Operational and Materials Aspects of Aging Management

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Abstract

Understanding degradation phenomena and managing the detrimental effects of aging are important aspects of commercial nuclear power plant operations. Potential for materials degradation should be considered early in the design and development stages; during manufacturing, construction, and installation; and during all aspects of plant operation and maintenance. This would lead to increased reliability during plant operations, and would reduce the need for mitigating actions and unplanned maintenance. Thus, it is necessary to instill a culture at the technical, administrative, and management levels that continually asks, "What happens with time?" The answer to this question is central to the continuous safe and economical operation of nuclear power plants. Based on the past 25 years of aging-related research at the U.S. Nuclear Regulatory Commission (NRC), the authors present an overview of the key elements of understanding and managing aging, and how they should be integrated for safe and economical power plant operation. The focus of this paper is hardware-oriented engineering and aging of materials. The paper discusses previous and ongoing NRC research studies on non-destructive examination and materials degradation that can be applied for proactive management of materials degradation and aging during plant operations.

Introduction

For many years, the U.S. Nuclear Regulatory Commission (NRC) has maintained active and comprehensive research focused on understanding age-related degradation in nuclear power plant systems, structures, and components (SSCs). The research results are utilized in the regulatory process and in the development of consensus codes and standards. This effort has become increasingly important for the safe operation of nuclear plants as the units continue to age and their licenses are being renewed for 20 years beyond the initial license period. Materials degradation in nuclear power plant SSCs has been experienced almost since the inception of nuclear power plant operations, and history and operating experience have shown that unanticipated forms of degradation continue to emerge as time progresses. It is anticipated that materials degradation will continue, and may increase, as plants age.

Reacting to unexpected degradation that has progressed to the point of adversely impacting plant safety dramatically increases the resource burden on both the nuclear industry and regulators, compromises regulatory effectiveness and efficiency, and lessens public confidence. In addition, individual licensees, and the nuclear industry in general, experience economic burdens associated with extended repair outages and purchasing replacement power. These costs are ultimately borne, in some fashion by the consumers. For these reasons, it is in the best interest of both the industry and regulators to proactively address materials degradation.

Materials Aspects of Plant Aging

For many years, the NRC's Office of Nuclear Regulatory Research (RES) has performed research focused on assessing known forms of materials degradation and identifying potential future problems. A particular challenge is the development of suitable models for aging degradation of passive components, such as the nuclear reactor pressure vessel, piping, steam generator tubes, and electric cables.

For example, the NRC has focused major elements of the materials research program on degradation of the reactor pressure vessel as a result of irradiation embrittlement. Continuing degradation in fracture toughness of the reactor pressure vessel steel was recognized early in the operation of nuclear power plants. Early research addressed concerns over the fracture behavior of thick-section steel components. In addition, research has characterized embrittlement attributable to neutron irradiation. These research results were used in developing regulations, based on conservative analyses and data, to address operational and accident conditions that could result in failure of the pressure vessel.

More recent data and analyses, including new information on vessel flaw distributions and improved irradiation embrittlement modeling, are now being used to update the relevant regulations and remove unnecessary conservatism. This work is also directly relevant to plant operations through the heat-up and cool-down limits imposed to preclude pressure vessel failure, and it has a major impact on license renewal decisions for some licensees. While the NRC continues to be a leader in this area, the agency interacts extensively with the international community in identifying embrittlement mechanisms and characterizing the fracture behavior of embrittled steels.

Environmentally assisted cracking (EAC) was identified as an active degradation mechanism in the mid-1970s, with the discovery of intergranular stress corrosion cracking (SCC) in boiling-water reactor (BWR) piping. Over time, various forms of EAC have been identified in both BWRs and pressurized-water reactors (PWRs). For example, intergranular SCC has been observed in BWR reactor internals, primary water SCC has been observed in a number of PWR components, primary and secondary side SCC have been experienced in steam generator tubes, and irradiation-assisted SCC has been observed in some reactor internals in both BWRs and PWRs. Research programs have been developed to address each of these forms of cracking as they have been identified. Today, EAC research is a major aspect of the NRC's materials research program, with the intent to assess detrimental effects of aging in operating nuclear power plants.

Reliable detection and characterization of flaws are needed to assess the integrity and safety of degraded components. This requires a strong capability in the area of nondestructive examination (NDE), and the NRC's research in this area is recognized in both the national and international technical communities. In fact, the NRC's research has resulted in several major accomplishments that have been incorporated into the Boiler and Pressure Vessel Code promulgated by the American Society of Mechanical Engineers (ASME). In particular, these accomplishments include requirements for in-service inspection (ISI) qualification by performance demonstration; implementation of risk-informed ISI programs; advanced ISI methods and techniques; and techniques for continuous monitoring of crack initiation, crack growth, and leakage. The continuous monitoring of crack initiation and growth can be a powerful tool in improving operational aspects of nuclear power plants, in that the early detection of cracking can result in orderly and planned repairs before degradation can adversely affect integrity and safety.

In the current program, the two key challenges being addressed are identifying highly sensitive and reliable techniques and procedures that can be used to monitor for coolant leakage from any source, and assessing inspection and monitoring systems that can be used to detect ongoing degradation before it penetrates the pressure boundary. The NRC is initiating new work to address these issues, and expects to build on previous agency research with national and international cooperation. While research is underway to address the key aspects of materials degradation, analytical techniques are also evolving. The NRC's research program includes activities to develop data, predictive models, and methodologies that (1) integrate time-dependent degradation mechanisms, NDE, and failure models into probabilistic risk assessment (PRA) to yield an overall assessment of the safety-significance of various forms of materials degradation and aging, and (2) can be used in developing regulatory positions.

The NRC's Nuclear Plant Aging Research (NPAR) program [Ref. 1] and materials engineering research programs developed the engineering data for understanding and managing aging in safety-significant SSCs. Research conducted by RES supported agency activities for the license renewal rulemaking and guidelines, including the Standard Review Plan (SRP) [Ref. 2] and the Generic Aging Lessons

Learned (GALL) report [Ref. 3]. Research results have also been incorporated into consensus standards promulgated by ASME, the Institute of Electrical and Electronics Engineers (IEEE), and the American Concrete Institute (ACI). In addition, research results have been applied in reviewing the industry-developed guidelines, as well as the licensees' programs for aging management during the license renewal period.

A Proactive Approach to Managing Materials Degradation

The NRC's materials research addresses both current and emerging issues relating to operating reactors, including those dealing with license renewal, repairs, and replacements. The NRC has research efforts planned and underway to support the evaluation of licensee programs for proactive management of materials degradation in nuclear power plant SSCs [Ref. 4].

The NRC is addressing the management of materials degradation through a four-pronged approach. First, RES has initiated a structured approach to identify light-water reactor (LWR) components that may be susceptible to future degradation. This approach involves examining components of which failure would adversely impact plant safety or lead to a release of radioactivity.

Second, RES will evaluate the expected performance of new materials, assess the capabilities of new inspection procedures and techniques, and conduct tests and analyses to identify potential new degradation mechanisms. It is this aspect of the NRC's program that most directly addresses inspection and monitoring programs that may be warranted to identify emergent degradation before it adversely affects plant safety.

Third, the NRC's research program will closely follow industry-proposed repair and mitigation strategies and perform confirmatory research to evaluate the effectiveness of these strategies and ensure that they do not introduce unanticipated problems. Some of the planned research will be accomplished through international cooperation.

Finally, through its regulatory efforts, the NRC will review licensee programs to manage identified degradation in operating plants and, in some cases, will mandate specific actions. Thus, the research program will support these regulatory activities by providing data and analysis tools that can be used to evaluate the licensee programs and support other regulatory actions.

A technically challenging step in the proactive materials degradation research program is the identification of materials and locations where degradation can reasonably be expected in the future. To address this challenge, the NRC has assembled a panel of eight world-class materials and degradation experts to conduct a systematic review of LWR components. This review will yield a list of LWR plant components with varying degrees of susceptibility to future degradation mechanisms, the reasoning behind their judgments, and an assessment of the knowledge base to develop mitigating actions for the materials and degradation mechanisms.

The list of LWR plant components with varying degrees of susceptibility to future degradation mechanisms and the assessment of the knowledge base will be used in developing an NRC-led integrated cooperative program that will share research results from U.S. and international government and industry organizations. Results from this cooperative research will provide the technical bases for effective implementation of proactive materials degradation management programs to ensure reliable and safe operation of nuclear power plants.

Improved Collection and Integration of Operating Experience Data

An important first step in proactive materials degradation management is the identification of components that can reasonably be expected to degrade in the future. This assessment must consider past operational experience, any potential mitigation applied, and the evaluation of time-dependent phenomena that may lead to later onset of degradation or development of new degradation modes.

Licensee event reports (LERs) and other reports related to plant occurrences need to be more widely available and must contain more detailed information on plant operating history, materials involved, and stressors (such as temperature, water chemistry, stresses, cycles, etc.). This information could be used to develop predictive models for understanding the implications of failures for other plants in the worldwide fleet of nuclear power plants. However, the needed operating experience data are not being collected and integrated in a fully effective manner. At present, regulatory bodies receive event reports and material non-conformance reports, but no formal system is in place to collect and integrate information describing routine degradation and plant repairs. Although it is below the threshold for event reporting, such information may identify accident precursors or emerging degradation issues that become evident with data trending. Additional information compiled by licensees (plant operators), including root cause analysis and corrective action reports, is usually compiled with great attention to detail and could be another source of data for trending and developing the predictive models discussed above. Some standards have been proposed for reporting operating experience that is not currently captured [Ref. 5], and their continued development is encouraged.

Concluding Remarks

Degradation experienced during nuclear power plant operations has resulted in significant operational challenges and potential safety problems. These challenges have required industry and regulators to make substantial investments in research, mitigation, repair, replacement, and inspection, with correspondingly intense regulatory actions.

Our expectation is that materials degradation from known and previously experienced aging mechanisms, as well as emerging mechanisms affecting different components, could continue and would likely accelerate as plants age, unless proactive actions are taken to manage potential degradation. Effective development and implementation of proactive materials degradation management (PMDM) programs will require commitment of the worldwide nuclear power plant community (including regulators and industry), extensive international research, and exchange of results. From an operational point of view, PMDM will involve more effective ISI and implementation of continuous online monitoring for crack initiation and growth to enable well-planned, orderly, and timely repair and replacement activities. Ultimately, these investments will yield dividends by maintaining the safety of operating plants, leading to more efficient and effective use of limited resources (for both regulators and industry), and improving public confidence regarding the safety of nuclear reactors.

References

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