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NUCLEAR PLANT AGING RESEARCH IN THE UNITED STATES

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ABSTRACT

NRC, EPRI, and the Department of Energy have implemented aging research programs to address the technical issues related to potential degradation of the capability of components and structures to perform their intended functions after being placed in service. Aging, the net degradation in physical condition due to normal and abnormal environment and service, was explicitly or implicitly addressed in the design of all components, systems, and structures in U.S. nuclear power plants. Although aging has not compromised the safe operation of U.S. nuclear power plants throughout their accumulated operation of over 1000 plant-years, the quest for improved availability and for safe plant operation during and beyond the current license period of 40 years has led to an increase in nuclear plant aging research over the past several years. This paper presents the aging research programs sponsored by the U.S. Nuclear Regulatory Commission (NRC) and by the U.S. utility industry through its research arm, the Electric Power Research Institute (EPRI). The research focuses on 1) increased understanding of aging mechanisms in a broad range of components, systems, and structures, and 2) more cost-effective ways of enhancing the management of aging via improved preventive and corrective maintenance (i.e., aging mitigation, inspection, surveillance, condition monitoring and refurbishment/replacement). The key aging-related technical issues are identified in the paper. Results of the research will be used by the NRC mainly to provide for timely and technically sound regulatory decisions regarding continued safe operation of nuclear plants of all stages of life. Utilities will use the results mainly to improve plant reliability in the short term and to realize the potential economic benefits of operating plants beyond their current licensed terms. The paper concludes that 1) continuing research is important for improving understanding of aging degradation and examining better ways to manage it and 2) consensus definitions of terms related to aging will facilitate resolution of aging issues and will improve the reporting and evaluation of plant experience.

INTRODUCTION

It is recognized that the effects of operating environments and service wear can degrade the condition of components, systems, and structures in all industrial facilities, including nuclear power plants. In nuclear power plants such degradation is typically addressed either implicitly or explicitly during the design phase by assigning a design or expected life to components, systems, and structures. This life generally has a large margin of safety. Short-lived components are replaced periodically, whereas other components and most engineered structures have expected lives in excess of the typical

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license term of 40 years. Inspection, surveillance and refurbishment of components, systems, and structures have the purpose of ensuring that aging effects do not become significant before replacement or before the plant reaches the end of its licensed term.

In the decades since nuclear plants were first built, the understanding of aging has advanced due to feedback from operating experience and research, and has contributed to the reliable and safe operation of plants to date. Nevertheless, two independent actions in the nuclear power industry motivate additional research into aging and its management. The goals of one action are improved aging management and availability; the goal of the other is assuring public health and safety during the current license period of 40 years and for license renewal for safe operation beyond current licensed terms. Aging management and improved availability require that predictive maintenance (inspection, surveillance, and condition monitoring), preventive maintenance (restoration before failure) and corrective maintenance (repair and replacement) are adequate for detecting aging and keeping its effects within acceptable limits, in the most efficient manner possible. The technical safety issues related to license renewal include residual life assessment of safety-related and risk-significant components, systems, and structures not normally replaced during the initial licensed term. In some cases, the currently assigned life of safety-related and risk significant components normally replaced during the initial licensed term will need to be reexamined. Such reexamination should include maintenance and quality practices and would occur even if license renewal was not sought.

For the past fifteen years, regulatory and industry research programs have addressed aging technology principally in areas such as pressure boundary integrity (fatigue, stress corrosion cracking and radiation embrittlement) and equipment qualification (testing for functional capability periodically and type testing of artificially aged components). Recently the NRC has recognized the need for improved understanding of aging to ensure that adequate safety margins are maintained as operating reactors advance in age. The industry has recognized the benefits of managing aging and establishing and maintaining a viable option for license renewal. In response to these recognized needs, the United States Nuclear Regulatory Commission (NRC) launched the Nuclear Plant Aging Research (NPAR) program in 1983 and the utility-sponsored Electric Power Research Institute (EPRI) in cooperation with the United States Department of Energy (DOE) launched its Nuclear Plant Life Extension program in 1984. Other organizations such as reactor suppliers, architect/engineers, and some utilities have also undertaken research in related areas.

In this paper we discuss the nature of aging degradation and identify key issues relating to aging. This is followed by an overview of aging-related research programs being sponsored by the NRC, EPRI, DOE and other U.S. organizations.

DEFINITION OF AGING

Despite decades of plant experience and aging research, there is still not a consensus on the definition of "aging" and related terms such as aging "mechanisms," "modes," "stressors," etc. It is important that such terms have a common meaning to all involved in plant operation (for reporting, evaluating

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and fixing failures) and in aging research (for focusing resources on the important aging phenomena associated with the most important components, systems and structures). In the following paragraphs we propose definitions that are essentially consistent with definitions used in the NPAR program (Ref. 1) and with utility perspectives of nuclear plant aging (Ref. 2).

We propose the following definitions related to aging in nuclear power plants:

- Aging is the net degradation in the physical condition of a component, system, or structure due to environment and service. Aging can degrade the capability of a component, system or structure to perform its intended function after being placed in service.

- The environments and service conditions that produce aging degradation are called aging stressors (e.g., heat, radiation, humidity, reactive chemicals, operational cycling, electrical/mechanical loads, vibration, testing).

- Aging degradation is the change in physical properties (such as crack growth, dimensions, ductility, fatigue capacity and mechanical or dielectric strength).

- Aging mechanisms are physical or chemical processes (such as wear, erosion, creep, corrosion, and oxidation) that result in aging degradation.

Expected aging degradation in <u>properly designed</u>, fabricated, applied, and maintained components, systems or structures does not cause failure within their specified design lives and an acceptable margin of safety on operation is maintained. Aging related failures within the design life are caused only by unanticipated aging which is defined below. Such failures can be generally accommodated because of the defense-in-depth philosophy of U.S. nuclear plant designs, including redundant safety systems that cannot be defeated by single random failures. Nevertheless, a safe, sound and economical approach to plant operation must minimize failures. Some failures can diminish the plant's margin of safety, all failures add to operation, maintenance and safety analysis costs and some failures may lead to plant unavailability.

Aging includes all degradation produced during operation or testing. This includes expected transients (upset plant condition) producing small, temporary increases in environmental conditions. Excluded from aging, for example, is the degradation produced by sudden and short-term environmental and service extremes such as loss of coolant accidents (emergency or faulted plant condition). However, that is not to say that such sudden or short-term extremes are unimportant. Although they are not characterized as aging, they do act upon aged components, systems and structures and might cause failures.

A distinction is made between normal and abnormal stressors.

- Normal stressors are the actual environments and service conditions (including upset conditions) experienced by a component that has been properly designed (for postulated environment and service conditions), fabricated, installed, operated, tested and maintained.

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- Abnormal stressors are environments and service conditions due to design errors, fabrication defects or improper installation, operation, or maintenance (including excessive testing).

As mentioned above, failures within the design life are caused only by <u>unanticipated aging degradation</u> which includes both unanticipated normal aging (not addressed in design or addressed incorrectly) and abnormal aging produced by abnormal stressors (errors, defects, etc.) It should be noted that ongoing industry programs and regulatory efforts are focussed on minimizing failures of safety related and risk significant components whether due to normal or abnormal aging (including effects of construction, design and maintenance errors).

Other terms for which a consensus definition would improve understanding and communication among plant operators and researchers include "failure mechanism," "failure mode," and "failure cause" (or "root cause"). The difficult process of accurately establishing the root causes of component failures in operating plants warrants special efforts for improvement in future evaluations and reporting. Uniform application of a failure categorization scheme such as proposed in Ref. 3 would be beneficial.

For U.S. commercial nuclear power plants, the original understanding of aging coupled with utility measures to manage aging via good operation and maintenance practices was intended to support an original licensed term of forty years. The understanding of aging increased over the years with feedback from accumulated plant maintenance and failure experience, and from aging research. A large portion of operational failures was caused by abnormal stressors resulting from errors. These failures can best be prevented by increased vigilance, responsiveness to prior operational experience, accountability, communication and improved quality and maintenance programs. Lessons learned from failures caused by normal aging mechanisms not addressed or addressed inadequately in design improved understanding of aging and led to reduced replacement intervals or redesigned components. In some cases, the failures also indicated the need for enhanced preventive maintenance, which would be able to detect both normal and abnormal aging degradation.

In summary, keys to understanding and managing aging are research and utility responsiveness to the feedback from experience in the areas of component failure, operation, preventive maintenance, and quality assurance. U.S. NRC and industry research programs are described in this paper.

<u>KEY AGING-RELATED ISSUES</u>

The perspectives on aging discussed above combine with the nuclear power industry's quest for safety and improved availability, and with its desire to maximize the benefits from existing generating capacity, to establish the following key aging related issues which need to be addressed.

Components, Systems, and Structures

- What components, systems, and structures are risk significant and susceptible to significant age-related degradation?
- Which of these are maintained and/or replaced?
- What components, systems, and structures are expensive to replace?
- Which should be selected for comprehensive aging assessment and residual life evaluation?

Understanding Aging

- What normal degradation mechanisms could cause premature failure during the expected life? (Note that such mechanisms were either not addressed or inadequately addressed in design and application.)

Managing Aging

- Are current programs for inspection, surveillance and condition monitoring adequate for timely identification/detection of significant aging degradation, whether normal or abnormal?

- What technically sound, practical, and cost-effective methods can be implemented to enhance the management of aging?

- Are measures in place for minimizing abnormal aging?

- Are current programs for maintenance, repair or replacement effective for mitigating aging?

- Can aging degradation be cost-effectively reduced by operational or environmental controls?

Life Assessment

- What are appropriate criteria for the evaluation of the residual life of components, systems and structures?

- What supporting evidence (data, analysis, inspection, etc.) is needed?

- How long can the original expected life be extended when evidence shows that operational stressors were less than assumed in the design or that net degradation results in a large margin against failure?

- Have there been any unanticipated stressors or aging mechanisms that can limit the original expected life?

Codes and Standards

- What changes in current codes and standards are needed to address important aging effects not adequately covered.

NRC AGING RESEARCH PROGRAM

The NRC Nuclear Plant Aging Research (NPAR) program is directed toward improving knowledge and understanding of degradation processes within nuclear power plants (Ref. 1). This hardware-oriented engineering program is a rigorous and systematic investigation into the potentially adverse effects of aging on plant components, systems, and structures during the period of normal licensed plant operation, as well as the period of extended operation that may be requested in utility applications for license renewals.

Program emphasis has been placed on 1) identifying and characterizing the mechanisms of material and component degradation during service and 2) utilizing research results in the regulatory process. The research includes evaluating methods of inspection, surveillance, condition monitoring, and maintenance as a means of managing aging effects that may impact safe plant operation. Specifically, the goals of the program are:

- Identify and characterize aging effects that, if unchecked, could cause unacceptable degradation of components, systems and structures and thereby impair plant safety.
- Identify methods of inspection, surveillance, monitoring, and evaluating residual life of components, systems, and structures that will ensure timely detection of significant aging effects before loss of safety function.
- Evaluate the effectiveness of maintenance, storage, repair and replacement practices in mitigating the rate and extent of aging degradation.

The NPAR program is based on a phased approach to research. The objectives of the Phase I studies are: 1) to identify and characterize aging and wear effects; 2) to identify failure modes and causes attributable to aging; and 3) to identify measurable performance parameters, including functional indicators. The functional indicators have a potential use in assessing the reliability and operational readiness of a component, system or structure, in establishing degradation trends, and in detecting incipient failures. The objectives of the Phase II studies are: 1) perform indepth engineering studies and aging assessments based on in situ measurements; 2) perform post-service examinations and tests of naturally aged/degraded components; 3) identify improved methods for inspection, surveillance, and monitoring, or for evaluating residual life; and 4) make recommendations for utilizing research results in the regulatory process.

The NPAR program consists of the following major research elements:

- Risk Significance of Aging. Aging models and risk assessment methodologies require development to provide quantitative determination of the effect that aging has on safety. The major activities within this research element are: (i) aging model development, including the treatment of active components, passive structures, and the influence and effects of testing and maintenance; (ii) failure data analysis, (iii) engineering information analysis, (iv) uncertainty analysis, (v) application and demonstration of the risk assessment methodology, and (vi) the development of procedures and guidelines for treatment of aging in probabilistic risk

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assessments (PRAs).

- Aging-Systems Interaction. A study of system interaction is essential to determine how aging is affecting component and system unavailability and to establish the relative contribution to risk from aging-related component and system failures. This element of the aging research program will facilitate the prioritization of plant safety systems and components for indepth engineering studies and then generate guidelines and recommendations for inspection and maintenance to alleviate aging concerns.

- Integrity of Primary System Components. This element of the aging research is focused on aging issues for the materials and components of LWR primary systems. The goal is to provide the confirmatory technical basis for regulatory decisions on the safe operation of reactor vessels, primary system piping, steam generators, and improvements in the techniques and equipment required for nondestructive in-service inspection of these components.

- Electrical and Mechanical Components. Some 30 categories of components (e.g., pumps, motors, valves, cables) are the subjects of current and planned research being studied by five national laboratories, and several private institutions and organizations.

- Shippingport Aging Evaluation. The Shippingport Atomic Power Station, now in the latter stages of decommissioning, has been a major source of naturally-aged materials and equipment for Nuclear Plant Aging Research (NPAR) and other NRC programs. More than 140 Shippingport Station items, ranging in size from small instruments and materials samples to one of the main coolant pumps, have been removed and shipped to designated NRC contractors. Data and records relevant to the procurement, operation and maintenance of these materials and components have been obtained to support the detailed aging evaluations. In-situ assessments of Shippingport Station components also have been conducted, including the pre-removal visual and physical examination of components, the testing of electrical circuits, and special measurements to assist in the selection of specific components for further evaluation. Although the detailed evaluation and testing of the naturally-aged materials and components obtained from Shippingport Station are just beginning, there are a number of preliminary studies and results that are indicative of the value of the aging information that ultimately will be obtained (Ref. 4).

Utilization of NRC Research Results

The NRC aging research program will result in better understanding of aging processes and improved confidence in methods for detecting and mitigating aging degradation. These will provide a basis for timely and sound regulatory decisions regarding continued operation of nuclear plants of all ages. Detection and timely mitigation of aging degradation at an early stage, before functional capability can be impaired and before continued safe operation can be questioned, will avoid unplanned and costly plant shutdowns. In addition, operating plant maintenance practices will become more effective. Wear from excessive testing can be minimized through use of more effective surveillance techniques and equipment reliability will be improved.

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To be useful to the NRC, the NPAR program is structured to integrate existing age related information and generate relevant aging data which can be used effectively in the regulatory process in the following ways:

1. Develop information that can be used in identifying and resolving technical safety issues related to plant aging and license renewal.

2. Support the NRC programs to resolve generic safety issues which have elements of aging and time-dependent degradation processes.

3. Support recommendations for surveillance and maintenance methods needed to provide assurance against unacceptable aging-related degradation and to support license renewal.

4. Support the development of inspection procedures suitable for aged components and equipment. In-service inspection is required for the components and systems in a nuclear power plant that are critical for safe operation. The NPAR program is intended to integrate the information required to implement improved techniques and to show what additional inspection requirements, if any, may be needed for aged components to support continued operation.

5. Recommend appropriate revisions of codes and standards. The NPAR program will generate recommendations to revise codes and standards to assure safe operation with aged components and systems and to support license renewal. For specific components and systems, NPAR will evaluate the in-service inspection methods to detect and quantify the aging damage.

<u>EPRI AGING RESEARCH</u>

Since its inception in 1973, EPRI has sponsored research on aging as part of its nuclear power research program, which has the goal of supporting the generation of safe, reliable and economical nuclear power. A large segment of the program has addressed piping and pressure boundary integrity including such topics as fatigue, thermal/radiation embrittlement, stress corrosion cracking and nondestructive evaluation and life assessment methodologies. References 5 through 9 are examples of this work. Another programmatic area has dealt principally with improving the means utilities use to manage aging of active components -- maintenance, trending of performance and reliability, monitoring and diagnostics, and human factors. Reference 10 is a source book on the research products in this area. The third area in EPRI's research program related to aging is equipment qualification. This research began with an extensive review of equipment aging theory and technology (Ref. 11) which focused on techniques for simulating thermal, radiation and cyclic aging in organic subcomponents of electrical equipment. Subsequent projects dealt with material property aging data (Ref. 12), how aging affects the seismic resistance of small components (Ref. 13), and condition monitoring techniques (Refs. 14 and 15). A long-term program is trending material degradation in component specimens placed in nine operating U.S. plants to compare their natural aging with artificially-induced aging of identical laboratory specimens (Ref. 16).

The general objectives of EPRI's aging-related research were to improve utilities' understanding of aging and provide them with effective ways to manage

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aging at reasonable cost.

Plant Life Extension Program

The aging-related research summarized above formed the groundwork for EPRI's Nuclear Plant Life Extension Program initiated in 1984 in cooperation with DOE. Objectives of this program are to establish and maintain the option for nuclear plant license renewal and to provide utilities with the technical basis for operating plants beyond their current 40-year licensed term. Life extension will be beneficial to utilities and consumers, being a prudent use of existing resources and providing near-term and long-term paybacks from improved plant maintenance and performance. Leadership for this U.S. utility initiative is being provided by the Nuclear Management and Resources Council (NUMARC) through the NUMARC NUPLEX Working Group. The objectives of this working group are to promote a stable, timely license renewal process and coordinate utility plant life extension efforts.

The initial research activity in the EPRI/DOE program consisted of two pilot plant projects involving one PWR and one BWR. Additional pilot studies are addressing variances in design specific to PWR reactors from two other suppliers. The pilot studies used specific reactor designs and plants to examine the technical and economic issues related to life extension. They concluded that none of these issues presents an insurmountable barrier to license renewal. The studies also introduce the concept of screening components to identify long-lived "critical" ones -- those that are either not normally replaced and subject to significant age-related degradation which could affect safety, or those so costly to replace that they could deter a utility decision to apply for license renewal. The screening methodology consists of (1) identifying critical components mainly by eliminating those normally replaced or closely inspected, (2) reviewing critical components to determine the impact, if any, of age-related degradation, and (3) establishing options for addressing potentially significant aging-related degradation.

Among the critical components evaluated thus far are PWR concrete containments and PWR and BWR reactor pressure vessels and their internals. Technical evaluations providing the basis for justifying extended life of these components are in preparation. The evaluations will be reviewed and revised with the aim of obtaining acceptance by the industry and the NRC.

Complementary research efforts in the nuclear plant life extension program are also underway in the following areas:

Reactor Pressure Vessel (RPV) Embrittlement. A program performed by NSSS vendors and Electricité de France to resolve thermal and radiation embrittlement issues concerning the useful life of light water reactor RPV's.

Component Life Estimating. Development of procedures adapted from ASME Code, Section XI, Appendix A, for demonstrating "fitness for service" by examining the relationships among deteriorating environments, degraded properties, flaw propagation/growth and component life.

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Cable Aging. Projects examining natural versus artificial aging of electric cables (Ref. 16) and in-situ, nondestructive techniques for monitoring the electrical and mechanical condition of safety-related cable inside containments (Refs. 15 and 17). These efforts are coordinated with complementary cable aging research sponsored by DOE (Ref. 18) and the NRC (Ref. 19 and 20). The intent of all this research is to confirm by experience, testing, and diagnostics that unacceptable degradation does not occur during the original 40-year qualified life of cables or during an extended operational period.

One of the most important products of the EPRI/DOE life extension program will be guidelines for activities utilities can initiate now to maximize their options for license renewal. These activities include (1) enhanced record-keeping and plant data such as operational and maintenance histories, (2) improved environmental measurement and control, and (3) improved preventive maintenance and failure evaluation/trending.

Another important activity of the EPRI/DOE life extension program is to support lead plants in the submittal and approval by NRC of first-of-a-kind license renewal applications.

Utilization of EPRI Research Results

Generally, the results of EPRI aging research have been used by utilities to maximize the useful life of components, systems, and structures and to reduce, where possible, the operations and maintenance costs as well. This has been accomplished by identifying components for which increased expenditures for inspection, surveillance, monitoring, and maintenance have the greatest payback in terms of increased component performance and reliability.

Another use of research results has been to enhance technology in areas where operational experience has pointed out unanticipated aging mechanisms such as keyway cracking in low-pressure turbine disks (Ref. 21) and BWR intergranular stress corrosion cracking (Ref. 22 and 23). Typical research products are improved analytical techniques for more accurate life prediction and improved monitoring or nondestructive examination techniques. The major benefit is a reduction in the frequency of forced plant outages.

The results of plant life extension research regarding aging will be used by utilities mainly for improved component life cycle management and in economically meeting future generation needs through extended plant operation. Life extension programs can pay off in the shorter term by identifying more efficient inspection, surveillance, and monitoring as well as by increasing reliability and availability via early problem detection and avoidance. Results will also be used to supplement codes and standards in areas where they do not contain adequate provisions for longer-term nuclear plant operation.

OTHER U.S. AGING RESEARCH

As discussed above, the U.S. DOE aging and plant life extension efforts are fully integrated with those of EPRI and the NUMARC NUPLEX Working Group toward developing the technology and information needed to establish and verify life extension and license renewal. These efforts are being supplemented with other programs conducted by nuclear plant owners groups in conjunction with their NSSS vendors and architect engineers. These programs address reactor-specific vessels and vessel internals, material degradation, coolant system components, recording of transient cycles, environmental measurements, monitoring techniques and component evaluation methodologies.

Codes and standards groups also have life extension activities under coordination by the American Society of Mechanical Engineers (ASME) through the Board of Nuclear Codes and Standards Life Extension Steering Committee. An ASME group will recommend or draft modifications to ASME code, Section XI to accommodate nuclear plant life extension. An Institute of Electrical and Electronics Engineers (IEEE) working group is assessing the adequacy of IEEE electrical component nuclear standards for life extension purposes. Other organizations involved in life extension activities include the American Concrete Institute and the American Nuclear Standards Institute.

CONCLUSIONS

U.S. nuclear power plants were designed with the best understanding of aging effects available at the time and, so far, have managed aging through programs tailored to achieve safe, reliable operation. Our understanding of aging and its management has improved through operating experience and aging research to date. Nevertheless, the continuing emphasis on safety and improved availability in operating plants, and the desire to preserve the option of nuclear plant operation beyond forty years motivate additional research focused on the key aging-related issues identified in this paper. Research results from current programs sponsored by the NRC, EPRI, DOE and other U.S. organizations will further improve our understanding and management of age related degradation, in safety significant components, systems, and structures. Research results can also allow informed evaluation and development of more cost-effective aging management programs by utilities. Fringe benefits include a reduction in excessive testing, improved reliability and fewer unplanned shutdowns.

Dialog on aging continues among the NRC, its NPAR contractors, and the industry via workshops, conferences such as this one, and information exchanges. All recognize the benefit of consensus definitions of aging terminology. This consensus would facilitate 1) mutual understanding of the real issues as coordinated research continues and 2) accuracy in the evaluation, reporting and trending of future operational failures. The ongoing dialog is intended to lead to greater utility participation in the NPAR program, such as providing the opportunity for in-situ assessments and making naturally aged components available for post service examinations and tests.

Coordinated NRC and U.S. industry aging research programs will contribute significantly towards ensuring safe, reliable, and economical operation during and beyond current licensed terms, maintaining U.S. nuclear power production well into the next century.

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