Long-Term Ageing Management Strategies for Nuclear Power Plants

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Abstract. All nuclear power plants have implemented some form of long-term ageing management at their facility. However, methodologies have been developed recently that can provide enhancements to the existing ageing management plans. Comprehensive long-term ageing management strategies consider the role of every system, structure, and component (SSC) in the nuclear power plant and assesses how ageing can prevent those SSCs from performing those roles. While the ultimate goal of the different methodologies is the same (that is, managing the ageing of plant SSCs to assure safety and cost efficiency) their focus and stakeholders are different, and therefore, there are differences in the specific methodologies. These categories of methodologies can be defined as experience-based, regulatory-based, and economic-based methodologies. This paper will provide an overview of the three different categories of ageing management methodologies.

1. INTRODUCTION

All nuclear power plants have implemented some form of long-term ageing management at their facility. However, methodologies have been developed that can provide enhancements to the existing ageing management plans. This paper presents these comprehensive ageing management strategies.

Comprehensive long-term ageing management strategies consider the role of every system, structure, and component (SSC) in the nuclear power plant and assess how ageing can prevent those SSCs from performing those roles. Many nuclear power plants have not yet implemented generic aging management methodologies for the long-term aging management of the plant. These plants typically utilize existing maintenance and inspection programs to manage plant ageing. While maintenance and inspection have not been traditionally called ageing management programs, they perform activities that are credited with managing ageing. These activities have been performed for many years, and many of these programs exist as a result of commitments to specific regulations (e.g. In-Service Inspection). Other programs exist because they have been identified by standards or industry best practices. Operating experience provides feedback when failures occur so that enhancements to programs can be developed through the corrective actions process.

While the above process has served the industry well and will continue, experience suggests that many gaps have been identified when a long-term ageing management strategy is implemented. These gaps include, for example, missing programs, key components that are experiencing ageing but aren’t covered by any program, deficient or out-dated techniques being used in existing programs, and enhancements in the acceptance criteria for the program.

Several methodologies have been developed to identify gaps in ageing management and/or to confirm that the existing ageing management is sufficient. These methodologies combine to provide a comprehensive long-term ageing management strategy. While the ultimate goal of these methodologies is the same (that is, managing the ageing of plant SSCs to assure safety and cost efficiency) their focus and stakeholders are different, and therefore, there are differences in the specific methodologies. These categories of methodologies can be defined as experience-based, regulatory-based, and economic-based methodologies. This paper will provide an overview of the three different categories of ageing management methodologies.

2. EXPERIENCE-BASED AGEING MANAGEMENT

The first methodology historically used for managing ageing is the experience-based methodology. This method is currently being used throughout the industry and has been employed since the birth of the nuclear industry. This method relies on preventive maintenance and corrective actions processes, operating experience, owners groups, industry message boards, and similar methods to disseminate information related to experience on issues related to component ageing.

2.1. Preventive Maintenance and Corrective Actions Process

Preventive maintenance is surely the most important form of ageing management performed in the power plant. Maintenance activities are established based on good engineering practice and manufacturers recommendations via vendor manuals or consultations. Maintenance is performed in accordance with procedures that are prepared based on these recommendations and practices. The initial frequency of the preventive maintenance is also established based on engineering practice/judgment and manufacturers recommendations. Work is implemented via the work control process.

All SSCs generally require some form of maintenance to maintain functionality; therefore, the scope of the Preventive Maintenance program is generally the entire plant. Preventive maintenance processes assess component functionality and assign the commensurate maintenance practices, with the goal of preventing failures on components whose functionality must be assured (e.g. those that are not assessed as ‘run to failure’). When failures occur, the corrective actions process requires evaluations of the root cause of the component failures. This process evaluates preventive maintenance to ensure that the preventive maintenance practices and procedures, as well as the frequency of maintenance, are consistent with the operational and/or functional goals for the subject SSCs. Necessary preventive maintenance enhancements (e.g. change in preventive maintenance frequency) are identified through the corrective actions process and implemented via procedure or work control changes. In this manner, the corrective actions process is relied upon for continuous improvement of the Preventive Maintenance program.

Due to the importance of adequate preventive maintenance to plant safety, in the early 1990’s the USNRC determined that a regulation was needed to ensure that the process described above worked as intended. As a result, the Maintenance Rule was implemented under 10CFR50.65. The Maintenance Rule is an ‘umbrella’ program over the Preventive Maintenance program. It assesses the adequacy of the Preventive Maintenance program and ensures that corrective actions are implemented when performance degrades. The Maintenance Rule is discussed later in this paper under regulatory-driven ageing management.

2.2. Information Sharing and Industry Organizations

While this category of ageing management is not a single specific ageing management methodology, the various methods of communication throughout the industry have been very effective at communicating and managing issues over the years. The methods employed in experience-based ageing management ranges from informal information sharing (e.g. between system engineers that have the same system in different plants) to formal industry groups as the Boiling Water Reactor Vessel Inspection Program (VIP) or Pressurized Water Reactor Materials Reliability Program (MRP).

2.3. The Example of the Alloy 600 Primary Water Stress Corrosion Cracking (PWSCC) Issue

The way the industry has treated the Alloy 600 Primary Water Stress Corrosion Cracking (PWSCC) issue is a great example and illustration of experience-based ageing management. Past industry experience with PWSCC has been a series of unwelcome surprises. To start with, Control Rod Drive Mechanism (CRDM) nozzle outside diameter circumferential cracking was considered implausible by utilities and the regulators until it appeared in multiple penetrations on one reactor head and then at other reactors. Cracking at other Alloy 600 locations (reactor vessel and pressurizer nozzle safe-ends, reactor vessel bottom head nozzles etc.) was also deemed to be unlikely based on lower operating temperatures and/or specific geometries and/or fabrication circumstances. All events occurred in the seventies, eighties and nineties were treated as isolated events. However, every surprise caused the staffs of the utility and the regulator to be taken away from important day to day activities in order to manage the event in crisis-mode until a comprehensive integrated effort of the whole industry (EPRI, NEI, Owners Groups, Utilities and Vendors) was launched in the year 2000, subsequent to the VC Summer event. As a result of that industry effort, the EPRI Materials Reliability Program (MRP) Alloy 600 Issue Task Group (ITG) determined that every plant should have an overall plan for managing Alloy 600 primary water stress corrosion cracking (PWSCC) degradation, see Reference 0. This decision was based on the need for the industry to stop reacting to each finding of Alloy 600 PWSCC degradation as an isolated event and start pro-actively managing the issue. The outcome of that effort is that tools were developed to use detailed plant specific information in order to identify and rank/prioritize locations/components as a function of their susceptibility to cracking. Following the susceptibility ranking, a specific plan was developed for determining the locations/components to be inspected, and to detect, repair, and mitigate PWSCC cracking of Alloy 600/82/182. This pro-active identification of degradation areas has been particularly important due to the impact on outage time, radiation exposure, and cost associated with inspections and repairs.

Following the previous resolution of that issue, the industry went then one step beyond and developed ageing management tools belonging to the other methodology categories described in the following sections, i.e. regulatory-based and economic-based approaches. The implication in terms of the regulatory-based approach is that, to date, most plants have addressed PWSCC of Alloy 600/82/182 in some way as part of ageing management and/or license renewal activities. Important resources for these activities include NUREG-1800, Standard Review Plan for Review of License Renewal Applications for Nuclear Power Plants, July, 2001 (Reference 0) and NUREG-1801, Generic Aging Lessons Learned (GALL) Report (Vol 1 and Vol 2), July, 2001 (Reference 0). Therefore, given the impact of the Alloy 600 issue on outage time, radiation exposure, and cost associated with inspections and repairs, the utilities and vendors have developed economical tools called “decision advisors”. For example, the Westinghouse Alloy 600 Decision Advisor is a computer-aided product that provides probabilistic projections as to when components will fail, and considers the cost and benefits of alternative PWSCC mitigation or repair options. Simultaneously, it optimizes such decisions across the whole plant for all affected components. This tool is based on the concepts described in Section 4 of this paper.

2.4. Conclusions on the Experience-Based Ageing Management Strategy

As a conclusion, the experience-based ageing management strategy has served nuclear power industry very well since start-ups. However, it can lead the industry to be in a reactive mode instead of adopting a systematic approach and develop inspection and mitigation plans to control events. As a consequence, this approach type does not allow identifying potential gaps that exist in the ageing management of some important SSCs (for example, safety-related structural components). Experience-based ageing management is thus obviously necessary and is incorporated in every other approach. When used as a single strategy and not built in as a step of another more global methodology, this approach is not sufficient to meet the challenges of long term operations and does not meet current ageing management standards for long-term operation specified for License Renewal and Periodic Safety Reviews.

3. REGULATORY-BASED AGEING MANAGEMENT

The second methodology used in the nuclear industry for managing ageing of components is regulatory-based ageing management. Similar to the experienced-based methodology, regulatory-based ageing management has been successfully used since the start of the nuclear industry. However, a major difference is that recent regulations have been developed that address ageing management in a generic and comprehensive manner. These recent regulations are intended to ensure long-term safe operation of plants, even after the initial design period for the plant is exceeded. Each of these categories of regulatory-based ageing management is discussed in the following section.

3.1. Rules-Driven Practices

Regulatory-based ageing management has existed since the beginning of the nuclear industry. Nuclear plants were required by regulatory rules to be constructed in accordance with codes and standards that existed at the time the plant was constructed. For example, piping specifications were developed to govern the materials and piping schedules that were installed in plant piping systems based on the codes (ASME, ASTM, etc.) that existed at the time the plant was designed. The codes were developed with design margins in their bases; therefore, building plants consistent with the codes and standards ensured that plants could be relied upon to function in the manner that they were intended. Regulators were tasked with oversight to ensure the plant was designed and constructed consistent with those standards.

After the plant went into operation, additional rules made sure the plant continued to operate in compliance with the codes and standards to which it was designed. In general, regulatory-based rules for the nuclear industry are imposed to ensure the health and safety of the public. These rules generally ensure that the material condition of the plant is consistent with the initial design and, accounting for ageing of components, ensure that sufficient design margin is maintained so that compliance with the initial codes and standards is maintained.

An example of a code-based ageing management regulation is the in-service inspection (ISI) program which is performed in accordance with ASME requirements. ASME codes provide specific requirements for performing inspections of components in the nuclear plant, and establishes acceptance criteria for the inspections based on the design, function, and margins considered when the plant was built. The purpose of the inspection is to determine that the material condition of the plant is consistent with the initial design, which provides reasonable assurance that the system, structure or component will continue to perform in a manner that is consistent with the licensing basis of the plant.

In a similar manner, the regulatory body may impose standards on the plant design that may not be based completely in codes, but based on the experience gained from plant operation. For example, after the Three-Mile Island event, standards were developed which required certain electrical components to be qualified to function in the post-accident environment. These standards were implemented throughout the nuclear industry as the Environmental Qualification rule, which is an ageing management program that periodically replaces electrical components based on component ageing considerations.

While the ageing management of plants based on codes and standards, as well as the experienced-based methodology outlined in the first section, has been effective during the early years of the plant life, experience has shown that there have been gaps identified where some important SSC are not having their ageing managed through these traditional methods. As plants get older, these gaps need to be filled because ageing components will continue to challenge the viability of plant operability and reliability, either through the real or perceived notion that older plants may be less safe. Generic methodologies have been developed to identify these gaps, and new regulations have been implemented to ensure the gaps are filled so that ageing is managed on important plant SSCs.

3.2. Generic Regulatory-Based Methodology for Ageing Management

Historically, all plants in the world have followed the experience and rules-driven ageing management practices that have been described up to this point in this paper. However, in the past ten or fifteen years, there have been additional generic processes implemented in the industry that enhance the identification and ageing management of important SSCs. These generic regulatory-based methodologies include the Maintenance Rule and License Renewal Rule.

As stated earlier in this paper, the Maintenance Rule is a regulatory program (imposed via 10CFR50.65) that provides oversight of the preventive maintenance that is performed at the plant. The regulatory focus is plant safety; therefore, the scope of the Maintenance Rule is limited to the SSC functions that are important to safety (including SR, NSR supporting SR, SSC supporting emergency operating procedures, and SSC whose failure could cause a scram). For those components in scope, preventive maintenance is assessed to ensure that the maintenance is supporting an overall goal of continuous improvement. To accomplish this objective, specific system performance goals are established and periodically measured and trended. When system performance degrades, the Maintenance Rule process requires actions to be implemented to reverse the trend. In this manner, the Maintenance Rule simply provides for regulatory oversight to ensure that the experienced-based preventive maintenance process outlined earlier this paper is adequately implemented (from both a scope and process perspective).

In the Statements of Consideration to the License Renewal Rule (Reference [4]), the USNRC states that as a result of the continued applicability of the Maintenance Rule and regulatory requirements, the active functions of SSCs will be reasonably assured in any period of extended operation. However, in this same document, the USNRC provides reasons that the Maintenance Rule does not provide sufficient ageing management of long-lived, passive SSCs. Two practical examples are safety-related structural components (e.g. passive structural supports) and electrical cables. Therefore, the focus for license renewal is the long-lived, passive SSCs and the design-basis calculations that have a time-limiting aspect.

The two regulations, taken together, provide regulatory oversight of the ageing management processes that ensure both the active and passive functions of SSCs that are important to plant safety. These regulations also provide the regulatory basis to ensure long-term operation of the nuclear power plant.
The generic process for performing ageing management under 10CFR54 involves three steps; performing plant scoping/screening, performing ageing management reviews, and evaluating Time-Limited Ageing Analyses (TLAAs).

The scope of SSCs within the scope of the ageing management process includes SSCs that are SR, NSR supporting SR, and SSC supporting each of five regulated events determined by the USNRC to be important to safety (fire protection, environmental qualification, station blackout, anticipated transients without scram, and pressurized thermal shock).

The components determined to be within scope require an ageing management review (AMR). AMRs are generally performed on a system basis. For each system, the ageing management process includes t he following activities:

- Determine component materials of construction
- Identify environments in which these components reside
- Determine the ageing effects for material/environment combinations
- For all components and all ageing effects, confirm that plant programs exist that manage ageing; or modify existing programs; or develop new programs
- Validate results with plant-specific and industry operating experience.

As stated earlier in this paper, implementing the ageing management process shown above has identified that there are gaps in ageing management that exist at all plants that have implemented the process. There are many reasons for these gaps, but typical reasons include SSCs not being within the scope of an ageing management program, the program does not adequately perform ageing management (for example, incorrect inspection methods for the ageing effect of concern, lack of trending where appropriate, etc), or there are no ageing management programs in place.

Existing programs are credited with managing ageing to the maximum extent possible. Many program s are crediting with managing ageing with no changes or program modifications necessary. Typical exi sting ageing management programs include:

- In-Service Inspection (code-required inspections)
- Water chemistry monitoring
- Flow-accelerated corrosion monitoring

Conversely, industry ageing management experience has shown that most plants need to modify some of their existing programs or implement new ageing management programs. Examples of typical modi fied and new programs include:

- Underground piping external surface inspections
- Structures and structural components inspections
- Cables and connections inspections

The final step in the generic process is to locate, review and, in some cases, revise plant analysis and/or calculations that have a time-limited aspect. For example, the original plant design included in the basis consideration of the number of fatigue cycles that certain components could experience during plant life. These fatigue cycles are typically monitored by counting the number of transients that the plant has experienced and comparing those against limits that are typically contained in the plant UFSAR, or in design basis documentation supporting the information in the UFSAR. The calculations supporting the UFSAR criteria are TLAAs and must be evaluated against the actual number of transients for life extension. In cases where the actual number of transients may be exceeded before the period of extended operation is over, additional analysis is needed to verify that the design basis for fatigue will not be violated.

3.3. NRC Regulations versus IAEA Guidelines

As discussed in the previous section, long-term ageing management is addressed through implementation of processes that assure ageing is managed for SSCs that are important to safety so that there is reasonable assurance that the active and passive component functions are maintained. In the US, this is ensured through implementation of the Maintenance Rule (10CFR50.65) for ageing management of active component functions and through the License Renewal Rule (10CFR54) for ageing management of passive component functions.

The IAEA has published guidelines that include ageing management objectives with similar goals as the regulations that have been implemented in the US. Specifically, the guideline governing Periodic Safety Reviews (Reference [5]) states that each SSC should be assessed against its design basis to confirm that ageing has not significantly undermined the design basis assumptions. Additional guidelines (Reference [6]) have been issued subsequent to the Periodic Safety Review that provide additional detail for long-term operation of nuclear power plants with regards to ageing management. While there are differences in the specific text between the IAEA and NRC documents, the intent of the NRC and IAEA documents is the same; to provide for the long-term ageing management of the important portions of the nuclear plant. Therefore, the generic regulatory-based methodologies discussed in this portion of the paper are compatible with the rules and regulations at all nuclear facilities in the world. In fact, this generic approach has been comprehensively implemented in ageing management projects in Spain and Slovenia, as well as through the license renewal process in over half of the plants in the US.

3.4. Conclusions on the Regulatory-Based Approach

While rules-driven ageing management provided an excellent methodology for managing ageing issues during the early years of plant life, the nuclear industry has recently successfully implemented generic methodologies throughout the world that provides reasonable assurance that plant ageing will not prevent the plant from performing important functions for long-term operation. Long-term operation includes time-periods extending beyond the initial design basis of the plant. For most plants, the initial design basis was forty years. The methodologies described in this paper have been successful in providing the bases for extending the initial operating period of the plant. For example, more than 50 plants (over half of the nuclear fleet) in the US have successfully justified plant operation for twenty additional years. Spanish plants have had similar successes, although Spanish utilities are currently negotiating about the details of the extended period of operation. The Slovenian plant is currently having the results of their process reviewed by the regulatory body, with the anticipation of successful long-term operation. All of these successes implemented processes that are similar to the generic regulatory-based methodologies described above.

As has already been mentioned in this paper, the focus of the regulatory-based methodologies is satisfying the rules that are implemented by the authorities to ensure public safety and health. While this focus is integral to long-term operation of the plant, it is also important to the utility owner-operator to ensure that ageing does not significantly impact the reliability and availability of the plant.

While many of the SSCs that support plant health and safety are the same SSCs that support plant availability and reliability, the population of the former are a different (and probably larger) population of SSCs than the latter. Therefore, the regulatory-based approach provides a very good starting point to the application of economic-based ageing management methodology which is described in the next section.

4. ECONOMIC-BASED AGEING MANAGEMENT

While regulatory requirements focus on the ageing management that is necessary to ensure public health and safety, the focus of economic-based ageing management methodologies is the efficient operation of the power plant. While ageing assessments for SSCs in this category of the plant are similar or the same as for the first category above, the consequences of the SSC ageing may not be the same. For example, while proactive ageing management of turbine components may not have any consequence to the health and safety of the public because their failure cannot impact safety or important to safety functions, failure of these components may have significant impact on plant availability and economic viability. Therefore, the economic-based ageing management methodologies evaluate SSC ageing against their importance to power production or other related economic criteria. They are also referred to as Plant LIfe Management (PLIM) as they result in the integration of ageing management and economic planning.

The primary difference between the methodologies for economic-based ageing management and regulatory-based ageing management is consideration of the economic impact of the consequences of the ageing management, or lack of ageing management being performed. For major components that impact power production (turbine, major heat exchangers, etc.) evaluations are performed using operating experience to predict component performance. These evaluations are then assessed and integrated with overall utility strategic investment objectives to optimize long-term planning.

4.1. Economic-Based Methodology for Ageing Management

The methodology to optimize the economics of plant-wide ageing management decisions (for inspection, testing, maintenance, repair and replacement of ag eing SSCs) is also aimed at identifying the benefit and optimal timing of the ageing management activi ties based on minimizing unplanned outage costs and maximizing station Net Present Value (NPV), i.e . the present value of investment costs and avoided costs. For that purpose, Westinghouse developed a methodology that is documented in Reference [7] and that is based on the following stages:

- A Proactive Asset Management (PAM) and evaluation process which has the goal to develop an understanding of what is important to the plant operator.
- The development of PLIM plans for the important plant components and structures.
- The optimization of the PLIM plans at the system or plant level that maximizes the NPV when remaining constrained by a given planned budget per year.

The PAM Evaluation Process consists of a screening, selection and prioritization of the SSCs that are critical to meeting station goals, i.e. prevent downtime or partial reduction of plant power level and reduce Unplanned Capacity Loss Factor (INPO Station Performance Index Indicator). The criteria are based also on importance to safety, regulatory compliance, importance to power production, risk significance, component failure cost significance etc. Following the selection of the SSCs, the ageing mechanism effects (generic and plant specific ageing issues, probable ageing or degradation mechanisms) and the associated ageing management activities are identified. From that point, station and expert input for components, including economic, technical, safety, performance data are collected. Based on these inputs, a set of desired alternatives is developed, there alternatives may include: proactive replacement, spares policy, Preventive Maintenance (PM) improvement, improved condition monitoring (to get advance warning of impending failure to take action before failure), run to failure etc.

Then, for each selected component, a PLIM plan is developed. That stage consists in evaluating the desired alternatives developed under the previous steps for the selected components. For those components that warrant detailed study, the net present value and timing for maintenance expenses can be optimized for specific options. The study is aimed at defining the optimum action timing, the cost effective condition monitoring parameters and the sensitivity of the model to the different parameters. Once, the PLIM plans at a component level are developed, the PLIM plans are integrated to perform a plant or system level PLIM plan optimization.

This last stage of plant or system level PLIM plan optimization allows optimizing several defined strategies for each component. Replacement of a component too early increases the net present value required for the maintenance as the maintenance budget is spent when the value of the component is not fully realized. On the contrary, replacement too late can drastically increase the probability of component failure, increasing also the costs of loss of power generation, as well as the possible regulatory costs associated with the restart. The optimization of the timing of maintenance, replacement or mitigation actions across a complete set of SSCs and over the life or extended life of the plant is based on mathematical models. Component failure rates are modeled and a probability density function associated to the time to failure is defined for the selected components. Then, an evolutionary “genetic” algorithm is used for optimizing the maintenance/replacement/mitigation dates for the defined population of components and ageing management alternatives. The optimization objective is to maximize revenue over the life of the station while minimizing the investments and considering a system or plant-wide budget constraint per year.

4.2. Conclusions of the Economic-Based Methodology

There are only a few utilities or operators in the world that have followed this process of applying regulatory-based approach to extend the operating time of their plants and complemented it by a Proactive Asset Management and Plant Life Management Optimization for integrating both the important to safety and important to power production SSCs in one single and comprehensive approach. NOK Beznau is however a very good illustration of the application of such a comprehensive plant-wide approach as presented in Reference [8]. The result is the demonstration that Long Term Operations up to 60 years is technically as well as economically possible

5. CONCLUSIONS

All nuclear power plants have implemented some form of long-term ageing management at their facility. However, methodologies have been developed recently that can provide enhancements to the existing ageing management plans. Comprehensive long-term ageing management strategies consider the role of every system, structure, and component (SSC) in the nuclear power plant and assess how ageing can prevent those SSCs from performing those roles. While the ultimate goal of the different methodologies is the same (that is, managing the ageing of plant SSCs to assure safety and cost efficiency) their focus and stakeholders are different, and therefore, there are differences in the specific methodologies. Three methodologies were described in this paper; experience-based, regulatory-based, and economic-based methodologies. While historical methodologies have served the industry well during the early years of plant operation, industry experience is that these methodologies must be supplemented with additional long-term ageing management strategies to ensure the goal of long-term operation is achieved. This paper provided some basic information to assist the reader to obtain a basic understanding of the generic methodologies the industry is using to address long-term operation of the nuclear power plant.

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