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# Nuclear Power Plant Containment Pressure Boundary Aging Research

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## ABSTRACT

Research to address aging of the containment pressure boundary in light-water reactor plants is summarized. This research is aimed at understanding the significant factors relating occurrence of corrosion, efficacy of inspection, and structural capacity reduction of steel containments and liners of concrete containments. This understanding will lead to improvements in risk-informed regulatory decision making. Containment pressure boundary components are described and potential aging factors identified. Quantitative tools for condition assessments of aging structures to maintain an acceptable level of reliability over the service life of the plant are discussed. Finally, the impact of aging (i.e., loss of shell thickness due to corrosion) on steel containment fragility for a pressurized water reactor ice-condenser plant is presented.

## INTRODUCTION

As of April 1998 there are 110 commercial power reactors that have been licensed for operation in the United States (US). By the end of this decade, over 60 or these plants will be 20 or more years old, with some nearing the end of their 40-year operating license. Under current economic, social, and political conditions in the US, the prospects for early resumption of building of new nuclear power plants (NPPs) to replace lost generating capacity are very limited (**1**). 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.

## CONTAINMENT PRESSURE BOUNDARY

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 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. Each containment type also 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).

The American Society of Mechanical Engineers (ASME) Code (**2**) 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. Tables 2.1 and 2.3 presented in Reference (**3**) 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. 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. 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.

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 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 its leaktight integrity. 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.

## OPERATING EXPERIENCE

As nuclear plant containments age, degradation incidences are starting to occur at an increasing rate, primarily due to environmental-related factors. Since 1986, there have been at least 32 reported occurrences of corrosion of steel containments or liners of reinforced concrete containments. In two cases, thickness measurements of the walls revealed areas that were below the minimum design thickness. There have been four cases where extensive corrosion of the liner has reduced the thickness locally by nearly one-half (4). Examples of problems identified include corrosion of the steel containment shell in the drywell sand cushion region (Oyster Creek), shell corrosion in ice condenser plants (Catawba and McGuire), corrosion of the torus of the steel containment shell (Fitzpatrick, Cooper, and Nine Mile Point Unit 1), coating degradation (Dresden 3, Fitzpatrick, Millstone 1, Oyster Creek, Pilgrim, and H. B. Robinson), and concrete containment liner corrosion (Brunswick, Beaver Valley, and Salem). There also have been incidences of transgranular stress corrosion cracking in bellows (Quad Cities 1 and 2, and Dresden 3).

## ASSESSMENT OF AGED/DEGRADED CONTAINMENTS

As a part of the overall USNRC research program to benchmark existing design criteria and evaluate containment performance under severe accident conditions, research is being conducted related to condition assessment and repair practices, and performance of degraded containments (i.e., corroded) during events at or beyond the design basis.

### Condition Assessment and Repair Practices

Condition assessments are an essential element of both continued service evaluations and informed aging-management decisions. Continued service evaluations are performed by qualified engineers and authorized personnel who determine the adequacy of components for their intended use (2,5). The decision-making process begins with an understanding of the in-service condition of each component or system. 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. A degradation assessment methodology for use in characterizing the in-service condition of containment pressure boundary components has been developed (6).

If undetected, the degradation effects may reduce the margin that a containment has to accommodate accidents. An essential element in the assessment of the integrity (or in the determination of available safety margin) of a containment structure is knowledge of the damage state of its materials of construction. In-service inspections and testing are performed to measure the current state of damage. The most common nondestructive examination (NDE) techniques in civil structures are visual inspection, liquid penetrant, magnetic particle, ultrasonic, eddy current, and radiography. A summary of these techniques is provided elsewhere (7). In addition to these techniques, 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., ultrasonic (8), electromagnetic acoustic transducers (9), magnetostrictive sensors (10), high frequency bistatic aperture imaging technology (11), and ultrasonic multimode guided wave techniques (12,13)]. Application of NDE while the component remains in-service (i.e., 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.

Whenever minor damage is detected, corrective actions are usually taken to identify and eliminate the source of the problem and thereby halt the degradation process. However, when significant wall thinning, cracking, surface defects, or leakage is detected and containment structural or leaktight integrity is potentially jeopardized, defective areas are either evaluated, repaired, or replaced before the plant is returned to service. The primary mechanism of concern to the containment pressure boundary is corrosion. Methods to prevent the occurrence of corrosion primarily include the application (or maintenance) of coatings to exposed steel that is at risk, and use of cathodic protection systems (i.e., impressed current or sacrificial anode). Repair methods generally include: (1) defect removal by mechanical means in which the unacceptable flaw is reduced and the resultant section thickness created by the removal process is equal to at least the minimum design thickness; (2) repair welding in which the design section thickness is reestablished (e.g., cladding); and (3) component replacement with items that meet acceptance standards. Repair options for restoring damaged bellows include replacement of penetration assembly, bellows replacement, installation of new enveloping bellows, in-place welding repairs, removal of severe dents, and blending the surface. Detailed information on repair of the containment pressure boundary components is available elsewhere (14).

### Performance of Degraded Containments

Structural aging as a result of the operating environment, improper construction, load history, and misuse can cause the strength and stiffness of a structure to deteriorate over its service life. The performance of a containment during events at or beyond the design basis is governed by factors that are uncertain in nature. These uncertainties must be taken into account in rational structural evaluation and decision making. Probability and statistics provide the framework for the analysis of these uncertainties (15). The resistance of a steel containment (or concrete containment with liner) can be modeled probabilistically by a containment fragility. Structural degradation causes the fragility to vary in time.

Fragility analysis is a technique for assessing the capability of a structural system to withstand specified (sometimes referred to as screening or review-level) events in excess of the design-basis event. This assessment process sometimes is referred to as a "safety-margin analysis." During the last decade it has been used to determine the capability of NPP structural components and systems to withstand, with high confidence, review-level earthquakes of a prescribed level in excess of the safe-shutdown earthquake. If the system can be shown by such an analysis to perform safely at the review level, it might be judged sufficient for public safety regardless of what the actual (unknown) hazard might be. A fragility analysis of a structure enables system vulnerabilities to be identified because of the supporting system analysis that underlies the fragility model. Moreover, it is a necessary ingredient, when integrated with stochastic hazard models, of a fully-coupled time-dependent reliability analysis.

The impact of postulated corrosion patterns in the Sequoyah Unit 1 containment behind the ice basket and at the level of the upper floor have been considered. First, the fragility of the undegraded (uncorroded) containment is established as a benchmark. Subsequently, corrosion patterns that are consistent with field investigation findings in similar containments are postulated, and the fragilities reassessed. For both analyses, the uncertainties are propagated using a Latin Hypercube sampling plan, and points of failure are identified through postprocessing the structural response data calculated by a nonlinear finite-element analysis (ABAQUS). The statistically-based sampling plan minimizes the finite element computations required to develop the fragility curve. The estimated 5-percentile then gives a statistically-based indication of the lower bound on containment capacity, and can be used as a screening tool to determine whether more refined further analyses or tests to support service life evaluations are warranted.

The statistics used to construct the Latin Hypercube samples and perform the fragility analysis are presented elsewhere (16). Fourteen Latin Hypercube samples were selected so that the minimum and maximum samples would plot at approximately the 5-percentile and the 95-percentile cumulative probabilities using plotting positions that approximate the rank medians. The results of the 14 benchmark containment analyses were post-processed, rank-ordered, and plotted on probability paper (Fig. 1). The mean (and median) containment capacity is 455 kPa, and the logarithmic standard deviation is 0.04. The 5-percentile exclusion limit is estimated at 427 kPa. Also shown in this figure are the fragilities for the postulated degraded (corroded) conditions (i.e., mean corrosion losses of 10% and 25% of the shell thickness behind the ice basket, and losses of 50% at the upper floor level). For 25% loss of section (approximately 4 mm) the mean pressure at containment failure by tensile instability was 386 kPa at an effective limiting plastic strain of 0.048; the estimated 5% and 95% values of capacity are 352 kPa and 427 kPa. The coefficient of variation in capacity has increased to 0.06 over the benchmark case. Overall, results show that the reduction in fragility at all fractiles is nonlinearly proportional to the median percentage loss in thickness, with a larger decrease occurring between the undegraded condition and 10% loss than between the 10 and 25% losses. This reduction occurs because the fracture ductility of a corroded section decreases by a factor of approximately 2, regardless of the corrosion penetration. The variability in section loss is relatively more significant for moderate corrosion penetration, and its effects on overall containment strength are highly localized. Despite the reduction in the 5-percentile capacity resulting from corrosion occurrence, the containment may still retain sufficient capacity and integrity to withstand challenges from events at or beyond the original prescriptive design basis. This additional margin of safety is due to a number of factors (e.g., material strengths assumed in design are substantially less than the median material strengths, design is based on assumption of elastic behavior, conservative assumptions are made regarding structural response corresponding to loss of containment integrity, and factors of safety of 1.5 to 2.0 are commonly used in structural design).

## SUMMARY AND APPLICATION OF RESULTS

Activities that address aging of the containment pressure boundary in light-water reactor plants are summarized. The objectives of these activities are 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. Containment pressure boundary components are described. Aging factors that can potentially impact performance of the containment pressure boundary are summarized as well as degradation experience. Current and emerging nondestructive examination techniques and a degradation assessment methodology for characterizing and quantifying the amount of damage present are noted. The use of time-dependent structural reliability analysis methods to provide a framework for addressing the uncertainties attendant to aging in the decision process are discussed (i.e., methods help provide assurances that degraded metallic pressure boundaries will be able to withstand future extreme loads during the desired service period with a level of reliability that is sufficient for public safety). The impact of aging (i.e., loss of shell thickness due to corrosion) on steel containment fragility for a pressurized water reactor ice-condenser plant is presented.

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. Information developed can be used in evaluations of (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 will provide a means of establishing the current capacity margin for the pressure boundary components of a structure or estimating future residual capacity margins. Program results also can be used to address the significance of reported containment degradation incidences. 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) evaluation criteria for safety assessment of issues related to containment degradation incidents; and (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.

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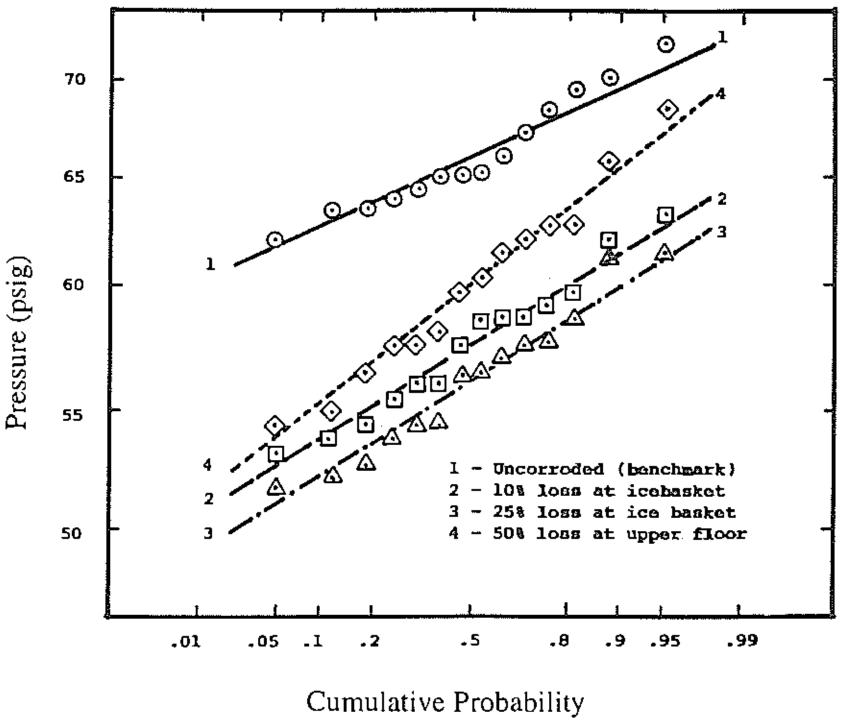

Figure 1 Cumulative fragility for postulated corrosion patterns.