ORNL/CP-100051



# INSPECTION OF NUCLEAR POWER PLANT CONTAINMENT STRUCTURES

W.E. Norris
U.S. Nuclear Regulatory Commission
Washington, D.C.

D.J. Naus
Oak Ridge National Laboratory
Oak Ridge, TN

H.L. Graves, III
U.S. Nuclear Regulatory Commission
Washington, D.C.

## SUMMARY

Safety-related nuclear power plant (NPP) structures are designed to withstand loadings from a number of low-probability external and interval events, such as earthquakes, tornadoes, and loss-of-coolant accidents. Loadings incurred during normal plant operation therefore generally are not significant enough to cause appreciable degradation. However, these structures are susceptible to aging by various processes depending on the operating environment and service conditions. The effects of these processes may accumulate within these structures over time to cause failure under design conditions, or lead to costly repair.

In the late 1980s and early 1990s several occurrences of degradation of NPP structures were discovered at various facilities (e.g., corrosion of pressure boundary components, freeze-thaw damage of concrete, and larger than anticipated loss of prestressing force). Despite these degradation occurrences and a trend for an increasing rate of occurrence, in-service inspection of the safety-related structures continued to be performed in a somewhat cursory manner. Starting in 1991, the U.S. Nuclear Regulatory Commission (USNRC) published the first of several new requirements to help ensure that adequate in-service inspection of these structures is performed.

Current regulatory in-service inspection requirements are reviewed and a summary of degradation experience presented. Nondestructive examination techniques commonly used to inspect the NPP steel and concrete structures to identify and quantify the amount of damage present are reviewed. Finally, areas where nondestructive evaluation techniques require development (i.e., inaccessible portions of the containment pressure boundary, and thick heavily reinforced concrete sections are discussed

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## INTRODUCTION

As of April 1998, there have been 109 commercial nuclear power reactors licensed for operation in the United States (US). The Atomic Energy Act (AEA) of 1954 limits the duration of operating licenses for most of these reactors to a maximum of 40 years. The median age of these reactors is 20 years, with 49 having been in commercial operation for 20 or more years. Expiration of the operating licenses for these reactors will start to occur early in the next century. Under current economic, social, and political conditions in the US, the prospects for early resumption of building of new NPPs to replace lost generating capacity are very limited (1). In some areas of the country it may be too late because of the 10 to 15 years required to plan and build replacement power plants. Continuing the service of existing NPPs through a renewal of their initial operating licenses provides a timely and cost-effective solution to the problem of meeting future energy demand.

The 40-year term for an operating license provided in the AEA of 1954 apparently was based on various financial considerations (e.g., bond maturity) and not on safety or technical concerns. No technical information was presented to suggest that the NPPs would become unsafe if they were to operate after 40 years (2). In fact, the AEA permits the renewal of operating licenses. Paragraph 50.51 of Part 10 of the *Code of Federal Regulations (CFR)* (3) implements the authority for license renewal; however, prior to release of a working draft of a Standard Review Plan (4), no standards had been provided for preparing or evaluating license renewal applications.

A major concern in the evaluation of applications to renew initial operating licenses is that the capacity of the safety-related systems to mitigate extreme events has not deteriorated unacceptably due to either aging or environmental stressor effects during their previous service history. Major mechanical and electrical equipment items in a plant could, in all likelihood, be replaced, if necessary. However, replacement of several of the structural components (i.e., steel and concrete containments) would not be economically feasible. Approval for service life extension must be supported by evidence that these structures will continue to be capable of withstanding potential future extreme events with adequate safety margins.

## CONTAINMENT STRUCTURES

From a safety standpoint, the containment is one of the most important components of a NPP because it serves as the final barrier to the release of fission products to the outside environment under postulated accident conditions. Ensuring that the structural capacity and leak-tight integrity of the containment has not deteriorated unacceptably due either to aging or environmental stressor effects is essential to reliable continued service evaluations and informed aging management decisions.

### General Description

Each boiling-water reactor (BWR) or pressurized-water reactor (PWR) unit in the US is located within a much larger metal or concrete containment that also houses or supports the primary coolant system components. Although the shapes and configurations of the containment can vary significantly from plant-to-plant, leak-tightness is assured by a continuous pressure boundary consisting of nonmetallic seals and gaskets, and metallic components that are either welded or bolted together. There are several CFR General Design Criteria (GDC) and American Society of Mechanical Engineers (ASME) Code sections that establish minimum requirements for the design, fabrication, construction, testing, and performance of containment structures. The GDC serve as fundamental underpinnings for many of the most important safety commitments in licensee design and licensing bases. General Design Criterion 16, "Containment Design," requires the provision of reactor containment and associated systems to establish an essentially leak-tight barrier against the uncontrolled release of radioactivity into the environment and to ensure that the containment design conditions important to safety are not exceeded for as long as required for postulated accident conditions. Criterion 53, "Provisions for Containment Testing and Inspection," requires that the reactor containment be designed to permit: (1) appropriate periodic inspection of all important areas, such as penetrations; (2) an appropriate surveillance program; and (3) periodic testing at containment design pressure of leak-tightness of penetrations that have resilient seals and expansion bellows.

Prior to 1963, metal containments for NPPs were designed according to rules for unfired pressure vessels that were provided by the ASME in Section VIII of the ASME Code (5). Subsequent metal containments were designed either as Class B vessels or as Class MC components according to rules provided in Section III of the ASME Code (6). Almost every aspect of metal containment design is addressed by the Code. The Code also recognizes that service-related degradation to pressure retaining components is possible, but rules for material selection and in-service degradation are outside its scope. It is the Owner's responsibility to select materials suitable for the service conditions and to increase minimum required thickness of the base metal to offset material thinning due to corrosion, erosion, mechanical abrasion, or other environmental effects. Current rules for construction of metal containments are provided in Section III, Division 1, Subsection NE of the ASME Code. Currently operating metal containments are freestanding, welded steel structures that are enclosed in a reinforced concrete reactor or shield building. The reactor or shield buildings are not part of the pressure boundary and their primary function is to provide protection for the containment from external missiles and natural phenomena (e.g., tornadoes or site-specific environmental events). Thirty-nine of the NPPs presently licensed for commercial operation in the US employ a metal containment.

Concrete containments are metal lined, reinforced concrete pressure-retaining structures that in some cases may be post-tensioned. The concrete vessel includes the concrete shell and shell components, shell metallic liners, and penetration liners that extend the containment liner through the surrounding shell concrete. The reinforced concrete shell, which generally consists of a cylindrical wall with a hemispherical or ellipsoidal dome and flat base slab, provides the necessary structural support and resistance to pressure-induced forces. Leak-tightness is provided by a steel liner fabricated from relatively thin plate material (e.g., 6-mm thick) that is anchored to the concrete shell by studs, structural steel shapes, or other steel products. Initially, existing building codes, such as American Concrete Institute (ACI) Standard 318, *Building Code Rules for Reinforced Concrete* (7), were used in the nuclear industry as the basis for design and construction of concrete structural members. However, because the existing building codes did not cover the entire spectrum of design requirements and because they were not always considered adequate, the USNRC developed its own criteria for design of seismic Category 1 (i.e., safety related) structures (e.g., definitions of load combinations for both operating and accident conditions). Plants that used early ACI codes for design were reviewed by the USNRC through the Systematic Evaluation Program to determine if there were any unresolved safety concerns (8). Current rules for construction of concrete containments are provided in Section III, Division 2 of the ASME Code. The USNRC (9,10) has developed supplemental load combination criteria and provides information related to concrete and steel internal structures of steel and concrete containments. Rules for design and construction of the metal liner that forms the pressure boundary for the reinforced concrete containments are found in ASME Section III, Division 1, Subsection NE of the ASME Code. Seventy of the NPPs that have been licensed for commercial operation in the US employ either a reinforced concrete (29 plants) or post-tensioned concrete (41 plants) containment.

**Potential Degradation Factors**

Service-related degradation can affect the ability of a NPP containment to perform satisfactorily in the unlikely event of a severe accident by reducing its structural capacity or jeopardizing its leak-tight integrity. Degradation is considered to be any phenomenon that decreases the load-carrying capacity of a containment, limits its ability to contain a fluid medium, or reduces the service life. The root cause for containment degradation can generally be linked to a design or construction problem, inappropriate material application, a base-metal or weld-metal flaw, maintenance or inspection activities, or excessively severe service conditions.

Steel containment degradation can be classified as either material or physical damage. Material damage occurs when the microstructure of the metal is modified causing changes in its mechanical properties. Degradation mechanisms that can potentially cause material damage to containment steels include (1) low-temperature exposure, (2) high-temperature exposure, (3) intergranular corrosion, (4) dealloying corrosion, (5) hydrogen embrittlement, and (6) neutron irradiation. Material damage to the containment pressure boundary from any of these sources is not considered likely, however. Physical damage occurs when the geometry of a component is altered by the formation of cracks, fissures, or voids, or its dimensions change due to overload, buckling, corrosion, erosion, or formation of other types of surface flaws. Changes in component geometry, such as wall thinning or pitting caused by corrosion, can affect structural capacity by reducing the net section available to resist applied loads. In addition, pits that completely penetrate the component can compromise the leak-tight integrity of the component. Primary degradation mechanisms that potentially can cause physical damage to containment pressure boundary components include (1) general corrosion (atmospheric, aqueous, galvanic, stray-electrical current, and general biological); (2) localized corrosion (filiform, crevice, pitting, and localized biological); (3) mechanically-assisted degradation (erosion, fretting, cavitation, corrosion fatigue, surface flaws, arc strikes, and overload conditions); (4) environmentally-induced cracking (stress-corrosion and hydrogen-induced); and (5) fatigue. Material degradation due to either general or pitting corrosion represent the greatest potential threat to the containment pressure boundary.

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

## OPERATING EXPERIENCE

As nuclear plant containments age, degradation incidences are starting to occur at an increasing rate, primarily due to environmental-related factors. There have been at least 66 separate occurrences of degradation in operating containments (some plants may have more than one occurrence of degradation). One-fourth of all containments have experienced corrosion, and nearly half of the concrete containments have reported degradation related to either the reinforced concrete or post-tensioning system.

Since 1986, there have been over 32 reported occurrences of corrosion of steel containments or liners of reinforced concrete containments. In two cases, thickness measurements of the walls revealed areas that were below the minimum design thickness. There have been four cases where extensive corrosion of the liner has reduced the thickness locally by nearly one-half (11). Only four of the degradation occurrences were detected through containment inspection programs prior to Type A leakage-rate testing conducted according to requirements in effect at the time [i.e., preadoption by reference of basic requirements in Subsection IWE (12)]. Nine of these occurrences were first identified by the USNRC through its inspections or audits of plant structures. Eleven occurrences were detected by licensees while performing an unrelated activity, or after they were alerted to a degraded condition at another site. Examples of problems identified include corrosion of the steel containment shell in the drywell sand cushion region (Oyster Creek), shell corrosion in ice condenser plants (Catawba and McGuire), corrosion of the torus of the steel containment shell (Fitzpatrick, Cooper, and Nine Mile Point Unit 1), coating degradation (Dresden 3, Fitzpatrick, Millstone 1, Oyster Creek, Pilgrim, and H. B. Robinson), and concrete containment liner corrosion (Brunswick, Beaver Valley, and Salem). There also have been incidences of transgranular stress corrosion cracking in bellows (Quad Cities 1 and 2, and Dresden 3).

Since the early 1970's, at least 34 occurrences of containment degradation related to the reinforced concrete or post-tensioning systems have been reported. Where concrete degradation incidences have occurred, they have generally done so early in the life of the structure and were corrected. Causes were primarily related to improper material selection, construction/design deficiencies, or environmental effects. Examples of some of the degradation occurrences include cracking in basemats (Waterford, Three Mile Island, North Anna, and Fermi), voids under the vertical tendon bearing plates resulting from improper concrete placement (Calvert Cliffs); failure of prestressing wires (Calvert Cliffs); cracking of post-tensioning tendon anchorheads due to stress corrosion or embrittlement (Bellefont, Byron, and Farley); containment dome delaminations due to low quality coarse aggregate materials and absence of radial reinforcement (Crystal River), or unbalanced prestressing forces (Turkey Point); corrosion of steel reinforcement in water-intake structures (Turkey Point and San Onofre); leaching of tendon gallery concrete (Three Mile Island); and low prestressing forces (Ginna, Turkey Point 3, Zion, and Summer). Other reported problems include occurrence of excessive voids or honeycomb in the concrete, contaminated concrete, cold joints, cadweld (steel reinforcement connector) deficiencies, materials out of specification, higher than code-allowable concrete temperatures, misplaced steel reinforcement, post-tensioning system buttonhead deficiencies, water contaminated corrosion inhibitors, leakage of corrosion inhibitors from tendon sheaths, and freeze/thaw damage to containment dome concrete.

## TESTING AND INSPECTION REQUIREMENTS

### Background

Proper maintenance is essential to the safety of NPP containments, and a clear link exists between effective maintenance and safety. To reduce the likelihood of failures due to degradation, the "Maintenance Rule" was issued by the USNRC as 10 CFR 50.65 ("Requirements for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants") on July 10, 1991. As discussed in the rule summary, in order to maintain safety, it is necessary to monitor the effectiveness of maintenance, and to take timely and appropriate corrective action, when necessary, to ensure that the maintenance process continues to be effective for the lifetime of NPPs, particularly as plants age. The rule requires that plant owners monitor the performance or condition of structures, systems, and components (SSCs) against owner-established goals, in a manner sufficient to give reasonable assurance that such SSCs are capable of fulfilling their intended functions. It is further required that the licensee take appropriate corrective action when the performance or condition of a SSC does not conform to established goals. In order to verify the implementation of 10 CFR 50.65, the USNRC issued Inspection Procedure 62002, "Inspection of Structures, Passive Components, and Civil Engineering Features at Nuclear Power Plants."

Subsequently, on May 8, 1995, the USNRC published a final rule amending 10 CFR Part 54, "Requirements for Renewal of Operating Licenses for Nuclear Power Plants," that contained the requirements an applicant must meet to renew their operating license. The final rule is intended to ensure that important SSCs will continue to perform their intended function in the period of extended operation. Only passive, long-lived structures and components are subject to an aging management review for license renewal, and the USNRC license renewal review will focus on the adverse effects of aging. The USNRC concluded that passive, long-lived components should be subject to an aging management review because, in general, functional degradation of these components may not be apparent so that the regulatory process and existing licensee programs may not adequately manage detrimental effects of aging in the period of extended operation.

In June 1995, the USNRC published NUREG-1522, "Assessment of Inservice Conditions of Safety-Related Nuclear Plant Structures." The report contains information from various sources on the condition of structures and civil engineering features at operating nuclear plants.

The most significant information came from inspections performed by the USNRC Staff of six plants licensed before 1977. Most of the information on degraded conditions of the containment structures was submitted by the licensees under the Licensee Event Reporting System (10 CFR 50.73), or in fulfilling the requirement under limiting conditions of operation of technical specifications for their plants. Most of the information on the degradation of other structures and civil engineering features come from an industry survey, reported incidences, and plant visits. Types of containment-related potential problem areas found included coating degradation and base metal pitting, leakage of tendon corrosion inhibitor, lower than anticipated tendon prestressing forces, bulging and spot corrosion of liner plate, concrete surface cracking, deteriorating concrete repair patches, and torus corrosion. The main conclusion of the report was that a properly established and periodically applied inspection and maintenance program would be beneficial to the plant owners in ensuring the integrity of the plant structures. The importance of periodic inspections of structures, as part of the systematic maintenance program, cannot be over emphasized. Substantial safety and economic benefit can be derived if the scope of the investigations is comprehensive and includes degradation sites having difficult access that may not otherwise be inspected. Timely remedial actions to arrest continuing or address benign degradations will ensure continued safety of the structures, particularly in areas of difficult access.

Most of the degradation occurrences noted above were first identified by the USNRC through its inspections or audits of plant structures, or by licensees while performing an unrelated activity or after they were alerted to a degraded condition at another site. Since none of the existing requirements for containment inspection provided specific guidance on how to perform the necessary containment examinations, there was a large variation with regard to the performance and effectiveness of licensee containment examination programs. Furthermore, based on results of the inspections and audits, the USNRC was concerned because many licensee containment examination programs did not appear to be adequate to detect degradation that could potentially compromise the containment leak-tight integrity. The number of occurrences and extent of degradation experienced by a few of the structures at some plants resulted in the USNRC publishing new rules regarding testing and in-service inspection.

**Testing**

One of the conditions of all operating licenses for water-cooled power reactors is that the primary reactor containments shall meet the containment leakage test requirements set forth in Appendix J, "Primary Reactor Containment Leakage Testing for Water-Cooled Power Reactors," to 10 CFR 50 (13). These test requirements provide for preoperational and periodic verification by tests of the leak-tight integrity of the primary reactor containment, and systems and components that penetrate containment of water-cooled power reactors, and establish the acceptance criteria for such tests. The purposes of the tests are to assure that (a) leakage through the primary reactor containment and the systems and components penetrating primary reactor containment shall not exceed allowable leakage-rate values as specified in the technical specifications or associated bases, and (b) periodic surveillance of reactor containment penetrations and isolation valves is performed so that proper maintenance and repairs are made during the service life of the containment, and systems and components penetrating primary containment.

Contained in this regulation are requirements pertaining to Type A, B, and C leakage-rate tests that must be performed by each licensee as a condition of their operating license. Type A tests are intended to measure the primary reactor containment overall integrated leakage rate (1) after the containment has been completed and is ready for operation, and (2) at periodic intervals thereafter. Type B tests are intended to detect local leaks and to measure leakage across each pressure-containing or leakage-limiting boundary for primary reactor containment penetrations (e.g., penetrations that incorporate resilient seals, gaskets, or sealant compounds; and air lock door seals). Type C tests are intended to measure containment isolation valve leakage rates. Requirements for system pressure testing and criteria for establishing inspection programs and pressure-test schedules are contained in Appendix J.

On September 26, 1995, the USNRC amended Appendix J (60 FR 49495) to provide a performance-based option for leakage-rate testing as an alternative to the existing prescriptive requirements. The amendment is aimed at improving the focus of the body of regulations by eliminating prescriptive requirements that are marginal to safety and by providing licensees greater flexibility for cost-effective implementation methods for regulatory safety objectives. Now that Appendix J has been amended, either Option A—*Prescriptive Requirements* or Option B— *Performance-Based Requirements* can be chosen by a licensee to meet the requirements of Appendix J. Licensees may voluntarily comply with Option B requirements rather than continue using established leakage-rate test schedules. Option B allows licensees with good integrated leakage-rate test performance histories to reduce the Type A testing frequency from three tests in 10 years to one test in 10 years. For Type B and C tests, Option B allows licensees to reduce testing frequency on a plant-specific basis based on the operating experience for each component and establishes controls to ensure continued performance during the extended testing interval. However, a general inspection of accessible interior and exterior surfaces of the containment structure and components must be performed prior to each Type A test and during two other refueling outages before the next Type A test if the interval for the Type A test has been extended to 10 years (13). The USNRC position on performance-based containment leakage-rate testing is discussed in Regulatory Guide 1.163 (14). Methods considered acceptable to the USNRC staff for complying with the provisions of Option B are provided in guidance documentation (15).

The Nuclear Energy Institute document (15) presents an industry guideline for implementing the performance-based option and contains an approach that includes continued assurance of the leak-tight integrity of the containment without adversely affecting public health and safety, licensee flexibility to implement cost-effective testing methods, a framework to acknowledge good performance, and utilization of risk and performance-based methods. The guideline delineates the basis for a performance-based approach for determining Type A, B, and C containment leakage-rate surveillance testing frequencies using industry performance data, plant-specific performance data, and risk insights. It does not address how to perform the tests because these details can be found in existing documents (16). Licensees may elect to use other suitable methods or approaches to comply with Option B, but they must obtain USNRC approval prior to implementation.

## Inspection

Appendix J to 10 CFR Part 50, requires a general inspection of the accessible interior and exterior surfaces of the containment structures and components to uncover any evidence of structural deterioration that may affect either the containment structural integrity or leak-tightness. The large number of reported occurrences (over 60) and the extent of the degradation led the USNRC to conclude that this general inspection was not sufficient. Thus, on August 8, 1996, the USNRC published an amendment (61 FR 41303) to 10 CFR 50.55a of its regulations to require that licensees use portions of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code) for containment in-service inspection. The regulations were amended to assure that critical areas of the containments are routinely inspected to detect and to take corrective action for defects that could compromise a containment's structural integrity. The amended rule became effective September 9, 1996. Specifically, the rule requires that licensees adopt the 1992 Edition with the 1992 Addenda of Subsection IWE, "Requirements for Class MC and Metallic Liners of Class Components of Light-Water Cooled Power Plants," and Subsection IWL, "Requirements for Class CC Concrete Components of Light-Water Cooled Power Plants," of Section XI, of the ASME Code. In addition, several supplemental requirements with respect to the concrete and metal containments were included in the rule. A five-year implementation period was permitted for licensees to develop and implement the examinations of Subsections IWE and IWL (i.e., no later than September 9, 2001). Also, any repair and replacement activity to be performed on a containment after the effective date of the amended rule has to be carried out in accordance with respective requirements of Subsections IWE and IWL of the ASME Code. However, the Director of the Office of Nuclear Reactor Regulation at his discretion can grant relief from the requirements of 10 CFR 50.55a relative to repair and replacement activities to licensees who submit a justifiable need to use an alternative that provides an acceptable level of safety or who encounter extreme hardship or unusual difficulty without a compensating increase in the level of quality or safety.

## CONDITION ASSESSMENTS

Operating experience has demonstrated that periodic inspection, maintenance, and repair are essential elements of an overall program to maintain an acceptable level of reliability over the service life of a nuclear power plant containment, or in fact, of any structural system. Knowledge gained from conduct of an in-service condition assessment can serve as a baseline for evaluating the safety significance of any degradation that may be present, and defining subsequent in-service inspection programs, and maintenance strategies.

Effective in-service condition assessment of a containment requires knowledge of the expected type of degradation, where it can be expected to occur, and application of appropriate methods for detecting and characterizing the degradation. Degradation is considered to be any phenomenon that decreases the containment load-carrying capacity, limits its ability to contain a fluid medium, or reduces its service life. Degradation detection is the first and most important step in the condition assessment process. Routine observation, general visual inspections, leakage-rate tests, and nondestructive examinations are techniques used to identify areas of the containment that have experienced degradation. Techniques for establishing time-dependent change such as section thinning due to corrosion, or changes in component geometry and material properties, involve monitoring or periodic examination and testing. Knowing where to inspect and what type of degradation to anticipate often requires information about the design features of the containment as well as the materials of construction. Figure 1 provides a flow diagram of one approach to the continued service evaluation process for NPP containments. Basic components of the process include damage detection and classification, root-cause determination, and measurement.

## NONDESTRUCTIVE TEST METHODS

The ASME Code requires that when defect flaws or evidence of degradation exist that require evaluation in accordance with Code acceptance criteria, either surface or volumetric examinations are to be conducted. Selection of the appropriate method depends on the type and nature of the degradation, the component geometry, and the type and circumstances of inspection. Cost and availability are also factors. Summarized below are several available nondestructive examination techniques for use in assessment of the significance of metallic* and concrete material degradation.

### Metallic Materials

Nondestructive examination methods for metallic materials (i.e., steel containments and liners of reinforced concrete containments) principally involve surface and volumetric inspections to detect the presence of degradation (i.e., loss of section due to corrosion or presence of cracking). The surface examination techniques primarily include the visual, liquid penetrant, and magnetic particle methods. Volumetric methods include ultrasonic, eddy current, and radiographic. Provisions are also included in the Code for use of alternative examination methods provided results obtained are demonstrated to be equivalent or superior to those of the specified method. Acceptance standards are defined in Article IWE-3000 of the ASME Code. In order to obtain repeatable and reproducible nondestructive examination results using any of the methods described below, several factors must be understood and controlled: material evaluated, evaluation procedure utilized, environment, calibration/baseline reference, acceptance criteria, and human factors. Table 1 presents a summary of the applications by flaw type and important material characteristics for the techniques discussed below. Table 2 presents the dominant sources of variance for these techniques.

Visual inspection is one of the most common and least expensive of the methods for evaluating the condition of a weld or component (e.g., presence of surface flaws, discontinuities, or corrosion). It is generally the first inspection that is performed as part of an evaluation process. It is beneficial for performing gross defect detection and to identify areas for more detailed examination. It can identify where a failure is most likely to occur and identify when failure has commenced (e.g., rust staining or coating cracks). Once a suspect area is identified all surface debris and protective coatings are removed so that the area can be inspected in more detail. Visual examinations can be performed either with the unaided eye or optical magnifiers. Inspection mirrors, video cameras, and boroscopes can be used for inspection of areas with limited accessibility. Three classifications of visual examinations are specified in the ASME

* Steel reinforcement and post-tensioning systems for concrete containments are addressed under concrete materials.

Code: (1) VT-1 (detect discontinuities and imperfections on the surfaces of components such as cracks and corrosion), (2) VT-2 (detect evidence of leakage from pressure-retaining components), and (3) VT-3 (determine general mechanical and structural condition of components and their supports). The effectiveness of a visual inspection is dependent on the experience and competence of the person performing the inspections. Also, without material or component removal, visual inspections are limited to accessible areas.

Liquid penetrant testing can be used to detect, define and verify surface flaws in solid or essentially nonporus components (e.g., cracks, porosity, laminations or other types of discontinuities that have a capillary opening to the surface). Indications of a wide spectrum of flaw sizes can be found with little capital expenditure regardless of the configuration of the test article or the flaw orientation. The procedure consists of cleaning the surface to be examined followed by application of a liquid penetrant. Surface defects or cracks absorb the penetrant through capillary action. After a dwell period, excess penetrant is removed from the surface and a developer is applied that acts as a blotter to draw penetrant from the defects to reveal their presence. Colored or fluorescent penetrants may be utilized, with white light or black light, respectively, used for viewing. Effectiveness of the method is dependent on the properties of the penetrant and the developer. Limitations of the technique are that operator skill requirements are fairly high, only surface flaw detects can be detected, area inspected must be clean as scale or paint film may hide flaws, results are affected by surface roughness and porosity, and no permanent record of inspection is provided.

Magnetic particle testing is used to detect surface and shallow subsurface discontinuities in ferromagnetic materials. A magnetic field is induced into the ferromagnetic material and the surface is dusted with iron particles that may be dry, suspended in a liquid, colored, or fluorescent. The magnetic lines of force (flux) will be disrupted locally by the presence of the flaw with its presence indicated by the iron particles that are attracted by leakage of the magnetic field at the discontinuity. The resulting magnetically-held collection of particles forms a pattern that indicates the size, shape, and location of the flaw. Effectiveness of the method quickly diminishes depending on flaw depth and type, and scratches and surface irregularities can give misleading results. Special equipment, procedures, and process controls are required to induce the required magnetic fields (e.g., use of proper voltage, amperage, and mode of induction). Also, linear discontinuities that are oriented parallel to the direction of the magnetic flux will not be detected.

Ultrasonic testing uses sound waves of short wavelength and high frequency to detect surface and subsurface flaws, and measure material thickness. The most commonly used technique is pulse echo in which sound is introduced into the test object and travels through the material examined with some attendant loss of energy. Reflections (echoes) are returned to the receiver from internal imperfections or the components surfaces. The returning pulse is displayed on a screen that gives the amplitude of the pulse and the time taken to return to the transducer. Inclusions or other imperfections are detected by partial reflection or scattering of the ultrasonic waves, time of transit of the wave through the test object, and features of the spectral response for either a transmitted or reflected signal. Operator interpretation is made by pattern recognition, signal magnitude, timing, and probe positioning. Flaw size, distance, and reflectivity can be interpreted. The technique has good penetration capability (i.e., up to 6 m for axial inspections), high sensitivity to permit detection of very small flaws, good accuracy relative to other nondestructive examination methods, only one surface has to be accessible, and rapid results are provided. For thickness measurements digital meters are commonly used. In the pulse-echo mode an ultrasonic transducer transmits waves toward the metal surfaces, signals are reflected from the front and back surfaces, and the difference in arrival times of the two signals is used to indicate the thickness. Metal loss is then calculated by taking the difference between the as-built thickness and the thickness measured. Two types of systems are available commercially – ultrasonic thickness gage (digital display) and digital gage (A-scan, echo signals are displayed on an oscilloscope). Ultrasonic testing is commonly used in nuclear plants to monitor wall thinning of the containment vessel caused by corrosion. Rough surface conditions such as could be present on the surfaces of the metal components of BWR containment systems present problems relative to signal scattering. Because of its complexity, ultrasonic testing requires considerable technician training and skill. Also, good coupling between the transducer and component inspected is important, defects just below the surface may not be detected, and reference standards are required.

Eddy current inspection methods are based on electromagnetic induction and can be applied to electrically-conductive materials for detection of cracks, porosity, and inclusions, and to measure the thickness of nonconductive coatings on a conductive metal. In the flaw detection mode eddy current can detect surface connected or near surface anomalies. It is based on the principle that alternating current flow in a coil proximate to an electrical conductor will induce current flow in the conductor. The current flow (i.e., eddy current) creates a magnetic field that opposes the primary field created by the alternating current flow in the coil. The presence of a surface or near surface discontinuity in the conductor will alter the magnetic field (i.e., magnitude and phase) and can be sensed as a change in the flow of current in a secondary coil in the probe or change of inductance of the probe. The output signal from the detection circuit is fed to an output device, typically a meter, oscilloscope, or chart recorder. Flaw size is indicated by extent of response change as the probe is scanned along the test object. Eddy current techniques do not require direct contact with the test piece, and paint or coatings do not have to be removed prior to its application. For surface discontinuities of a given size, the sensitivity of eddy current decreases with distance below the surface. Best results are obtained when the magnetic field is in a direction that will intercept the principal plane of the discontinuity. Also, the technique requires calibration, is sensitive to geometry of the test piece, results may be affected by material variations, no permanent record is provided, and demagnification may be necessary following inspection.

Radiographic techniques involve the use of penetrating gamma or X-radiation and are based on differential absorption of the radiation. X-radiographic inspection is applied to the detection of surface connected and internal anomalies as well as the internal configuration of a test object. The source is placed close to the material to be inspected and the radiation passes through the material and is captured on film placed on the opposite side of the test article from the source. A two-dimensional projection of the area being inspected is displayed on the film (permanent record). The thickness, density, and absorption characteristics of the material affect the intensity of radiation passing through an object. Possible imperfections are indicated on the film as density changes (i.e., series of gray shades between black and white). The choice of type of source is dependent on the thickness of material to be tested. Gamma rays have the advantage of portability. Gamma radiometry systems consist of a source that emits gamma rays through the specimen and a radiation detector and counter. Direct transmission or backscattering modes can be used to make measurements. The count or count rate is used to measure the specimen dimensions or physical characteristics (e.g., density and composition). Primary limitations of radiography are that radiation protection has to be observed while applying the method, personnel must be licensed or certified, results are not immediately available, the structure must be accessible from both sides, and detection of crack-like anomalies is highly dependent on the exposure geometry and orientation of the crack with respect to incident irradiation.

Acoustic emission inspection is based on monitoring and interpretation of stress waves generated by a structure under load. Acoustic emissions are small amplitude stress waves resulting from release of kinetic energy as a material is strained beyond its elastic limit (e.g., crack growth and plastic deformation). Material stress can come from mechanical or thermal loading, as well as from a variety of other means. The stress waves propagate throughout the specimen and may be detected as small displacements by piezo-electric transducers positioned on the surface of the material. A typical acoustic emission system consists of a number of sensors, preamplifiers, signal filters, amplifier, and a recording system. Signal measurement parameters most commonly used to interpret results include ringdown counts (threshold-crossing pulses), energy counts (area under rectified signal envelope), duration (elapsed time for ringdown counts), amplitude (highest peak voltage), and rise time (time from first threshold crossing to signal peak). Primary applications of acoustic emission inspection include continuous monitoring or proof testing of critical structures, monitoring of production processes, and experimental research related to material behavior. Advantages of acoustic emission are that it is extremely sensitive, the entire structure can be monitored, it is relatively unobtrusive, onset of failure can be identified, and triangulation can be used to identify source location. Certain aspects of the corrosion process are detectable by acoustic emission (e.g., stress-corrosion cracking, hydrogen cracking, and gas evolution) (17). Disadvantages are that it requires considerable technical experience to conduct the test and interpret results, background noise can interfere with signals, and a material may not emit until the stress level exceeds a prior applied level (i.e., Kaiser effect).

Thermographic inspection methods are applied to measure a variety of material characteristics and conditions. In the flaw detection mode they are used for detection of interfaces and/or variation of properties of interfaces within layered systems. The test object must be thermally conductive and reasonably uniform in color and texture. The procedure involves inputting a pulse of thermal energy that is diffused within the test object according to thermal conductivity, thermal mass, inherent temperature differentials, and time of observation. The thermal state of the test object is monitored by a thermographic scanner camera that has infrared energy spectrum detection capability. Interpretation of results is done through visual monitoring of the relative surface temperature as a function of time and relating the time-dependent temperature differences to the internal condition of the test object. Results are recorded as a function of time and the process is relatively rapid. Specialized equipment is required and since the method is a volume inspection process, resolution is lost near the edges and at locations of nonuniform geometry change. Thermal inspection becomes less effective in the detection of subsurface flaws as the thickness of the object increases. Pulsed infrared techniques have been developed that can perform inspections through the thickness of test objects. The process basically entails providing heat through a thermal pulse or step heating, and dynamically collecting infrared images of the material surface. To be successful the heat applied at the top surface must penetrate to the bottom surface with a temperature differential of several degrees for good infrared contrast.

Electrochemical corrosion monitoring techniques are available to make measurements directly related to corrosion rate rather than indirectly in terms of the flaws produced by corrosion. Potential surveys, linear polarization, and AC impedance are techniques that have been utilized. Electrochemical potential measurements using a standard half-cell (e.g., copper-copper sulfate) can be used to locate anodic portions of a structure (i.e., potential gradients indicate possibility of corrosion). The linear polarization resistance method impresses DC current from a counter electrode onto the working electrode (e.g., steel structure). Current is passed through the counter electrode to change the measured potential difference by a known amount with the working electrode being polarized. An electronic meter measures the potential difference between the reference electrode and the working electrode. Measurements as a function of DC voltage applied across the cell provide an indirect measure of the corrosion current. The AC impedance-polarizing technique utilizes an alternating applied voltage with the data analyzed as a function of frequency. The AC technique provides polarization resistance as well as information on polarization mechanisms at the anode and cathode which is important for interpretation of the AC impedance data. The technique requires rather sophisticated equipment (e.g., AC frequency generator and analyzer system) and the Tafel slopes must be known to convert AC impedance data into corrosion rate information. Each of these methods requires contact with the part of the structure monitored, and where corrosion rates are provided the rates are only since installation and monitoring.

**Concrete Materials**

A number of nondestructive or semi-destructive examination methods are available for application to concrete and concrete-related materials (i.e., steel reinforcement and post-tensioning systems) contained in nuclear power plant containments. Primary objectives for testing concrete structures include: strength determination, comparative quality assessments, examination of local integrity, assess potential durability, and identify causes of deterioration.

## Concrete

Primary manifestations of distress that are present or can occur in concrete materials include cracking, chemical deterioration, delaminations, and strength losses. Methods used to detect discontinuities in concrete structures generally fall into two categories: direct and indirect. Direct methods involve a visual inspection of the structure, removal/testing/analysis of material(s), or a combination of the two. The indirect methods generally measure some parameter from which an estimate of the extent of degradation can be made through existing correlations. Quite often, however, evaluation of concrete materials and structures requires use of a combination of test methods since no single testing technique is available that will detect all potential degradation factors. Table 3 presents a summary of applications to determine concrete properties or characteristics for the techniques discussed below. Table 4 provides information on applications of specific methods to assess concrete degradation.

**Nondestructive Testing**. Nondestructive test methods can be used to indicate the strength, density and quality of concrete; locate voids or cracks in concrete; and locate steel reinforcement and indicate depth of concrete cover. Nondestructive testing methods include: visual inspection, audio, infrared thermography, magnetic, stress wave transmission, ground-penetrating radar, radioactive/nuclear, tomography, rebound hammer, ultrasonic pulse velocity, and modal analysis.

Visual inspection generally is the basic method used as a first step in a typical inspection program. A high quality visual inspection of exposed concrete is able to detect and define areas of aging-related distress that result in visible effects on the surface of the structure (e.g., cracking, spalling, volume change, or cement/aggregate interactions). Visual inspections also include periodic mapping and measurements to provide a history of crack appearance and development that can assist in identifying the cause and establish whether the crack is active or dormant. The primary limitation of this method is that it cannot reveal internal degradation of the concrete structure when there are no visible symptoms on the surface (e.g., subsurface cracking, voids, and delaminations; and extent of cracking). Also it is limited to accessible surfaces of the structure.

By dragging a chain across a concrete surface or using a metallic object to strike the concrete surface, it is possible to locate areas of delamination, voids, etc., through sound differentials that occur between good and defective concrete. Solid areas of concrete will produce a characteristic "metallic ringing" sound when impacted, while defects in the form of debonds, cracks, or other delamination, will produce a "hollow" sound when struck. Basic limitations of this method are that it only can be applied to local and selected test areas because of accessibility constraints and the large size of containments, it is usually effective for defects not exceeding the concrete cover depth, and it may miss small delaminations.

Infrared thermography is based on the theory of heat transfer. Since subsurface anomalies in a material affect heat flow through the material, heat transfer sensed through surface temperature variations can be used to locate subsurface voids, delaminations, or other defects. The basic equipment includes an infrared scanner head and detector capable of measuring small temperature variation to 0.1°C. The magnitude of the temperature difference between deteriorated and sound areas provides an indication on the depth of the defect. The advantage of this method is its capability to remotely cover a vast area of a concrete surface within a short period of time. The primary limitation of this method is that in order to execute this inspection method, it is necessary to produce a movement of heat in the structure, therefore, some in situ parameters such as surface moisture, ambient temperature, and wind speed could influence the accuracy of the readings.

The magnetic methods are based on the principle of magnetic induction and are applicable only to ferromagnetic materials. The method is useful in measuring the thickness of the concrete cover, and determining the size, orientation, and spacing of embedded steel reinforcement. The accuracy of rebar sizing is better than 90% when the equipment is properly calibrated. Basic limitations of this method are that for best results the spacing between two adjacent reinforcement bars must be greater than the concrete cover, and since the method is based on the induction principle, the results are affected by anything that affects the magnetic field within the range of the instrument (e.g., electrical cables, metal tie wires, iron content of cement, etc.). Experience is required for data interpretation.

The stress wave transmission methods include pulse-echo, impact-echo, and stress wave refraction. The basic principle used in all three methods is that when a stress wave produced by an impact at the concrete surface is generated, it propagates into the material as spherical and surface waves that are reflected by flaws or interfaces (e.g., voids or delaminations). Receivers, consisting of piezo-electric crystals (pulse echo) or accelerometers (impact echo), are used to pick up the return signal. Received output is displayed on a digital oscilloscope or wave-form analyzer. Analyses of results can be used to determine member thickness and to indicate the depth and approximate size of defects. The primary limitations of this method are that geometric conditions must be such that the thickness and lateral dimension of the structure have to exceed minimum requirements so that the input and reflected waves do not interfere with each other, and sophisticated signal processing is required for interpretation of the response spectra.

Ground-penetrating radar is a type of pulse-echo employing short-pulse signals with high frequency. Its most common application has been in geophysical investigations. Specialized surface-penetrating radar equipment can be used to identify reinforcing bars, voids, ducts, delaminations, and similar features. The thickness of slabs and zones of wet concrete can also be determined. The equipment consists of transmitting and receiving antennae together with a control unit and recorder. Resolution is dependent on frequency used which in turn influences the depth of penetration. Frequencies in the range of 500 MHz to 1.2 GHz typically are used to examine the reflections of short duration pulses from interfaces between materials having different dielectric constants. Results generally are presented in the form of a trace of reflected signals generated as the transmitting/receiving transducer scans the concrete surface. The method has advantages of not requiring surface contact and large areas can be quickly surveyed. Two antenna systems (Subsurface Interface Radar) have been developed that provide a more accurate determination of the amount of deterioration present (i.e., different frequency antennas detect different types and severities of defects). Disadvantages are that the equipment is expensive and highly specialized, considerable skill and experience are required to analyze and interpret data, only defects that are perpendicular to the travel of the radar pulse are detected, and the presence of moisture or nonuniform moisture distributions (e.g., thick sections) affect penetration depth.

Radioactive and nuclear techniques involve radiometry, radiography, and neutron source. Of these methods, radiography is a well established and the method most often used to examine the quality of construction or materials in concrete (e.g., prestressing cables and presence of voids, poor compaction, and reinforcement). The basic system consists of a radiation source (gamma ray) emitting a beam through the test article and a photographic film placed on the opposite side of the test article from the source. Since a high-density medium absorbs a greater amount of emitted energy, the density of the material determines the energy being absorbed by the film. A two-dimensional projection of the area being inspected is displayed on the film. Other factors that can affect the intensity of radiation passing through the test article include its thickness and absorptive characteristics. Gamma radiometry systems consist of a source that emits gamma rays through the specimen and a radiation detector and counter. Direct transmission or backscattering modes can be used to make measurements. The count or count rate is used to measure the specimen dimensions or physical characteristics (e.g., density and composition). Neutron methods consist of an emission source and a gamma ray collection and counting system. The method can be used to measure the moisture content in a structure. Primary limitations of the most commonly used of these methods, radiography, are that radiation protection has to be observed while applying this method, personnel must be licensed or certified, and the concrete structure must be accessible from both sides.

Tomography is an advanced nondestructive evaluation method based on radiography that is used to examine concrete structures for cracks, voids, and other internal defects. The advantage of this method over radiography is that it provides the possibility of internal inspections through development of three-dimensional displays from a series of reconstructed digitized detector measurements obtained from planes or slices through the thickness of the object inspected. This is accomplished by conducting a large number of two-dimensional examinations of the structure and analyzing the results with sophisticated computer software that has been developed especially for this application. Recently this technique has been extended to acoustical-based measurements in which the resulting output is a three-dimensional representation of the structure showing a spatial distribution of ultrasound data. Various aspects of the ultrsound data such as velocity and attenuation are related to concrete quality, and the location and orientation of areas of inferior material or discontinuities can be identified. In this technique a large number of measurements (e.g., ultrasonic pulse velocity) are taken to provide a network of velocities across the section. Algebraic tomographic techniques are applied to reconstruct a two-dimensional image. Then, by taking a series of continuous sections and stacking them together, a three-dimensional model is created. The primary limitations of this method are that if a complete examination is not possible because of geometrical boundary conditions, additional calculations must be made for those areas, and the method is presently costly to perform.

The rebound hammer is one of the most commonly used of the nondestructive evaluation methods. The method uses the rebound distance (measured on an arbitrary scale) of a spring-loaded weight impacted against the concrete to estimate quality or compressive strength of the in situ concrete. The primary usefulness of the rebound hammer is in assessing concrete uniformity in situ, delineating zones (or areas) of poor quality or deteriorated concrete in structures, and indicating changes with time of concrete characteristics. Primary limitations of this method are that the test results may be influenced by parameters such as the test surface smoothness, hardness, and moisture content; orientation of the hammer during impact; type of cement used; and type of aggregate. To obtain best results, application-specific calibration curves have to be developed.

Ultrasonic pulse velocity methods are commonly used to examine homogeneous materials such as metals. The method is based on the principle that the velocity of sound in a material is related to its elastic modulus and material density. Basic components of the equipment include a means for producing and introducing a pulse into the material examined, and a means for accurately measuring the time required for the pulse to travel through the material to a receiver. The condition of the material is assessed through determination of the pulse velocity and the amplitude of the stress wave at the receiver. When displaying the travel time of the sound waves between the generator and receiver versus the location, there will be a deviation in the curve at the position of the subsurface defect. By using this method it is possible to determine the concrete dynamic modulus of elasticity, Poisson's ratio, thickness, and estimate in situ compressive strength. The method also can be used to detect concrete internal structure changes, cracking or voids, and changes due to freezing and thawing or other aggressive environments. For concrete strength and related properties, the test must be calibrated to the specific concrete as the results are influenced by aggregate size, type, and gradation; cement type; water-cement ratio; admixtures; degree of compaction; curing conditions and age of the concrete; acoustical contact; concrete temperature; moisture content; size and shape of specimen; and presence of reinforcement.

Modal analysis is used to obtain response data of a structure under external or internal stimulus. Basically, the dynamic response of a structure is used to indicate its condition (i.e., defects or deterioration can be detected through comparisons of measured dynamic behavior to expected behavior. Mathematical modeling is used to compare field measured and theoretically obtained vibration modes. Two different approaches are used to obtain the dynamic response of a structure: (1) theoretical approach – involves use of models to describe structure's physical characteristics (e.g., mass, stiffness, and damping properties), structure's behavior as a set of vibration modes, and structure's vibration response under given excitation conditions; and (2) experimental approach – response of structure to a certain excitation mode is determined. The response simulation can be used to evaluate the structure. The primary limitation of this method is that modal analysis has to be executed by experienced staff and a baseline response is required for comparison.

**Destructive Testing**. Destructive tests can be utilized to determine concrete strength, density, and quality; locate voids or cracks in concrete; locate steel reinforcement and determine depth of concrete cover; and detect corrosion of steel reinforcing materials. Destructive testing techniques include (1) air permeability, (2) break-off, (3) core testing, (4) probe penetration, (5) pullout, (6) chloride-ion content, (7) carbonation depth, and (8) petrography.

The air permeability method is used to obtain values of air permeability of concrete structures. These values can give indications of the concrete resistance to carbonation, and the potential for steel reinforcement corrosion (i.e., penetration of aggressive ions). The test is conducted by first drilling a small diameter hole into the concrete and sealing it with a rubber plug. Air is extracted from the sealed hole by means of a needle that is inserted through the rubber seal and connected by a rubber hose to a mercury manometer and vacuum pump. The rate of recovery of air to the hole provides a value of the concrete air permeability. Primary limitations of this method are that sealing of the drilled hole must be complete, and the results may be affected by number of neighboring holes, diameter of test hole, moisture of the concrete, and presence of cracks.

The break-off method is used in situ to indicate concrete compressive strength. To perform this test, a 55-mm-diameter and 70-mm deep specimen is formed using a plastic cylinder placed in the fresh concrete, or drilling a core with the same outer dimensions in existing concrete. A load cell is placed into a circular groove at the top of the concrete surface and load is applied using a hydraulic pump until failure of the specimen occurs in flexure. The pressure reading of the load cell is correlated to the concrete strength by using calibration curves. The method is relatively quick to perform. Limitations of this method are that it can not be used with concrete mixes having maximum aggregate sizes exceeding 19 mm or concrete structures having sections less than 100-mm thick, it requires specialized drilling equipment for cutting a core with enlarged surface groove, and the surface may require repair.

Removal and evaluation of concrete core samples from structures provides a direct method for examination of the concrete. Cores provide the most reliable method for assessing in situ strength. Requirements for obtaining concrete samples to provide a sufficient number of specimens for statistical evaluations are generally described in national codes and standards for building and construction. When cores are removed from areas exhibiting distress, strength tests and petrographic studies (discussed later in this section) can be used to investigate the cause and extent of deterioration. Other applications of concrete cores include calibrations of nondestructive testing devices, and down-hole cameras can be used to examine the interior of the structure in locations where concrete cores were removed. Primary limitations of the method are with respect to the number of samples that must be removed to meet requirements related to ensuring that the probability of obtaining a strength less than desired is below a certain level, the results can be influenced by several factors (e.g., core diameter and slenderness ratio), and areas where cores are removed may require repair.

Probe penetration tests estimate concrete compressive strength, uniformity, or general quality through measurements of the resistance of concrete to penetration of a steel probe that is driven by a given amount of energy. Compressive strength is determined by using calibration curves. Advantages of the method are that it is quick and relatively simple to operate and the results correlate fairly well to concrete compressive strength. Primary limitations of this method are that the thickness of the specimen to be tested has to be at least three times the depth of the penetration, the method should not be applied within about 200 mm of specimen edges or other tests, and aggregate size and hardness influence results.

Originally known as cast-in-place pullout, the pullout test is performed by using a hydraulic device to pull an embedded metallic disc from concrete. The concrete compressive strength is related to the pullout force through calibration curves. It is one of the most reliable of in situ methods for concrete strength assessment. Recent developments have eliminated the requirement that the pullout inserts be cast into the specimen. Primary limitations of the test are that the results are affected by the size of coarse aggregate, and a correlation relationship between pullout strength and compressive strength is required. Also, each test may take up to 30 minutes to perform, and some repair may be required.

Determination of the concrete chloride-ion content is an important aspect of the analysis of concrete structures relative to the potential for corrosion of embedded steel reinforcement. Two of the most commonly used methods for determination of chloride contents in concrete are the water-soluble and total-chloride tests. The water-soluble test involves obtaining concrete samples by coring or drilling, and grinding the sample to produce a powder. The powder is boiled in water for five minutes and soaked for twenty-four hours. The water is then tested for dissolved chlorides with results presented as a percentage of the cement or concrete. The total-chloride test is an acid-soluble test and involves digesting a ground sample of hardened concrete in nitric acid. The solution is then tested for chloride content with results presented as a percentage by weight of the material being analyzed. Other methods that require a powder sample include x-ray fluorescence, gas chromatograph, Quantab chloride titrator strips, specific ion electrode, spectrophotometer, and argentometric digital titrator. Primary limitations of these methods are that they require coring or drilling to obtain samples at locations in a structure where chloride ion contents are desired, the test methods may be time consuming, and the chloride content reported includes chlorides that were present in the concrete mix constituents.

Depth of carbonation can be easily determined by treating a freshly broken concrete surface with phenolphthalein. The carbonated portion will be uncolored. Multicolored indicators can identify a range of pH values. Periodic determinations can be used to establish the rate of penetration. The primary limitation of this method is that it requires exposure of a fresh concrete surface for each test.

Petrographic examinations of samples of hardened concrete removed from existing concrete structures can provide valuable information for use in an aging management program. Several purposes for which petrographic examinations may be conducted include detailed determination of the condition of the concrete; determination of causes of inferior quality, distress, or deterioration; determination of whether the concrete in the structure is as specified; description of the cementitious materials matrix (e.g., kind of binder, degree of hydration, nature of hydration products, and presence of mineral admixtures); determination of the presence of alkali-aggregate reactions; determination if the concrete has been subjected to chemical attack or early freezing; determination of the nature of the air void system; and survey of the structure relative to its safety. The primary disadvantage of petrographic examinations is that they require removal of samples from the structure for test and evaluation.

## Reinforcing Steel

Assessments of mild steel reinforcing materials are primarily related to determining its characteristics (e.g., location and size) and evaluating the occurrence of corrosion. Only evaluation of the occurrence of corrosion will be addressed in this section as magnetic methods associated with determining characteristics of embedded steel reinforcing were addressed previously. Methods available for corrosion monitoring and inspection of steel include visual inspection, mechanical and ultrasonic tests, core sampling with chemical and physical testing, electrical methods (four-electrode and half-cell potential), and rate of corrosion probes. Only the electrical and rate of corrosion probe methods will be discussed as the other methods have been addressed previously.

The four-electrode method measures the apparent electrical resistivity of concrete and relates it to the probability of reinforcement corrosion. Alternating current is passed through the outer electrodes of four linearly arranged and equally spaced contact points and the potential drop between the two inner electrodes is measured. The resistivity is then determined (in ohm-cm). Depending on the value of resistivity measured, corrosion is unlikely, corrosion will probably occur, or corrosion is almost certain to occur. Limitations of this method are that the resistivity measurements are limited to relatively close to the concrete surface, and when probe spacings are increased to allow evaluations at deeper concrete depths, the steel reinforcement may interfere with results obtained. Also, actual corrosion rates can not be determined and result interpretation requires considerable experience.

An active electrochemical cell requires the presence of an electrolytic solution and a potential difference between anodic and cathodic regions. Potential measurements at a number of locations on the concrete surface using a reference half cell (e.g., copper-copper sulfate) connected to the steel reinforcement can be used to indicate the likelihood of corrosion occurrence (i.e., >90% probability of no corrosion, corrosion activity is uncertain, or >90% probability that corrosion is occurring). The surface of the concrete being investigated is usually divided into a grid system to define measurement locations. Results generally are plotted in the form of an equipotential diagram so that areas exhibiting potential corrosion can be readily identified. Modified types of instrumentation, consisting of a number of half cells mounted in parallel or on a roller bar, have been developed to accelerate the examination process. Primary limitations of this method are that neither the magnitude nor rate of corrosion are provided, surface coatings or coated steel reinforcement present problems, measurements are affected by temperature and moisture, and concrete constituents can affect results (e.g., type of cement and chloride ingress).

Probes embedded into the concrete can be used to indicate the rate of corrosion. Two primary types are available: (1) two to three short sections of steel wire or reinforcement in conjunction with polarization techniques, and (2) steel wire or hollow cylinder to provide cumulative rate of corrosion data from periodic measurements. The primary limitation of this technique is that it requires some excavation of the concrete. As a consequence, rate of corrosion probes have found primary application in evaluation of the effectiveness of rehabilitation procedures.

## Post-Tensioning Systems

Current examination methods are able to detect most postulated post-tensioning system problems as they develop. Trends established by examinations performed at the specified intervals can provide indications that the following characteristics are acceptable at least until the time of the next scheduled inspection: lift-off force, wire/strand strength and ductility, sheathing filler chemical properties, and corrosion of metallic components. The primary potential aging mechanisms associated with the post-tensioning systems in nuclear power plant containments are excessive corrosion of the prestressing steel and larger than anticipated loss of prestressing force. Inspection methods associated with detection of both of these manifestations are discussed in the balance of this section. Although both grouted and nongrouted prestressing systems have been used in the construction of concrete containments, only the nongrouted systems will be addressed because of the difficulties associated with inspection of grouted tendon systems, and prestressed concrete containments in the US primarily utilize nongrouted systems.

The end anchorage system (e.g., end cap, exposed bearing plate surfaces, and anchorheads) is examined visually for evidence of cracking, distortion, major corrosion, and broken or protruding wires. Visual inspection also includes examination of the concrete adjacent to the bearing plates for cracking or spalling that would be indicative of a bearing failure. The primary limitation of this procedure is that only visible locations can be examined.

Loss of prestressing force is not completely predictable and is measured at regular intervals to ensure that the concrete containment retains adequate capacity to resist accident pressure and coincident design loads with acceptable margins. The containment design establishes the minimum prestressing force necessary to maintain the concrete in compression (full prestressing), with a reasonable margin, under the postulated loads. Determination of the level of prestresing force is performed routinely at prescribed inspection intervals, primarily through lift-off force measurements. Results obtained are compared to design calculations of prestressing force versus time and if determined to be unacceptable, specific actions are required (e.g., increased inspection, retensioning, or replacement). It has been noted that measured tendon forces exhibit considerable scatter and there does not appear to be a consistent relationship between end anchorage force and the remaining force along the tendon length (e.e., average force may decrease with time more rapidly than the lift-off force) (18). In fact, there is the possibility that the actual minimum force in the tendon could be lower than that obtained from the measured end anchorage force. This implies that the time-dependent losses along the length of the tendon could be higher than those at the end anchorages. One opinion on this subject is that if the tendon end anchorage forces are accurately measured and if they are above the conservatively calculated lower limits, the prestressing tendon behavior can be considered as acceptable (19).

Representative samples of the tendon materials are removed to monitor for any aging effects, notably corrosion. Sections of the wire or strand, depending on tendon type, are obtained from each end and the midlength of selected tendons, cleaned, visually examined for evidence of corrosion, and tensile tests conducted (e.g., tensile strength, yield strength, and elongation). The primary limitation of this procedure is that the number of tendons examined represents a small percentage of the total population.

In order to provide a corrosion protection medium to the nongrouted tendons, the space between the post-tensioning tendon and metal sheath is filled with grease. As part of the inservice inspection program for the tendons, samples of the grease are taken at both ends of the tendons selected for examination and analyzed for free water content, reserve alkalinity, and presence of aggressive ions (i.e., chloride, sulfide, and nitrate ions). Limitations of this procedure are that only a limited sample size is evaluated and the samples may not reflect conditions at tendon midlength.

## NEEDED NONDESTRUCTIVE EXAMINATION DEVELOPMENTS

Inspection of nuclear power plant structures can be difficult because there are a number of functionally different components in a variety of environments. In the previous section it was noted that there are many techniques, both nondestructive and semi-destructive, that are available for indicating the condition of the basic components that comprise nuclear power plant containments. Application of these techniques is most effective when an approach is utilized in which the structures have been prioritized with respect to such things as aging significance, structural importance, environmental factors, and risk. Guidance on component selection is provided elsewhere (20,21). Once the components have been selected for inspection, however, there are several conditions in nuclear power plants where performing the inspections may not be straightforward. Examples of these situations where the capabilities of inspection methods require improvements or development include: inaccessible areas of containment pressure boundaries, and thick heavily-reinforced concrete sections.

## Inaccessible Area Considerations

Inspection of inaccessible portions of metal pressure boundary components of nuclear power plant containments (e.g., fully embedded or inaccessible containment shell or liner portions, the sand pocket region in Mark I and II drywells, and portions of the shell obscured by obstacles such as platforms or floors) requires special attention. Embedded metal portions of the containment pressure boundary may be subjected to corrosion resulting from groundwater permeation through the concrete; a breakdown of the sealant at the concrete-containment shell interface that permits entry of corrosive fluids from spills, leakage, or condensation; or in areas adjacent to floors where the gap contains a filler material that can retain fluids. Examples of some of the problems that have occurred at nuclear power plants include corrosion of the steel containment shell in the drywell sand cushion region, shell corrosion in ice condenser plants, corrosion of the torus of the steel containment shell, and concrete containment liner corrosion. In addition there have been a number of metal pressure boundary corrosion incidents that have been identified in Europe (e.g., corrosion of the liner in several of the French 900 MW(e) plants and metal containment corrosion in Germany). Corrosion incidences such as these may challenge the containment structural integrity and, if through-wall, can provide a leak path to the outside environment. Although no suitable technique for inspection of inaccessible portions of containment pressure boundaries has been demonstrated to date, several techniques have been proposed (i.e., ultrasonic inspection, electromagnetic acoustic transducers, half-cell potential measurements, high frequency acoustic imaging, magnetostrictive sensor technology, and guided plate waves).

Ultrasonic testing is commonly used to monitor wall thinning and can be used to detect and monitor corrosion if at least one side of the structure is accessible. In Germany, an extensive study was conducted to evaluate the feasibility of using ultrasonic methods to investigate inaccessible portions of the containment pressure boundary (22). Nondestructive tests were performed on a containment and on calibration blocks containing corrosion damage. Results of this study indicated that it was possible to detect well developed corrosion pits using 45° angle beam 2 MHz search units at distances up to 130 mm from the interface between the concrete and steel. General corrosion was found to be difficult to detect.

Electromagnetic acoustic transducers (EMATs) consist of a transmitter and receiver, both of which contain a permanent magnet or electromagnet and a coil. The transmitter coil is excited by high radio-frequency current to induce an eddy current into the surface of the metal examined. The eddy current interacts with the magnetic field generated by the transmitter coil to produce a Lorentz force in the metal that produces guided plate waves in the metal. EMATs have advantages for detection of corrosion because a couplant is not needed, the ultrasound is generated directly in the metal rather than the transducer, the high-energy waves can travel relatively long distances parallel to the plate surface, the wave velocity is independent of plate thickness, and the ultrasound can be generated through a surface coating up to about 1.5-mm-thick. EMATs were used in the laboratory to detect simulated corrosion-like defects in a 2.1-m-wide by 4.9-m-long by 25.4-mm-thick plate (23). Pulse-echo and through transmission-modes were evaluated. In the pulse-echo mode a flaw at least half-way through the plate thickness could be detected at distances to 4.6 m. In the through transmission-mode it was felt that deep corrosion damage (i.e., >75% of the plate thickness) could be detected at a distance to 15 m or more, but its location could not be determined.

As noted previously, half-cell potential measurements have been used with great success in the detection of corrosion of steel reinforcement in concrete structures. In order to obtain potential measurements on inaccessible portions of the containment metal pressure boundary the electrodes would have to be placed near the pressure boundary surface. For portions of the pressure boundary embedded in concrete this may entail drilling access holes so that the steel reinforcement in the concrete would not interfere with results provided. Although application of this technique to embedded portions of the containment pressure boundary appears feasible, no attempts at its application have been identified.

A preliminary study using analytical simulations was conducted to investigate the feasibility of using high-frequency bistatic acoustic imaging techniques for the detection and localization of thickness reductions in the metallic pressure boundary of nuclear power plant containments (24). An elastic layered media analysis code was used to perform a series of numerical simulations to determine the fundamental two-dimensional propagation physics of the nuclear power plant containment pressure boundary. Studies were conducted relative to frequency, flaw size, interrogation distance, and sensor incident angle. The analytical simulations suggest that for the case of embedded steel containments, significant (e.g., 2 mm) degradations of the containment thickness below the air/concrete interface give reasonable intrinsic backscatter signal levels of approximately –15 dB, that are 10-15 dB above the expected effective noise level due to surface imperfections. Although the embedding concrete introduces large losses, 3-4 dB two-way loss per cm of concrete, given enough sensor input power, acoustic imaging technology can be applied to this scenario. The analytical simulation also suggests that for the case of embedded steel-lined concrete containments, the thin steel liner and additional concrete backing contribute to give unacceptable loss of signal to the concrete. Approximately 100 dB of signal loss is incurred for a small degradation close to the interface. Due to this loss, it appears unlikely that acoustic imaging technology can be applied to this scenario. The study also determined that currently available piezo-electric sensors cannot be used in array configurations to interrogate a large area due to their intrinsic narrow beam pattern, which does not allow steering. This limits these sensors to spot detection and mapping scenarios, where degradation is already suspected. For wide area surveys, the use of scannable sensors appears to be applicable, but they will require development. The sensors would be manufactured by bonding many signal wires to a solid piezo-electric block on a substrate and then cutting the block into individual sensors, leaving a line array of sensors in the substrate

Magnetostrictive sensors are devices that launch guided waves and detect elastic waves in ferromagnetic materials electromagnetically to determine the location and severity of a defect based on timing and signal amplitude. Its primary application has been to piping systems (25), but preliminary numerical modeling results indicate that the technique is applicable to plate-type components. The technique is noncontact, couplant free, and requires minimum surface preparation. In addition, the technique has a sensing or inspection range from a single sensor location that can exceed several hundred feet on bare metals, the sensor can detect defects on the inside and outside diameters of pipe surfaces, and it can inspect structures whose surfaces are not directly accessible due to the presence of paint or insulation. Studies are presently underway at

Southwest Research Institute to demonstrate the feasibility of detecting and locating defects in plate-type components.

The guided wave technique (multi-mode guided plate waves) is more sensitive than techniques which utilize shear waves ( e.g., electromagnetic acoustic transducers), provides a global inspection technique for characterizing corrosion damage, follows the contour of the structure and can travel long distances (e.g., 100 m depending on frequency and mode characteristics), and can interegate different regions or cross sections (i.e., depths) of the component inspected (26,27). The guided plate waves can be excited at one point on the structure, propagate over considerable distances, and be received at a remote point on the structure. This technique has been used with success to detect defects in piping materials, but no applications to plate-type materials have been identified.

### Thick Heavily-Reinforced Concrete Sections

Current nondestructive evaluation methods for identifying concrete cracking, voids, and delaminations; and indicating the relative quality of the concrete are well developed. Nondestructive examination techniques are available for corrosion monitoring (e.g., half-cell potential and resistivity measurements). However, inspection of nuclear power plant reinforced concrete structures presents challenges different from conventional civil engineering structures in that wall thicknesses can be in excess of one meter; the structures often have increased steel reinforcement density with more complex detailing; there can be a number of penetrations or cast-in-place items present; and accessibility may be limited due to the presence of liners and other components, harsh environments, or the structures may be located below ground. Techniques are required for characterization, inspection, and monitoring of thick heavily-reinforced concrete structures to provide assurances of their continued integrity. Methods that can be used to inspect the basemat without the requirement for removal of material and techniques that can detect and assess corrosion are of particular interest. Noninvasive evaluation of the basemat and other massive concrete structures will provide assurances of their continued structural integrity, and corrosion measurements will provide information that can be used to schedule remedial actions to help plan for future expenditures and also limit the extent of structural damage. The present status of work in this area is available in proceedings of an Organization for Economic Cooperation and Development (Nuclear Energy Agency) workshop (28). The workshop objective was to develop nondestructive evaluation priorities for concrete structures in nuclear plants. Radar, acoustic, and radiography methods were identified as having the greatest potential to meet needs related to inspection of these structures. Application and qualification of these techniques to nuclear power plant structures of interest, however, requires demonstration and at present the techniques provide data that is more qualitative than quantitative.

## SUMMARY AND CONCLUSIONS

Steel and concrete containment structures in nuclear power plants are described and their potential degradation factors identified. Reported incidences of containment degradation are summarized. Current regulatory in-service inspection requirements are reviewed. Nondestructive examination techniques commonly used to inspect NPP steel and concrete capabilities and limitations identified. Techniques for inspection of metallic components to detect section thinning or flaws are fairly well established and effective where either one or both surfaces of the component are accessible. Methods for evaluating concrete structures are good at indicating the general quality of concrete, and detecting cracking, voids, or delaminations; however, methods for indicating concrete strength generally are more qualitative than quantitative because of the requirement for correlation curves. Finally, areas where nondestructive evaluation techniques require development (i.e., inaccessible portions of the containment pressure boundary, and thick heavily reinforced concrete sections) are identified and prior research addressing these needed developments summarized.

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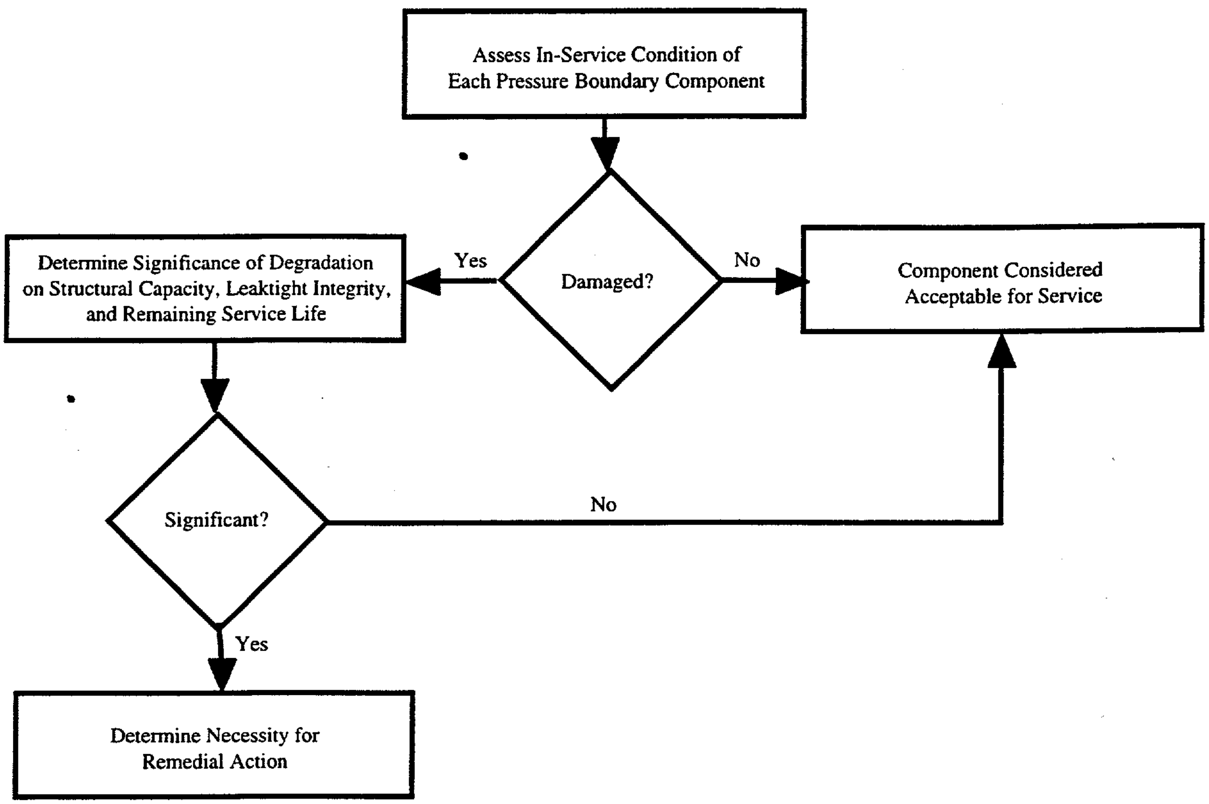


Fig. 1. Continued service evaluation process for containment pressure boundary components.

Table 1. Applicability and Important Material Characteristics of Selected Metallic Materials NDE Methods*

| Technique | Applicability by Flaw Type | | | | Important Material Characteric |
|---|---|---|---|---|---|
| | Surface | Planar** | Interior | Volumetric | |
| Visual | X | X | | X[3] | None, accessibility |
| Liquid Penetrant | X | | | X[3] | Flaw must intercept surface |
| Magnetic Particle | X | X | X[1] | X[3,4] | Material must be magnetic |
| Ultrasonic | X | X | X | X | Acoustic properties |
| Eddy Current | X | X | X | X | Material must be electrically/magnetically conductive |
| Radiography | | | X | X | Changes in thickness and density |
| Acoustic Emission | X | X | X | | Material sensitive since is AE source |
| Thermography | X | X | X[2] | X | Material heat transfer characteristics |

*Adaptation of: J. D. Wood, "Guide to Nondestructive Evaluation Techniques," ASM Handbook, Vol. 17, pp. 49-51. ASM International, Materials Park, Ohio, 1992.
**Thin in one direction.
1 = limited application, 2 = possible, 3 = surface, and 4 = subsurface.

Table 2. Dominant Sources of Variance of Selected Metallic Materials NDE Methods*

| Technique | Variance Sources | | | | | |
|---|---|---|---|---|---|---|
| | Materials | Equipment | Procedure | Calibration | Criteria | Human Factors |
| Visual | | | X | | X | X |
| Liquid Penetrant | X | | X | | | X |
| Magnetic Particle | X | X | X | | | X |
| Ultrasonic | | X | X | X | X | X |
| Eddy Current | | X | X | X | X | X |
| Radiography | X | X | X | | | X |
| Acoustic Emission | X | X | X | X | X | X |
| Thermography | | X | X | X | | X |

*Adaptation of Table 7-1 in "Nondestructive Evaluation (NDE) Capabilities Data Book," prepared by W. D. Rummel et al., Nondestructive Testing Information Analysis Center, Texas Research Institute Austin, Inc., Austin ,Texas, May 1996.

Table 3. Methods to Assess Concrete Properties or Characteristics.

| Concrete Property or Characteristic \ Evaluation Method* | Air Permeability (S) | Audio Methods (N) | Break-off Methods (S) | Carbonation Depth (D) | Chloride Testing (S) | Core Testing (D) | Infrared Thermography (N) | Instrumentation (N) | Magnetic Methods (N) | Modal Analysis (N) | Petrographic Methods (D) | Probe Penetration (S) | Pullout Testing (S) | Radar (N) | Radiation/nuclear (N) | Rebound Hammer (N) | Stress Wave Transmission (N) | Tomography (N) | Ultrasonic Pulse Velocity (N) | Visual Inspection (N) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Alkali-Carbonate Reaction | | | | | | | | | | | X | | | | | | | | | |
| Air Content | X | | | | | | | | | | X | | | | | | | | | |
| Acidity | | | | X | X | | | | | | | | | | | | | | | |
| Alkali-Silica Reaction | | | | | | | | | | | X | | | | | | | | | |
| Bleeding Channels | | | | | | | | | | | X | | | | | | | | | X |
| Cement Content | | | | | | | | | | | X | | | | | | | | | |
| Chemical Composition | | | | | | | | | | | X | | | | | | | | | X |
| Chloride Content | | | | | X | X | | | | | | | | | | | | | | |
| Compressive Strength | | | X | | | X | | | | | | X | X | | | X | | | X | |
| Concrete Cover | | | | | | X | | | X | | | | | X | | | | | | |
| Aggregate Content | | | | | | | | | | | X | | | | | | | | | |
| Mixing Water Content | | | | | | | | | | | X | | | | | | | | | |
| Corrosive Environment | X | | | X | X | | | | | | | | | | | | | | | X |
| Cracking | | X | | | | X | | X | | | X | | | X | X | | X | X | X | X |
| Creep | | | | | | X | | X | | | | | | | | | | | | |
| Delamination | | X | | | | X | X | | | | X | | | X | X | | X | X | X | X |
| Density | | | | | | X | | | | | | | | | X | | | | | |
| Elongation | | | | | | X | | X | | | | | | | | | | | | |
| Embedded Parts | | | | | | | | | | | | | | X | X | | | X | | |
| Frost Damage | | | | | | | | | | | X | | | | | | | | | |
| Honeycomb | | | | | | X | | | | | X | | | | X | | | X | X | X |
| Modulus of Elasticity | | | | | | X | | | | | | | | | | | | | | |
| Modulus of Rupture | | | | | | X | | | | | | | | | | | | | | |
| Moisture Content | | | | | | X | | | | | X | | | | | | | | | |
| Structural Performance | | X | | | | | | X | | X | | | | | | | | | | X |
| Permeability | X | | | | | | | | | | X | | | | | | | | | |
| Pullout Strength | | | | | | | | | | | | | X | | | | | | | |
| Aggregate Quality | | | | | | | | | | | X | | | | | | | | | X |
| Freeze/Thaw Resistance | | | | | | | | | | | X | | | | | | | | | |
| Soundness | | | | | | X | | | | | | | | | X | | | X | | |
| Splitting-Tensile Strength | | | | | | X | | | | | | | | | | | | | | |
| Sulfate Resistance | | | | | | | | | | | X | | | | | | | | | |
| Tensile Strength | | | X | | | X | | | | | | | | | | | | | | |
| Concrete Uniformity | | | | | | | | | | | X | | | | | X | | | | X |
| Voids | | | | | | X | | | | | | | | X | X | | X | X | X | X |
| Water-Cement Ratio | | | | | | | | | | | X | | | | | | | | | |

*(N) = nondestructive method, (S) = semidestructive method, and (D) = destructive method.
Source: "Asseessment and Management of Ageing of Major Nuclear Power Plant Components Important to Safety: Concrete Containment Buildings," IAEA-TECDOC-1025, International Atomic Energy Agency, Vienna, Austria, June 1998.

Table 4. Recommended Testing Methods to Assess Concrete Degradation

| Degradation Factor | Symptom | Testing Methods | |
|---|---|---|---|
| | | To Identify Occurrence | To Assess Extent of Damage* |
| Alkali-aggregate reactivity | Cracking<br>Expansion | 1. Core/petrography | 1. Visual and petrography<br>2. Pulse velocity<br>3. Impact echo<br>4. Pulse echo<br>5. Modal analysis |
| Sulfate attack | Cracking<br>Expansion | 1. Core/petrography<br>2. Core/chemical | 1. Visual and petrography<br>2. Pulse velocity<br>3. Impact echo<br>4. Pulse echo<br>5. Modal analysis |
| Efflorescence and leaching | Surface deposits of efflorescence | 1. Visual<br>2. Core/petrography<br>3. Sample/X-ray diffraction | 1. Visual and petrography |
| Bases/acids/salt crystallization | Disintegration and loss of paste | 1. Core/petrography<br>2. Chemical analysis | 1. Visual and petrography |
| Freeze/thaw | Scaling<br>Spalling<br>Cracking | 1. Visual<br>2. Core/petrography | 1. Visual and petrography<br>2. Pulse velocity<br>3. Impact echo<br>4. Pulse echo |
| Thermal/irradiation | Spalling<br>Cracking<br>Loss of strength | 1. Visual<br>2. Core/petrography | 1. Visual and petrography<br>2. Pulse velocity<br>3. Impact echo<br>4. Pulse echo |
| Fatigue/vibration | Microcracking<br>Cracking<br>Excessive deflection | 1. Visual<br>2. Core/petrography | 1. Visual and petrography<br>2. Pulse velocity<br>3. Impact echo<br>4. Pulse echo<br>5. Modal analysis |
| Creep | Cracking<br>Excessive deflection | 1. Visual | 1. Visual and petrography<br>2. Modal analysis |
| Reinforcement corrosion | Corrosion | 1. Visual<br>2. Core/petrography<br>3. Electrical methods<br>4. Chemical methods<br>5. Air permeability<br>6. Nuclear (moisture content) | 1. Visual and petrography<br>2. Impact echo<br>3. Pulse echo<br>4. Radiography |
| | Cracking<br>Delamination | 1. Visual<br>2. Core/petrography<br>3. Audio methods<br>4. Impact echo<br>5. Pulse echo | 1. Visual and petrography<br>2. Infrared thermography<br>3. Audio methods<br>4. Pulse velocity<br>5. Impact echo<br>6. Pulse echo |
| *Rating is based on simplicity of method and practical experience in applying method. | | | |

Source: Adaptation of "IN-Service Inspection and Structural Integrity Assessment Methods for Nuclear Power Plant Concrete structures," by T.M Refai and M. K. Lim, ORNL/NRC/LTR-90/29, Oak Ridge National Laboratory, Oak Ridge, Tennessee, September 1991.