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CONSIDERATIONS IN THE EVALUATION OF CONCRETE STRUCTURES FOR CONTINUED SERVICE IN AGED NUCLEAR POWER PLANTS (NPPs)*

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INTRODUCTION

Although nuclear power currently provides about 17-18% of the electricity in the U.S., the current trend is toward deferral (or cancellation) of plants that are currently under construction; i.e., no new plants have been ordered since the late 1970s, and over 90 plants have been cancelled or indefinitely deferred. This trend has resulted in a large degree from a slowdown of the growth in demand for electricity, but there are other factors that have eroded the economic advantage nuclear power once had over other forms of energy production. For example, escalation of material and labor costs, higher interest rates, etc., have resulted in a significant increase in the average duration of plant construction and almost an order of magnitude increase in cost of generating capacity additions since the mid-1960s (1). These factors have resulted in a hesitancy on the part of utilities to consider the construction of new nuclear power plant facilities.

Currently, there are ~119 commercial nuclear power plants (NPPs) in the U.S. either under construction, operating at low-to-full power, or awaiting an operating license. Together, these units have a net generating capacity of ~110 GW(e). Assuming no life extension of present facilities, the operating licenses for these plants will start to expire in the middle of the next decade with Yankee Rowe being the first plant to attain this status. The potential impact of the expiration of operating permits is pointed out in Reference 2, where it is noted that with no life extension of facilities, a potential loss of electrical generating capacity in excess of 75 GW(e) could occur during the time period 2006 to 2020 when the operating licenses of 80 to 90 NPPs are scheduled to expire. A potential timely and cost-effective solution to meeting future electricity demand, which has worked well for non-nuclear generating plants, is to extend the service life (operating licenses) of existing NPPs. Since the concrete components in these plants provide a vital safety function, any continued service considerations must include an in-depth assessment of the safety-related concrete structures.

BACKGROUND

ELECTRIC POWER RESEARCH INSTITUTE (EPRI) STUDIES

Two EPRI studies have addressed life extension and the longevity of light-water reactor (LWR) plants, with the concrete structures considered to a limited degree in each. In the first study (3), the concept of operating a LWR power plant beyond its initial license life was studied from both economic and technological aspects. Conclusions of the study were that: (1) extending the life of LWRs was economically beneficial if, up to the first decade of the 21st century, the nuclear fuel costs remain low relative to other feasible baseload power generation technologies (allowable down time for refurbishment can be several years and cost on the order of several 100 million 1979 dollars before economic feasibility becomes borderline); (2) even in situations where a large piece of equipment such as a reactor pressure vessel or steam generator required replacement, case studies have shown that replacement is feasible;

and (3) major repairs or replacement of the concrete structure in the base mat, containment walls, or biological shield within the containment could result in significant cost. The second EPRI-funded study considered the feasibility of extending the life of existing nuclear power plants and concluded that power reactors should have useful service lives substantially in excess of the licensed 40 years from the date of issuance of the construction permit, and that a generic method for verifying the continued integrity of concrete structures should be developed (4). Secondary conclusions of the above studies were that (1) concrete durability (aging) under the influence of either material interactions, aggressive environments (freeze-thaw, wetting-drying, or chemical), or exposure to extreme environments (elevated temperature, irradiation or seismic) is one of the key issues in continuing the service of a nuclear power plant past its initial licensing period; and (2) although operating plants have reported little difficulty with concrete materials, an evaluation of the long-term effects of the environmental challenges to which these structures are subjected has not been adequately addressed.

UNITED STATES NUCLEAR REGULATORY COMMISSION (USNRC) STUDY

Under the USNRC Nuclear Plant Aging Research (NPAR) Program, a study was conducted to (1) expand upon the work that was initiated on the first two EPRI studies (3,4) relative to the longevity and continued service considerations of safety-related concrete components in LWR facilities and (2) to provide background that would logically lead to development of a methodology for assessing and predicting the effects of aging on the performance of the concrete-based materials and components (5). Applications of safety-related concrete components to LWR technology were identified, and pertinent components (containment buildings, containment base mats, biological shield walls and buildings, and auxiliary buildings), as well as the materials of which they are constructed (concrete, mild steel reinforcement, prestressing systems, embedments, and anchorages), were described. Historical performance of concrete components was established through information presented on concrete longevity, a review of concrete component performance in civil engineering applications, and component behavior in both LWR and high-temperature gas-cooled reactor applications. Potential environmental stressors and aging factors to which LWR safety-related components could be subjected were identified and discussed in terms of durability factors related to the materials used to fabricate the components. The current technology for detection of concrete aging phenomena was presented in terms of methods applicable to the particular material system that could experience deteriorating effects. Remedial measures for the repair, replacement or retrofitting of degraded concrete components were discussed and examples of pre- and post-repair structural performance were presented to indicate the effectiveness of these measures. Finally, considerations relative to the development of a damage methodology for assessment of durability factor deterioration rates and prediction of structural reliability were discussed.

Conclusions derived from this investigation were that:

1. Under normal environmental conditions, aging of concrete does not have a detrimental effect on its strength for ages up to 50 years (limit for which documented results are available). Data on the performance of concrete over the time period of interest, 40 to 70 years, however, are extremely limited.
2. The performance of concrete-based components in general civil engineering applications has been exemplary, with incidences of distress related primarily to either construction or design detail mistakes.
3. The performance of concrete-based components in nuclear power plant applications has also been very good with the majority of problems identified being minor and involved either concrete cracking, concrete voids, or low concrete strengths at early ages. Five incidences involving LWR concrete containments were identified, however, which were considered significant, were related to

construction, design, or human error, and involved two dome delaminations, voids under tendon-bearing plates, anchor head failures, and corrosion-induced failures of prestressing tendon wires.

4. Techniques for detecting the effects of environmental stressors on concrete materials are sufficiently developed to provide qualitative data. However, quantitative interpretation can be difficult because of either the requirement for development of correlation curves, embedment effects on measured quantities, or accessibility. Also, none of the techniques provide rate data such as required for residual life determinations.
5. Remedial measures for repair of degraded concrete components are capable of completely restoring structural integrity when proper techniques and materials are used.
6. A damage methodology to provide a quantitative measure of the durability (residual life) with respect to meeting potential future requirements does not presently exist.

Results of this study were utilized to provide several recommendations:

1. Existing facilities that have been shut down after an extended period of service should be used to obtain aging-related data for concrete materials. Also, these facilities could be used to evaluate the applicability of various techniques (either existing or in the developmental stage) for detecting the effects of environmental stressors — primarily elevated temperature and irradiation — on the concrete materials.
2. Accelerated aging techniques should be investigated as a method for supplementing the extremely limited data base on concrete aging.
3. Available prestressing tendon inservice inspection records and data obtained during containment integrated leak-rate tests should be examined as potential sources of information for trending concrete component behavior.
4. Criteria on durability factor significance need to be established (i.e., identification of the various deterioration phenomena acting

on a particular structure and the assignment of a weighting factor to each of the phenomena based on its significance relative to continued service considerations).

5. A methodology needs to be developed to provide a quantitative measure of structural reliability, either now or at some future time.

Many of these recommendations are being implemented by the Structural Aging Program which is being carried out by the Oak Ridge National Laboratory (ORNL) under sponsorship of the Structural and Seismic Engineering Branch, Office of Nuclear Regulatory Research, Division of Engineering, USNRC.

STRUCTURAL AGING PROGRAM

PROGRAM OBJECTIVE

The Structural Aging Program has the overall objective of preparing an expandable handbook or report which will provide USNRC license reviewers and licensees with the following: (1) identification and evaluation of the structural degradation processes; (2) issues to be addressed under NPP continued service reviews, as well as criteria, and the bases for resolution of these issues; (3) identification and evaluation of relevant inservice inspection or structural assessment programs in use, or needed; and (4) issues still unresolved that need continuing or future research for development of criteria, including recommended priorities based on perceived need as well as estimated time required for their resolution.

PROGRAM DESCRIPTION

The Structural Aging Program is composed of three technical tasks which have goals of: (1) establishing a material properties database, (2) evaluating structural component assessment and repair technologies, and (3) developing a quantitative methodology for assessment of present and future structural reliability of aged concrete structures. Objectives and planned activities for each of these tasks are discussed below.

Materials Property Database (MPDB)

The objective of this task is to develop a computer-based structural materials property database which will contain information on the time variation of material properties under the influence of pertinent environmental stressors and aging factors. The database will be used to assist in the prediction of potential long-term deterioration of critical structural components in nuclear power plants and to establish limits on hostile environmental exposure for these structures or materials. In meeting the above objective, three primary activities are being undertaken: (1) formulation of a handbook, (2) collection of data, and (3) modeling of material behavior.

A review and assessment of materials property databases, hardware, and software has been completed (6). Conclusions derived from the investigation were that: a concrete materials property database suitable for use by the Structural Aging Program does not exist; data on aging of concrete materials are very limited; the use of personal computers provides the most economical approach in setting up the desired database; and a "canned" commercial database, which can be formatted to meet program requirements, should be used to provide the starting point for development of the required database. Results of this review are being utilized to develop the Structural Materials Information Center (SMIC) which will be composed of an electronic database, the Structural Materials Database, and a handbook, the Structural Materials Handbook. Initially, only concrete material systems (portland cement concretes, specialty concretes, bonded steel reinforcement and prestressing systems) will be considered while the database is being formatted. As the database develops, other structural materials will be included as separate chapters in the handbook.

Once the SMIC has been developed and its capabilities demonstrated, aging-related materials property data will be incorporated. Due to the limited availability of pertinent data, obtaining and testing of prototypical materials and accelerated aging experiments will be utilized. Potential sources of "aged" material samples include NPPs that have been shut down (Shippingport, LaCrosse, Humbolt Bay, Dresden I), experimental and research reactors, fossil plants, and building structures. Once concrete samples and supporting documentation (mix design, control specimen test results, environmental exposure, etc.) have been obtained from these facilities, strength tests and petrographic examinations will be conducted. Accelerated aging tests provide another potential source of representative data. Such a program would be analytical-experimental in nature and based on a procedure such as the American Society for Testing and Materials practice for developing accelerated aging tests to aid in the prediction of building component service life (7).

Prediction or explanation of the complex interrelationships that occur between concrete's constituents and between concrete and its environment requires the development of mathematical models based on scientific and engineering principles. Such models play a vital role in the development of techniques for reliability-based life prediction of concrete structures in NPPs. Models developed will address aging factors (cement hydration, alkali-aggregate reaction, etc.) and environmental stressors (temperature, irradiation, freeze-thaw, etc.) pertinent to critical safety-related structures in NPPs as well as incorporating synergistic effects to predict behavior where more than one environmental stressor or aging factor is present.

Structural Component Assessment and Repair Technology

The overall objectives of this task are to: develop a systematic methodology which can be used to make a quantitative assessment of the presence, magnitude, and significance of any environmental stressors or aging factors which could impact the durability of safety-related concrete components in NPPs and provide recommended inservice inspection or sampling procedures which can be utilized to develop the data required both for evaluating the current structural condition as well as trending the performance of these components for use in continued service assessments. Results of this task will have a major impact on NPP continued service considerations since residual life determinations cannot be made unless all degradation mechanisms are evaluated and environmental factors quantified, and each structure is examined and evaluated in detail. Basic components of the approach utilized under this task include development of: (1) classification scheme for critical structural components and deterioration causes and effects, (2) methodology for conducting a quantitative assessment of the presence of active deteriorating influences, and (3) remedial measure considerations to reestablish the capability of degraded structures or components to meet potential future requirements.

Critical structural components will be described and a listing of their functional and performance requirements provided. Critical components will then be subdivided into elements and their importance to the integrity of the component assessed; i.e., ranked. The expected type and range of degradation factors (aging, environmental stressors, operation, testing, etc.) that can impact each element will be identified.

In order to simplify continued service evaluations of nuclear safety-related concrete components, it would be advantageous to have a standardized inservice inspection program which would provide data that could be used to identify and quantify deteriorating influences as well as provide rate of change information on these influences. Basic activities under this subtask include an evaluation of: nondestructive and sampling procedures which are available for performing inservice inspections of the critical concrete components identified above, and methodologies which have been utilized to perform a condition assessment of concrete components and structures. Recommended criteria will be provided for use in performing inspections of these components to assess their current condition as well as to develop trending information for use in continued service assessments. Periodic inspections performed in compliance with this methodology will help identify any potential problems before they become safety-significant and allow corrective actions to be taken at an early stage.

When concrete structures have been fabricated with close attention to the factors related to the production of good concrete (material selection, production control, desirable properties, economy), the concrete should exhibit infinite durability; however, where there has been a breakdown in any one of these factors or the component was subjected to an extreme environmental stressor or adverse aging factor, distress can occur. Basic activities under this subtask are related to an assessment of repair procedures for concrete material and structural systems and establishment of criteria for their utilization. Methods available for evaluating the performance of repair materials as well as any potential impact of a repair on the inspection procedures will be addressed. Techniques which can be used to mitigate the effects of environmental stressors or aging factors will be identified. Recommended preventative measure procedures which can be used to effectively offset, counteract, or minimize any minor deterioration effects to prevent them from becoming significant will be established.

Quantitative Methodology for Continued Service Determinations

The objective of this task is to develop a methodology which can be used for performing condition assessments and making reliability-based life predictions of critical concrete safety-related components in NPPs. The methodology will integrate information on degradation and damage accumulation, environmental factors, and load history into a decision tool that will provide a quantitative measure of structural reliability and performance under projected future service conditions based on a condition assessment of the existing structure. Pertinent activities under this task include development of predictive models, data assemblage and implementation, methodology development, and validation studies.

Predictive or damage models will be identified or developed that will be utilized in the formulation of procedures for assessing the current condition as well as the development of reliability-based future condition assessment of critical safety-related concrete components. The models will enable the change in strength of concrete structures over time to be evaluated in terms of initial conditions, applied load history, and a parameterization of environmental stressors and aging factors.

Pertinent data for use in establishing functional and performance requirements for critical components and in development of the predictive models will be assembled. Requirements used in the design, fabrication, erection, and testing of the critical components will be identified. Quantitative performance data on the factors which can impact structural durability will be identified or developed. Uncertainties (error bands) associated with this data will be established. Service history effects, including the impact of remedial measures, will be evaluated under this subtask.

Methodologies will be formulated to facilitate quantitative assessments of structural reliability and performance of concrete structures in NPPs, taking into account environmental stressors, aging, and other factors that might diminish their ability to withstand future operating, extreme environmental, or accident conditions. Sources of variability and uncertainty that arise from the damage accumulation modeling assumptions, material properties, and applied loads will also be incorporated. The methodologies developed will enable a current condition assessment to be made as well as determining future structural reliability, taking into account initial conditions of the structure, service history, nondestructive condition assessment techniques, and inspection and maintenance strategies. The role of periodic nondestructive evaluation and testing, and maintenance on the future reliability of concrete structures will be examined.

The condition assessment models will be refined and validated through application to laboratory and prototypical structures. Laboratory tests will enable degradation factor effects (load and environmental stressor) to be evaluated under controlled conditions. Ideally, the prototypical structures tests will involve an existing concrete structure such as a decommissioned nuclear plant. Initial conditions will be defined from the codes used in design, available structural design documents, and inspection and construction data. Best estimates of applied service loads and environmental parameters will be factored into the evaluation as well as available information from inspection data, or repairs. The analysis will be run forward to the present time and the current predicted strength compared to the actual present strength. Results will then be utilized to modify the predictive methodology.

SUMMARY

The Structural Aging Program is carried out by the Oak Ridge National Laboratory under the sponsorship of the United States Nuclear Regulatory Commission. The program has evolved from preliminary studies conducted to evaluate the long-term environmental challenges to light-water reactor safety-related concrete civil structures. An important conclusion of these studies was that a damage methodology, which can provide a quantitative measure of a concrete structure's durability with respect to potential future requirements, needs to be developed. Under the Structural Aging Program, this issue is being addressed in three task areas: establishment of a structural materials information center, evaluation of structural component assessment and repair technologies, and development of a quantitative methodology for structural aging determinations. Objectives of each of these task areas are presented as well as planned activities.

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