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AGING OF STEEL CONTAINMENTS AND LINERS IN NUCLEAR POWER PLANTS

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ABSTRACT*

Aging of the containment pressure boundary in light-water reactor plants is being addressed to understand the significant factors relating occurrence of corrosion, efficacy of inspection, and structural capacity reduction of steel containments and liners of concrete containments, and to make recommendations on use of risk models in regulatory decisions. Current regulatory in-service inspection requirements are reviewed and a summary of containment-related degradation experience is presented. Current and emerging nondestructive examination techniques and a degradation assessment methodology for characterizing and quantifying the amount of damage present are described. Quantitative tools for condition assessment of aging structures using time-dependent structural reliability analysis methods are summarized. Such methods provide a framework for addressing the uncertainties attendant to aging in the decision process. Results of this research provide a means for establishing current and estimating future structural capacity margins of containments, and to address the significance of incidences of reported containment degradation.

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INTRODUCTION

Background

Presently there are 109 nuclear power plants (NPPs) licensed for commercial operation in the United States with 1 reactor still under construction and 5 reactors partially completed, but under a deferred construction schedule (USNRC, 1997). The Atomic Energy Act (AEA) of 1954 limits the duration of operating licenses for most of these reactors to a maximum of 40 years. Forty-nine of these reactors have been in commercial operation for 20 or more years. Expiration of the operating licenses for these reactors will start to occur early in the next century. Under current economic, social, and political conditions in the United States, the prospects for early resumption of building of new NPPs to replace lost generating capacity are very limited (Kouts, 1995). In some areas of the country it may be too late because of the 10 to 15 years required to plan and build replacement power plants. Continuing the service of existing NPPs through a renewal of their initial operating licenses provides a timely and cost-effective solution to the problem of meeting future energy demand.

The 40-year term for an operating license provided in the AEA of 1954 apparently was based on various financial considerations (e.g., bond maturity) and not on safety or technical concerns. No technical information was presented to suggest that the NPPs would become unsafe if they were to operate after 40 years (Eisenhut and Stetson, 1987). In fact, the AEA permits the renewal of operating licenses. Paragraph 50.51 of Part 10 of the *Code of Federal Regulations (CFR)* (Office of Federal Register, 1995) implements the authority for license renewal; however, prior to recent release of a working draft of a Standard Review Plan (USNRC, 1997), no standards had been provided for preparing or evaluating license renewal applications.

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

Objective

The objectives of this work are to (1) understand the significant factors relating occurrence of corrosion, efficacy of inspection, and structural capacity reduction of steel containments and liners of concrete containments, and to make recommendations on use of risk models in regulatory decisions; (2) provide NRC reviewers a means of establishing current structural capacity margins for steel containments, and concrete containments as limited by liner integrity; and (3) provide recommendations, as appropriate, on information to be requested of licensees for guidance that could be utilized by NRC reviewers in assessing the seriousness of reported incidences of containment degradation.

Utilization of Results

Results being developed under this activity will provide background data and information for use by reviewers or licensees as part of the assessment to determine if the intent of the license renewal (*10 CFR Part 54*) and maintenance (*10 CFR Part 50.65*) rules are being met with respect to the containment pressure boundary. Information developed can be used in evaluations of the (1) in-service inspection techniques and methodologies that have been utilized as part of an overall program to ensure that the containment pressure boundary will continue to provide the required safety margins, and (2) root-cause resolution practices that have been applied to restore containment pressure boundary components that have been damaged or degraded in service. Methods established under the reliability-based condition assessment activity provide a means of establishing current capacity margin for the pressure boundary components of a structure or estimating future residual structural capacity margins.

CONTAINMENT PRESSURE BOUNDARY COMPONENTS

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

General Description

Each boiling-water reactor (BWR) or pressurized-water reactor (PWR) unit in the United States 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 depending on the nuclear steam supply system vendor, architect-engineering firm, and owner preference, leaktightness is assured by a continuous pressure boundary consisting of nonmetallic seals and gaskets, and metallic components that are either welded or bolted together. Nonmetallic components are used to prevent leakage from pumps, pipes, valves, personnel airlocks, equipment hatches, manways, and mechanical and electrical penetration assemblies. The remaining pressure boundary consists primarily of steel components such as metal containment shells, concrete containment liners, penetration liners, heads, nozzles, structural and nonstructural attachments, embedment anchors, pipes, tubes, fittings, fastenings, and bolting items that are used to join other pressure-retaining components. Each containment type includes numerous access and process penetrations that complete the pressure boundary (e.g., large opening penetrations, control rod drive removal hatch, purge and vent system isolation valves, piping penetrations, and electrical penetration assemblies). More details on information provided below can be obtained elsewhere (Smith and Gregor, 1994; Deng et al., 1994; Shah et al., 1994).

Except for spherical containments (i.e., Yankee Rowe,* Big Rock Point, and San Onofre 1*) that are exposed to the natural environment but employ extensive coating systems for protection, metal containments are free-standing, 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., earthquakes, tornadoes, or site-specific environmental events). Thirty-nine of the NPPs presently licensed for commercial operation in the United States employ a metal containment. These containments fall into six general categories: (1) BWR Mark I, (2) BWR Mark II, (3) BWR III, (4) BWR and PWR spherical, (5) PWR cylindrical with hemispherical top and ellipsoidal base, and (6) PWR cylindrical with hemispherical dome and flat base.

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. Leaktightness 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. Seventy of the NPPs that have been licensed for commercial operation in the United States employ either a reinforced concrete (30 plants) or post-tensioned concrete (40 plants) containment.

Requirements for Design and Construction

The basic laws that regulate the design (and construction) of NPPs are contained in Title 10, "Energy," of the *CFR* that is clarified by Regulatory Guides (e.g., R.G. 1.29) (USNRC, 1972), NUREG reports, Standard Review Plan [e.g., Concrete Containment (USNRC, 1981)], etc. General Design Criteria 1, "Quality Standards and Records;" 2, "Design Bases for Protection Against Natural Phenomena;" and 4, "Environmental and Dynamic Effects Design Bases," of Appendix A, "General Design Criteria for Nuclear Plants," to *10 CFR Part 50*, "Domestic Licensing of Production and Utilization Facilities," require, in part, that structures, systems, and components be designed, fabricated, erected, and tested to quality standards commensurate with the safety functions to be performed and that they be designed to withstand the effects of postulated accidents and environmental conditions associated with normal

* Presently shut-down.

operating conditions. General Design Criterion 16. "Containment Design." requires that a reactor containment and associated systems be provided to establish an essentially leaktight barrier against the uncontrolled release of radioactivity to the environment and to assure that the containment design conditions important to safety are not exceeded for as long as postulated accident conditions require. General Design Criterion 50. "Containment Design Basis." requires, in part, that the containment structure and associated systems be designed to accommodate, without exceeding the design leakage rate and with sufficient margin, the calculated pressure and temperature conditions resulting from any loss-of-coolant accident. Finally, General Design Criterion 53. "Provisions for Containment Testing and Inspection." requires that the 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 the leaktightness of penetrations which have resilient seals and expansion bellows. The General Design Criteria provide essential safety requirements for design and licensing. Basic rules for the design and construction of metal and concrete containments are prepared by the American Society of Mechanical Engineers (ASME) and published in the *ASME Boiler and Pressure Vessel Code* (ASME, 1995).

Metal Containments. Prior to 1963, metal containments for NPPs were designed according to rules for unfired pressure vessels that were contained in Section VIII of the ASME Code (ASME, 1965). 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. Almost every aspect of metal containment design is addressed by the Code, including methods for calculating required minimum thickness of pressure retaining components. 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. According to the Code, it is the Owner's responsibility to select materials that are 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. Piping, pumps, and valves that are part of the containment system or that penetrate or are attached to the containment are classified as Class 1 or Class 2 components. These components are covered by rules that appear in other subsections of Section III, Division 1 of the ASME Code.

Concrete Containments. Initially, existing building codes such as American Concrete Institute (ACI) Standard 318, *Building Code Rules for Reinforced Concrete* (ACI, 1971) 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 U.S. Nuclear Regulatory Commission (NRC) developed its own criteria for design of seismic Category I (i.e., safety related) structures (e.g., definitions of load combinations for both operating and accident conditions). Current requirements for concrete reactor vessels and containments were developed by joint technical committees of the ACI and ASME and first published in 1977 (ACI and ASME, 1977). Supplemental load combination criteria are presented in Section 3.8.1 of the NRC *Regulatory Standard Review Plan* (USNRC, 1981). Section 3.8.3 of the NRC *Regulatory Standard Review Plan* (USNRC, 1981a) provides information related to concrete and steel internal structures of steel and concrete containments. 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 (Lo et al., 1984).

Current rules for construction of concrete containments are provided in Section III, Division 2, Subsection CC of the ASME Code. Parts or appurtenances that are not backed by structural concrete for load-carrying purposes are covered by appropriate rules that appear in Section III, Division 1 of the ASME Code. 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.

Construction Materials

All containments include pipes, electrical penetration assemblies, equipment hatches, manways, air locks, etc., as part of the pressure boundary. These components generally are either welded or bolted to the liners and shells and typically have compositions and properties that are significantly different from those of the liner and shell materials. Leaktightness of the containment pressure boundary is provided by a combination of nonmetallic seals and gaskets, and metallic components that are either welded or bolted together. The metallic components of the containment pressure boundary (i.e., metallic containment and liner of reinforced concrete containments) and assessing the presence and significance of any degradation that might occur are of primary interest in this study.

The ASME Code only permits the use of certain materials for fabrication of containment pressure boundary components. These materials must conform to ASME or American Society for Testing and Materials (ASTM) specifications. Section II, Parts A and D of the ASME Code provide specifications and property values for ferrous materials that are acceptable for use. The ASME Code also specifies which grade, class, or type of steel is permitted for a particular application. Tables 2.1 and 2.3 developed by Oland (1995) provide a listing of material specifications permitted for construction of metal containments and concrete containment liners. Although the list of acceptable materials provided in this reference is fairly extensive, metal containments have primarily been fabricated of ASME SA-516 (Gr. 60 or Gr. 70), ASTM A 212 (Gr. B), and ASME SA-537 (Gr. B) materials. Mark III free-standing steel containments primarily utilize ASME SA-516 (Gr. 70) material for construction, with the shell plate in the suppression pool clad with ASME SA-240 (Type 304) stainless steel to avoid contact of the carbon steel plate with water. The steel liner plate that acts as a leaktight barrier for the reinforced concrete containments has primarily been fabricated from ASME SA-36, ASME SA-285 (Gr. A or Gr. C), ASME SA-442 (Gr. 60), or ASME SA-516 (Gr. 60 or Gr. 70) materials. Stainless steel [ASTM SA-240 (Type 304)] also has been used as liner material in some of the reinforced concrete containments.

Potential Degradation Mechanisms.

Service-related degradation can affect the ability of the containment pressure boundary to perform satisfactorily in the unlikely event of a severe accident by reducing its structural capacity or jeopardizing its leaktight integrity. Degradation is considered to be any phenomenon that decreases the load-carrying capacity of a pressure-retaining component, limits its ability to contain a fluid medium, or reduces its service life. The root cause for component 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 an excessively severe service condition. Component degradation can be classified as either material or physical damage. Determining whether material or physical damage has occurred often requires information about the service conditions to which the component was exposed and an understanding of the degradation mechanisms that could cause such damage. Information on the potential degradation mechanisms associated with these two damage classifications is provided elsewhere (Oland and Naus, 1996). Only a brief description of material and physical damage is provided below.

Material Damage. Material damage occurs when the microstructure of a metal is modified causing changes in its mechanical properties. When produced under controlled conditions, changes in the microstructure of a metal can have a beneficial effect (e.g., heat treating to produce a specified hardness). However, when the exposure conditions are not controlled, the mechanical properties (e.g., tensile and yield strength) of the affected metal can degrade to such an extent that the component is no longer suitable for its intended use. 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. 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 leaktight integrity of the component. Primary degradation mechanisms that potentially can cause physical damage to containment pressure boundary components include (1) general corrosion (atmospheric, aqueous, galvanic, stray-electrical current, and general biological); (2) localized corrosion (filiform, crevice, pitting, and localized biological); (3) mechanically-assisted degradation (erosion, fretting, cavitation, corrosion fatigue, surface flaws, arc strikes, and overload conditions); (4) environmentally-induced cracking (stress- corrosion and hydrogen-induced); and (5) fatigue. Material degradation due to either general or pitting corrosion represent the greatest potential threat to the containment pressure boundary.

Requirements for Testing and Examination

Continued integrity of the containment pressure boundary is assessed through periodic testing and examinations.

Leakage-Rate Testing. Regulations for preservice and subsequent periodic containment leakage-rate testing are provided in Appendix J to 10 CFR 50 (Office of Federal Register, 1995a, 1995b). This regulation contains 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. In September 1995, the NRC 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.

Option A—Prescriptive Requirements

According to Option A requirements, Type A, B, and C leakage-rate tests must be performed at prescribed time intervals without regard for past operations or performance history.

Type A tests are designed to measure the overall leakage rate of the entire containment system. Three Type A tests must be conducted at approximately equal time intervals during each 10-year service period. The maximum allowable leakage rate (La) for the containment system is specified in the plant technical specifications, but the acceptable leakage rate for a Type A test may not exceed 0.75 La. A general inspection of accessible interior and exterior surfaces of the containment structure and components must be performed prior to each Type A test. The purpose of the inspections, which are usually based on visual observations, is to detect any evidence of structural deterioration that could adversely affect containment structural capacity or leaktight integrity. If structural deterioration is detected, corrective actions must be taken before the Type A test can be conducted.

Type B tests are conducted to detect local leaks and to measure leakage rates across penetrations with flexible metal seals, bellows expansion joints, airlock door seals, doors and penetrations with resilient seals or gaskets, and other components. Except for airlocks, these tests are conducted during the time the reactor is shut down for refueling or at other convenient intervals, but in no case at intervals greater than two years. Airlocks must be tested at least once every six months or at more frequent intervals depending on usage. The test pressure must not be less than the pressure associated with the design basis accident.

Type C tests measure isolation valve leakage rates. These tests are conducted each time the reactor is shutdown for refueling, but in no case at intervals greater than two years. The test pressure must not be less than the pressure associated with the design basis accident. Combined allowable leakage for all penetrations and valves subject to Type B and C tests is 0.60 La.

A summary technical report containing leakage rate test results must be prepared and submitted to the NRC for each periodic test. The report must include Type A, B, and C test results, an analysis and interpretation of the Type A test results, and a summary analysis of periodic Type B and C tests that were performed since the last Type A test. A separate summary report must also be provided if any Type A, B, or C test fails to meet the acceptance criteria.

Option B—Performance-Based Requirements

Licensees may voluntarily comply with Option B requirements rather than continue using established leakage-rate test schedules. Option B allows licensees with good integrated leakage-rate test performance histories to reduce the Type A testing frequency from three tests in 10 years to one test in 10 years. For Type B and C tests, Option B allows licensees to reduce testing frequency on a plant-specific basis based on the operating experience for each component and establishes controls to ensure continued performance during the extended testing interval. The NRC position on performance-based containment leakage-rate testing is discussed in Regulatory Guide 1.163 (USNRC, 1995). Methods considered acceptable to the NRC staff for complying with the provisions of Option B are provided in guidance documentation (Nuclear Energy Institute, 1995).

The Nuclear Energy Institute document presents an industry guideline for implementing the performance-based option and contains an approach that includes continued assurance of the leakage 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 (American Nuclear Society, 1994). Licensees may elect to use other suitable methods or approaches to comply with Option B, but they must obtain NRC approval prior to implementation. However, a general inspection of accessible interior and exterior surfaces of the containment structure and components must be performed prior to each Type A test and during two other refueling outages before the next Type A test if the interval for the Type A test has been extended to 10 years (USNRC, 1995).

In-Service Inspection. Preservice and in-service inspection requirements for metal containments and liners of concrete containments, and rules for containment pressure testing, are provided in Section XI, Division 1, Subsection IWE of the ASME Code (ASME, 1995a). This consensus standard addresses examination of accessible metal surfaces; seals, gaskets, and moisture barriers; dissimilar metal welds; and pressure-retaining bolting. Requirements for system pressure testing and criteria for establishing inspection programs and pressure-test schedules are contained in Appendix J. The inspections are intended to detect problems that could adversely affect the structural capacity of the containment and to periodically verify its leaktight integrity. Inspection requirements contained in Subsection IWE of the ASME Code (1992 Edition with 1992 Addenda) have been incorporated by reference into USNRC regulations. This amendment became effective on September 9, 1996 and the utilities have five years to implement the examinations.

Containment Surfaces

Containment surface inspection requirements apply to metal containment pressure-retaining components and their integral attachments and to metallic shell and penetration liners of concrete containments. Areas requiring inspection include base metal and pressure-retaining weld surfaces that are accessible for either direct or remote visual examination. Surfaces that do not require in-service inspection include inaccessible portions of the containment and parts that are embedded in concrete. However, if there is degradation in an accessible region in close proximity to an inaccessible area, more detailed examination of this area is required. Inspection requirements for piping, pumps, and valves that complete the pressure boundary are provided elsewhere in Section XI.

Rules for containment surface inspection are intended to address the general inspection requirements specified in 10 CFR 50, Appendix J, and to provide requirements for periodic visual examinations of weld and base metal surfaces. According to the rules, containment surfaces must be inspected three times in a 10-year inspection interval. The inspections are performed during times when the plant is shutdown for refueling or maintenance. Rules pertaining specifically to general visual examinations; examinations of coated, non-coated, and weld surfaces; and containment surfaces requiring augmented examinations are provided in Subsection IWE and summarized below.

General visual examinations. A general visual examination of all accessible containment weld and base metal surfaces (not including surface areas that are submerged or insulated) is required prior to each Type A leakage-rate test or during two other refueling outages before the next Type A test if the interval for the Type A test has been extended to 10 years (USNRC, 1995). The examination is performed either directly or remotely. Conditions considered suspect are required to be further evaluated, repaired, or replaced before the Type A leakage-rate test can be performed.

Coated, non-coated, and weld surface examinations. Detailed inspections of specific containment surface areas and pressure-retaining welds are required in conjunction with the general visual examination. These inspections are conducted by direct visual examination. In areas that are painted or coated, evidence of flaking, blistering, peeling, discoloration, and other signs of distress may be considered suspect and could require further evaluation, repair, or replacement. In areas that are not coated or painted, evidence of cracking, discoloration, wear, pitting, excessive corrosion, arc strikes, gouges, surface discontinuities, dents, and other signs of surface irregularities may also require further evaluation, repair, or replacement.

When surface flaws or suspect areas requiring further evaluation are detected, supplementary surface or volumetric nondestructive examinations may be required to determine the character of the flaw or to measure the extent of degradation. Magnetic particle and liquid penetrant are two surface examination techniques that could be used to establish the size, shape, and orientation of flaws. Radiographic, ultrasonic, and eddy current are three volumetric examination techniques that are commonly used to measure the extent of subsurface degradation.

Decisions to accept, repair, or replace defective areas are often based on comparisons between current nondestructive examination results and recorded results from preservice and prior in-service examinations. Areas that have experienced change but are considered acceptable can be placed back into service without repair or replacement. However, the nondestructive examination results must be recorded for use in future evaluations, and the defective areas must be periodically reexamined until the area remains essentially unchanged for three consecutive inspection periods.

Containment surfaces requiring augmented examinations. Surface areas likely to experience accelerated degradation and aging require augmented examinations. These areas are specifically identified in the inspection program document prepared by the licensee and may include interior and exterior containment surfaces. Coated and uncoated areas requiring augmented examination are visually examined for evidence of coating degradation or surface flaws. Areas requiring further evaluation are then inspected using supplemental surface or volumetric examination techniques.

Examinations that reveal material loss exceeding 10 percent of the nominal containment wall thickness must be documented, evaluated, and then either accepted, repaired, or replaced. Flaws or degraded areas that are evaluated and considered nonstructural in nature or have no effect on the structural integrity of the containment can be considered acceptable for continued service without repair or replacement. However, areas that contain these flaws or degradation must be periodically reexamined until the area remains essentially unchanged for three consecutive inspection periods.

Seals, Gaskets, and Moisture Barriers

Containment seals, gaskets, and accessible surfaces of moisture barriers are required to be visually examined during each in-service inspection to detect wear, damage, erosion, tear, surface cracks, or other defects that could affect leaktight integrity. Seals and gaskets that are used to prevent leakage through airlocks, hatches, and other devices are required to be examined over their entire length. However, disassembly of sealed or gasketed connections is not required to merely provide access for inspection. Surfaces of containment moisture barriers that include flashing, caulking, and other sealants must be inspected if they are accessible. Moisture barriers (e.g., flashing, caulking, and other sealants), which may be located on the inside or outside of the containment and used at concrete-to-metal interfaces to prevent intrusion of moisture between the steel shell or liner and the concrete, must be inspected if they are accessible. Items considered defective must either be repaired or replaced.

Dissimilar Metal Welds

Surfaces of pressure-retaining dissimilar metal welds subject to cyclic loads and thermal stresses during normal plant operations are required to be visually examined during each in-service inspection. Dissimilar metal welds include those between carbon or low-alloy steels and high-alloy steels, carbon or low-alloy steels and high nickel alloys, and high-alloy steels and high nickel alloys. The examination area includes the weld metal and the base metal for 12.7 mm beyond the edge of the weld. Surface examinations are performed to detect planar flaws, but during any particular in-service inspection, only 50 percent of the dissimilar metal welds require inspection. Allowable flaw sizes are provided in Section XI, Division 1, Subsection IWB of the ASME Code (ASME, 1995b).

Pressure-Retaining Bolting

Pressure-retaining bolted connections are required to be examined and tested during each in-service inspection. Surfaces of bolts, studs, nuts, bushings, washers, and threads in base metal and flange ligaments must be visually inspected for defects that could cause the connection to violate either leaktight or structural integrity requirements. However, disassembly of the connection is not required to provide access for inspection. Items considered defective must be replaced.

Bolt torque or tension testing is also required during the inspection, but only for bolted connections that were not disassembled and reassembled during the inspection interval. Either bolt torque or bolt tension are required to be within limits specified in the original design documents. When no limits have been specified, acceptable bolt torque or bolt tension limits must be established and used.

System Pressure Tests

Containment system pressure testing requirements also are provided in Subsection IWE and are essentially the same as those provided in Appendix J for Type A and Type B leakage-rate testing. Requirements for Type C pressure testing of isolation values are not included because these components are not considered an integral part of the containment pressure vessel system.

Operating Experience

The carbon steel materials utilized to fabricate the steel containments and liners of reinforced concrete containments are susceptible to corrosion. As the nuclear plant containments age, degradation incidences are starting to occur at an increasing rate. Since 1986, there have been over 30 reported occurrences of degradation associated with the containment pressure boundary at U.S. commercial nuclear power plants. In two cases, thickness measurements of the walls revealed areas that were below the minimum design thickness. There have been four cases where extensive corrosion of the liner has reduced the thickness locally by nearly one-half (ASME, 1996). Table 1 presents a summary of documented instances of containment pressure boundary degradation. More detailed information related to these occurrences is aprovided by Oland and Naus (1996).

Of the over 30 instances of degradation since 1986, only four were detected through containment inspection programs conducted prior to Type A testing that were in effect at the time (i.e., preadoption by reference of basic requirements in ASME Subsection IWE). Nine of these occurrences were first identified by the NRC through its inspections or audits of plant structures. Examples of problems identified by the NRC were corrosion of the steel containment shell in the drywell sand cushion region, corrosion of the torus of the steel containment shell, and concrete containment liner corrosion. Eleven occurrences were detected by licensees while performing an unrelated activity, or after they were alerted to a degraded condition at another site.

INSPECTION OF AGED/DEGRADED CONTAINMENTS PROGRAM

The Inspection of Aged/Degraded Containments Program has several objectives that will be accomplished prior to the program's completion. Corrosion mechanisms and susceptible pressure boundary material types and locations will be identified and discussed. An assessment of available destructive and nondestructive techniques for examining the containment pressure boundary will be conducted. Effectiveness and limitations of methods available to prevent or mitigate corrosion, and root-cause resolution practices to maintain or reestablish structural capacity margins and leaktight integrity will be established. Techniques for assessing the presence and rate of occurrence of corrosion, particularly in inaccessible regions of steel containments and liners, will be identified and evaluated. Criteria will be established for evaluating weld and base metal integrity, penetration and bellows integrity and leaktightness, potential for intergranular stress corrosion cracking and fatigue cracking in metal containments, and flaw and crack sizes. A quantitative structural reliability analysis methodology will be developed for application to degraded steel containments and liners of reinforced concrete containments. Methods will be developed and implemented for estimating containment degradation rates and remaining service lives. Factored into development of the methodology will be an assessment of probabilistic risk assessment models used in previous risk assessments, and time-dependent models developed to investigate the structural reliability under both design basis and severe accident loading conditions of steel containments and liners experiencing various degrees of degradation. Fragility curves will be utilized to model the probability of structural failure under various scenarios. The methods developed for assessing the probability that containment capacity has degraded below a specified level will incorporate uncertainties in material properties, inspection/sampling results, as well as future demands imposed by operating conditions. In meeting these objectives, activities are conducted under three task areas: (1) program management, (2) steel containment/liner assessment and root-cause resolution practices, and (3) reliability-based condition assessment.

Program Management

The overall objective of the program management task is to effectively manage the technical tasks undertaken to understand the significant factors relating to occurrence of corrosion, efficacy of inspection, and structural capacity margins of steel containments and liners. Primary activities have included program planning and resource allocation, program monitoring and control, and documentation and technology transfer. Under the first of these activities a subcontract has been implemented to meet objectives of the third task area. The program monitoring and control activity has primarily addressed the preparation of management and financial reports, and participation in NRC information and review meetings. Documentation and technology transfer activities include program coordination with other government activities, participation in technology working groups such as ASME Section XI, coordination with foreign technologies, and technology exchange through participation in national and international activities such as the International Atomic Energy Agency Coordinated Research Program on Concrete Containment Buildings and the International Union of Testing and Research Laboratories for Materials and Structures committee on service life prediction of concrete structures in NPPs.

Steel Containment/Liner Assessment and Root-Cause Resolution Practices

The overall objectives of this task are to (1) identify procedures to quantitatively assess the presence, magnitude, and significance of any degradation factors that could impact structural capacity margins; and (2) provide data for use in current and future structural condition assessments. In addition, techniques will be established for (1) characterization of steel containment, steel liner, coating, and sealant materials; (2) mitigation of environmental stressor or aging factor effects; and (3) root-cause resolutions. Current activities include characterization of containment pressure boundary materials, development of a degradation assessment methodology, and evaluation of destructive and nondestructive evaluation techniques and methodologies.

Characterization of Containment Pressure Boundary Materials. Characterization of containment pressure boundary materials addressed the collection and presentation of data and information on these materials, and quantifying the affects (if any) of degradation factors such as corrosion on their properties. Desired data and information requirements for characterization of containment pressure boundary materials have been developed (i.e., general information covering a description of the material, processing information, and baseline data; material composition in terms of chemistry; and mechanical, physical, and other properties). Structural steels acceptable for use in the construction of the containment pressure boundary have been identified along with their corresponding American Society of Mechanical Engineers (ASME) and American Society for Testing and Materials specifications (ASTM) (e.g., carbon steel, ASME SA-36, and ASTM A 36). Potential nuclear power plant-related degradation factors for these materials have been identified, with corrosion being the most important. Two options were identified for presentation of the materials property data and information —incorporate additional chapters into the existing Structural Materials Information Center (Oland and Naus, 1994), or use of object-oriented relational data base software to develop a customized data base. Recommendations to guide the collection and incorporation of data and information into a database on containment pressure boundary materials have been developed (Oland, 1995).

Degradation Assessment Methodology. A degradation assessment methodology intended for use in characterizing the in-service condition of metal and concrete containment pressure boundary components and quantifying the amount of damage present has been developed (Oland and Naus, 1996). Because information required to characterize and quantify the condition of degraded components must be established on a case-by-case basis taking into consideration unique containment design features and plant operating constraints, the methodology does not include a step-by-step procedure. It has been developed in the form of general, non-prescriptive guidance.

Condition assessments are an essential element of both continued service evaluations and informed aging-management decisions. From an aging management perspective, metal and concrete pressure boundary components that exhibit satisfactory long-term performance and do not experience in-service degradation can be considered acceptable for continued service. However, components found by in-service testing or examination to be deteriorated or damaged must be evaluated to determine whether continued service is appropriate or whether repairs, replacements, or retrofits are needed. Damage is considered significant when it adversely affects structural capacity, leaktight integrity, or remaining service life. Requirements for corrective actions to be taken when evidence of structural deterioration is discovered have been identified (USNRC, 1995). More detailed acceptance standards and evaluation criteria for use in determining the acceptability of degraded components for continue service are provided in Section XI, Division 1, Subsection IWE of the ASME Code (ASME, 1995a). A diagram that illustrates the continued service evaluation process presented in Subsection IWE is shown in Fig. 1.

Continued service evaluations are performed by qualified engineers and authorized personnel who determine the adequacy of components for their intended use (ASCE, 1991). The decision-making process begins with an understanding of the in-service condition of each containment component. Condition assessments that provide essential information for continued service evaluations involve detecting damage, classifying the types of damage that may be present, determining the root cause of the problem, and quantifying the extent of degradation that may have occurred. Knowledge gained from condition assessments can serve as a baseline for evaluating the safety significance of any damage that may be present and defining in-service inspection programs and maintenance strategies. Condition assessment results can also be used to estimate future performance and remaining service life. Four primary topics are associated with in-service condition assessments for metal and concrete containment pressure boundary components – damage detection, damage classification, root-cause determination, and damage measurement. Additional details on each of these topics and their interaction are provided elsewhere (Oland and Naus, 1996).

Damage Detection

Damage detection is the first and most important step in the condition assessment process. Routine observation, general visual inspections, leakage-rate testing, and nondestructive examinations are techniques frequently used to identify areas of the containment that have experienced degradation. However, damage such as wall thinning caused by corrosion can occur in inaccessible locations making detection difficult or impossible. Knowing where to inspect and what type of damage to anticipate often requires information about the design features of the containment and the materials used to construct its pressure-retaining components.

Damage Classification

Damage occurs when the microstructure of a material is modified by exposure to a severe environment or when the geometry of a component is altered. Determining whether material or physical damage has occurred often requires information about the service conditions to which the component was exposed and an understanding of the degradation mechanisms that could cause such damage.

Root-Cause Determination

The root cause for component degradation can generally be linked to a design or construction problem, inappropriate material application, a base-metal flaw, or an excessively severe service condition. Determining what caused the degradation helps identify the type of damage that has occurred and define appropriate actions to be taken to reduce or eliminate further deterioration.

Damage Measurement

One way to evaluate the significance of containment pressure boundary component degradation on structural capacity and leaktight integrity is by comparing its preservice condition to its condition after degradation has occurred. Condition assessment accuracy depends on the availability of quantifiable evidence such as dimensions of corroded surface areas, depths of corrosion penetration, or changes in material properties that indicate the extent and magnitude of the degradation. Methods for quantifying component degradation involve either nondestructive examination or destructive testing. Results from these investigations provide a measure of the extent of degradation at the time the component was examined. Techniques for establishing time-dependent change such as corrosion and wear rates involve periodic examination or testing. In-service monitoring provides a way to measure time-dependent changes in component geometry or material properties and to detect undesirable changes in operating conditions that could affect useful service life.

Destructive and Nondestructive Evaluation Techniques. Although the performance of the containment pressure boundary has been good, as the plants age, degradation incidences (e.g., corrosion) are starting to emerge. If undetected, the possibility exists that the degradation effects may reduce the margin that the containments have to accommodate accidents. An essential element in the assessment of the integrity (or in the determination of available safety margins) of a containment structure is knowledge of the damage state of its materials of construction. Future condition assessments require not only knowledge of the current damage state, but knowledge of the change in damage state with time. In-service inspections and testing are performed to measure the current state of damage. Changes in damage state with time can be estimated through approaches such as physical models, correlation relations, or trending analyses. Many of the existing in-service inspection techniques have been developed primarily for the detection and assessment of fabrication-related flaws under controlled conditions. These techniques may not be adequate for use in helping to effectively manage the aging of the containment pressure boundary in NPPs. In addition, accessibility of the containment pressure boundary may be restricted due to the presence of coatings, its location below water level or embedded in concrete, or certain areas may be accessible only from one surface. Because of the safety significance of the containment pressure boundary, the in-service inspections generally require a higher level of reliability and more quantitative definition of defects present then those associated with the general manufacturing sector. Basic approaches used to quantify the extent of damage present, or its change with time, include nondestructive examination, destructive testing, and in-service monitoring.

Nondestructive Examination

Nondestructive examination (NDE) is the development and application of technical methods to examine materials or components in ways that do not impair their future usefulness and serviceability in order to detect, locate, measure, and evaluate discontinuities, defects, and other imperfections; to assess integrity, properties, and composition; and to measure geometrical characteristics (ASTM, 1991). From an operational viewpoint, such examinations are required to identify potential challenges to structural or leaktight integrity in time to take remedial action. They also play an important role in structural reliability assessment, especially when combined with failure analysis techniques such as fracture mechanics. Nondestructive examination provides an opportunity to revise and update the probability models used to determine current margins of safety and to forecast future reliability and performance. Factors that are important in a condition assessment include probability of detection, threshold of detection and flaw size distribution, and sizing accuracy.

The most common NDE techniques in civil structures are visual inspection, liquid penetrant, magnetic particle, ultrasonic, eddy current, and radiography. In addition to these methods, which are discussed below, there are several others in various stages of development that offer potential for detecting and quantifying defects present in inaccessible regions of the containment pressure boundary (e.g., electromagnetic acoustic transducers, magnetostrictive sensors, and high frequency bistatic aperture imaging technology) that are currently being evaluated. Visual inspection is the oldest and still most widely used NDE method. Visual inspection can identify regions of corrosion, or peeling or blistering of coatings that may indicate damage to the substrate. Liquid penetrant is effective in locating surface flaws in essentially nonporous materials. The fluorescent or visible penetrant seeps into various types of minute surface openings by capillary action, giving indications of defects. The advantage of this method is that it depends neither on ferromagnetism (as does, for example, magnetic particle inspection) nor on defect orientation as long as only surficial flaws are considered. The major limitation of liquid penetrant inspection is that it cannot detect subsurface flaws and can be excessively influenced by the surface roughness or porosity. Magnetic particle inspection is utilized to reveal surface and subsurface discontinuities in ferromagnetic materials. When the material is magnetized, a leakage field is generated by magnetic discontinuities that lie in a direction transverse to the direction of the magnetic field. The leakage field gathers and holds some of the fine ferromagnetic particles that are applied over the material surface. This forms an outline of the discontinuity and indicates its location, size, and shape. Magnetic particle inspection is capable of detecting fine, sharp and shallow surface cracks, but is not good for wide and deep defects. It cannot be used for nonferromagnetic materials. The magnetic field must be in a direction that intercepts the principal plane of discontinuity for a good result. Thin coatings of paint and other nonmagnetic coverings will adversely affect the sensitivity. Ultrasonic inspection is used to detect both surface and internal discontinuities in materials and can also be used to identify areas of thinning due to corrosion. Beams of high frequency sound waves introduced into the material attenuate due to wave scattering and are partially or completely reflected at interfaces. The reflected beam is displayed and analyzed to define the presence and location of defects such as cracks or voids. Ultrasonic inspection also can be used to measure thickness and extent of corrosion by monitoring the transit time of a sound wave through the component, or the attenuation of its energy. Ultrasonic inspection can be performed under water. Its principal advantages are its portability, and superior penetrating power and volumetric scanning ability which allow the detection of deep flaws. Its disadvantage is that defects in parts that have rough or irregular surfaces, or are very small, thin or nonhomogeneous, are difficult to detect. Eddy current is effective in detecting defects at or within a few millimeters of the surface. It is based on the principle of electromagnetic induction. Induced current flow in the test article is impeded and its direction changed (i.e., electromagnetic field is altered) by the presence of a flaw or discontinuity. Thus surface discontinuities having a combination of predominantly longitudinal and radial dimensional components can readily be detected. A majority of surface discontinuities can be detected by eddy current with high speed and low cost. If a coating is present, it need not be removed. However, the sensitivity of eddy current to defects beneath the surface is decreased. Also, laminar defects may not alter the current flow enough to be detected. Radiography methods are based on the differences in absorption by different portions of a component of penetrating radiation, such as X-ray or γ-ray. The images produced can be analyzed to locate flaws. Planar defects cannot be detected unless their principal plane is essentially parallel to the radiation beam. Tight cracks are difficult to detect regardless of orientation. In contrast to the other methods, radiography requires access to both sides of the component. Safety protocols also must be followed and radiography is relatively expensive.

None of the NDE techniques noted above are perfect. Results obtained depend on many factors, including the sensitivity of the instruments to different types of flaws; human factors such as education, training and proficiency of operators; geometry and microstructure of the component inspected; and size of flaws. Many of the NDE methods may be difficult to use in condition assessment and aging management, where quantification of flaw size is necessary and limitations on the sensitivity of NDE are amplified by difficult field conditions. The procedures used in service frequently are manual and time consuming. A flaw of a given size can be detected only with a certain probability; for any but the largest defects, however, there is a finite probability that the flaw escapes detection. Conversely, there is a possibility that NDE indicates a flaw when none is present (a so called false call); remedial actions in such a case not only would be unnecessary but might damage the structure. Moreover, the actual flaw present may not be measured accurately by the NDE method chosen.

Destructive Testing

Tests that alter the shape, form, size, or structure of the material being tested are considered destructive tests. These tests may be performed to determine mechanical, physical, chemical, thermal, or other properties of the material, or to examine the material for microstructural imperfections, voids, or inclusions. Destructive tests are commonly used to determine mechanical properties of metallic materials and can involve tension, compression, ductility, shear, torsion, bend, creep, stress-relaxation, hardness, fatigue, or fracture testing. These tests are usually conducted in room-temperature air, but they can also be performed at higher or lower temperatures or under other environmental conditions. Test methods that require the removal and testing of representative portions of material from a component are also considered destructive tests when the affected component is rendered useless or unfit for future service. As part of a damage assessment process, tension, hardness, and metallographic testing may be conducted on material samples removed from containment pressure boundary components. Measurements obtained during tension testing can be used to develop stress-strain curves and to establish mechanical property values such as the modulus of elasticity, ultimate tensile elongation, ultimate tensile strength, yield strength, and reduction of area. Property values obtained from tension testing are generally used to determine conformance or nonconformance with material specifications. However, test results can also be used to compare the performance and properties of replicate specimens tested under a variety of exposure conditions or using different testing methods. Replicate specimen results can provide a basis for establishing limits on environmental exposure, working stresses, or operating temperatures. Hardness testing (e.g., Brinell or Rockwell) that uses small diamond points or hardened round steel balls to produce permanent indentations or deformations in the surface of the material being tested, is widely used for determining the relative quality of a metallic component and to establish the uniformity of its material properties. It is relatively easy to perform, requires very little material or surface preparation, and usually causes minimal surface damage to the material or component. Metallography is the branch of science that relates to the constitution and structure, and their relation to the properties of metals and alloys. Testing is usually performed in a laboratory set up where metallic specimens are prepared for microscopic examination. These examinations are conducted to reveal the constituents and structure of the material. Metallography is probably the most useful destructive testing method available for identifying differences in material microstructure caused by exposure to high temperatures or severe environments.

In-Service Monitoring

In-service monitoring involves examination of a component while it remains in service. It is generally used for repeated examinations of a flawed component or suspect area to monitor change with time. Data collection can be performed on a case-by-case basis at irregular intervals or at prescribed times using a computer-controlled data acquisition system. Results from in-service monitoring can provide valuable information for assessing the current condition of a degraded component, estimating its remaining useful service life, and making informed aging-management decisions. An example of in-service monitoring would be on-line electrochemical measurements to establish the average degradation rate of a component caused by corrosion, or the cumulative metal loss or the instantaneous corrosion rate of a component under actual service conditions.

Reliability-Based Condition Assessments

The objectives of this task are to (1) identify mathematical models from principles of structural mechanics to evaluate degradation in strength of containment pressure boundary structures over time; (2) recommend statistically-based sampling plans for inspection of steel structures to ensure that any damage that is present will be detected with a specified level of confidence; and (3) develop reliability-based methods to assess the probability that steel containment capacity has degraded below a specified level. This task is aimed at providing quantitative evidence that the strength of the containment pressure boundary is sufficient to withstand operating and environmental events with a level of reliability that is sufficient for public health and safety.

Structural aging may cause the integrity of the containment pressure boundary to evolve over time. In particular, a hostile service environment may cause structural strength and stiffness to degrade from corrosion, fatigue, chemical attack, or internal material changes. Any evaluation of the reliability or safety margin of the containment during its service life must take into account these effects, plus any previous challenges to its integrity that may have occurred. The stochastic nature of degradation also must be taken into account: in structural condition assessment, in evaluations of proposals for service life extension, and in development of risk management policies and procedures. Numerous uncertainties complicate the evaluation of aging effects in structures. Among these are inherent randomness in structural loads, lack of in-service records of performance, epistemic uncertainties in available models for quantifying time dependent material changes and their contribution to pressure boundary degradation, inaccuracies of nondestructive evaluation techniques applied in difficult field circumstances, and shortcomings in existing methods for repair and retrofit.

Predictive models of structural performance should be based on principles of structural mechanics, supported by experimental data, to enable the changes in the structure that occur over time to be evaluated in terms of initial conditions, applied load history, and the operating environment. Unfortunately, at the current state-of-the-art, this often is not possible. For some mechanisms of degradation, such as stable crack growth under cyclic load, the mechanics of deterioration are reasonably well established. The behavioral models of other mechanisms are less certain or even unsuitable for structural analysis purposes. In some cases the models currently available for structural evaluation purposes are phenomenological in nature.

Surveys of steel containments and liners indicates that corrosion is the most significant damage mechanism affecting the NPP pressure boundary. Uniform corrosion causes a thinning of the shell, leading eventually to gross inelastic deformations or instability of the shell. Pitting corrosion is a localized effect, leading to leakage or loss of the pressure boundary. In either case, the penetration, $X(t)$, of the corrosion can be modeled by the kinetic equation.

$$X(t) = C\ (t-T_I)^m \qquad (1)$$

in which C = rate parameter, m = time-order parameter, and T_I = random corrosion initiation period. The units in Eqn. (1) are such that $X(t)$ is in μm when t and T_I are in years. The rate parameter depends on the nature of the environment, and must be determined experimentally. Typical values for uniform corrosion are in the range 100 to 200 μm. Similarly, T_I depends on the nature of the environment, and the effectiveness of protective coatings or electrochemical devices. The time-order parameter, m, typically is about 2/3 for carbon steels, and may be treated as deterministic. Statistics of the parameters C and T_I must be determined from experimental data, and depend on whether the corrosion mechanism gives rise to uniform or pitting corrosion. One must be cautious about extrapolating laboratory data to a prototype.

Structural aging and deterioration (due, e.g., to corrosion) cause the reliability of that structure to deteriorate with time. We illustrate this point with a time-dependent reliability analysis of an axisymmetric cylindrical steel ring-stiffened shell, structurally similar to a steel containment. The shell has a radius, r, and thickness, h_o, with a hemispherical end closure of the same thickness. It has ring stiffeners of cross-sectional area, A_1, placed circumferentially at intervals of S_1, and vertical stringers of area A_2 placed at intervals S_2 circumferentially in the cylindrical portion of the shell. While a finite element analysis of shell behavior often is required, particularly when the shell contains changes in thickness or penetrations, a simpler limit analysis is conservative and sufficient for purposes of this illustration. The shell is fabricated of SA516/70 steel, which has a specified yield strength of 262 MPa and a tensile strength of 483 MPa.

The design equation for this shell is (Ellingwood, et al. 1996).

$$S_{mc} = F_{yn}/SF = \sigma_d + \sigma_{pa} \qquad (2)$$

in which S_{mc} = allowable stress, F_{yn} = specified yield strength (here, 262 MPa), SF = 1.97 is the safety factor at first yield, and σ_d and σ_{pa} = stresses caused by dead load and accidental pressure load, respectively. Assuming that $\sigma_d << \sigma_{pa}$, the design thickness of the shell (based on an elastic analysis for design purposes) is.

$$h_o = P_a r/S_{mc} \qquad (3)$$

Using the nominal (design) values in Table 2, h_o = 35 mm.

Accidental pressure loads due to loss of coolant accidents are accompanied by a rise in pressure (and temperature) within the containment. As the shell begins to deform due to pressure buildup, attachments begin to fail well before general shell rupture. Thus, the governing limit state is one of excessive general inelastic deformation. The limit pressure, P_o, corresponding to the onset of critical deformation for an axisymmetric shell is.

$$P_o = F_y(h(t)/r)\gamma \qquad (4)$$

in which F_y = (random) yield strength, γ is a factor that takes into account the plastic deformation of the shell and the contributions of the stiffness (Greimann, et al. 1982).

$$\gamma = (2/\sqrt{3}) + A_1/(S_1 h(t)) \qquad (5)$$

The parameter $h(t)$ is the random thickness of the shell at time, t, taking into account any corrosion loss: $h(t) = h_o - X(t)$ (cf Eqn. 1). The margin of safety at any time thus is.

$$M(t) = P_o(t) - P(t) \qquad (6)$$

in which $P(t)$ = random pressure arising from the accident. Substituting Eqns. (4 and 5) into Eqn. (6) yields.

$$M(t) = F_y(h(t)/r)\gamma - P(t). \qquad (7)$$

With the margin of safety thus defined, the time-dependent reliability analysis can proceed using stochastic methods similar to those already developed for the analysis of degrading reinforced concrete structural components and systems (Ellingwood and Mori, 1993; Naus, et al. 1993; Ellingwood and Bhattacharya, 1997). The probability of surviving interval of time (0,t) is defined by the reliability function, L(t):

$$L(t) = P[M(t_1) > 0,\ M(t_2) > 0, \ldots,\ M(t_N) > 0] \qquad (8)$$

in which $t_1, t_2, \ldots, t_N$ = times at which the extreme loads occur. Accidents are extremely rare and, for purposes of reliability analysis, their occurrence can be modeled as a Poisson (Hwang, et al. 1985). Table 2 summarizes statistical data on other parameters required to evaluate Eqns. (7) and (8). The corrosion rate parameter C = 300 μm/yr leads to a loss of 10% of the shell thickness in 60 years. Dimensional variabilities are insignificant in NPP construction, and thus structural dimensions are assumed to be deterministic.

Figure 2 shows the effect of corrosion rate and mean rate of occurrence of accidental pressurization on cumulative failure probability (CFP), defined as 1 - L(t). The reliability of the shell is found to depend significantly on the corrosion rate, severe corrosion causing an increase in the CFP of four orders of magnitude. Sensitivity studies conducted with this simple model allow insights and perspectives that can guide and channel subsequent finite element analyses of degraded steel containments, which are computationally more involved. For example, preliminary results indicate that the random corrosion initiation period, T_c in Eqn. 1, is more significant for structural reliability assessment than the corrosion rate parameter, C, for steel plates with thicknesses that are typical in NPPs (25 - 35 mm). Moreover, as observed earlier with NPP concrete structures (Naus, et al. 1996) the conditional failure rate of an aging steel structure increases nonlinearly with time. Finally, curves such as those presented in Fig. 2 can be used to schedule in-service inspection and repair, once a target reliability goal is identified.

In contrast to corrosion, some damage mechanisms, such as fatigue crack initiation, elevated temperature creep, and irradiation effects involve microstructural changes in the steel that either may not become detectable with common NDE methods until significant damage has already occurred, or may become evident only at the point at which damage is accelerating rapidly. Continuum damage mechanics (CDM) deals with the characterization and analysis of growth of strength-reducing microstructural defects with the help of macroscopic state variables (Lemaitre, 1984). CDM makes it possible to predict the effects of damage processes on structures prior to the development of detectable flaws. Expressions for damage can be developed from principles of thermodynamics, and have been validated with limited experimental data (Bhattacharya and Ellingwood, 1996). Damage accumulation can be described by a stochastic differential equation, which can be solved numerically (Bhattacharya and Ellingwood, 1996 a).

Statistical data are necessary to support the predictive damage models and reliability analyses described above. Quantification of uncertainties in loads, degradation mechanisms, and structural response is essential. A preliminary assessment of NDE methods also has been performed (Ellingwood, et al. 1996), with particular attention to determining probabilities for detecting flaws of various sizes and quantifying flaw measurement errors statistically.

APPLICATION OF RESULTS

Potential regulatory applications of this work include (1) improved predictions of long-term material and structural performance and available safety margins at future times; (2) establishment of limits on exposure to environmental stressors; (3) capability for assessment of structural integrity through a combination of reliability-based condition assessment and inspection/surveillance (pre- or post-accident) with possible lengthening of inspection frequencies for some components; (4) improvements in damage inspection methodology through potential incorporation of results into national standards that could be referenced by standard review plans.

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Table 1. Summary of metal and concrete containment pressure boundary component degradation occurrences.

Containment Type	Degradation Description	Affected Component	Number of Similar Occurrences
Metal	Corrosion	Steel shell or other pressure-retaining component	12
Metal	Cracking	Bellows	4
Metal	Coating degradation in high-temperature environment	Steel shell	2
Metal	Coating degradation in aqueous environment	Steel shell (torus)	4
Metal	Cracking	Steel shell (torus)	1
Metal	Brittle fracture	Vent header (inside torus) or nitrogen purge line	2
Metal	Torus anchor bolt deformation	Anchor bolts (torus)	1
Concrete	Corrosion	Steel liner	6
Concrete	Coating degradation	Steel liner	2
Concrete	Liner plate separation	Steel liner	2
Concrete	Liner leakage	Steel liner	1

Table 2. Statistical Data

Variable	Nominal	Mean	Coefficient of Variation	Probability Distribution Function
Radius, r	17m	17m	-	-
Thickness, h_o	35 mm	35 mm	-	-
Stringer area, A_1	155 cm^2	155 cm^2	-	-
Stringer spacing, S_1	3 m	3 m	-	-
Yield strength, F_y	262 MPa	288 MPa	0.07	Lognormal
Corrosion rate, C	-	300 μm/yr	0.30	Lognormal
Initiation time, T_I	-	10 yr	0.30	Lognormal
Peak pressure, P_a	0.28 MPa	0.22 MPa	0.20	Type I

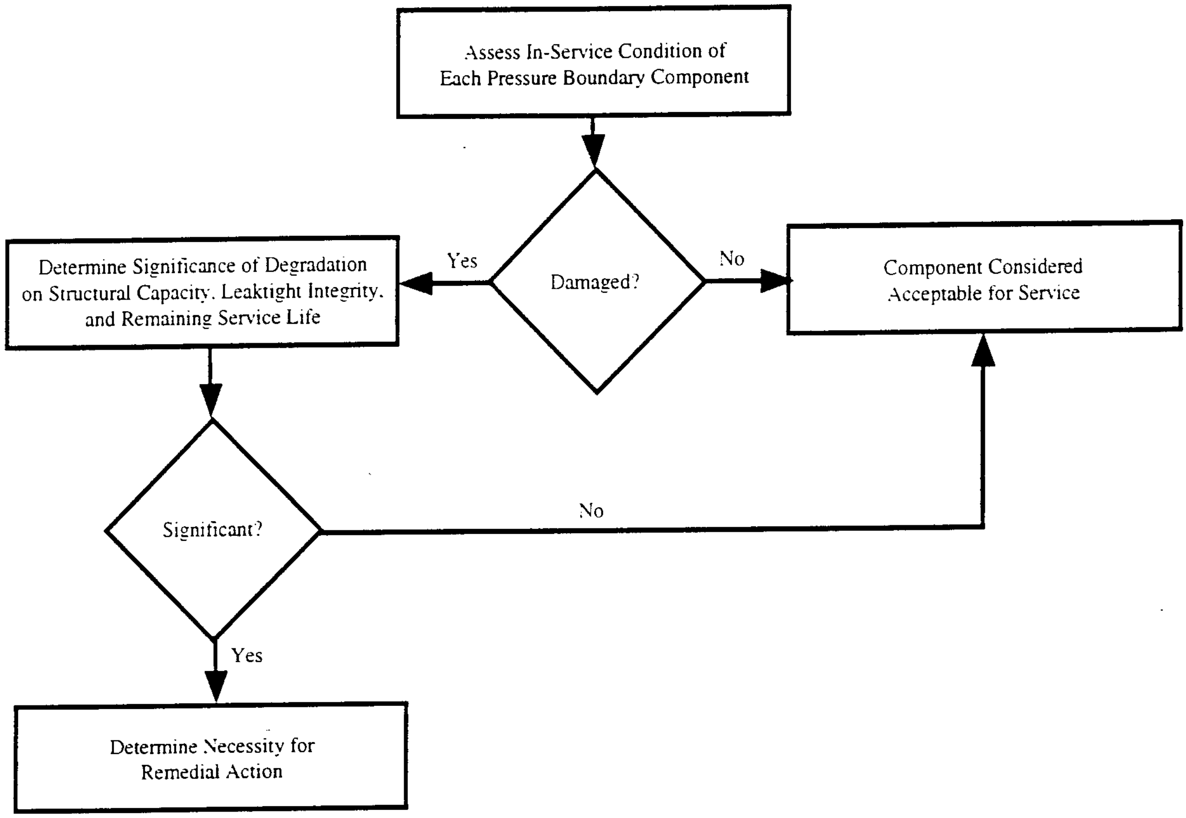

Fig. 1. Continued service evaluation process for containment pressure boundary components

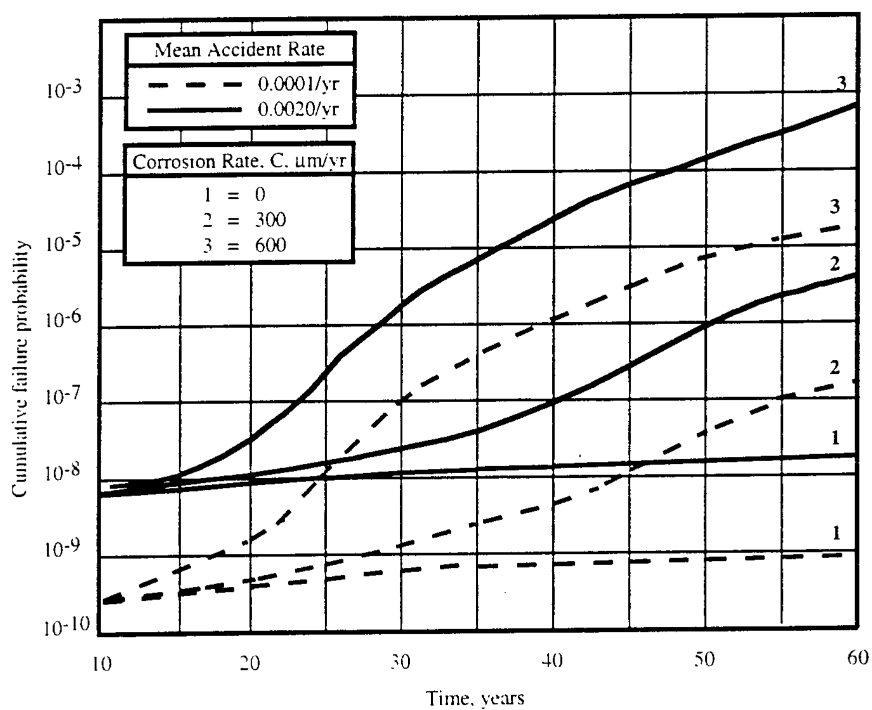

Fig. 2. Time-dependent reliability of steel cylindrical shell: effect of corrosion and load rate

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