, and other salts, as well as the pH and conductivity of the fluid or solid.

Invasive testing also provides the necessary information to determine the remaining durability of the concrete cover, structural concrete, and steel reinforcement through testing of exposed or removed samples. Factors that are important to concrete durability include permeability, porosity, reactivity among constituents, chloride-ion content, degree of carbonation, and chemically-induced degradation. Factors important to the durability of the steel reinforcement system include electric half-cell potential and polarization resistance, degree of surface corrosion, and permeability of the surrounding concrete (monolithic behavior).

Petrography (ASTM C856) involves the study of removed concrete samples for determination of carbonation, physical condition, uniformity, and presence of degradation

such as microscopic cracking or cement-aggregate reaction. The removal of core samples from a structure could allow the determination of strength via testing and provide a sample for petrographic analysis. For further information on material sampling and petrographic analysis, refer to [ASTM C42/C42M](#), [C823/C823M](#), and [C856](#). Similar to NDE, the number of samples or tests taken and the reliability of the results are also important.

Limitations to the use of invasive testing include the cost for retrieving samples and performing testing; radiological concerns such as sample contamination and personnel exposure during retrieval; limits on testing; local effect of sampling on the structure; and reliability and interpretation of the data obtained from certain tests. Invasive testing, however, provides especially useful data for assessing the ultimate effect of degradation and a baseline comparison for any future testing.

3.6.4 Analytical methods—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. In some cases, it may be necessary to reevaluate the structural capacity of the structure or structural component in question because the design calculations are not available, or the design basis may have been governed by calculations for a physically similar, but different, structure. In general, some form of analysis will be required when any potentially significant degradation is found during the inspection and testing phase. After determining design basis requirements and in-place material properties, a useful analytical exercise for a degraded structure is to perform an independent structural calculation and compare it with the design calculations and as-built records. This exercise can identify conservatism in the design or confirm the need to implement a rehabilitation program.

The role of analytical methods is to evaluate the structural integrity of a structural component in its degraded condition, and to identify any requirements for rehabilitative techniques such as repair, which may include strengthening. In addition, it may be necessary to evaluate the effectiveness of the existing concrete cover in protecting the steel reinforcement system from the environment and fire effects. The acceptance criteria to be used for evaluating the results of a structural analysis should be available from the design codes specified in the design basis and plant licensing documents.

Probabilistic methods, such as a probabilistic risk assessment (PRA) ([ASME RA-S-2008](#)), individual plant examination of external events (IPEEE), and time-dependent reliability analyses ([Mori and Ellingwood 1993](#)) are also useful during an evaluation. In addition, such methods may have already been used that provide access to significant existing data. The conclusions from any of these studies are useful for prioritizing structures and determining the degree of degradation that can be accepted while also meeting functional requirements. Probabilistic concepts are also extremely valuable when limited data are known on the material properties, applied loads, and condition of a structure. [ASTM C823/C823M](#) provides an overview on test sample size determina-

tion in an existing concrete structure to be subjected to NDE and invasive testing methods. Bayesian statistics can also be used to improve the responsible engineer's confidence in the measured results of material properties from a reduced quantity of test data. A summary of this method, which can also be used to reduce the required number of tests, is found in [Bartlett and Sexsmith \(1991\)](#) and [ACI 562](#), which addresses the use of these concepts to support the scheduling of evaluations such as inspection and testing activities.

Analytical methods can also be used in combination with limited invasive testing and NDE to examine the structural capacity of the existing structure on the basis of in-place concrete strength. In-place concrete strength can be higher than considered in the design basis (for example, design calculations), even in the presence of degradation. Another valuable analytical method is load reconciliation. This method involves review of the as-built dead and live loadings applied to the structure to determine its actual loading exposure and reassess the use of the structure in the plant's operation. The results of this in-place review are compared with the design basis (for example, design loads and loading combinations) to identify the presence of strength margins. The margin should ensure that appropriate safety factors are maintained to support the structural function. The balance of the strength margin can be used to justify a limited amount of discontinuities or degradation in the structure.

3.7 Overview—The evaluation and inspection practices noted in the reference documents, such as [ACI 201.1R](#), [207.3R](#), [364.1R](#), [ACI 562](#), and other ACI reports, and appropriate references identified by the evaluation team, should be used in the development of the evaluation procedure document. Ultimately, the acceptance of a degraded or repaired structure should be based on the demonstrated and continued ability to meet the design basis and plant licensing commitments.

The selection and use of inspection and testing methods in the evaluation process should be well established in the evaluation procedure document and carefully planned and implemented. Determination of the type(s) of test method(s), desired accuracy, and quantity and location of inspections and tests should be established on a structure-specific basis. In general, visual inspections and condition surveys for periodic evaluations should involve the viewing of all accessible surfaces of the structure. The scope for selective evaluation may differ. For NDE or other test methods, the use of a statistically significant quantity of tests and adequate test coverage is important in the evaluation of the structures. Where analytical methods are used, an assessment of the accuracy and robustness of conclusions drawn should be included in the evaluation report.

The conditions noted during the visual inspection or use of other evaluation techniques should be classified as acceptable or require further evaluation. This classification should consider the functional and performance requirements of the structure. The recommended acceptance criteria for visual inspection is discussed in [Chapter 5](#). To assist in decision-making, it may be necessary to monitor the condition of a structure.