DETECTION OF AGING OF NUCLEAR POWER PLANT STRUCTURES*
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ABSTRACT

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 numerous 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, inservice inspection (ISI) of the safety-related structures continued to be performed in a somewhat cursory manner. Starting in 1991, the U.S. Nuclear Regulatory Commission (NRC) published the first of several new requirements to help ensure that adequate ISI of these structures is performed.

Current regulatory ISI 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. The status of techniques (bistatic acoustic imaging, magnetostrictive sensors, and multimode guided waves) addressing inspection

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of inaccessible portions of the NPP containment pressure boundary and heavily-reinforced thick concrete sections is summarized. Finally recommendations for future activities are presented.

1. INTRODUCTION

1.1 Background

As of August 1998, 104 nuclear power reactors were licensed for commercial operation in the United States (1). 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 over 20 years, with 61 having been in commercial operation for 20 or more years. Expiration of the operating licenses for these reactors will start to occur early in this 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 (2). 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. A concern as plants approach the end of their initial operating license 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. One of the focusses of operating plants therefore has been benchmarking of existing design criteria and assessment of containment performance under severe accident conditions.

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 repair.

1.2 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.

1.2.1 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 *Code of Federal Regulations* (CFR) (3) 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 (4). 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 (5). 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-two of the NPPs 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* (6), 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 (7). Current rules for construction of concrete containments are provided in Section III, Division 2 of the ASME Code. The USNRC has developed supplemental load combination criteria and provides information related to concrete and steel internal structures of steel and concrete containments (8,9). 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-two of the NPPs licensed for commercial operation in the US employ either a reinforced concrete (37 plants) or post-tensioned concrete (35 plants) containment.

1.2.2 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 represents 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.

1.3 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 (10).

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 of steel containments revealed areas that were below the minimum design thickness. Two instances have been reported where corrosion has completely penetrated the liner of reinforced concrete containments. There have been four additional cases where extensive corrosion of the liner has reduced the thickness locally by nearly one-half (10). Only four of the reported 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 (11)]. 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, North Anna 2, Brunswick 2, and Salem). Also there have been incidences of transgranular stress corrosion cracking in bellows (Quad Cities 1 and 2, and Dresden 3). Table 1 presents a listing of instances of containment pressure boundary degradation at commercial NPPs in the US.

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. Additional information on degradation of reinforced concrete containments is available (12,13).

2. TESTING AND INSPECTION REQUIREMENTS

2.1 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 an 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.

2.2 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

(14). 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 (a) after the containment has been completed and is ready for operation, and (b) 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 ten 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 ten years. The USNRC position on performance-based containment leakage-rate testing is discussed in Regulatory Guide 1.163 (15). Methods considered acceptable to the USNRC Staff for complying with the provisions of Option B are provided in guidance documentation (16).

The Nuclear Energy Institute document (16) 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 (17). Licensees may elect to use other suitable methods or approaches to comply with Option B, but they must obtain USNRC approval prior to implementation.

2.3 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 CC 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.

3. 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 and environmental factors. Basic components of the continued service evaluation process for NPP containments include damage detection and classification, root-cause determination, and measurement.

3.1 Degradation Detection

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.

3.1.1 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., coating deterioration, 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 2 presents a summary of the applications by flaw type and important material characteristics for the techniques discussed below. Electrochemical corrosion monitoring techniques are also addressed.

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

Visual inspection is one of the most common and least expensive 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 in identifying areas for more detailed examination. It can identify where a failure is most likely to occur and 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 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, the 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 component's 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, 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) (18). 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 (19). Each of these methods requires contact with the part of the structure monitored, and where corrosion rates are provided the rates are only since equipment installation and initiation of monitoring.

3.1.2 Concrete Materials

Primary manifestations of distress that can occur in reinforced concrete structures include cracking and delaminations (surface parallel cracking); excessive deflections; and mechanical property (strength) losses. Whether the concrete was batched using the proper constituents and mixture proportioning, or was properly placed, compacted, and cured are important because they can affect the service life of the structure. Measurement of these factors should be part of the overall evaluation process. In-situ permeability tests can also be conducted on concrete to locate areas that are more susceptible to degradation.

3.1.2.1 <u>Nondestructive Test Methods</u>

Nondestructive test methods are used to determine hardened concrete properties and to evaluate the condition of concrete in structures. Tables 3 and 4 present nondestructive test methods for determining material properties of hardened concrete in existing construction, and to determine structural properties and assess conditions of concrete, respectively (20). A description of the method and principle of operation, as well as applications, for the most commonly used nondestructive test methods is provided elsewhere (20-24). Also, nondestructive examination of NPP concrete structures was the subject of a prior Nuclear Energy Agency workshop (25).

3.1.2.2 Destructive Test Methods

Visual and nondestructive testing methods are effective in identifying areas of concrete exhibiting distress, but often cannot quantify the extent or nature of the distress. This is generally accomplished through removal of cores or other samples using an established procedure (26).

When core samples are removed from areas exhibiting distress, a great deal can be learned about the cause and extent of deterioration through strength (27) and petrographic studies (28). Additional uses of concrete core samples include calibration of nondestructive testing devices, conduct of chemical analyses, visual examinations, determination of steel reinforcement corrosion, and detection of the presence of voids or cracks (29,30).

3.1.2.3 Mixture Composition

The question of whether the concrete in a structure was cast using the specified mixture composition can be answered through examination of core samples (31). By using a point count method (32), the nature of the air void system (volume and spacing) can be determined by examining a polished section of the concrete under a microscope. An indication of the type and relative amounts of fine and coarse aggregate, as well as the amount of cementitious matrix and cement content, can also be determined (28, 33). Determination of the original water-cementitious materials ratio is not covered by a standard test procedure, but the original water (volume of capillary pores originally filled with capillary and combined water) can be estimated (34). Thin-section analysis can also indicate the type of cementitious material and the degree of hydration, as well as type and extent of degradation. A standard method also does not exist for determination of either the type or amount of chemical admixtures used in the original mix. Determination of mixture composition becomes increasingly difficult as a structure ages, particularly if it has been subjected to leaching, chemical attack, or carbonation.

3.1.3 Steel-Reinforcing Material Systems

Assessments of the steel-reinforcing system are primarily related to determining its presence and size, and evaluating the occurrence of corrosion. Determination of material properties such as tensile and yield strengths, and modulus of elasticity, involves the removal and testing of representative samples. Pertinent nondestructive test methods that address the steel-reinforcing material system are also in Tables 3 and 4. Detailed information on the mechanism of corrosion of steel in concrete and procedures for identifying the corrosion environment and active corrosion in reinforced concrete is available (35).

3.1.4 Anchorage Embedments

Failure of anchorage embedments in concrete structures occurs as a result of either improper installation, cyclic loading, or deterioration of the concrete. Visual inspections can evaluate the general condition of the concrete near an embedment and provide a cursory examination of the anchor to check for improper embedment, weld or plate tearing, plate rotation, or plate buckling. Mechanical tests can verify that pullout and torque levels of embedments meet or exceed values required by design. Welds or other metallic components can be inspected using magnetic-particle or liquid-penetrant techniques for surface examinations, or if a volumetric examination is required, radiographic, ultrasonic, and eddy current techniques are available. Additional information on anchorage to concrete is available (36-38).

3.1.5 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. Also, loss of prestressing forces of both grouted and nongrouted systems was addressed at a prior Nuclear Energy Agency workshop (39).

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.g., average force may decrease with time more rapidly than the lift-off force) (40). 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 (41).

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.

3.2 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 (12,42). 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: thick heavily-reinforced concrete sections and inaccessible areas of containment metallic pressure boundaries.

3.2.1 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 a prior Nuclear Energy Agency workshop (25). The workshop was heldto 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.

3.2.2 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 (43). 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 (44). 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.

Exploratory analytical and experimental simulations have been conducted to investigate the feasibility of high frequency acoustic imaging techniques for the detection and localization of thickness reductions in the metallic pressure boundaries of nuclear power plant containments (45,46). The analytical study used an elastic layered media code (OASES Code, Massachusetts Institute of Technology) to perform a series of numerical simulations to determine the fundamental two-dimensional propagation physics. The analytical simulation suggests that for the case of 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 small degradations near the concrete interface. Due to this loss, it appears unlikely that acoustic imaging technology can be applied to this scenario. For embedded steel containments, analytical simulation suggests that significant degradations (i.e., 2 mm) of containment thickness below the concrete/air interface provide reasonable backscatter signal levels of approximately –15bB. This yields signals that are 10-15 dB above the expected effective noise level due to surface imperfections. It was concluded from this that given enough sensor input power, acoustic imaging technology can be applied to this scenario. The study also concluded that currently available sensors can not be used in array configurations to interrogate a large area (global inspection) 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. The competing signals from unfocused source transducers and waveguide signal distortion remain as two significant barriers for localizing and characterizing degradations. The experimental study utilized a commercial ultrasonic testing system to carry out several full-scale tests. The experimental studies were designed to also effectively restrict case scenarios to two dimensions. Measurements of 0.5 MHz shear wave levels propagated in 25-mm-thick steel plates embedded in concrete showed 1.4 to 1.6 dB of signal loss for each centimeter of two-way travel in untreated plates (compared with prior numerical predictions of 3-4 dB), and 1.3 dB of signal loss per centimeter of two-way travel in steel plates embedded in concrete prior to concrete setting (i.e., plastic). Negligible losses were measured in plates with a decoupling treatment applied between the steel and concrete to simulate unbonded portions of the pressure boundary. Scattered signals from straight slots of different size and shape were investigated. The return from a 4-mm rectangular slot cut across the width of a 25-mm-thick steel plate levels 23 dB down relative to the incidence and 4-6 dB higher than those obtained from both "V" shaped and rounded slots of similar depth. The system displayed a dynamic range of 125 dB and measurement variability less than 1-2 dB. Based on these results, a 4-mm-deep round-faced degradation embedded in 30 cm of concrete has expected returns of –73 dB relative to input and should be detectable. Analytical and experimental results indicate that this approach has merit, but needs to be demonstrated in the field.

Magnetostrictive sensors are devices that launch guided waves (or Lamb waves) and detect elastic waves in ferromagnetic materials electromagnetically to determine the location and severity of a defect based on timing and signal amplitude. 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. Its primary application has been to piping systems (47). A preliminary study has been conducted to investigate the feasibility of applying magnetostrictive sensor technology to inspection of plate type materials and evaluate its potential for detecting and locating thickness reductions in the containment metallic pressure boundary resulting from corrosion (48). In addition under this study, potential approaches for guided-wave inspection, modeling of guided-wave dispersion in plates with different boundary conditions (e.g., free standing and backed by concrete on one or both sides), and assessment of magnetostrictive sensor-based system requirements for practical implementation were evaluated. It was concluded that guided waves provide an effective means of inspection of the metallic pressure boundary in a nuclear plant and are capable of performing global, long-range inspection of plates, including areas that are difficult to access because of the presence of other equipment or attachments, or the presence of concrete on one or both sides. Limited modeling studies suggest that a low-frequency A0 mode wave (below approximately 0.5 MHz-mm, which corresponds to approximately 40 kHz in a 12.7-mm-thick plate or 20 kHz in a 25.4-mm-thick plate) would be best suited for inspection of containment pressure boundaries that are either backed on one or both sides by concrete. Other frequencies or modes such as S0 would have the inspection range significantly reduced because of the increased wave attenuation due to the concrete presence. Of the guided-wave approaches reviewed, the magnetostrictive sensor technique has the best performance in

the low-frequency operation required for a global, long-range inspection. As a result of development of this technology for commercial applications related to piping systems, tailoring an existing system to containment pressure boundary inspection should be straight forward. Results of a limited experimental study involving free plates confirms the capability of the technique to generate and detect guided waves in plates and detect a defect over a long range. Field validation of the technique is required, however.

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, can travel long distances (e.g., 100 m depending on frequency and mode characteristics), and can interrogate different regions or cross sections (i.e., depths) of the component inspected (49,50). 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 its applicability to plate-type materials has not been demonstrated. As a result, a limited investigation has been initiated to demonstrate the feasibility of the technique for identification and location of thickness reductions in the metallic pressure boundary of nuclear power plant containments (51). Although the study has only recently been initiated, initial theoretical modeling studies of the dispersion curves and scattering are available. Results for a 25.4-mm-thick steel plate show that the A0 and S0 phase velocity curves degenerate into surface wave velocities with additional guided wave modes appearing as the frequency goes higher. When the guided wave is non-dispersive (i.e., A0 and S0 modes at high frequency), there is no difference between the phase and group velocities. Group velocity is what can be measured based on the arrival time of the waveforms. An analytical experiment was conducted in which a 25.4-mm-thick free plate containing elliptical (5-mm-deep), "V" shaped (4-mm-deep), and rectangular defects (9- or 12-mm-deep) were considered. Boundary Element Methods were used to calculate the reflection and transmission ratios of various modes when the A0 or S0 mode guided wave impinges onto the defect. The frequency range used for calculations was 50kHz – 300kHz. Different modes were studied and compared in terms of testing ability and capability to properly locate defects. Results demonstrated good penetrability and sensitivity of the guided waves and have been used to select the mode for examining defects in 25.4-mm-thick by 1-m long plates embedded in concrete. One free plate and three plates embedded in concrete were considered. The free plate contained two defects ("V" and rectangular) and was useful for guided wave mode selection. Among the three plates embedded in concrete, two were embedded in larger blocks, while one was embedded in a smaller concrete block. Considering the transducer performance and the main bang length, the working frequency range was limited to 350 - 650 kHz. In this frequency range, A0 and S0 modes had the same phase velocity and the wave subsequently degenerates into surface waves, or "psuedo-surface waves". In order to generate psuedo-surface waves, the wedge angle was fixed at 75 degrees. The psuedo-surface waves were used to test the free plate and the signal obtained exhibited a clear echo from the first defect (triangular). The signal from the second defect (rectangular) was "messy." The reason for this was that for psuedo-surface waves, the energy is focussed along the plate boundary. Therefore, most of the energy will be reflected back if it impinges onto a defect close to the boundary as in this case. After the free plate tests were completed, the same mode was used for the plates embedded in concrete. Results from the first plate tested show that reflected echoes from the defects can be received from both ends of the plate, and by measuring the arrival times of the echoes, it is

known that echoes received at different ends came from different defects. This means that the signals indicate that there are two defects in the plate. Both are very close to the concrete edges. By comparing the amplitudes, it can see that one defect is most likely bigger than the other. It also can be determined which side the large defect is on by comparing the signals, assuming a pseudo-surface wave propagation mode. Tests were then conducted using the other two plates embedded in concrete blocks larger than used with the first embedded plate. The tests were run from only one side. The signals received indicate that there were also two defects in each plate embedded in the concrete. Based on the acquired signals, defect locations could be estimated. These results, although preliminary, show that the pseudo-surface waves are sensitive to defects and have good penetration ability through a plate embedded in concrete. The advantages of pseudo-surface waves include sensitivity to defects, ability to judge which side of an embedded plate the defects are located on, and good signal quality as the result of the non-dispersion feature of the mode. However, there are also some problems with the initial mode that was selected. Inspections tend to be misled somewhat by reflections from the non-uniform interface between the plate and concrete. At the high frequency range selected, the Lamb waves degenerate into pseudo-surface waves having most of the energy distribution close to the plate surface and thus are sensitive to both defects and surface conditions. This mode has difficulty in testing the defects on the bottom side of a free plate. Also the mode can not identify a second defect beyond the first defect as most energy is reflected by the first defect. One way to overcome this problem is to use lower frequency guide waves in which the A0 and S0 Lamb wave modes are generated separately so that the energy distributes itself across the plate thickness and is less sensitive to interface conditions. However, lower frequency transducers having suitable performance are not easily found and are costly. For this reason, EMATs have been tried to generate SH (horizontal shear) guided waves in the plate in a frequency range 200 kHz to 300 kHz. Early results indicate that the lower frequency SH guided waves are sensitive to the defects and not to the nonuniform plate concrete interface. Although results are preliminary, SH guided waves appear to show more promise than the pseudo-surface wave mode initially used.

4. 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 structures to identify and quantify the amount of damage present are described and their 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 research addressing these needed developments is summarized.

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Table 1. Instances of containment pressure boundary component degradation at commercial nuclear power plants in the United States.

Plant Designation (Occurrence Date) Plant Type (Source)*	Containment Description (No. of Similar Plants)	Degradation Description	Detection Method
Vermont Yankee (1978) BWR/4 (Ref. 52)	Mark I Steel drywell and wetwell (22)	Surface cracks in the overlay weld-to-torus base metal heat-affected zone	Visual examination (As part of modifications to restore the originally intended design safety margins)

Hatch 2 (1984) BWR/4 (Refs. 53, 54, and 55)	Mark I Steel drywell and wetwell (22)	Through-wall cracks around containment vent headers within the containment torus (Brittle fracture caused by injection of cold nitrogen into torus during inerting)	Visual examination of torus interior
Hatch 1 (1985) BWR/4 (Ref. 55)	Mark I Steel drywell and wetwell (22)	Through-wall crack in nitrogen inerting and purge line (Brittle fracture caused by injection of cold nitrogen during inerting)	In-service inspection testing using magnetic particle method
Monticello (1986) BWR/3 (Ref. 56)	Mark I Steel drywell and wetwell (22)	Polysulfide seal at the concrete-to-shell interface became brittle allowing moisture to reach the steel shell	Visual examination (A small portion of the drywell shell was excavated as a part of a life extension study)
Dresden 3 (1986) BWR/3 (Ref. 57)	Mark I Steel drywell and wetwell (22)	Coating degradation due to exposure to fire with peak metal temperatures of 260°C (500°F) and general corrosion of metal shell by water used to extinguish fire	Visual examination (Polyurethane between the drywell shell and concrete shield wall was ignited by arc-air cutting activities producing smoke and heat)
Oyster Creek (1986) BWR/2 (Refs. 58, 59, and 60)	Mark I Steel drywell and wetwell (22)	Defective gasket at the refueling pool allowed water to eventually reach the sand cushion region causing drywell shell corrosion	Visual examination of uncoated areas and ultrasonic inspection
Fitzpatrick (1987) BWR/4 (Refs. 56 and 61)	Mark I Steel drywell and wetwell (22)	Degradation of torus coating with associated pitting	Visual examination of uncoated areas and ultrasonic inspection (Technical specification surveillance performed during outage)
Millstone 1 (1987) BWR/3 (Ref. 61)	Mark I Steel drywell and wetwell (22)	Degradation of torus coating	Visual examination of uncoated areas and ultrasonic inspection (The torus had been drained for modifications)
Oyster Creek (1987) BWR/2 (Ref. 61)	Mark I Steel drywell and wetwell (22)	Degradation of torus coating with associated pitting	Visual examination of uncoated areas and ultrasonic inspection

Table 1. Instances of containment pressure boundary component degradation at commercial nuclear power plants in the United States (cont.).

Plant Designation (Occurrence Date) Plant Type (Source)*	Containment Description (No. of Similar Plants)	Degradation Description	Detection Method

Brunswick 1 (1987) BWR/4 (Ref. 62)	Reinforced concrete with steel liner (9)	Corrosion of steel liner	General visual examination of coated areas
Nine Mile Point 1 (1988) BWR/5 (Ref. 63)	Steel drywell and wetwell (22)	Corrosion of uncoated torus surfaces	Visual examination of uncoated areas and ultrasonic inspection
Pilgrim (1988) BWR/3 (Ref. 61)	Steel drywell and wetwell (22)	Degradation of torus coating	Visual examination of uncoated areas and ultrasonic inspection (Licensee inspection as a result of occurrences at similar plants)
Brunswick 2 (1988) BWR/4 (Ref. 62)	Reinforced concrete with steel liner (9)	Corrosion of steel liner	General visual examination of coated areas
Dresden 2 (1988) BWR/3 (Ref. 64)	Steel drywell and wetwell (22)	Coating, electrical cable, and valve operator component degradation due to excessive operating temperatures	Visual examination of uncoated areas and ultrasonic inspection (Ventilation hatches in the drywell refueling bulkhead inadvertently left closed)
Hatch 1 and 2 (1989) BWR/4 (Ref. 65)	Steel drywell and wetwell (22)	Bent anchor bolts in torus supports (due to weld induced radial shrinkage)	Visual examination
McGuire 2 (1989) PWR (Ref. 66)	Ice Condenser Reinforced concrete with steel liner (4)	Corrosion on outside of steel cylinder in the annular region at the intersection with the concrete floor	General visual examination prior to Type A leakage rate test
McGuire 1 (1989) PWR (Ref. 66)	Ice Condenser Reinforced concrete with steel liner (4)	Corrosion on outside of steel cylinder in the annular region at the intersection with the concrete floor	General visual examination (Inspection initiated as a result of corrosion detected at McGuire 2)
Catawba 1 (1989) PWR (Refs. 66 and 67)	Ice Condenser Steel cylinder (5)	Corrosion on outside of steel cylinder in the annular region	General visual examination (Inspection initiated as a result of corrosion detected at McGuire 2)
Catawba 2 (1989) PWR (Ref. 66)	Ice Condenser Steel cylinder (5)	Corrosion on outside of steel cylinder in the annular region	General visual examination (Inspection initiated as a result of corrosion detected at McGuire 2)

Table 1. Instances of containment pressure boundary component degradation at commercial nuclear power plants in the United States (cont.).

Plant Designation (Occurrence Date) Plant Type (Source)*	Containment Description (No. of Similar Plants)	Degradation Description	Detection Method

McGuire 1 (1990) PWR (Ref. 68)	Ice Condenser Reinforced concrete with steel liner (4)	Corrosion on outside of steel cylinder in the annular region	General visual examination (Follow-up inspection by licensee)
McGuire 1 (1990) PWR (Ref. 68, 69, and 70)	Ice Condenser Reinforced concrete with steel liner (4)	Corrosion on inside surface of coated containment shell under the ice condenser and between the floors near the cork filler material	Visual examination and ultrasonic inspection (Degradation possibly caused by moisture from the ice condenser or condensation)
Quad Cities 1 (1991) BWR/3 (Refs. 71, 72, and 82)	Steel drywell and wetwell (22)	Two-ply containment penetration bellows leaked due to transgranular stress-corrosion cracking	General visual examination (Excessive leakage detected)
Quad Cities 2 (1991) BWR/3 (Refs. 71 and 72)	Steel drywell and wetwell (22)	Two-ply containment penetration bellows leaked due to transgranular stress-corrosion cracking	General visual examination (Excessive leakage detected)
Dresden 3 (1991) BWR/3 (Ref. 72)	Steel drywell and wetwell (22)	Two-ply containment penetration bellows leaked due to transgranular stress-corrosion cracking	General visual examination (Excessive leakage detected)
Point Beach 2 (1992) PWR (Ref. 73)	Post-tensioned concrete cylinder with steel liner (35)	Liner plate separated from concrete	General visual examination
H. B. Robinson (1992) PWR (Ref. 73)	Post-tensioned concrete cylinder (vertical only) with steel liner (35)	Degradation of liner coating	General visual examination
Cooper (1992) BWR/4 (Ref. 73)	Steel drywell and wetwell (22)	Corrosion of interior torus surfaces and corrosion stains on exterior torus surface in one area	General visual examination
Beaver Valley 1 (1992) PWR (Refs. 73 and 74)	Subatmospheric Reinforced concrete cylinder with steel liner (7)	Corrosion of steel liner, degradation of liner coating, and instances of liner bulging	General visual examination prior to Type A leakage rate test
Salem 2 (1993) PWR (Ref. 75)	Reinforced concrete cylinder with steel liner (13)	Corrosion of steel liner	General visual examination prior to Type A leakage rate test

Table 1. Instances of containment pressure boundary component degradation at commercial nuclear power plants in the United States (cont.).

Plant Designation (Occurrence Date) Plant Type (Source)*	Containment Description (No. of Similar Plants)	Degradation Description	Detection Method

Sequoyah 1 (1993) PWR (Ref. 76)	Ice Condenser Steel cylinder with concrete shield building (5)	Degradation of moisture barriers resulting in corrosion of the steel shell	General visual examination and visual examination of coated areas
Sequoyah 2 (1993) PWR (Ref. 76)	Ice Condenser Steel cylinder with concrete shield building (5)	Degradation of moisture barriers resulting in corrosion of the steel shell	General visual examination and visual examination of coated areas
Brunswick 2 (1993) BWR (Refs. 62 and 77)	Reinforced concrete drywell and wetwell with steel liner (9)	Corrosion of steel liner	General visual examination and visual examination of coated areas (Follow-up inspection based on conditions noted in 1988)
Brunswick 1 (1993) BWR/4 (Ref. 77)	Reinforced concrete drywell and wetwell with steel liner (9)	Corrosion of steel liner	General visual examination and visual examination of coated areas (Inspection initiated as a result of corrosion detected at Brunswick 2)
McGuire 1 (1993) PWR (Ref. 78)	Ice Condenser Reinforced concrete with steel liner (4)	Main steam isolation line bellows leakage	Leakage testing conducted on bellows following successful Type A leakage rate test
Braidwood 1 (1994) PWR (Ref. 79)	Post-tensioned concrete cylinder with steel liner (35)	Liner leakage detected but not located	Type A leakage rate test
North Anna 2 (1999) PWR (Ref. 80)	Subatmospheric Reinforced concrete with steel liner (7)	6-mm-diameter hole in liner due to corrosion	General visual examination and visual examination of coated areas
Brunswick 2 (1999) BWR/4 Ref. 81)	Reinforced concrete drywell and wetwell with steel liner (9)	Corrosion of liner ranging from clusters of surface pitting corrosion to a 2-mm-diameter hole	General visual examination and visual examination of coated areas (Inspection initiated as a result of corrosion detected at Surry)

Table 2. 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 3.: – Nondestructive test methods for determining material properties of hardened concrete in existing construction (20)*

Property	Possible Methods		Comment
	Primary	Secondary	
Compressive strength	Cores for compression testing (ASTM C 42 and C 39)	Penetration resistance (ASTM C 803; pullout testing (drilled-in)	Strength of in-place concrete; comparison of strength in different locations. Drilled-in pullout test not standardized
Relative compressive strength	Rebound number (ASTM C 805); Ultrasonic pulse velocity (ASTM C 597)		Rebound number influenced by near surface properties; Ultrasonic pulse velocity gives average result through thickness
Tensile strength	Splitting-tensile strength of core (ASTM C 496)	In-place pulloff test (ACI 503R; BS 1881; Part 207)	Assess tensile strength of concrete
Density	Specific gravity of samples (ASTM C 642)	Nuclear gage	
Moisture content	Moisture meters	Nuclear gage	
Static modulus of elasticity	Compression test of cores (ASTM C 469)		
Dynamic modulus of elasticity	Resonant frequency testing of sawed specimens (ASTM C 215)	Ultrasonic pulse velocity (ASTM C 597); impact-echo; spectral analysis of surface waves (SASW)	Requires knowledge of density and Poisson's ratio (except ASTM C 215); dynamic elastic modulus is typically greater than the static elastic modulus
Shrinkage/expansion	Length change of drilled or sawed specimens (ASTM C 341)		Measure of incremental potential length change
Resistance to chloride penetration	90-day ponding test (AASHTO-T-259)	Electrical indication of concrete's ability to resist chloride ion penetration (ASTM C 1202)	Establishes relative susceptibility of concrete to chloride ion intrusion; assess effectiveness of chemical sealers, membranes, and overlays
Air content; cement content; and aggregate properties (scaling, alkali-aggregate reactivity, freeze/thaw susceptibility	Petrographic examination of concrete samples removed from structure (ASTM C 856, ASTM C 457); Cement content (ASTM C 1084)	Petrographic examination of aggregates (ASTM C 294, ASTM C 295)	Assist in determination of cause(s) of distress; degree of damage; quality of concrete when originally cast and current
Alkali-silica reactivity	Cornell/SHRP rapid test (SHRP-C-315)		Establish in field if observed deterioration is due to alkali-silica reactivity
Carbonation, pH	Phenolphthalein (qualitative indication); pH meter	Other pH indicators (e.g., litmus paper)	Assess corrosion protection value of concrete with depth and susceptibility of steel reinforcement to corrosion; depth of carbonation
Fire Damage	Petrography; rebound number (ASTM C 805)	SASW; Ultrasonic pulse velocity; impact-echo; impulse-response	Rebound number permits demarcation of damaged concrete
Freezing and thawing damage	Petrography	SASW; Impulse response	
Chloride ion content	Acid-soluble (ASTM C 1152) and water-soluble (ASTM C 1218)	Specific ion probe (SHRP-S-328)	Chloride ingress increases susceptibility of steel reinforcement to corrosion
Air permeability	SHRP surface airflow method (SHRP-S-329)		Measures in-place permeability index of the near-surface concrete (15 mm)
Electrical resistance of concrete	AC resistance using four-probe resistance meter	SHRP surface resistance test (SHRP-S-327)	AC resistance useful for evaluating effectiveness of admixtures and cemetitious additions; SHRP method useful for evaluating effectiveness of sealers

* References to test methods are provided in Ref. 20 of this paper.

Table 4 – Nondestructive test methods to determine structural properties and assess conditions of concrete(20)*

Property	Methods		Comment
	Primary	Secondary	
Reinforcement location	Covermeter; Ground penetrating radar (GPR) (ASTM D 4748)	X-ray and g-ray radiography	Steel location and distribution; concrete cover
Concrete component thickness	Impact-echo (I–E); GPR (ASTM D 4748)	Intrusive probing	Verify thickness of concrete; provide more certainty in structural capacity calculations; I–E requires knowledge of wave speed, and GPR of dielectric constant
Steel area reduction	Ultrasonic thickness gage (requires direct contact with steel)	Intrusive probing; radiography	Observe and measure rust and area reduction in steel; observe corrosion of embedded post-tensioning components; verify location and extent of deterioration; provide more certainty in structural capacity calculations
Local or global strength and behavior	Load test, deflection or strain measurements	Acceleration, strain, and displacement measurements	Ascertain acceptability without repair or strengthening; determine accurate load rating
Corrosion potentials	Half-cell potential (ASTM C 876)		Identification of location of active reinforcement corrosion
Corrosion rate	Linear polarization (SHRP-S-324 and S-330)		Corrosion rate of embedded steel; rate influenced by environmental conditions
Location of delaminations, voids, and other hidden defects	Impact-echo; Infrared thermography (ASTM D 4788); Impulse-response; Radiography; GPR	Sounding (ASTM D 4580); pulse-echo; SASW; intrusive drilling and borescope	Assessment of reduced structural properties; extent and location of internal damage and defects; sounding limited to shallow delaminations

* References to test methods are provided in Ref. 20 of this paper.