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Evaluation of Existing Nuclear Safety-Related Concrete Structures

Reported by ACI Committee 349

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This report recommends guidelines for the evaluation of existing nuclear safety-related concrete structures. The purpose of this report is to provide the plant owner and engineering staff with an appropriate procedure and background for examining the performance of facility structures 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 is provided.

Keywords: corrosion; cracking; degradation; inspection; load test; nuclear power plant; reinforced concrete; reinforcement; reinforcing steels; safety; serviceability; structural design; test.

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CHAPTER 1—INTRODUCTION

This report supplements the ACI 349 code by recommending an evaluation procedure for nuclear safety-related concrete structures. Before initiating this report, the scope of ACI Committee 349 was self-limited to the design and inspection of newly constructed concrete nuclear structures. As the nuclear facilities in the United States grow older and become susceptible to the adverse effects of aging, periodic inspection and proper evaluation have become important issues. Recent U.S. Nuclear Regulatory Commission programs such as 10 CFR 50.65, Maintenance Rule,[1] and 10 CFR 54, The License Renewal Rule,[2] require licensees to inspect and evaluate the condition of concrete nuclear structures that may have experienced age-related degradation. Effective maintenance, modification, and repair of any concrete structure begins with a comprehensive program of inspection and evaluation. For this report, evaluation is defined as an engineering review of an existing concrete nuclear structure with the purpose of determining physical condition and functionality of the structure. This evaluation may include a review of previously accomplished repairs or maintenance, and performing condition surveys, testing, maintenance, and structural analysis. This report does not address the evaluation requirements for concrete containment vessels (ACI 359, ASME Section III, Division 2, Boiler & Pressure Vessel Code). The term "concrete nuclear structure" denotes concrete structures used in a nuclear application; the term "nuclear safety-related concrete structure" refers to a specific quality classification and is a subset of "concrete nuclear structures."

Nuclear safety-related concrete structures are designed to resist the loads associated with plant operating conditions, postulated accidents, and environmental conditions. These structures provide protection for 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 may 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 and components they support and protect to restrict the spread of radiation and radioactive contamination to the general public. An effective evaluation procedure should provide the rational methodology to maintain the serviceability of nuclear safety-related structures. Each evaluation should consider the original design basis for the affected structure(s) in the disposition of findings and results. This includes qualification of any damage or degradation found, or 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 non-nuclear concrete structures: cement, fine aggregate, coarse aggregate, and water. Admixtures that enhance the constructibility and durability of concrete are also permitted in nuclear structures, with certain limitations as defined in ACI 349. Nuclear safety-related structures may be similarly reinforced with normal reinforcing steel or prestressing steel, and may contain various structural steel embedments. Over time, operational and environmental conditions and loads can result in degradation of these constituents 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 are necessary to minimize the potential for degradation during service. Sound inspection programs, in which the performance and condition of plant 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 non-nuclear concrete structures, practices and procedures used for their inspection and maintenance are also similar.

The purpose and final scope of an evaluation procedure is defined by the plant 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:

- Provide documented evidence of continued performance and function by periodic evaluation;
- Identify and mitigate age-related degradation at early stages;
- Provide guidance for the development of an effective plant-maintenance program;
- Support the application for an extended operating license;
- Provide baseline condition data for comparison following an earthquake, a short-term environmental load, or a plant accident; and
- 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.

CHAPTER 2—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 safety-related concrete structures. Through proper inspection and evaluation, the most likely locations for degradation and its causes within the plant's safety-related structures can be identified. A thorough survey of these critical locations will provide 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, the individual responsible for administering the evaluation procedure, can then review the information to evaluate the severity of the condition. The condition may be acceptable as is or may require further in-depth examination and evaluation. The plant owner may opt to monitor the condition over a period of time to obtain more data. In more severe cases, the observed condition can require repair, rehabilitation, or replacement of the affected structure. In each case, the evaluation and ultimate corrective actions are based upon interpretation of both qualitative and quantitative information regarding the structure in question.

The recommendations in this report use many established ACI reports developed for general concrete structures (see Chapter 9). By implementing established recommendations in typical nuclear power plant (NPP) applications, an effective evaluation procedure can be developed for nuclear safety-related concrete structures. Emphasis on the use of general condition survey (visual inspection) practices in the evaluation, supplemented by additional testing or analysis as required, is a recommended approach and common theme.

CHAPTER 3—EVALUATION PROCEDURE

3.1—Scope

Evaluation of existing nuclear safety-related concrete structures may be required as a result of identified degradation or abnormal performance, in support of physical modifications, or for periodical validation of structural integrity. Comprehensive evaluation of all safety-related plant structures at periodic intervals is also desirable to monitor operational effects and possible degradation due to environmental conditions. Economics and scheduling concerns, however, can prohibit this level of evaluation. This chapter describes the procedural steps that can be used to effectively monitor and maintain the safety-related concrete structures via prioritized evaluation.[3]

An evaluation procedure document should be developed by the plant owner (Section 3.4). This document 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" and "periodic" evaluations (Sections 3.2 and 3.3, respectively). These two methods use similar evaluation tools, such as visual inspections, but are quite different in terms of scope. The primary components of an evaluation procedure and guidelines for preparing the evaluation procedure document are further discussed in Section 3.4.

3.2—Selective evaluation

The selective evaluation method is used when an evaluation of a specific structure or structural component is needed to provide information such as structural condition data or other input for structural re-analysis or modification design. When the selective evaluation method is used, the structure in question and the desired outcome of the evaluation, such as in-place compressive strength and physical condition, are generally known and predefined. The appropriate evaluation techniques—such as visual inspection and testing—used to support the selective evaluation may be selected from 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.

3.3—Periodic evaluation

The periodic evaluation method can be used to demonstrate satisfactory performance of concrete safety-related structures, identify the presence and activity of age-related degradation, or for other reasons as noted in Chapter 1. It is different from selective evaluation in that specific structure and desired outcomes are generally not defined initially. Periodic evaluations are often repeated at a certain frequency using a standardized procedure. 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 plant. Periodic evaluation can be scheduled by prioritizing the structures in terms of safety significance, environmental exposure, and anticipated tolerance to degradation.[3] This section discusses the basic criteria for prioritizing and selecting structures for periodic evaluation.

The intent of this prioritization process is to inspect a representative sample of the areas most likely to have degraded, and inspect those areas where degradation is critical to the structural integrity of 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 may not be readily accessible for evaluation, but may 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.

Three primary factors pertinent to each plant structure are common to the prioritization process in periodic evaluation: degree of safety significance, location and accessibility, and exposure conditions. Safety significance is regulated by the requirements of 10 CFR 50[1] and 10 CFR 100,[4] from which the basic structural function and performance requirements are determined. Certain structures can provide multiple safety-related functions and are more important to overall plant safety. Location and accessibility dictate the availability to inspect the structure at varying plant operating conditions and the need for special access requirements, such as excavation, and consideration of temporary loads and other conditions. Exposure conditions are related to the aggressiveness of the 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 safety-related concrete nuclear structures for inspection:[3]

- List all primary safety-related structures;
- Categorize structures by location and accessibility; for example, external to plant, internal, and subterranean;

- Identify and list each structural component of each structure by function, such as wall, column, and slab;
- Identify and evaluate the safety significance of each structure and structural component and specify the extent of their boundaries, interfaces, and connectivity;
- Examine the aggressiveness of the operating and environmental exposure(s) and local conditions according to their propensity to promote various degradation mechanisms;
- Develop a prioritized listing of both structures and structural components for inspection. Those most critical to the structural integrity and safety of the plant and those most likely to have degraded should be given the highest priority; and
- Assemble current drawings, specifications, original design calculations, and other information addressing each structure on the prioritized listing.

The number of structures to be included in a specific evaluation is dictated by the specific use. As an example, it may be necessary to consider the complete listing of structures to support a license-renewal application. Following prioritization and determination of an implementation schedule, the evaluation procedure is applied to the selected structures by the evaluation team. Chapter 7 addresses the qualifications of the evaluation team. Typically, the initial evaluation activity involves a visual condition survey of exposed surfaces. This survey can be supplemented with other testing or analytical methods as required because certain structures or structure surfaces have either limited access, exist in high radiation fields, or are susceptible to degradation.

3.4—Evaluation procedure development

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

- Scope and applicability;
- Evaluation-team qualifications and responsibilities (Chapter 7);
- Structures selected for periodic evaluation and reasons for selection (Chapter 3);
- Documentation and archival requirements;
- Approved evaluation methods (including uses and limitations—Section 3.5) for selective and periodic evaluations;
- Evaluation criteria (Chapter 5);
- Evaluation equipment use and calibration; and
- Frequency of periodic evaluation (Chapter 6).

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

One prerequisite activity during the implementation process is to ensure that a qualified team of engineers and inspectors is assembled. The selection of a responsible engineer should also take place. Each evaluation team member should be familiar with the evaluation procedure document and his or her responsibilities before conducting an evaluation.

3.5—Evaluation techniques

The various concrete degradation mechanisms (Chapter 4) 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. The evaluation of suspected low-strength concrete also requires supplemental testing, using the methods and process defined in Chapter 20 of ACI 349. This chapter summarizes the available evaluation techniques. Such techniques are also discussed in ACI 437R.

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.

The following "as-built" 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. These evaluation techniques can be directly used by the evaluation team or coordinated and performed by a subcontracted testing laboratory or engineering firm. The capabilities and qualifications of the selected subcontractors should be in accordance with Chapter 7.

3.5.1 *Visual inspection*—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, and protective coatings review. This technique can be used to define the current condition of an accessible concrete structure in terms of the extent and cause of degradation, material deficiencies, performance of coatings, condition of cover concrete, damage from past service loads, and current response to applied loads, as evidenced by vibration, deflection, settlement, cracking, and spalling. Typically, visual inspection is the initial technique used for any evaluation. 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 sampling, soil testing, and initial test methods such as core sampling and nondestructive testing. 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 contained in ACI 201.1R, ACI 207.3R, and ASCE Standard 11.

The scope of the visual inspection should include all exposed surfaces of the structure; 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 600 mm [24 in.] focal distance), and photographs or video images taken of any discontinuities, defects, and significant findings, if possible. 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.

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, a feeler gage, optical crack comparator, and mechanical movement indicator and data acquisition system (ACI 224.1R) should be used for quantifying the activity, 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.

The 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 thermal effects and time-varying or vibratory loads, consideration should be given to supplementing any visual inspections with nondestructive or invasive testing (as discussed in Sections 3.5.2 and 3.5.3).

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, videotapes, 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 videotaping to serve as a scaling factor for interpretation of the image. In the event that additional testing is needed, any limitations on the use of equipment should be noted.

3.5.2 *Nondestructive evaluation*—Nondestructive examination (NDE) or testing techniques require the use of special equipment to obtain specific data. The nonhomogeneity 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. Refai and Lim[5] identified the following NDE methods as being potentially applicable to safety-related concrete structures:

Structure performance testing (integrity);

1. Load testing,
2. Modal analysis,
3. Vibration and structural motion monitoring,
4. Settlement monitoring,

Hardened concrete testing;

1. Audio and sonic methods,
   a) Chain drag or hammer sounding
   b) Ultrasonic pulse-velocity and echo
   c) Impact-echo
2. Impulse radar techniques,
3. Infrared thermographic testing,
4. Acoustic emission methods,
5. Resonant frequency methods,
6. Surface hardness and strength methods,
   a) Rebound hammer
   b) Penetration resistance (Windsor probe)
   c) Pullout
   d) Break-off

Reinforcement and embedment tests;

1. Magnetic methods,
2. Electrical half-cell potential and polarization resistance measurements,
3. Radiographic methods,

Coating system tests;

1. Adhesion testing,
2. Holiday testing.

Descriptions of each of these methods, including equipment required and application to concrete, can be found in a variety of publications.[5-10] In general, structure performance tests are used to assess the global performance of a structure under load and, over time, these test methods have limited application to nuclear structures because of size, integrated performance of surrounding 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 and also to estimate strength (ACI 228.1R). Numerous ACI and industry publications document the evolution of these methods into practical tools for the evaluation of a concrete structure. (See references listed in Chapter 9.) Continued improvement of equipment, a better theoretical understanding of test methods, and new tools to analyze and process signals received from sonic, radar, infrared, and other methods will increase the value of these techniques for the evaluation of nuclear structures.

Reinforcement and embedment test methods have been developed to aid in the verification of steel location and examination of reinforcement and embedded structural steel for corrosive activity without cover concrete removal.[6] 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 noncongested 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.

The nondestructive 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, 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 techniques 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 size; large-size reinforcing bars; limited accessibility due to radiological conditions, expense, and reliability of equipment; and interpretation of results. Some test methods also require a representative calibration standard comprised of similar materials to conduct the work. Limited published and industry-accepted procedures exist for many of the methods listed. If NDE is used, significant background and experience with the testing methodology is required. The accuracy of the obtained results also requires consideration; further discussion of this topic is contained in Section 3.5.5. In spite of these limitations, NDE is often a valuable tool in the evaluation of existing structures.

In the event that 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.

3.5.3 *Invasive testing*—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. Generally, this technique is limited to a controlled number of samples to minimize any detrimental effects on remaining structural performance. 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, groundwater, 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, and the pH and conductivity of the fluid or solid.

Invasive testing also provides information needed to determine the remaining durability of the cover concrete, structural concrete, and steel reinforcement through testing of exposed or removed samples. Factors 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[11] involves the study of removed concrete samples for carbonation depth, physical condition, uniformity, and presence of degradation, such as microscopic cracking or cement-aggregate reaction. The removal of core samples from a structure can allow the determination of strength via testing and provide a sample for petrographic analysis. Further information on material sampling and petrographic analysis is contained in ASTM C 42, C 823, and C 856. Similarly to NDE, the number of samples or tests taken and reliability of the obtained results are also important.

Limitations to the use of invasive testing include the cost for retrieving samples and performing testing, radiological concerns (contamination of samples) during retrieval and 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 and reliable data for assessing the ultimate effect of degradation and provides a baseline for comparison in any future testing.

3.5.4 *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. Structural re-analysis techniques, which use strength-design provisions that have been added to ACI 349 since the original design phase of many existing plants may also be used. 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. After determining design-basis resistance 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 original. 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 strengthening or repair. In addition, it may be necessary to evaluate the effectiveness of the existing cover concrete 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, such as ACI 349 and ASCE 43, specified in the plant licensing documents.

Probabilistic methods, such as a probabilistic risk assessment (PRA), Individual Plant Examination of External Events (IPEEE), and time-dependent reliability analyses[12] can also be useful during an evaluation. In addition, such methods may have already been used at the specific plant. The conclusions from any of these studies are useful for prioritizing structures and determining the degree of degradation that can be accepted while 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 C 823 provides an overview on test sample size determination in an existing concrete structure to be subjected to nondestructive and invasive testing methods. Bayesian statistics can also be used to improve the engineer's confidence in the measured results of material properties from a reduced quantity of test data. A summary of this method, which may also be used to reduce the required number of tests, is contained in Reference 13. Chapter 6 addresses the use of these concepts to support the scheduling of inspection and testing activities.

Analytical methods can also be used in combination with limited invasive testing 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 original design calculations, even in the presence of degradation. Another valuable analytical method is load reconciliation. This method involves the 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 original 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.

3.5.5 *Summary*—The evaluation and inspection practices noted in the reference documents, such as ACI 201.1R, 207.3R, and 364.1R; other ACI reports; and other appropriate references identified by the responsible engineer 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 original and current 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 also occur on each structure 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.

The conditions noted during the visual inspection or using other evaluation techniques should be classified as acceptable or requiring further evaluation. This classification should consider the functional and performance requirements of the structure. The recommended acceptance criteria for visual inspection are in Chapter 5. It may be necessary to monitor the condition of a structure over a short period of time (less than 1 year) to assist in decision-making.

All significant findings and their classification and treatment should be reviewed by the responsible engineer in the form of an evaluation report. The evaluation report should identify:

- The structure(s) involved;
- Summarize the procedural activities performed (Section 3.4);
- Results of any inspections and testing;
- Acceptance criteria used for comparison;
- Summary of the evaluation conducted;
- Evaluation team members participating;
- Responsible engineer;
- Applicable dates; and
- Final disposition(s).

The format for the report should be defined in the evaluation procedure document. Any photographs, video images, test data, calculations, or other supporting data used should also be attached. Evaluation reports and inspection records should be compiled in accordance with plant engineering procedures and ACI 349, and maintained for the life of the plant.

CHAPTER 4—DEGRADATION MECHANISMS

4.1—General

The term "degradation mechanism" or "age-related degradation mechanism" is defined to be any internal or external effect that can reduce the load-carrying ability or function of the material or structure over time. This definition applies to effects produced by internal material reactions, the external environment, and normal plant operations. The effects of fires, pipe breaks, environmentally produced missiles, or other excessive short-term loads or events are not considered in this report, but these effects can also degrade exposed structures. The manifestation of aging and degradation results in physical discontinuities and reduced performance in the affected structure. The acceptance criteria for these discontinuities are given in Chapter 5.

Table 4.1—Degradation mechanisms for concrete

Abrasion/erosion
Chemical attack
Thermal exposure
Fatigue
Cement-aggregate reaction
Freezing-and-thawing cycling
Irradiation
Leaching
Volume changes
External loads
Fire damage
Steam impingement
Settlement

Table 4.2—Degradation mechanisms*

Corrosion
Fatigue
Thermal stresses
Irradiation

*For steel reinforcement, structural steel, and stainless steel components.

Table 4.3—Degradation mechanisms for prestressing steel

Corrosion
Stress corrosion and embrittlement
Loss of prestress
Thermal effects
Irradiation

The severity of the degradation can range from aesthetic degradation to complete structural failure. Those mechanisms that produce rapid loss of material, strength, or other performance function are obviously of greatest importance. These mechanisms and their most common locations are cited in this report. To date, the documented effects of concrete degradation in U.S. nuclear power plants has been limited to local conditions and problems.[3,14-17] The potential for age- or operations-related degradation occurrence increases with increasing plant age. Mechanisms that have been cited as having the greatest threat to long-term performance include steel reinforcement corrosion, sulfate attack of concrete, leaching and cement-aggregate reactions in the concrete, and corrosion or loss of prestress in prestressed-concrete systems.[3] The primary concern for safety-related structures is their ability to withstand extreme design-basis events given the presence of degradation during their service life.

Safety-related structures in nuclear concrete construction can comprise the following noninclusive list of constituents:

1. Concrete:
   a) Normal-density aggregate concrete;
   b) High-density aggregate concrete; and
   c) Grout, mortar, shotcrete.
2. Steel reinforcement:
   a) Deformed bars;
   b) Plain bars;
   c) Welded-wire fabric; and
   d) Structural steel embedments, mechanical splices, and supplementary steel.
3. Prestressing steel:
   a) Tendons (strand or wire);
   b) Bar stock anchors;
   c) Rock anchors;
   d) Stressed anchorages (such as buttonheads); and
   e) High-strength bars.
4. Structural and stainless steel:
   a) Structural shapes, piping, and plate;
   b) Anchor bolts, studs, and inserts;
   c) Liner plates; and
   d) Metal decking.
5. Other materials:
   a) Waterproofing, liners, and waterstops;
   b) Embedded components (such as piping, drains, and conduit); and
   c) Caulking, sealants, and protective coatings.

Each of the constituents listed above can be influenced by various mechanisms of degradation. Tables 4.1, 4.2, and 4.3 which are based on constituent type, have been identified as being plausible within nuclear power plants.[14,16] These mechanisms can act singularly or more commonly in combination with one another.

Many of these potential degradation mechanisms are common to concrete structures in other industries. Experience with the effects of these mechanisms has led to inclusion of special design and construction provisions to prevent or limit their occurrence. Knowledge of mechanism behavior, appearance, and susceptible locations within the plant structures, however, are important to the evaluation of structural performance and condition. Other plant-specific conditions, such as performance of rock anchors, cathodic protection influences on durability, and behavior of foundations should also be acknowledged. This chapter briefly addresses degradation effects. Each section also cites appropriate references that describe the specific degradation mechanism in further detail.

4.2—Concrete degradation

4.2.1 *Abrasion and erosion*—Abrasion and erosion are produced by mechanical contact, exposure to flowing water or particulates, or vapor bubble implosion on exposed surfaces (cavitation). The primary result is material loss, which may be gradual over time or enhanced by short-term events such as floods.

Abrasion commonly occurs at a local area on the surface area rather than over the complete cross section. Common sources of abrasion include vehicular traffic, traversing of heavy loads, and material handling systems. Locations where abrasion is likely at nuclear facilities include floors and walls surrounding major equipment that is frequently dismantled for maintenance, general floor slabs in aisleways, radioactive waste management building floors and slabs, steam turbine and generator laydown areas, and other locations where heavy loads are handled, such as trackways.

Erosion occurs as a result of a flowing medium acting upon the surface of a concrete structure (ACI 210R). Within nuclear power plants, structures where erosion has been observed include hydraulic structures (water intake and discharge structures), guide and diversion structures located within the cooling water source, near leaking chemical addition pumps and equipment, and site-specific structures located along steep embankments.

Visible signs of abrasion and erosion typically include worn protective coatings and loss of cover concrete in either an uneven or a locally well-defined pattern. The rate of attack is highly related to the aggressiveness of the contacting fluid or solid and its frequency (continuous or discrete pattern). The geometry of the material loss and the maximum and average depths should be documented to allow proper evaluation. Observed damage to steel reinforcement or structural concrete, resulting from coating and cover concrete loss, should also be identified and evaluated.

4.2.2 *Chemical attack*—Chemical attack can occur due to exposure to aggressive groundwater; acidic rain or condensation; seawater or salt spray; or exposure to acids, caustics, and other materials. The effects of chemical attack vary but generally include staining, erosion, degradation of the concrete matrix, cracking, and spalling. Often, the chemicals corrosively attack the steel reinforcement and other embedded items. Water-treatment chemicals; acidic compounds, such as boric acid; seawater; and sulfates in the groundwater or soil are particularly aggressive. Areas that are susceptible to chemical attack include hydraulic and below-grade structures, floor slabs in water-treatment system areas, and external vertical and horizontal surfaces exposed to condensation.

As noted, manifestation of chemical attack often occurs as loss of concrete cover accompanied by staining and cracking or spalling. The visual survey should quantify the effects of damage, including any steel reinforcement corrosion, and identify possible sources and composition of the aggressive chemical. ACI 515.1R contains a chart that is useful in the evaluation of the chemical effects on concrete, rate of attack, and proper method for mitigating exposure.

4.2.3 *Thermal exposure*—Production and handling of the steam and nuclear fission process generate large thermal loads on nuclear plant components. Sustained exposure of concrete to temperatures over 150°C (300°F) or to numerous hot-cold cycles can cause a loss of mechanical properties and result in cracking.[18,19] Key locations in nuclear power plants include hot process and steam-piping penetrations, reactor and nuclear-steam-supply system (NSSS) shield walls, steam-driven equipment pedestals, locations in the turbine building near high-temperature piping, structures inside primary containment, and certain operating equipment supports.

The visual survey should carefully identify the geometry of observed cracking and spalling and the presence of other damage, including staining and deflections. Crack widths should be measured at the surface using feeler and crack gages, and should account for local widening due to abrasion or other effects. Crack depths should also be quantified through measurement, inspection of the structural component, or estimation. If possible, the surface temperatures of the concrete and surrounding components should be measured using infrared thermography, a contact pyrometer, or thermometer.

4.2.4 *Fatigue*—Fatigue is produced by periodic applications of load or stress by means of mechanical, thermal, or combined effects. Fatigue loading can be characterized as high-cycle/low amplitude, such as vibration from operating equipment, or as low-cycle/high amplitude, as at crane supports. Concrete is quite resistant to the effects of repetitive loads, but under certain vibration patterns can suffer loss of mechanical properties and cracking (ACI 215R). The most likely location for fatigue effects in nuclear structures is under rotating or vibratory equipment or vessels. Typical structures experiencing fatigue loadings include the NSSS support pedestal, pump foundations, and local surfaces at pipe-support attachments.

Fatigue in concrete often initiates as microscopic cracking at the steel reinforcement-to-concrete interface. Propagation of these fine cracks to the surface occurs with time, and the accumulated damage reduces mechanical properties. The visual survey should quantify any observed damage in the affected structure and nearby structural components, such as cracked grout. The amplitude and frequency of the applied load should be established using the appropriate instrumentation.

4.2.5 *Cement-aggregate reactions*—Three types of expansive reactions have been documented in concrete between the highly alkaline cement and certain types of reactive aggregates: alkali-silica reaction (ASR), alkali-carbonate reaction (ACR), and the less-common alkali-silicate reaction. Such reactions typically result in concrete paste expansion, cracking, and loss of strength (ACI 201.2R and 221.1R). The rate of each of these mechanisms depends on the structure's surface exposure to moisture. ASR has been the most prevalent reaction, although no occurrences of ASR have been documented for nuclear safety-related concrete structures in the United States. The possibility for such reactions has been recognized for some time. Most utilities and owners have checked for the presence of reactive aggregate before construction by using ASTM standard tests or have used pozzolans or ground granulated blast-furnace slag in the concrete mixture proportion to avoid or reduce these effects. The accuracy of these reactive aggregate tests and the potential for sudden occurrence after long-term performance have been identified as possible problems.[20] Key locations for this effect include any structure periodically exposed to moisture, condensation, or the natural environment in combination with structures constructed of concrete containing an abnormally high alkali content or potentially reactive aggregate without mineral admixtures.

Manifestation of cement-aggregate reactions is generally in the form of one or more of the following: significant surface aggregate popouts, patterned crack formations in the cover concrete, and discolored rings around the reactive aggregates upon examination using petrographic techniques (ACI 201.1R). Original construction records can be useful to assess the presence of aggregates that have been determined to be reactive.

4.2.6 *Freezing and thawing*—The effects of freezing and thawing in concrete can be quite damaging at a critical saturation level. For nuclear plants located in weathering regions (as defined in ASTM C 33), cycles of freezing and thawing can be of some concern for externally exposed structures. The key factors involved include concrete properties, such as water-cementitious materials ratio (*w/cm*), entrained-air void size and distribution, aggregate type and strength, and environmental factors such as number and severity of freezing cycles and supply of critical moisture levels. Very little damage has been reported in safety-related structures as a direct result of cycles of freezing and thawing.[14] This performance record is likely the result of prudent materials selection, concrete testing, quality control, and structural design. Degradation from freezing-and-thawing cycles initiates as scaling and cracking in the cover concrete. Propagation results in steel reinforcement exposure, loss of structural concrete section, and loss of bond between the concrete and the reinforcement. Wedging effects from freezing of condensation in surface irregularities, such as popouts, joints, and anchor bolt sleeves, are also a local possibility.

The visual survey should quantify the degree of scaling and cracking, including the affected surface area and depth of damage. Any contributing factors, such as surface geometry supporting ponding of moisture or lack of air entrainment, should also be documented.

4.2.7 *Irradiation*—Concrete structures located within the primary containment of a light water reactor can be subjected to fairly high levels of gamma and neutron radiation, the intensity of which is typically characterized by the measure of its field or fluence. Both forms of radiation tend to produce internal heating and, at high fluence levels, loss of certain mechanical properties (for example, compressive strength and modulus of elasticity) and cracking. Critical, cumulative fluence levels from historical testing results[21] are 1×10^{25} neutrons/m^2 and 10^{10} rad (gamma dose). A limit of 1×10^{17} neutrons/m^2 fluence is recommended for preventing any lifetime radiation-related degradation. The most likely location for irradiation degradation exists in the primary reactor and sacrificial shield walls, proximate to the reactor core, structures near the reactor coolant piping nozzles, and reactor vessel support structures. Other safety-related concrete structures are likely to be subjected to below-critical fluence and dose levels.

The most likely visible effect of irradiation degradation is in the form of concrete cracking. Any suspected damage from this mechanism will require material sampling and laboratory testing for verification of the properties of the concrete in the affected portion thereof.

4.2.8 *Leaching*—Exposure of concrete to flowing or penetrating water can result in the leaching of certain salts, including calcium hydroxide, from the concrete paste. If this leaching progresses without mitigation, the leaching process can produce a loss of mechanical properties, such as compressive strength and modulus of elasticity. Because exposure to moisture or other fluid is required to produce leaching, the structures most likely to be influenced are those located below grade, those used to convey water (hydraulic structures), support water storage (tanks), or those exposed to a large hydrostatic head. Leaching typically results in staining of the cover concrete in the form of efflorescence, which is generally white in color and consists of removed hydroxides and salts, at the affected area or crack boundary. Leaching is a concern for potentially increasing the exposure of steel reinforcement to corrosion cell formation and for reducing the compressive strength of concrete.

Leaching often occurs at locations of high moisture penetration and flow, such as cracks. Leaching effects have been locally observed at nuclear power plants, and have prompted the initiation of a research program,[22] that identified the depletion of calcium hydroxide, increasing the porosity of the concrete to a depth of 3 mm; leaching of calcium silicate and aluminate hydrates together with alkali cations was also reported, contributing to an increase of porosity up to a depth of 9 mm. The visual survey should identify any contributory effects, the coloration and consistency of leached material, the presence of groundwater or other fluid, and any local damage evident in the affected concrete.

4.2.9 *Volume changes*—Moisture loss during the initial drying process and the hydration of concrete result in volume changes. Creep, shrinkage, and autogenous volume change may be significant in safety-related, mass concrete structures due to their massive size, influence of liner plates, applied load, and other effects, such as construction sequence. Although most design codes and reports contain provisions (with reference to ACI 209R) to limit the net effect, significant volumetric changes can still result. The effect of volume changes commonly results in the occurrence of cracking or component deflection. Volume changes in prestressed construction should be considered at the design phase to account for losses in the prestressing steel forces. Volume changes can occur in any safety-related structure; any severe effects, other than long-term creep effects, are usually dominant and noticeable during the early life of the structure.

4.2.10 *External loads*—Degradation can result from loading conditions generated external to the safety-related structures. These loads can be from environmental conditions, such as earthquakes, hurricanes, floods, and tornadoes, or abnormal operations such as pipe breaks, water hammer effects, or missile impacts. Although these effects are all considered in structural design, some degradation can result due to such loading. Primary damage will be concentrated in the cover concrete, although internal structural degradation can also occur.

4.2.11 *Fire damage*—Fires within the protected area of a nuclear plant can produce locally severe thermal stresses on exposed concrete structures. Any degradation is typically in the form of staining, spalling, and cracking of the cover concrete, unless the exposure time or generated temperature values are excessive. Even relatively minor fires will typically degrade any exposed coating systems, necessitating replacement. Additional information regarding the effects of fire on concrete structures and structural behavior is contained in ACI 216R.

Visible damage in the exposed concrete should be both quantified and described in terms of degree of surface staining, damage caused by neighboring or constraining equipment and structures, and degree of cracking, spalling, and deflection. More severe fires and thermal exposure can produce differential expansion between the steel reinforcement and concrete and the loss of bond between the concrete and the reinforcement. Explosive spalling of the heated outer concrete in layers from differential temperature and the formation of compressive stresses in concrete, or from the vaporization of moisture (expansion) in the cover concrete could also occur.

4.2.12 *Steam impingement*—Leakage from steam-filled vessels or piping can produce local steam impingement on the adjoining concrete structures. The typical effect is discoloration and subsequent erosion of the cover concrete, with propagation of damage likely if the steam source is not arrested. Similarly to the case of abrasion and erosion, the cause of material loss and its depth should be investigated in the visual survey.

4.2.13 *Settlement*—Although differential settlement is not an aging effect, it is still a time-dependent mechanism deserving consideration. Settlement of a structure occurs as a result of subgrade consolidation or movement of soils upon which the structure is founded or, in the case of a dynamic event such as an earthquake, the liquefaction of the soils. Provisions for a limited amount of settlement are generally taken into account at the design phase based on predicted soil behavior; such settlements typically manifest themselves within the first three years of the service life. An error made in the design or construction phase of a structure could result in excessive settlement. Although not widespread, soil settlement has caused significant problems within the nuclear power industry and was a primary factor in the discontinuation of a midwestern nuclear power plant during its final construction stages.[14]

Ongoing settlement can be observed in the form of active structural cracking, differential movements between the exterior and interior structural components of a building, or in the behavior of piping systems passing between the affected and adjacent structures. Settlement can be measured by periodically using land-surveying techniques and permanent elevation markers in the plant buildings. The occurrence of excessive settlement (beyond design basis) represents a potentially significant time-dependent aging mechanism, which can require large capital investments to resolve.

4.2.14 *Tendon grease leakage effects*—Leakage of protective grease from prestressing tendon ducts has been observed at several nuclear plants.[15,23] These leaks are commonly found near tendon end anchorages, often emanating through cracks that pass through the cover concrete from the tendon duct. Although ACI 515.1R indicates that paraffin and petroleum-based and organic fluids (other than acids) have little effect on concrete, the effect of long-term exposure on behavior is not well documented. Loss of tendon grease also signals the potential for tendon exposure to a locally aggressive environment. Little research has been performed to determine the acceptability of grease leakage and whether it is a primary concern to concrete or tendon materials.

4.3—Steel reinforcement and structural steel degradation

4.3.1 *Corrosion*—Corrosion of carbon steel reinforcement and embedded structural shapes is of concern in any reinforced concrete structure (ACI 201.2R, ACI 222R). Corrosion can cause a loss of the load-carrying capacity in a concrete structure, which could lead to brittle response. Although the design codes contain provisions to control or prevent steel reinforcement corrosion, such as sufficient cover thickness and crack control, certain environmental conditions can promote corrosion cell formation. For steel reinforcement corrosion to occur, several events must take place to alter the protective influence of the surrounding concrete. These include an increase in concrete permeability, the carbonation of concrete, the penetration of chloride ions, the diffusion of oxygen to support the corrosion cell, and presence of an electrolyte (water). Should significant levels of chlorides, acids, or other aggressive materials be present, the rate of corrosion can be accelerated. Corrosion from microbiological attack is also possible, especially where moisture stagnates on the surface of a structure for an extended period and within intake and discharge structures continuously exposed to water-bearing living organisms.[24,25] The initial stage of corrosion often produces cracking, spalling, and staining in the surrounding concrete. Steel reinforcement corrosion also occurs in combination with other degradation mechanisms in concrete. For corrosion of structural embedments and anchorages to occur, an initial breakdown of the applied coating system on the exposed surface usually occurs. The causes for corrosion of the exposed steel portions are similar to those noted for steel reinforcement.

Visual inspection, coupled with nondestructive testing methods, such as half-cell potential testing (ASTM C 876), can be used to determine whether corrosion is active and influencing the structural materials. The visual survey should identify the source of any staining or corrosion-related activity and the degree of damage. Exposed steel reinforcement, corroded anchorages and embedments, severe staining, or suspected loss of monolithic behavior should be further evaluated with other testing methods.

4.3.2 *Fatigue*—Fatigue degradation of steel reinforcement depends on the surrounding concrete. The result of large repeated or cyclic loads on a reinforced concrete structure typically results in microscopic cracking (cracks less than 0.03 mm [0.001 in.] wide) of the concrete and loss of bond between the concrete and steel reinforcement. There have been few documented cases of steel reinforcement fatigue failures in reinforced concrete components, and those published have been produced by high-cycle, high-stress combinations. ACI 215R notes that the lowest stress range known to have caused a straight bar fatigue failure is 145 MPa (21 ksi), after 1,250,000 cycles on a beam containing a No. 36, Grade 420 (No 11, Grade 60) bar when the minimum stress level was 121 MPa (17.5 ksi). Safety-related structures exposed to repeated loads include NSSS equipment supports, rotating equipment pedestals, and crane-support systems. Because the safety-related concrete structures are designed for low-probability/high-consequence loadings, degradation due to fatigue is unlikely. Highly visible signs of this mechanism are not likely to be reflected in the cover concrete until major damage has occurred.

4.3.3 *Thermal effects*—Although unlikely, the steel reinforcement and embedments in certain safety-related structures can be adversely affected by operating temperature exposure. Data from testing[19,26] have indicated that, for temperatures up to 200 °C (400 °F), the yield stress can be reduced by 10%; and that, above 500 °C (1000 °F), this mechanical property losses approach 50%. A threshold temperature of 300 °C (600 °F) for bond loss events has also been documented.[18] Because these temperatures exceed ACI 349 (Appendix A) recommendations by a large margin, steel degradation from thermal effects should be negligible if operating exposures are properly maintained within technical specification limits. For locally high temperatures, such as around NSSS equipment and certain high-energy pipe penetrations, verification of surface temperatures should be performed. Visible signs of this mechanism will not be present, except for paralleling damage in the cover concrete.

4.3.4 *Irradiation*—Neutron irradiation produces changes in the mechanical properties of carbon steel (increase in yield stress and rise in the ductile-brittle transition temperature). As a consequence, steel reinforcement exposed to high cumulative neutron fluence (above 1×10^{24} neutrons/m^2)[27,28] can experience reduced ductility. Based on generic light water reactor (LWR) data, the only steel reinforcement likely to receive this fluence is the inner layer of bars in the primary shield wall (biological shield) and sacrificial shield wall around the reactor vessel. The fluence on outer steel reinforcement in this wall is also attenuated by cover concrete that is present. Gamma radiation exposure at high doses is not considered to have a high probability of occurrence, and any effects are likely to be very localized. Visible signs of this mechanism will not be present, except for corresponding damage in the cover concrete.

4.4—Prestressing steel degradation

4.4.1 *Corrosion*—Similarly to steel reinforcement, prestressing steels can experience corrosion from chemical contamination of the corrosion-inhibiting system (inside post-tensioned tendon ducts) or reduction of the protective behavior of surrounding concrete (pretensioned). The corrosion of prestressing steels is discussed in ACI 222.2R. Most prestressing steel corrosion failures have been the result of localized pitting, stress corrosion, hydrogen embrittlement, or a combination thereof.[3] General surface corrosion is also a potential problem. Because this reinforcement is continuously stressed, any corrosion can be detrimental to the integrity of the affected tendon. Most reported cases of prestressing steel corrosion are from commercial structures, such as parking decks. For corrosion to occur in a safety-related structure, the presence of moisture, chlorides, or other aggressive material is necessary. Few reported corrosion events have been documented in safety-related structures,[14,15] although the population of noncontainment structures reinforced with prestressing steel is quite small.

Visible signs of corrosive activity in anchorage components, cover-concrete cracking oriented along tendon spans, and observed corrosion or duct water in tendons removed for inspection all require additional testing for disposition. Corrosion of grouted tendons will generally require degradation of the cover concrete before damage is suspected, unless formal testing is used to identify corrosion.

4.4.2 *Stress corrosion cracking and hydrogen embrittlement*—Stress-corrosion cracking (SCC) occurs when a normally ductile metal is exposed to a specific corrosive environment and cracks either transgranularly or intergranularly while under tensile stress (imposed or residual). SCC in prestressing steel systems (high-hardness steel) can occur as a result of chemical attack and corrosion of the tendon or other prestressing system component. Failure of the prestressing system component is often sudden (brittle), with little material loss, and often without warning. Most prestressing steel failures from SCC have occurred in parking garages, bridge structures, and concrete tanks.[3,14]

Hydrogen embrittlement is another form of brittle attack on prestressing steels. This mechanism is caused by the presence of hydrogen at the surface of the tendon, either from hydrogen-sulfide solutions, an inclusion or impurity in the tendon steel, or from hydrogen emitted from a chemical reaction or on-going general corrosion process. Hydrogen-embrittled areas typically fracture in a brittle fashion.

There have been no occurrences of brittle fracture from these mechanisms in a nuclear safety-related structure (other than containment vessels).[3,14] The most likely locations for occurrence of SCC or hydrogen embrittlement would be at tendon jacking points or other locations of relatively high-stress concentration. Additional testing and evaluation is needed to confirm the presence of these mechanisms, unless complete tendon failure is discovered during a planned inspection.

4.4.3 *Loss of prestress*—Loss of prestress is considered during the design phase, with provisions taken to ensure that the design prestressing forces are maintained throughout the life of the structure. The primary contributions to loss of prestress are friction, slippage or deflection during anchorage, elastic shortening, tendon relaxation, and creep and shrinkage of the concrete.[29] Friction losses occur due to curvature of the tendon, wobble of duct, friction in the tensioning jack, and friction at the anchorages. Anchorage slippage occurs during tensioning where slipping of wedges and shims or deflection of the bearing components can occur. Losses due to elastic shortening are related to the compressive strain in the concrete taking place at the transfer of prestress to the concrete. Tendon relaxation is defined as the loss of stress in the steel at constant strain (elongation). Relaxation is related to material properties, initial stress level, operating temperature, and time. Creep and shrinkage of concrete represent volume changes in the hardening concrete and are separately addressed. Of these, anchorage slip and elastic shortening generally occur at, or shortly after, the installation of the tendon.

The prestressing used in safety-related structures has generally been of the post-tensioned variety. The use of prestressing has not been extensive; hence, minimal performance data exist. Loss of prestress without other related effects, such as corrosion, generally occurs slowly over time. No data exist regarding experience with loss of prestress in safety-related structures, other than that for containment vessels.[15,30] Such losses, however, are a potential degradation mechanism in noncontainment structures if they exceed design-basis acceptance limits. In general, additional testing and evaluation would be required to detect any abnormal relaxation or losses. One potential test for measuring steady-state tendon stress, provided end anchorages are accessible, is the lift-off test.[30] This test measures the force required to lift the tendon anchorage from the bearing plate, often by use of hydraulic jack with a calibrated pressure gage or with a load cell. This force can be used to estimate the level of prestress in the specific tendon at the time of testing.

4.4.4 *Thermal effects and irradiation*—These degradation mechanisms were previously described in Sections 4.3.3 and 4.3.4. The threshold levels for these mechanisms in both prestressing steel and steel reinforcement are similar in magnitude. The limited application of prestressing steels in noncontainment concrete structures and their typical location away from the NSSS equipment, however, reduces the potential for degradation from these effects. Certain plant-unique cases can exist where these mechanisms may need to be examined.

CHAPTER 5—EVALUATION CRITERIA

This chapter provides recommended guidelines for the treatment of conditions or findings that might result from an evaluation. These guidelines focus on common conditions that have a higher probability of occurrence and are not meant to be all-inclusive. These criteria primarily address the classification and treatment of visual inspection findings, because this technique will have the greatest usage. The guidelines are presented in a three-tiered hierarchy as shown in Fig. 5.1. Certain conditions are considered acceptable if their dimensions or observed effects are not severe and they are within first-tier limits. For observations exceeding the initial first-tier quantitative limits (Section 5.1), further evaluation is needed to determine acceptability. Observations exceeding a second-tier set of quantitative limits (Section 5.2) require further technical evaluation and analysis to validate the existing condition or repair to preserve structural function. Section 5.3 provides recommendations for classifying conditions of greater severity. The evaluation team should be able to distinguish between relevant findings and insignificant conditions; application of this tiered approach will assist in such determinations.

The evaluation team should document and quantify observed surface conditions for comparison with the evaluation criteria listed in this chapter. In general, the visual evaluation criteria serve as a means to focus on present conditions that need further evaluation and are listed as maxima. Cracking or other conditions that are actively growing in size over time should be further evaluated as noted in Section 5.3. In the absence of any previous inspection information about a concrete structure, the first-tier evaluation criteria in Section 5.1 should be used to determine whether the surface condition requires further evaluation under Sections 5.2 or 5.3. If subsequent inspections indicate that the observed condition is inactive, then only those locations exceeding second-tier evaluation criteria need to be considered for further evaluation under the provisions in Section 5.3. The evaluation criteria for visual discontinuities and various test methods, such as for passive crack width, were derived from an industry review[31] of publications from various organizations.

The first-tier evaluation criteria represent general quantitative limits of observed surface conditions developed for the wide range of nuclear safety-related concrete structures, typically designed under ACI 349. The application of first-tier evaluation criteria can be overly conservative for massive concrete structures, structures not exposed to certain degradation mechanisms, or structures possessing concrete cover in excess of the minimum requirements of ACI 349, Chapter 7, such as concrete tank foundations, retaining walls, and concrete containment structures. For these types of structures, it is acceptable to compare the observed surface conditions with the second-tier evaluation criteria parameters.

For evaluations in which the primary goal is to determine material properties or retrieve samples for testing, the provisions of ASTM C 42 and C 823 should be followed to define the number and location of sampling points. For evaluations involving nondestructive testing, the recommendations of ACI 228.2R should be used to confirm the method to be used and to identify the number and location of tests based on the desired accuracy. Guidelines and acceptance criteria for specialized nondestructive and invasive tests, such as for chloride-ion content or tensile strength, are available from ASTM C 1218 and ACI 349 Section 4.4.1, and from other organizations that publish and sponsor such test methods. Because of the many parameters involved in these test methods, no acceptance criteria are cited in this report. The following criteria pertain to evaluations conducted to evaluate current condition, and are oriented primarily to visual inspections.

5.1—Acceptance without further evaluation

The following findings from a visual inspection or condition survey are considered acceptable without requiring any further evaluation, and are termed the first-tier criteria. The basis for these criteria include other ACI and industry documents, such as ACI 224R and References 5, 15, 27, and 29, as well as experience and judgement. Definition and pictorial representation of many of these indications can be found in ACI 201.1R. In the event that these criteria are exceeded or the observed conditions need further evaluation, the criteria in Section 5.2 should be considered. Structures that are partially lined, protectively coated, or partially or wholly inaccessible should be carefully evaluated, because several environmental conditions can be present and degradation may be masked or hidden.

5.1.1 *Concrete surfaces*—Concrete surfaces that are exposed for inspection and meet the following surface condition attributes are generally acceptable without further evaluation:

- Absence of leaching and chemical attack;
- Absence of abrasion, erosion, and cavitation;
- Absence of drummy areas (poorly consolidated concrete with paste deficiencies, per ACI 201.1R);

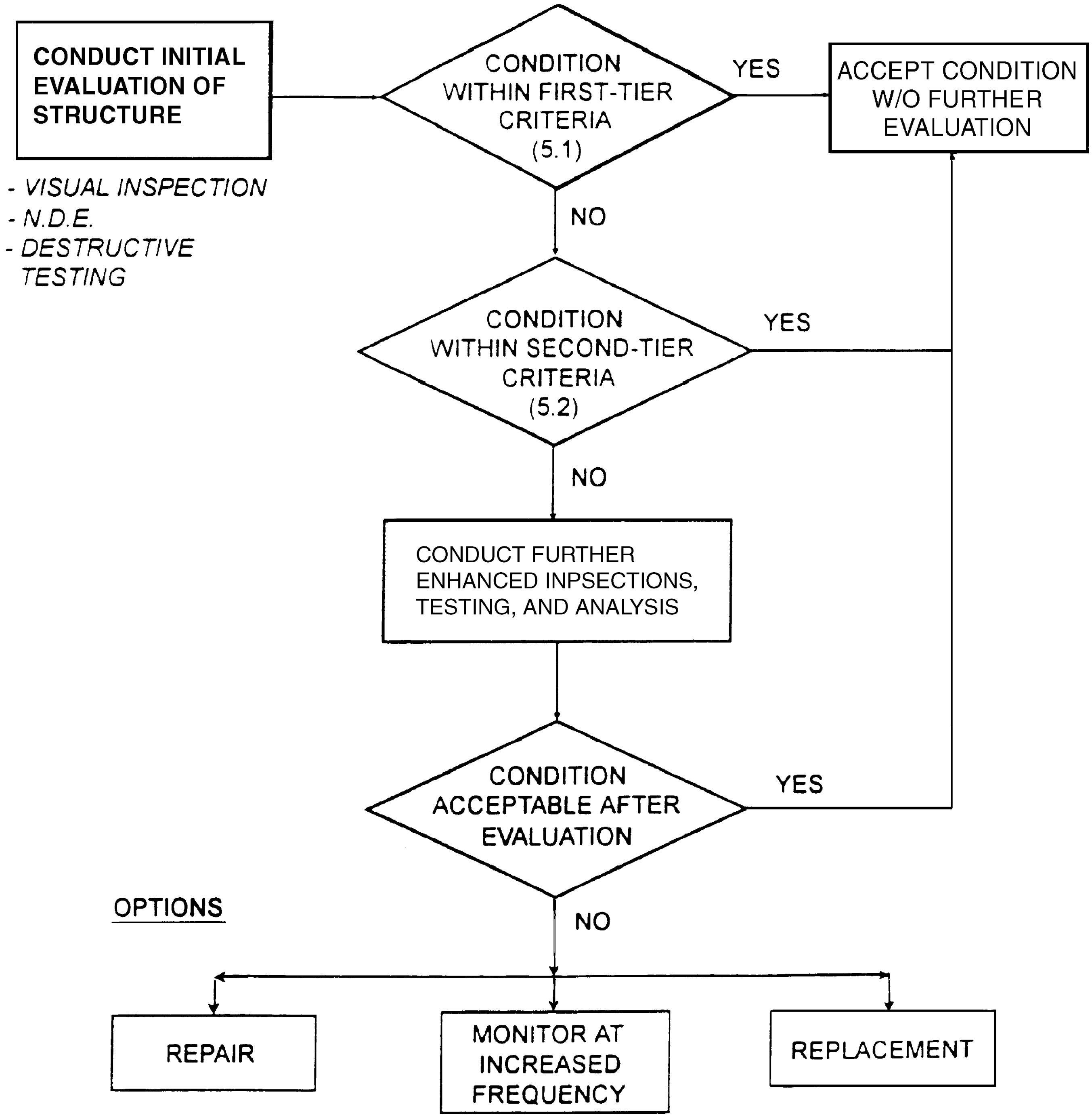

Fig. 5.1—Evaluation criteria hierarchy.

- Popouts and voids less than 20 mm (3/4 in.) in diameter or equivalent surface area;
- Scaling less than 5 mm (3/16 in.) in depth;
- Spalling less than 10 mm (3/8 in.) in depth and 100 mm (4 in.) in any dimension;
- Absence of any signs of corrosion in the steel reinforcement or anchorage components;
- Passive cracks less than 0.4 mm (0.015 in.) in maximum width—passive cracks are defined as those having an absence of recent growth and an absence of other degradation mechanisms at the crack; and
- Absence of excessive deflections, settlements, or other physical movements that can affect structural performance.

5.1.2 *Concrete surfaces lined with metal or plastic*—Concrete surfaces that have been protectively lined with either a metallic or plastic system are acceptable under the following criteria:

1. Without an active leak-detection system:

a) Absence of bulges or depressions in liner plate—those that appear age-related as opposed to being created during construction;

b) Absence of any form of corrosion or other liner damage; and

c) Absence of cracking or degradation of base and weld metal.

2. With an active leak-detection system:

a) No detectable leakage observed in leak-detection system; and

b) Absence of bulges or depressions in liner plate—those that appear age-related as opposed to construction phase-related.

5.1.3 *Areas around embedments in concrete*—The condition of the concrete areas around the embedments is acceptable if the following criteria are met:

- Concrete surface condition attributes of Section 5.1.1 are met;
- Absence of corrosion of the exposed embedded metal surfaces and corrosion stains around the embedded metal;
- Absence of detached embedments or loose bolts; and
- Absence of indications of degradation due to vibratory loads from piping and equipment.

5.1.4 *Joints, coatings, and nonstructural components*—The condition of joints, protective coatings, waterproofing membranes, and other nonstructural elements is acceptable if the following criteria are met (further information and acceptance criteria for coatings and membranes are contained in References 9 and 10):

- No signs of separation, environmental degradation, or water leakage are present in joints or joint material;
- Loss or degraded areas of coatings are limited in surface area to 4000 mm^2 (6 $in.^2$) or less at one area, and 10,000 mm^2 (16 $in.^2$) over the gross surfaces of the structure. These criteria apply to structures that do not serve as a barrier to aggressive chemical flows;
- Absence of degradation in any waterproofing membrane protecting below-grade concrete surfaces (within the inspected area); and
- Nonstructural elements appear to be serving their design function.

5.1.5 *Prestressing-steel systems*—Exposed surfaces of components of a prestressing steel reinforcement system are acceptable if the following conditions are met:

- Absence of grease or corrosion-inhibiting wax on exposed concrete or steel surface;
- Absence of corrosion on exposed grease cans, bearing plates, anchorages, or other components;
- Configuration of anchorage components remains unchanged, conforming to structural drawings;
- Absence of concrete degradation (see Section 5.1.1) around anchorages;
- No signs of corroded, broken, or failed prestressing elements; and
- No loss of prestress below acceptable levels established during the design and construction phases (percent maximum loss), as measured by lift-off testing on accessible tendons, using a similar technique.[32]

5.2—Acceptance after review

The following criteria represent a second set of acceptable conditions for observed degradation that have been determined to be inactive. These criteria are termed "second-tier." Inactive degradation can be determined by the quantitative comparison of current observed conditions with that of prior inspections. If there is a high potential for progressive degradation or propagation to occur at its present or accelerated rate, the disposition should consider more frequent evaluations of the specific structure or initial repair planning. Accessibility during plant operations should also be considered in decision-making. Section 5.3 addresses the aspect of further technical evaluation and repair for those observed degradations which exceed these second-tier criteria.

5.2.1 *Concrete surfaces*—The observed condition of the structure shall be compared with the following second-tier criteria to determine whether the structure is acceptable, requires further evaluation, or requires repair. Measurable discontinuities exceeding the quantitative limits should be classified and treated per Section 5.3:

- Appearance of leaching or chemical attack;
- Areas of abrasion, erosion, and cavitation degradation;
- Drummy areas that can exceed the cover concrete thickness in depth;
- Popouts and voids less than 50 mm (2 in.) in diameter or equivalent surface area;
- Scaling less than 30 mm (1-1/8 in.) in depth;
- Spalling less than 20 mm (3/4 in.) in depth and 200 mm (8 in.) in any dimension;
- Corrosion staining of undefined source on concrete surfaces;
- Passive cracks less than 1 mm (0.04 in.) in maximum width; and
- Passive settlements or deflections within the original design limits.

5.2.2 *Concrete surfaces lined by metallic or plastic liners*—For structures without an active leak-detection system, the presence of any condition listed in Section 5.1.2 should be further evaluated to determine acceptability.

For structures with an active leak-detection system, the presence of leakage in excess of amounts and flow rates committed in the original design or technical specification will necessitate a root-cause investigation and assessment of the need for follow-up action; that is, notification to jurisdictional and regulatory authorities. Leakage within the prescribed limits may be acceptable if the leaking material and source are known and it has been determined that they have no adverse consequences.

5.2.3 *Areas around embedments in concrete*—The presence of any condition listed in Section 5.2.1 shall be further evaluated to determine acceptability.

5.2.4 *Joints, coatings, and nonstructural components*—The presence of any condition exceeding the limits and descriptions of Section 5.1.4 should be further evaluated to determine acceptability. Any observation of widespread adhesion and cohesion problems, environmental attack, or poor performance indicators are considered unacceptable.

5.2.5 *Prestressing-steel systems*—The presence of corrosion or another condition exceeding the limits and descriptions of Section 5.1.5 should be further evaluated to determine acceptability.

5.3—Conditions requiring further evaluation

Observed concrete surface conditions that exceed the acceptance limits provided in Section 5.2, or conditions found to be detrimental to the structural or functional integrity as a result of a Section 5.2 review should be considered unacceptable and in need of further technical evaluation. If steel reinforcement-system corrosion or another mechanism causes a loss of monolithic behavior, the degree of degradation and structural effect should be characterized during the evaluation. Active cracking, settlements, or deflections that are observed in a structure should be treated because cracking damage can continue or intensify.

The acceptance of a structure that has been evaluated with the aid of nondestructive testing or other analytical method should be determined by the responsible engineer. Verification that suitable evaluation techniques were used and that accurate conclusions were reached should be made by the responsible engineer.

Further evaluation should consider the use of other inspection, testing, or analytical tools previously noted in Chapter 3 to obtain condition and functional information of the structure(s) in question. At this stage of the evaluation process, re-analysis of structural capacity and behavior under degraded physical conditions is often necessary. Existing mechanical and thermal properties should be obtained for use in this re-analysis. Should it be determined that the original design requirements and licensing commitments can no longer be achieved, repair or replacement options should be examined for the affected structure.

Decision-making that is performed at this stage of the evaluation should consider a number of factors, including desired service life, costs for various corrective actions, accessibility, and desired performance. Any repair, rehabilitation, or corrective action of an unacceptable condition taken should be in accordance with Chapter 8.

CHAPTER 6—EVALUATION FREQUENCY

The frequency at which periodic evaluations are conducted within the evaluation procedure should be defined by the plant owner. Evaluation frequency should be based on the aggressiveness of environmental conditions and physical conditions of the plant structures. The established frequencies should also ensure that any age-related degradation is detected at an early stage of degradation and that appropriate mitigative actions can be implemented. Inspection frequencies can also be determined through the use of a time-dependent reliability study,[14] where maximum acceptable probability of failure is used to establish the maximum duration between inspections and other actions, such as repair. All safety-related structures should be visually inspected at intervals not to exceed 10 years. Additionally, the frequency of inspection for other components should follow those in Table 6.1. For consistency with ASME (B&PVC), Section XI in-service inspection (ISI) requirements, the frequencies in Table 6.1 are alternately expressed in terms of years and in-service inspection interval.

The integrity of any prestressing system used at a plant, including anchorage hardware, effectiveness of corrosion-inhibiting material (grease or grout), and level of prestress, should be assessed at five-year intervals or per licensing requirements.

Table 6.1—Frequency of inspection

Structure category	Frequency of visual inspection
Below-grade structures	10 years (each ISI interval)
Structures exposed to natural environment (direct and indirect)	5 years (two per ISI interval)
Structures inside primary containment	5 years (two per ISI containment interval)
Continuous fluid-exposed structures	5 years (two per ISI structures interval)
Structures retaining fluid and pressure	5 years (two per ISI pressure interval)
Controlled interior environment	10 years (each ISI interval)

These suggested frequencies of plant evaluations are subject to change depending upon structure environment and the observed conditions. In the event that degradation is observed in excess of the Chapter 5 second-tier acceptance criteria, increased visual inspection frequencies or enhanced testing may be required—for example, microbiological corrosion in structures.[24] For structures located below grade or otherwise inaccessible, testing activities oriented at quantifying the aggressiveness of the environment to which the structure is exposed may be performed. For below-grade structures, these tests may require an examination of soils and groundwater chemistry and an evaluation of their propensity to cause concrete degradation or steel reinforcement corrosion. If these environmental tests suggest that an aggressive environment exists, further evaluation at an increased frequency may be warranted.

CHAPTER 7—QUALIFICATIONS OF EVALUATION TEAM

The quality and value of results obtained from an evaluation of an existing concrete structure depend, to a great extent, upon the qualifications and capabilities of the evaluation team. To ensure that the evaluation procedure is properly implemented, minimum personnel qualifications should be defined and met. The evaluation team should include both civil/structural engineers and concrete inspectors and technicians familiar with concrete degradation mechanisms and long-term performance issues.

The qualifications for personnel performing an evaluation of safety-related concrete structures is within the mission of ACI Committee 349. The responsible engineer should possess one of the following sets of qualifications:

- Licensed professional engineer, knowledgeable in the design, evaluation, and in-service inspection of concrete structures and performance requirements of nuclear safety-related structures; or
- Civil or structural engineering graduate of an ABET-accredited college or university with at least 10 year’s experience in the design, construction, and inspection of concrete structures, and with knowledge of the performance requirements of nuclear safety-related structures and potential degradation processes.

The personnel performing the inspections or testing at the plant, under the direction of the responsible engineer, should meet one of the following qualifications:

- Civil or structural engineering graduate of an ABET-accredited college or university who has over one year of experience (or are ACI inspector certified) in the evaluation of in-service concrete structures or quality assurance related to concrete structures; or
- Personnel possessing at least five years experience (or are ACI inspector certified) in the inspection and testing of concrete structures and having qualifications acceptable to the responsible engineer.

Structural calculations prepared as part of an evaluation should be prepared by graduate civil or structural engineers appointed by the responsible engineer. The qualifications should be similar to those for the responsible engineer. These calculations should be prepared and reviewed in accordance with accepted plant engineering procedures.

Any subcontracted testing work should also be performed by personnel experienced (or ACI certified) and qualified to perform the specific inspection or testing activities. For laboratory testing, or field inspection or testing, the subcontracted inspection and testing agency should meet the provisions of ASTM C1077 and E329, with ACI-certified personnel in their respective fields as appropriate. For other subcontracted activities, including nondestructive testing and structural analysis, the assigned personnel should have prescribed certifications and registrations to ensure that the assigned activities are completed in a technically competent manner and the results are correctly interpreted. There are no prescribed certifications for some concrete-testing applications, particularly those involving NDE (ASTM E543). The responsible engineer should confirm that assigned personnel are properly qualified, that a QA procedure is implemented, and that the results and use of the results are prudent.

The personnel performing visual inspections should have annual verification of near and far-distance vision acuity. The personnel should demonstrate natural or corrected near-distance acuity of 20/25 or greater Snellen fraction with at least one eye, by reading words or identifying characters on a near-distance test chart, such as a Jaeger chart. Equivalent measures of near-distance acuity can be used. The personnel should also demonstrate natural or corrected far-distance acuity of 20/30 or greater Snellen fraction or equivalent with at least one eye. Additionally, the personnel should demonstrate the capability to distinguish colors and to differentiate contrast between the colors applicable to concrete examination.

CHAPTER 8—REPAIR

The structures identified in the evaluation procedure as requiring repair should be restored to their desired strength, durability, and performance characteristics. Numerous ACI and industry documents cover concrete, liner plate, and coating repair, and many of the methods cited in these documents are well suited for use in nuclear power plants. A compilation of repair documents is available from ACI.[32] A survey[33] was also initiated to further define current concrete repair programs in use at nuclear power plants. This section of the report provides an overview of issues to consider in the development of prudent repair methods and procedures—it is not intended to be a comprehensive repair guide. Of greatest importance in the selection and implementation of a repair procedure are the following:

- Environmental conditions affecting the structure, such as radiation and temperature;
- Type and degree of degradation, such as structural or aesthetic;
- Mitigation of degradation source in the repair process;
- Existing material properties for repair material compatibility;
- Desired service life of structure and the proposed repair;
- Availability of repair material qualification data;
- Economics;
- Restoration of structural capacity;
- Restoration of service and performance characteristics; and
- Compatibility with existing concrete to be repaired.

With many repair materials and methods available, the responsible engineer and evaluation team should examine each of the noted factors when selecting a proper repair for the degraded structure. Certain repairs, such as restoring the structural behavior in a structure affected by steel reinforcement corrosion, require more attention than others such as repairing scaling degradation in cover concrete. In addition, the massive size of most safety-related structures requires careful evaluation to ascertain the degree of degradation and its cause. All repair efforts should consider the degradation mechanisms and mitigation of future degradation from the same phenomenon. In all repairs, the licensing commitments for the specific plant should be recognized and fulfilled.

A number of repair materials have been widely used commercially in the repair of concrete cracks, spalls, subsurface voids, and other defects. The use of these materials in a nuclear plant environment, however, can be inappropriate because of differences in thermal properties, inadequate durability, or other factors. The repair process and materials selected should consider the environmental exposure, expected performance, strain and deflection compatibility between the in-place structure and the repair material, structural capacity, and desired longevity of the repaired structure. The responsible engineer should ensure that the necessary research to assess available options and validate a specific repair is performed.

The selected repair process should be well documented and a plant-specific repair procedure should be prepared by the evaluation team, or reviewed and approved by the evaluation team if prepared by others, to ensure that the repair requirements are properly understood and implemented. Any vendor-specific information and warnings regarding use of the repair materials should be incorporated in the repair procedure. The craftsmen performing the repair should be experienced with the repair method and materials, plant procedures, operations of the equipment, and in-process behavior and any health concerns of the repair materials. The selected repair procedure should be focused toward the mitigation of the root cause for repair, removal of degraded material, and restoration of structural integrity.

Following the selection of a repair material and process and completion of necessary supportive documents and calculations, the responsible engineer for repair should prepare a summary report identifying the source or root cause of degradation and reason for the evaluation, the decision-making for the repair method selection, repair material qualification data, summary of structural calculations, repair drawings, and all documents related to the evaluation. This summary report should be preserved for the life of the plant as defined in the plant engineering procedures and ACI 349.

During the repair process, it is necessary to provide quality control in the form of inspections—possibly including nondestructive testing—or other reviews to verify the adequacy of the repair process and materials. If replacement of existing concrete is a part of the repair, the required quality assurance and controls specified should conform to ACI 349, subject to plant licensing commitments. During and following completion of the repair, the evaluation process should include several checkpoints to validate the material condition and structural performance of the repaired structure. If further remedial actions or corrections are needed, they should be completed at this time.

CHAPTER 9—REFERENCES

9.1—Referenced standards and reports

The standards and reports listed as follows were the latest editions at the time this document was prepared. Because these documents are revised frequently, the reader is advised to contact the proper sponsoring group if it is desired to refer to the latest version.

American Concrete Institute

201.1R Guide for Making a Visual Inspection of Concrete in Service
201.2R Guide to Durable Concrete
207.3R Practices for Evaluation of Concrete in Existing Massive Structures for Service Conditions
209R Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures
210R Erosion of Concrete in Hydraulic Structures
215R Considerations for Design of Concrete Structures Subjected to Fatigue Loading
216R Guide for Determining Fire Endurance of Concrete Elements
221.1R Report on Alkali-Aggregate Reactivity
222R Protection of Metals in Concrete Against Corrosion
222.2R Corrosion of Prestressing Steels
224R Control of Cracking in Concrete Structures
224.1R Causes, Evaluation, and Repair of Cracks in Concrete Structures
228.1R In-Place Methods to Estimate Concrete Strength
228.2R Nondestructive Test Methods for Evaluation of Concrete in Structures
349 Code Requirements for Nuclear Safety Related Concrete Structures
364.1R Guide for Evaluation of Concrete Structures Prior to Rehabilitation
437R Strength Evaluation of Existing Concrete Buildings
515.1R Guide to the Use of Waterproofing, Dampproofing, Protective, and Decorative Barrier Systems for Concrete

ASCE

11 Guideline for Structural Condition Assessment of Existing Buildings
43 Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities

ASME

Section III Boiler and Pressure Vessel Code (B&PVC), Rules for Construction of Nuclear Power Plant Components, Division 2, Concrete Reactor Vessels and Containments
Section XI B&PVC, Inservice Inspection

ASTM International

C 33 Standard Specification for Concrete Aggregates
C 42 Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete—AASHTO No.: T24
C 823 Standard Practice for Examination and Sampling of Hardened Concrete in Constructions
C 856 Standard Practice for Petrographic Examination of Hardened Concrete
C 876 Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete
C 1077 Standard Practice for Laboratories Testing Concrete and Concrete Aggregates for Use in Construction and Criteria for Laboratory Evaluation
C 1218 Standard Test Method for Water-Soluble Chloride in Mortar and Concrete
E 329 Standard Specification for Agencies Engaged in Construction Inspection and/or Testing
E 543 Standard Specification for Agencies Performing Nondestructive Testing

These publications may be obtained from the following organizations:

American Concrete Institute
P.O. Box 9094
Farmington Hills, MI 48333-9094
www.concrete.org

American Society of Civil Engineers
1801 Alexander Bell Drive
Reston, VA 20191
www.asce.org

American Society of Mechanical Engineers
Three Park Avenue
New York, NY 10016-5990
www.asme.org

ASTM International
100 Barr Harbor Drive
West Conshohocken, PA 19428
www.astm.org

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