Approaches for selection of components sensitive to ageing

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ABSTRACT

Over the years, the increasing age of components and systems has the potential to cause deterioration of their operability and by that to prejudice the safely operation of the facility. For this reason, in order to manage the degradation in a proper manner, and to assure the safe operation, it is essential to assess the effects of age-related degradation of facility structure, systems and components.

Each facility and especially NPP has thousands of components made from a variety of materials with ageing at different rates. Experience shows that ageing mechanisms, which result in the reduction of functional capabilities of components and systems, are operative to different degrees throughout facility (depending on many stressors).

Some of the safety related components contribute more than others towards ensuring facility safety and the extend to which these components are susceptible to ageing degradation also differ considerably. Also, all facilities have a large variety of testing, maintenance and inspection programs, which can mitigate more or less the effects of ageing.

To evaluate each of facility components in terms of its life would be a difficult task, and the process of evaluation and quantification of ageing degradation of the many thousand of individual components is not practicable nor is it necessary. A more rational and cost-effective approach is required, based on a selection process. Components should be carefully selected and prioritized to maximize the effective use of limited resources and to prioritize the work.

The paper will present an outline of the practical methods used for selection and prioritization of components susceptible to ageing, with their benefits and limitations in applicability, and will propose, on the basis of existing knowledge and on a systematic examination of system and structures, a selection method for determining the components susceptible to ageing degradation whose failures could have a significant adverse effect on facility safety.

INTRODUCTION

Over the years, the increasing age of components and systems has the potential to cause deterioration of their operability and by that to prejudice the safely operation of the facility. For this reason, in order to manage the degradation in a proper manner, and to assure the safe operation, it is essential to assess the effects of age-related degradation of facility structure, systems and components.

Studies on the management of ageing are aimed at identifying problems that may result from the plant ageing and the actions or initiatives that are available to manage ageing degradation of plant components. These studies should addressed the following technical issues:

-which NPP components are susceptible to ageing degradation that could adversely affect plant safety? Which of these components are renewable (by maintenance, refurbishment or replacement)?

-what are the degradation processes of materials and components that could, if unchecked, affect plant safety?

-are current methods for testing, inspection, surveillance, maintenance and replacements adequate to detect and mitigate ageing problems before they significantly affect plant safety? If not, what additional measures are needed?

-are current analytical models and criteria adequate to evaluate the residual life of key components and structures? If not, what additional criteria and supporting evidence are needed?

-how should structures and components be selected for comprehensive assessment of ageing and evaluations of residual life?

-what kinds of records and documentation are needed to support effective ageing management?

In the last years, ageing assessments have become an important tool for understanding and managing the effects of time-dependent degradation in nuclear power plants. The ageing assessment study should take into consideration:

• Active mechanical components, such as pumps, valves, motors, and circuit breakers;
• Passive elements, such as structures, electric cables, and piping;
• Large-scale infrastructure systems, such as buildings and facility-support systems.

The value and effectiveness of an ageing assessment is based on the premise that understanding how a component or system ages will provide insights that aid in:

-understanding the effects of degradation on performance

-identifying appropriate mitigation techniques which can be applied through operating and/or maintenance practices.

The need for understanding ageing and for conducting ageing assessments are numerous, as follows:

- for ageing plants – because of the large number of aged plants, research studies have been and continuous to be performed to assess the effects of ageing degradation on plant performance and safety.
- in the demonstration of the effectiveness of the plant maintenance programs
- in the licensee renewal – the requirement is to ensure that age related degradation unique to the licensee renewal period is identified and managed
- in other nuclear aged facilities, in which exist similar ageing concerns
- for advanced reactors – the lesson learned from ageing research on current nuclear reactors can provide information that will be useful in the design and operation of advanced reactors, as the selection of ageing resistant materials, identification of suitable inspection and monitoring techniques, optimization of design configurations or operating strategies.

An universal methodology for performing ageing assessments has not been developed, even as for guidance can be used the IAEA methodology and the methodology which has been developed and refined under NRC Nuclear Power Plant Ageing Research (NPAR) program. Plant specific evaluations could provide additional insights into the proper management of ageing degradation at a particular plant.

The selection of components which are important to safety and susceptible to ageing degradation also, is very useful, because focuses resources on most important items.

In the selection process, the following methods can be used:

- analysis of operating experience
- expert judgment
- probabilistic techniques for prioritization and for determining risk significance of ageing

Operating experience

Analysis of operating experience data is a valuable method of identifying key components and systems susceptible to ageing degradation. The analysis of Licensee Event Reports and plant reliability databases permits:

- to identify the extent to which the performance of systems and components has been affected by ageing, and the ageing mechanisms responsible.
- to identify methods of failure detection and the severity of the failures
- to identify specific ageing failure causes for selected systems and components

Periodic assessment of databases can yield information on increasing component failure rates (sign of ageing), thereby giving vital information for focusing maintenance and surveillance activities.

By interviewing personnel on:

- current equipment problems and possible root causes related to ageing,
- anticipated equipment performance or reliability problems,
- historical ageing problems which were expensive to rectify,

important operating information can be collected and significant safety component can be identified.

Comments

- *Since the operational data is scattered in a wide range of reporting systems, the determination of the accuracy and quality of data requires consultation of a large volume of technical documents*
- *Most of available databases were not designed to provide the data needed for the proper evaluation of ageing effects (they do not include data on equipment age, service life or service conditions, maintenance histories of the failed components, or records related to incipient failures)*
- *One aspect of database analysis is that it may yield different results, depending on the period of time over which the database is sampled, especially for those components with moderately long lifetimes. As plants get older, these types of components may become more prominent in the population of failures occurring owing to ageing*
- *The operating experience information should be periodic analyzed, and databases should be periodically up-dated to ensure that data (materials, service conditions and their interactions) needed to evaluate the effects of the ageing of an actual system and component performance are collected*

For a simple ageing trend investigation, either simple graphs can be constructed, or simple test of hypotheses can be performed.

Graphs

A trend analysis of the data can be done by calculating failure rates for the components at various ages, and plotting them as a function of time. Once plotted, any increase in the failure rate will become evident, indicating that ageing degradation may not be properly controlled.

Comments:

- *easy and comfortable methods for evidence of trends*
- *visual assessment of data could help to identify potential issues, but hey don't offer any quantitative estimation about the size of the trends*

Hypotesis tests

In case of large population of the SSCs and well doing operating experience data collection, the statistical methods could be applied to identify the appearance of ageing effect to SSC reliability.

The hypothesis can give a quantitative answer to the question of whether ageing appears to be present, by measuring the strength of the evidence against the hypothesis H_0: no ageing occurs.

The various statistical tests (Laplace, chi-squared, inversion test) could be used to validate or to refuse this assumption.

Some deficiencies to use a failure statistic considered in PSA could relate to the following issues :

- component reliability parameters are usually estimated on the basis of recent period of NPP operation and do not cover component history from the beginning of operation,
- for some types of safety components the population is not large enough to have sufficient failure statistic,
- information about component commissioning, replacement and maintenance are not usually considered in the frame of PSA reliability data elaboration.

In those cases some additional efforts to enlarge available statistic are usually required.

Comments:

- *non -parametrical tests are very simple to apply*
- *they don't apply any assumptions concerning the type of random value distribution*
- *results have to be always interpreted taking into account engineering considerations and qualitative assessment of data*
- *the method could be applied for preliminary data analysis in Ageing PSA to identify the component groups with ageing trend and, as a consequence, to select the components for further age-dependent models construction*
- *lack of strong evidence for ageing does not prove that no ageing is occurring, there may just not be enough data to draw firm conclusions*

The analyst should keep in mind that any statistical findings must be interpreted carefully and thoughtfully.

Modelling a trend

If the evidence justifies further work, a model for the data and for the trend should be assumed. Modeling a trend normally involves some detailed mathematics. It can be assumed that the data come from a Poisson process, with a failure rate λ that may be a function of age.

Comments

- *Parametrical tests are more complex but more powerful then non -parametrical ones*
- *Data homogeneity have to be verified (units, systems, environment, operating conditions, etc.) if possible*
- *Maintenance renewal, performed modifications could change the component reliability and impact significantly on data*
- *All conclusions are valuable since there is a large statistic, if not is recommended not to use the method*
- *Some of the models which are widely used, are chosen mainly for their simplicity and convenience, not for their theoretical validity*
- *Any model must be checked for goodness of fit (fitting the model with the data test) before drawing any conclusion about trend*
- *No model should be extrapolated far into the future — even if some convenient algebraic formula fits a trend well in the past, that is no guarantee that the data will continue to follow that formula in the future*

Probabilistic methods

The probabilistic safety analysis (PSA) is an efficient system analysis method which is used to assess risk of operation of nuclear power plants.

A standard probabilistic safety assessment does not include time dependent effects, and in the process of determining the risk level at a plant, it generally use a time averaged unavailability which limits the utility of the information that can be extracted from a PSA (ageing is a time dependent phenomenon).

In order to characterize the risk impact of component ageing and service wear effects, it is necessary to characterize the time dependent nature of the change in plant risk. That is,

$$I_A = \frac{\partial R}{\partial t} \qquad (1)$$

where I_A represents the risk impact of ageing, and R is the plant risk.

The plant risk is a function of the component unavailability q_j and the component unavailability is a function of the component failure rate λ; For the ageing studies, the failure rate is a function of time t. By the chain rule, changes in plant risk are expressed as:

$$\frac{\partial R}{\partial t} = \frac{\partial R}{\partial q_j} \cdot \frac{\partial q_j}{\partial \lambda_j} \cdot \frac{\partial \lambda_j}{\partial t} \qquad (2)$$

Risk ageing sensitivity to failure rate can be defined as:

$$G_j = \frac{\partial R}{\partial \lambda_j} = \frac{\partial R}{\partial q_j} \cdot \frac{\partial q_j}{\partial \lambda_j} \qquad (3)$$

The first term of the equation is equivalent to the Birnbaum measure, and the second term is the partial derivative of the component unavailability with respect to the component failure rate.

Those components with the highest ageing sensitivity cause the greatest impacts on risk if their failure rates increase substantially.

Comments

- *This adaptation of PRA results enables the identification of the components that have the most significant impact on risk if their failure rates increase, due to ageing or service wear effects without describing the time dependent behavior of the failure rate.*

- *The results are subject to the uncertainties inherent in PRAs including component failure data uncertainties, modeling uncertainties, and uncertainties in human actions and response. An important limited factor for the applicability of reliability methods may be the quality and quantity of collected operating experience. Since the methodology only relies on importance measures to provide a "go/no-go" answer to the question on screening, it can be considered that general importance measure limitations are not critical. Sensitivity analysis can be used to identify the importance of assumptions and areas where more in-depth analysis is needed.*
- *Investigation of components that do not appear in PRA dominant cut-sets is also necessary (components assumed to have negligible failure rates can be important to risk if their failure rates increase substantially)*
- *The usability of PSA for the selection and prioritization of components depends on several features. The models must be detailed enough to describe the impact of single components (or groups of components) on the plant safety*
- *The particular PRAs utilized to determine the component results may not include treatment of all aspects of risk such as external event analysis.*
- *Most current PRA analyses are level 1 PSA, and consequently, components (especially passive) that may be important to containment response or consequence reduction are not modelled. The importance to risk of components that mitigate accident consequences is not easy to determine in light of the large uncertainties associated with the phenomenology and fission product behavior of severe accidents*
- *The analysis is limited to the effects of complete failure (loss of function); the effects-of degradation (incipient failures) are not specifically addressed.*
- *A necessary complement to the risk ageing sensitivity measure is a description of the time-dependent effects of ageing on component failure rates. Initial estimates of these effects could possibly be estimated from older plant operating history and component failure data. A complete description will include:*

  -identification of component types that are susceptible to ageing

  -the environmental conditions and system applications that influence component ageing

  -time-dependent functions defining component failure rates

  These factors should be investigated first for the components that have high potential risk impact as determined by the risk ageing sensitivity measure.

Expert Assessment

<u>Expert panel</u>

Another method for identification of safety significant systems and components which may be subject to age related degradation is to consult members of plant personnel, engineers and scientists working in the nuclear power research and regulatory organizations who have a deep knowledge and experience of NPP performance and behaviour.
Generally speaking, an expert panel can be used:

- to assess the ageing of plants
- to incorporate an understanding of ageing and its effects (e.g., define the list of components susceptible to ageing and the contribution of SSC ageing to plant risk)
- to assess the adequacy of current practices for managing component ageing within acceptable levels of risk
- to determine the importance of SSC ageing of individual components/ component groups on plant risk
- to prioritize the components taking into account their risk significance of ageing

The following risk-based criteria can be used in the assessment process:
* the potential increase in plant risk from component ageing;
* the adequacy of current ageing management practices for maintaining risk at acceptable levels.
and supplemented, if needed with other technical criteria.
The panel membership should represent expertise in a full spectrum of relevant technical areas: PRAs, structures, electrical and mechanical components, component reliability, materials behavior and failure analyses, in-service inspection, operations and maintenance, as well as safety, regulatory, ageing and life extension issues.

The expert panel should be supplied with all the necessary information for a clear judgment (list of components, prioritization criteria, prioritization methodologies, and technical support material). The panel can use judgment to score the SSCs for specific criterion and to rank the SSCs relative to one another.

Risk Significance of Component Ageing and Ageing Management Practices model (RSCAAMP)
The RSCAAMP model allows the assessment of both the risk significance of component ageing and the effectiveness of current management practices for maintaining an acceptable plant risk level in the presence of component ageing.
The general model equation is:

$\Delta R = N \times A \times \frac{1}{2}\left(\frac{L_{ind}}{P_D \times P_{R/D}}\right)^2$ - relative contribution to plant risk of aged components

The model use as risk based criteria the following factors:

- N : normal risk importance of the SSC – equivalent to Birnbaum risk importance measure
- A : increase in SSC failure rate due to ageing
- L_{ind} : surveillance/test interval representative of current practice
- P_D : probability of successfully detecting ageing degradation within the surveillance or test interval
- $P_{R/D}$: probability of successfully mitigating ageing given successful detection

Each factor is normalized in a scoring scheme, with a score of 5 representing the highest risk effect from that factor and 1 representing the lowest risk effect on a logarithmic scale.
Final ranking (prioritization) of the SSC is based upon these calculated ΔR values. This ranking incorporates both the risk significance of ageing and the effectiveness of practices in maintaining ageing within an acceptable risk level.
The overall scheme of the process is presented below:

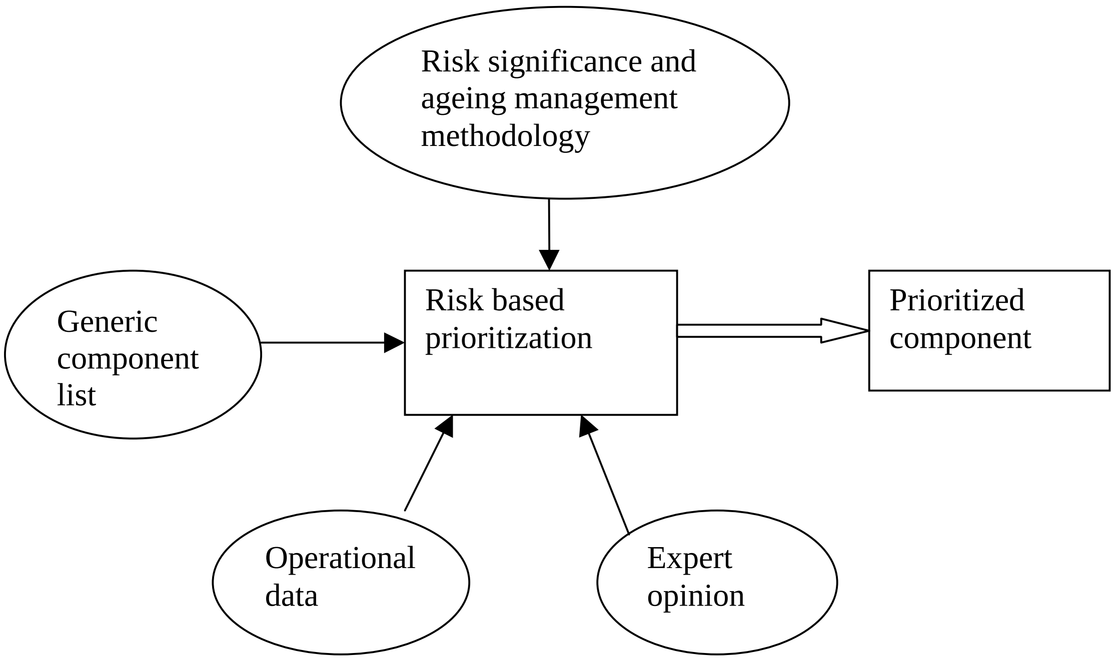

Figure 1: Overview of the process necessary for prioritization of component (RSCAAMP)

Because it facilitates an examination of the individual factors that contribute to the risk impact of aged components, RSCAAMP methodology has three other applications:

- it identifies the relevant factors for each component that need to be examined (the risk-important failure mode, ageing failure rate and its mechanisms; the adequacy of surveillance/test frequencies and methods; and the adequacy of mitigation methods);
- it identifies the ageing risk significant components, and for these, the inspection/test frequencies and methods necessary to detect the risk-significant failure modes, ageing mechanisms and the mitigation methods required to reduce risk;
- it provides guidance to utilities to reduce the risk contribution of their aged components (reducing N through changes in system design, added redundancy, etc.; reducing Δ through improved materials, upgraded operating conditions and environments, etc.; reducing the actual (effective) ageing interval (L_{act}) through a combination of reducing L_{ind} and increasing P_D and $P_{R/D}$).

Comments

- *Expert panels represent an useful approach for identifying ageing problems to be addressed. They can be very useful if the participants have a good knowledge of reactor safety and findings from the analysis of operating experience.*
- *A proper expert judgment treatment is a quite costly procedure, as it requires the efforts of many experts from varying fields of science, and takes quite a lot of time to carry out as well. Thus it appears that a reasonable combination of statistical, structural reliability and expert panel methods would be an appropriate approach in the failure probability assessments. If enough data of enough good quality is available, statistical methods could be used, and when the data is too scarce for that, a practical structural reliability analysis tool could be used to supplement the data, and when such is not available for the considered degradation mechanisms, expert panel judgment could be used to supplement the data.*
- *If adequate data are not currently available, the expert opinion process is the only way in which ageing issues assessment can be accomplished.*

Ageing Failure Mode and Effects Analysis (AFMEA)

The purpose of the AFMEA is to study the results or effects of item failure caused by ageing, on system operation and to classify each potential failure according to its severity.
For each system element, AFMEA can provides answer to the following questions:

- What are the ageing failure modes for a particular component?
- What will happen to the system and its environment if this element does fail in each of the ways caused by ageing and available to it (failure effects caused by ageing)?

The qualitative report will identify also the modalities in which the ageing failure can be detected and will specify (if any) the safeguards against significant failures caused by ageing
The method can be performed anytime in the system lifetime.
The method has the following advantages:

- it permits identification of potential component/process failure modes caused by ageing
- it prioritizes system vulnerabilities to ageing
- it provides guiding in improvement/ changing of operating condition
- it permits identification of stress factors and provides recommendation for their decreasing
- it emphasizes ageing prevention
- it documents risk and actions taken to reduce risk
- it provides justification for improving testing and maintenance activities
- it complements Fault Tree Analysis and other techniques

All recommended actions which result from the FMEA shall be evaluated for implementation or documented justification for no action.

Comments

- *FMEA is useful mostly as a survey method to identify major failure modes in a system. It is not able to discover complex failure modes involving multiple failures or subsystems, or to discover expected failure intervals of particular failure modes. For these, fault tree analysis is used.*
- *Performing the analysis will require lots of time, money, and effort. In case of complex systems, the process can be extraordinarily tedious and time consuming.*
- *The methods doesn't take into considerations the human errors or the passive elements located in non-hostile environments, as well as static or non-loaded elements.*

- *Failure probabilities can be hard to obtain; obtaining, interpreting, and applying those data to unique or high-stress systems introduces uncertainty which itself may be hard to evaluate.*

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Some of the safety related components contribute more than others towards ensuring facility safety and the extend to which these components are susceptible to ageing degradation also differ considerably. Also, all facilities have a large variety of testing, maintenance and inspection programs, which can mitigate more or less the effects of ageing.

To evaluate each of facility components in terms of its life would be a difficult task, and the process of evaluation and quantification of ageing degradation of the many thousand of individual components is not practicable nor is it necessary. A more rational and cost-effective approach is required, based on a selection process. Components should be carefully selected and prioritized to maximize the effective use of limited resources and to prioritize the work.

The selection process could be performed mainly by two screenings: the first screening is related to system level, and the second one is performed at component level (it is performed an evaluation of all component within the selected systems and structures).

Screening after the contribution of system or structure to plant safety
In order to do this selection, the entire list of NPP system and structures should be reviewed, and in the screening, the safety classification system (which already exist), and the results of PSA study can be used.
A way of setting priorities is to class the different systems of a plant by identifying the systems important for safety and important for availability. A system which does not belong to any of the above lists, it can be removed from the list for further analyses.

As a result, it is obtained a shorter list of systems and structures (important from the safety or availability point of view) to be evaluated at component level.

Screening after the impact of component failure to system function
This step should consider the significance of component failure that could be caused by ageing degradation.

If the components do not contribute to the performance of the system safety function, they could be omitted from further ageing evaluation, and they could be screening-out from the list. On the other hand, if there are components without safety functions, but whose failure could prevent other SSC from performing their safety functions, such components should be included in further ageing evaluation. The list should include both redundant and diverse components as ageing is a common cause mechanism and diversity may not protect against all ageing effects. If further analyses are needed, the observed and potential failure modes should be studied in detail, accounting for environmental and operational conditions, and safety and availability aspects.

If the component cannot be related to any of the above criteria, the component should not be included on the list for further ageing evaluation.
In this screening, the results from PSA studies, operational history, and expert opinion can be used.

Screening after the component susceptibility to age related failure
This step should evaluate the potential of ageing degradation to cause component failure, taking into account:

- *significance of known ageing mechanisms*
- *all applicable operating experience*

For this task, the responses could came from operational data and from expert opinion (using AFMEA procedure).

The final step of the selection is represented by the checking of the adequacy of current operational and maintenance activities to detect and mitigate significant ageing degradation

In order to do that, the following factors should be taken into account:

- the availability and adequacy of condition indicators to detect and predict components ageing degradation
- the adequacy of existing techniques to monitor these condition indicators
- the adequacy of existing operating and maintenance practices to mitigate components ageing degradation

The method which can be used in providing answers to this task is the experts assessment (using Risk Significance of Component Ageing and Ageing Management Practices model).

After the screening process, it will be obtained a list of SSC which are sensitive for ageing and important from risk and safety point of view.

CONCLUSIONS:

- A prioritization of selected components is recommended and can be performed if there are limited resources and a desire to deal first with components of high safety significance, which are also sensitive to ageing
- For the prioritization, a hybrid approach which combine the trend analysis, expert judgment and PSA techniques can be used. Ageing studies requires multidisciplinary analyses where the specific expertise should be combined.
- To provide more detailed information on how to control more effectively ageing at specific facilities, these ageing assessments should be performed on a plant specific bases.
- The identification and evaluation of degradation is based on knowledge of material degradation properties and on plant operating experience. The analysis of this information can be enhanced by using both qualitative and quantitative reliability engineering approaches and statistical analysis.

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