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Research addressing aging management of nuclear power plant concrete and steel containment structures is summarized. Accomplishments related to concrete containment structures include formation of a materials' property database; an aging assessment methodology to identify critical structures and degradation factors; guidelines and evaluation criteria for use in condition assessments; and a time-dependent reliability-based methodology for condition assessments and estimations of future performance. Under the steel containments and liners activity, a degradation assessment methodology has been developed, mathematical models that describe time-dependent changes in the containment due to aggressive environmental factors have been identified, and statistical data supporting the use of these models in time-dependent reliability analysis have been summarized.

INTRODUCTION

By the year 2000, over 60 of the 109 commercial nuclear power plants (NPPs) that have been licensed for commercial operation in the United States (US) will be over 20 years old, with some nearing the end of their 40-year operating license. Faced with the prospect of having to replace the lost generating capacity from other sources and the potential for substantial shutdown and decommissioning costs, many utilities are expected to seek extensions to their initial plant operating licenses. Renewal of the initial operating licenses must be based on an assessment that the capacity of the safety-related systems to mitigate extreme events has not deteriorated unacceptably due to either aging or environmental stressor effects. Reinforced concrete and metal containment structures are extremely important to the safety of NPPs in that they provide the final barrier to the release of fission products to the outside environment under postulated accident conditions. Thus, ensuring that the structural capacity and leaktight integrity of the containment have not deteriorated unacceptably is essential to reliable continued service evaluations and informed aging management decisions.

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Each pressurized-water reactor (PWR) or boiling-water reactor (BWR) unit in the US is located within a much larger metal or concrete containment. Although the containment shapes and configurations can vary significantly from plant to plant, leaktightness is assured by a continuous pressure boundary consisting of nonmetallic seals and gaskets, and metallic components. Concrete containments are metal-lined, reinforced concrete pressure-retaining structures that in some cases may be post-tensioned. Metal containments are free-standing, welded steel structures that are enclosed in a reinforced concrete reactor or shield building. Descriptions of PWR and BWR containments in the US are provided in reports by Deng et al (1) and Smith and Gregor (2), respectively.

Nuclear power plant containments are susceptible to aging (e.g., deterioration in strength and stiffness) by various processes depending on the operating environment and service loading conditions. The effects of these processes may accumulate within the structure over time and cause failure under design conditions, or lead to costly repair. Structural failures create the potential for loss of human life, infringe on public safety, and have severe economic and social consequences.

Concrete containments are composed of several constituents (i.e., concrete, steel reinforcement, and metallic liner) that, in concert, perform multiple functions – load-carrying capacity, radiation shielding, and leaktightness. Concrete durability can be limited as a result of adverse performance under chemical or physical attack. Forms of chemical attack include efflorescence or leaching, sulfate attack, attack by acids and bases, salt crystallization, and alkali-aggregate reactions. Physical attack mechanisms include freeze/thaw cycling, thermal expansion/thermal cycling, abrasion/ erosion/cavitation, irradiation, and fatigue or vibration. Degradation of steel reinforcing materials can occur as a result of corrosion, irradiation, elevated temperature, or fatigue effects. Post-tensioning systems are susceptible to the same degradation mechanisms as mild steel reinforcement plus loss of prestressing force. Additional information related to these degradation mechanisms is provided by Naus et al (3). Information specifically addressing prestress losses in NPP containments has been assembled by the Nuclear Energy Agency (4).

Steel containment degradation can be classified as either material (microstructure of the metal is modified) or physical (component geometry altered) damage. Physical damage to steel containments (and liners of reinforced concrete containments) is most likely with the primary mechanisms being general and pitting corrosion. Wall thinning caused by general corrosion can affect structural capacity. Pits that completely penetrate a steel containment or liner of a reinforced concrete containment can compromise leaktight integrity. Oland and Naus (5) provide additional information on degradation due to material and physical damage.

Since 1986, there have been over 30 reported occurrences of containment pressure boundary degradation at US commercial NPPs (6). In two cases, thickness measurements of the walls revealed areas that were below the minimum design thickness. Four cases occurred where extensive corrosion of the liner had reduced the thickness locally by nearly one-half. Most of the reported concrete containment-related degradation generally occurred relatively early in the life of the structure, primarily due to improper material selection, or construction/design deficiencies, and were corrected. Recently, however, incidences of age-related degradation have started to occur (e.g., freeze-thaw damage of containment dome concrete, larger than anticipated losses of prestressing force, and steel corrosion in water intake structures). More detailed information related to degradation occurrences is provided by Oland and Naus (5) and the IAEA (7).

CONCRETE AND STEEL CONTAINMENT AGING PROGRAMS

It is essential to be able to quantify structural deterioration and estimate residual strength (or safety margins) and service life of a degrading containment structure. Methods for estimating structural deterioration ideally should be able to detect/estimate unacceptable levels of damage early enough so that costly and disruptive repairs can be avoided. If undetected, the possibility exists that the degradation effects may reduce the margin that the containments have to accommodate design basis events (e.g., structures experiencing degradation may be more vulnerable to seismic loads). Systematic condition assessment programs need to be developed and conducted at regular intervals to assure that any incidences of degradation are detected and remedial action is implemented.

Information summarized above indicates that a need exists for improved surveillance, inspection/testing, and maintenance to enhance the technical bases for assurances of continued safe operation of NPPs. Under USNRC sponsorship, ORNL is addressing aging management of NPP containment structures.

Concrete Containment Program

The concrete containment program, conducted from 1988 to 1996, prepared documentation that provides USNRC license reviewers with (1) identification and evaluation of the potential structural degradation processes; (2) issues to be addressed under NPP continued service reviews, as well as criteria and bases for resolution; (3) evaluations of relevant in-service inspection, structural assessment or remedial measures programs; and (4) methodologies to perform current assessments and reliability-based life predictions of safety-related concrete structures. To meet this objective, activities were conducted under three task areas: (1) materials property database, (2) structural component assessment/repair technologies, and (3) quantitative methodology for continued service determinations. Final results of this program are reported by Naus et al (3).

Material Properties Database. Oland (8) developed a reference containing information on the time variation of material properties under the influence of pertinent environmental stressors and aging factors. Oland and Naus (9) provide summary descriptions of the over 140 database files available in both hard copy and electronic formats to assist in the prediction of potential long-term deterioration of critical structural components in NPPs and to establish limits on hostile environmental exposure for these structures.

Additional activities under this task included review of service life models by Clifton (10), durability assessments of several United Kingdom (UK) NPP concrete structures by Hartley and Bamforth (11), and assessment of the performance of post-tensioning systems in both UK and US nuclear power facilities by Dawson and Wilson (12) and Hill (13), respectively.

Structural Component Assessment/Repair Technologies. Hookham (14) developed a methodology to identify the critical concrete structural elements in a NPP and the degradation factors that can impact their performance. Determining the existing performance characteristics and extent and causes of any observed distress in the critical structures is accomplished through a condition assessment. The condition assessment involves the conduct of a field survey involving visual examination and application of nondestructive and destructive testing techniques, followed by laboratory and office studies. Perenchio (15) and ASCE (16) provide guidelines and direction on conduct of surveys of existing buildings. Assistance in identification of various forms of degradation has been prepared by ACI (17). Suspect areas of the structure are studied in greater detail using techniques such as (1) petrography, (2) chemical analysis, and (3) concrete and steel property testing. After the field and laboratory results have been collated and studied, and structural calculations completed, a report is prepared. Hookham (18) provides guidance on interpretation of visual inspection results and an example of an inspection program for a concrete containment building.

Techniques to detect degradation of concrete structures were reviewed by Refai and Lim (19). Recommendations were developed on application of testing methods to identify and assess damage resulting from typical factors that can degrade reinforced concrete. Information specifically addressing application of nondestructive examination (NDE) methods to NPP concrete structures and research needs has been assembled by the Nuclear Energy Agency (20).

Damage repair practices commonly used for reinforced concrete structures in Europe and North America were reviewed by Price et al (21) and Krauss (22), respectively. In Europe, activities have concentrated on repair of damage resulting from corrosion of steel reinforcement. Basic repair solutions include realkalization, changing the environment to reduce the electrolytic conductivity, steel reinforcement coating, chloride extraction, and cathodic protection. Krauss provides guidance on development and implementation of a repair strategy, and presents detailed information on repair materials and techniques applicable NPP concrete structures.

Quantitative Methodology for Continued Service Determinations. Structural loads, variations in engineering material properties, and strength degradation mechanisms are random in nature. Time-dependent reliability analysis methods provide a framework for performing condition assessments of existing structures and for determining whether in-service inspection and maintenance are required to maintain reliability and performance at the desired regulatory level. The strength, R(t), of the component and the applied loads, S(t), both are functions of time and at any time, t, the margin of safety, M(t), is equal to the difference. Making the customary assumption that R and S are statistically independent random variables, the probability of failure at a particular time is,

$$P_f(t) = P[M(t) < 0] = \int_0^\infty F_R(x)\, f_S(x)\, dx. \tag{1}$$

in which $F_R(x)$ and $f_S(x)$ are the probability distribution function of R and density function of S, respectively. Equation (1) provides one quantitative measure of structural reliability and performance, provided P_f can be estimated and validated.

For service life prediction and reliability assessment, one may be more interested in the probability of satisfactory performance over some period of time, say (0,t). For example, if n discrete loads S_1, S_2,..., S_n occur at times t_1, t_2,..., t_n during (0,t) the probability that a structure survives during interval of time (0,t) is defined by a reliability function, L(0,t),

$$L(0,t) = P[R(t_1) > S_1 . . . . , R(t_n) > S_n]. \tag{2}$$

The conditional probability of failure within time interval (t,t+dt), given that the component has survived during (0,t), is defined by the hazard function,

$$h(t) = -d(\ln L(0,t))/dt. \tag{3}$$

The hazard function is especially useful in analyzing structural failures due to aging or deterioration, and evaluating the effect of an in-service inspection/maintenance activity. With structural aging, the strength deteriorates, characteristically causing h(t) to increase with time (usually nonlinearly). In-service inspection and maintenance cause the hazard function to change discontinuously at the time an inspection is performed.

The methodology can be used to estimate the strength degradation of a component, estimate service life, evaluate the effect of periodic maintenance, and develop optimum inspection/maintenance strategies. Additional information and examples of application of the methodology are available in papers by Mori and Ellingwood (23, 24) and Ellingwood and Mori (25).

<u>Steel Containment Program</u>

The steel containment program objectives include identification of corrosion mechanisms and susceptible pressure boundary material types and locations, assessment of techniques for examining the containment pressure boundary, evaluation of methods available to prevent or mitigate corrosion, and development of a quantitative structural reliability analysis methodology. Activities are conducted under two technical task areas: assessment and repair practices, and reliability-based condition assessment.

<u>Assessment and Repair Practices</u>. Task objectives are to identify procedures to assess degradation factors that could impact structural capacity margins; and to provide data for current and future structural condition assessments.

Oland and Naus (5) developed a degradation assessment methodology for characterizing the in-service condition of metal and concrete containment pressure boundary components and quantifying any damage present. Methodology components include damage detection, damage classification, root-cause determination, and damage measurement. Requirements for corrective actions when evidence of structural deterioration is discovered have been identified by the

USNRC (26), with acceptance standards and evaluation criteria for degraded components provided by ASME (27).

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 that is obtained from in-service inspections and testing. Nondestructive examination techniques common in civil structures (i.e., visual inspection, liquid penetrant, magnetic particle, ultrasonic, eddy current, and radiography) were reviewed by Oland and Naus (5). None of the techniques was perfect and results obtained depended on many factors (e.g., technique, type flaw, flaw location, component geometry, material, and proficiency of operator). Also, detectability functions required for reliability assessments are not generally available for the NDE techniques (e.g., flaw size vs probability of detection). Several techniques are currently under investigation for detecting and quantifying defects present in inaccessible regions of the containment pressure boundary. Studies have been conducted by Bondaryk et al (28) using an elastic layered media analysis code to evaluate acoustic imaging technology. Parameters investigated were frequency, flaw size, interrogation distance, and sensor incident angle. Preliminary results indicate that thickness reductions $\geq$2-mm in embedded portions of steel containments can be detected, but the technique does not appear to be applicable to embedded liners because of significant concrete-related signal losses.

Reliability-Based Condition Assessments. Principles of structural mechanics principles are being used to develop mathematical models for evaluations of pressure boundary strength degradation over time, and reliability-based methods to assess the probability that the containment capacity has degraded below a specified level.

Evaluations of the reliability or safety margin of the containment during its service life must take into account aging 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 - 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.

Surveys of steel containments and concrete containment liners indicate that uniform and pitting corrosion are the most significant damage mechanisms affecting the NPP pressure boundary. In either case, the penetration, X(t), of the corrosion can be modeled by the kinetic equation,

$$X(t) = C\,(t-T_I)^m \qquad (4)$$

in which C = rate parameter, m = time-order parameter, and T_I = random corrosion initiation period. The units in Eqn. (4) 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/yr. 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 about 2/3 for carbon steels, may be treated as deterministic. Statistics of the parameters C and T_I are determined from experimental data and depend on whether the corrosion mechanism gives rise to uniform or pitting corrosion. However, one must be cautious about extrapolating laboratory data to a prototype. Information on the methodology and its application to an axisymmetric cylindrical steel ring-stiffened shell, structurally similar to a steel containment, subjected to corrosion is provided by Ellingwood and Bhattacharya (29).

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