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Reliability methods in nuclear power plant ageing management

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Abstract

The aim of nuclear power plant ageing management is to maintain an adequate safety level throughout the lifetime of the plant. In ageing studies, the reliability of components, systems and structures is evaluated taking into account the possible time-dependent degradation. The phases of ageing analyses are generally the identification of critical components, identification and evaluation of ageing effects, and development of mitigation methods.

This thesis focuses on the use of reliability methods and analyses of plant-specific operating experience in nuclear power plant ageing studies. The presented applications and method development have been related to nuclear power plants, but many of the approaches can also be applied outside the nuclear industry. The thesis consists of a summary and seven publications. The summary provides an overview of ageing management and discusses the role of reliability methods in ageing analyses. In the publications, practical applications and method development are described in more detail.

The application areas at component and system level are motor-operated valves and protection automation systems, for which experience-based ageing analyses have been demonstrated. Furthermore, Bayesian ageing models for repairable components have been developed, and the management of ageing by improving maintenance practices is discussed. Recommendations for improvement of plant information management in order to facilitate ageing analyses are also given. The evaluation and mitigation of ageing effects on structural components is addressed by promoting the use of probabilistic modelling of crack growth, and developing models for evaluation of the reliability of inspection results.

Preface

This thesis is based on research work done at VTT Automation (former Laboratory of Electrical and Automation Engineering) in the context of ageing analyses of nuclear power plants. The research documented in this thesis has mainly been conducted on projects belonging to research programmes on nuclear power plant safety, and financed by the Ministry of Trade and Industry, VTT Automation, and the Finnish Radiation and Nuclear Safety Authority, STUK.

I am truly grateful to my instructor Dr. Urho Pulkkinen for his guidance while I was working on this thesis. He has also been an irreplaceable source of support and advice for my work since 1987, and it has been a great pleasure working with him throughout these years. I also thank my supervisor, Professor Raimo Hämäläinen from the Systems Analysis Laboratory of Helsinki University of Technology, for his encouragement and interest in my work.

I want to thank all my close colleagues at VTT Automation, in the former group of reliability engineering, and in the present team of system reliability. I am especially indebted to Dr. Kari Laakso for his collaboration and guidance in the field of nuclear power maintenance. I would also like to express my gratitude to our group leader Dr. Olli Ventä for his support.

Part of the work carried out for this thesis involved international co-operation co-ordinated by the International Atomic Energy Agency (IAEA), and Nordic co-operation, especially within the Nordic Nuclear Safety Research (NKS). I wish to thank all the experts whom I have met in connection with this work.

Finally, I want to thank my husband, Kimmo, for all his support and understanding. I dedicate my thesis to our marvellous children Inka and Toni.

List of publications

This thesis consists of the present summary and the publications listed below. The author's contribution to the preparation of the publications is briefly reviewed.

[I] Simola, K. 1998. The role of reliability methods in nuclear power plant ageing management. In: Lydersen, S., Hansen, G. & Sandtorv, H. (eds.). *Safety and Reliability. Vol. 2*. Proceedings of ESREL'98, Trondheim, June 1998. A.A. Balkema, Rotterdam. Pp. 903–910.

The paper discusses the use of reliability methods in nuclear power plant ageing analyses, and gives examples of applications. The paper summarises some research work carried out by the author. The work has also been reported to the International Atomic Energy Agency, mainly within the IAEA co-ordinated research programme on management of ageing of motor-operated isolating valves, where the author was responsible for the task: 'Risk and reliability assessment of MOV ageing'.

[II] Simola, K. 1998. Experience based ageing analysis of NPP protection automation. In: Mosleh, A. & Bari, R.A. (eds.). *Proceedings of the 4th International Conference on Probability Safety Assessment and Management*. Springer-Verlag, London. Pp. 483–488.

The paper presents a methodology for an experience-based ageing analysis and reports applications on protection automation systems. The author has written the paper based on three successive research projects, of which she was in charge.

[III] Simola, K., Laakso, K, Hänninen, S., Kosonen, M. & Unga E. 1991. Systematic analysis of operating experiences – an application to motor operated valve failure and maintenance data. In: Holmberg & Folkeson (eds.). *Operational Reliability and Systematic Maintenance*. Elsevier Applied Science. Pp. 129 – 150.

The paper describes the results of a study on motor-operated valve operating experience. The author was responsible for the data analyses, and participated in the development of the analysis method. The author has written the paper.

[IV] Pulkkinen, U. & Simola, K. 1999. Bayesian ageing models and indicators for repairable components. Helsinki University of Technology, Systems Analysis Laboratory Research Reports A77. 23 p. + app. 4 p.

The paper introduces repairable components ageing models, which are mainly developed by the co-author. The author participated in the verification of the models and computer codes, and in the development of ageing indicators. She also performed the calculations for the case studies. The author actively participated in the writing of the paper.

[V] Aaltonen, P., Saarinen, K. & Simola, K. 1993. The correlation of IGSCC propagation with the power plant transient history. In: *Int. J. of Pressure Vessels and Piping, Vol. 55, pp. 149–162.*

The paper discusses the possible correlation between crack propagation and plant transients. In this work, the author was responsible for comparing the identified crack profiles with transient data and for proposing probabilistic models. The author actively participated in the writing of the paper.

[VI] Simola, K., Laakso, K. & Skogberg, P. 1998. Evaluation of existing maintenance programmes using RCM methodology. In: Lydersen, S., Hansen, G. & Sandtorv, H. (eds.). *Safety and Reliability. Vol. 1*. Proceedings of ESREL'98, Trondheim June 1998. A.A. Balkema, Rotterdam. Pp. 207–213.

The paper describes a method which combines experience-based maintenance analysis with decision analysis for the re-evaluation of the maintenance action programme. The author participated in the development of the method and she was responsible for the writing of the paper.

[VII] Simola, K. & Pulkkinen, U. 1998. Models for non-destructive inspection data. In: *Reliability Engineering and System Safety, Vol. 60, pp. 1–12.*

The paper describes statistical models for the evaluation of the reliability of non-destructive inspections. The author participated in the development of the models and applied them to ultrasonic inspection results. The author actively participated in the writing of the paper.

Contents

Appendices of this publication are not included in the PDF version. Please order the printed version to get the complete publication (http://www.inf.vtt.fi/pdf/publications/1999/)

1. Introduction

The aim of nuclear power plant ageing management is to maintain an adequate safety level throughout the planned and possibly extended lifetime of a plant. Ageing management has become a major concern during the past 10 – 15 years, as the operating power plants have got older, and several units in many countries are approaching the end of their intended lifetime. The ageing management decisions include consideration of the cost-effectiveness of continuing plant operation while maintaining the required safety margins. From a broad perspective, the ageing management includes the consideration of material degradation, technological obsolescence, and human and organisational aspects.

A process to manage technical ageing consists principally of three parts (IAEA 1992): (1) selection of components, systems and structures for analyses, (2) understanding the ageing process including the identification of ageing mechanisms, and (3) the prevention or mitigation of ageing. However, these steps cannot be pursued one after another, and they must be considered partly simultaneously. The first step of ageing analysis, the component selection, requires information concerning the second and third steps. For example, a preliminary identification of the principal ageing mechanisms is needed in an early stage of the ageing analysis.

The determination of mitigating methods is based on the information on the safety significance of a component, its expected ageing degradation, current operating and maintenance procedures, and economical aspects. In the evaluation of safety significance, the analyst should consider the possible increasing trend in the failure rate due to ageing which partly depends on maintenance practices.

Besides the technical aspects of ageing management, the human and organisational aspects are of importance. The knowledge of experienced plant personnel should be transferred to a new generation in order to avoid loss of information e.g. due to the retirement of individuals. The maintenance and operation personnel must also have adequate training in the use of new and automated equipment. The growing number of plant modernisation projects implies an increasing need for revision of technical and safety documents in order to keep them up-to-date after modifications. Another important concern is the organisation of the ageing management programme, which is discussed in an IAEA safety report (IAEA 1998).

The objective of this thesis has been to develop and apply reliability methods and analyses of plant-specific operating experience in ageing studies. The summary is organised as follows. First, an overview of ageing management is given. As the plant operating experience plays an essential role in ageing management, some guidance on plant information management is given in connection with this. In Chapter 3, the role of reliability methods in ageing studies is discussed. This is also the topic of paper [I] of this thesis. Applications of reliability methods in the various phases of ageing management and for different components, systems and structures are discussed, with examples of studies published in papers [I] – [VII]. In paper [II], approaches for analysing system ageing, including selection and prioritisation of components for in-depth studies, are introduced, with applications to automation systems. Examples of both qualitative and quantitative reliability analysis methods for the identification and evaluation of ageing are presented in paper [III], where operating experiences of motor-operated valves are analysed in detail. Ageing models and indicators based on Bayesian statistics are proposed in paper [IV]. Paper [V] discusses the improvement in the understanding of a structural degradation mechanism by the evaluation of ageing rates. The management of ageing by improved maintenance practices is discussed in paper [VI]. Paper [VII] introduces models for evaluating the reliability of non-destructive inspections, and proposes an approach to account for the uncertainties related to results of inspections in the evaluation of flaw sizes.

2. Ageing management

An essential part of ageing management is the evaluation of technical systems to ensure that the required safety margins are maintained. Often in engineering, ageing is considered in such a purely technical sense, meaning degradation of materials. The technical definition of ageing given by the International Atomic Energy Agency (IAEA) is the following: *ageing is the continuous time-dependent degradation of materials due to normal service conditions, which include normal operation and transient conditions* (IAEA 1990). Rather similar definitions are also proposed by the U.S. Nuclear Regulatory Commission (NRC) and the Electric Power Research Institute (EPRI) (NRC 1991, EPRI 1992). From a broader perspective, which is needed, for example, in the overall ageing management of power installations, the term ageing should include not only technical but also human and organisational aspects. In this chapter, the principles of ageing analyses of technical systems are described first. After that, ageing is discussed from a managerial perspective. Finally, the plant information management is considered separately because of its importance in ageing studies.

2.1 Ageing analyses of technical systems

As plants are getting older, the significance of ageing management has become increasingly important. Ageing research programmes have been conducted in several countries, e.g. in the U.S., Japan and France (see DuCharme et al. (1987), Morris & Vora (1985), Mishima (1987), Noël et al. (1987)). In principle, these research programmes follow similar phases of ageing analyses, namely:

1. Identification of critical components
2. Identification and evaluation of ageing effects
3. Development of mitigation methods.

In the first phase – *component selection* decisions are made on the prioritisation of systems and equipment to be analysed. The prioritisation is based on the assessment of the impact on the plant safety and expected sensitivity for ageing. Factors to be accounted for include spares availability, expected obsolescence, and other economic aspects. Methods for selection and prioritisation of components are analysis of operating experience, expert judgement, and probabilistic techniques. Age-related degradation is often identified through operating experience, including both plant specific records and international data sources. In the expert judgement approach, plant personnel, engineers and scientists are consulted. In a probabilistic approach, plant-specific probabilistic safety analyses (PSA) are used to prioritise components according to their risk importance.

An understanding of the dominating ageing effects and the severity of the degradation phenomena is needed at the start, in the selection phase. In the second phase, *identification and evaluation of ageing effects*, the ageing mechanisms and their effects are studied in detail for the selected components. As the ageing depends on environmental conditions, methods of operation, and maintenance, detailed studies require specific information on these relevant factors. Information is obtained from such documents as failure records, condition monitoring measurements, and plant operation history including transients and other deviations from normal conditions.

The goal in ageing analyses is to find efficient methods for preventing or mitigating the ageing effects. In this third phase – *selection of a suitable ageing management practice* – the basic alternatives are:

1. Controlling the ageing process by verification of the proper performance of equipment with periodic tests, and using condition monitoring to identify degradation in critical plant equipment

2. Slowing down the ageing process by either optimising the maintenance procedures, reducing stressful testing, or changing the operating or environmental conditions

3. Scheduled replacement or refurbishment of components.

2.2 Ageing management programmes

In the previous section, the discussion about ageing analyses was limited to degradation of technical equipment. When the management of ageing at a power plant is considered, the ageing should be seen from a broad perspective, taking into account, also, aspects of operation and maintenance, obsolescence, and human and organisational issues. The various aspects to be considered in ageing management are illustrated in Figure 1.

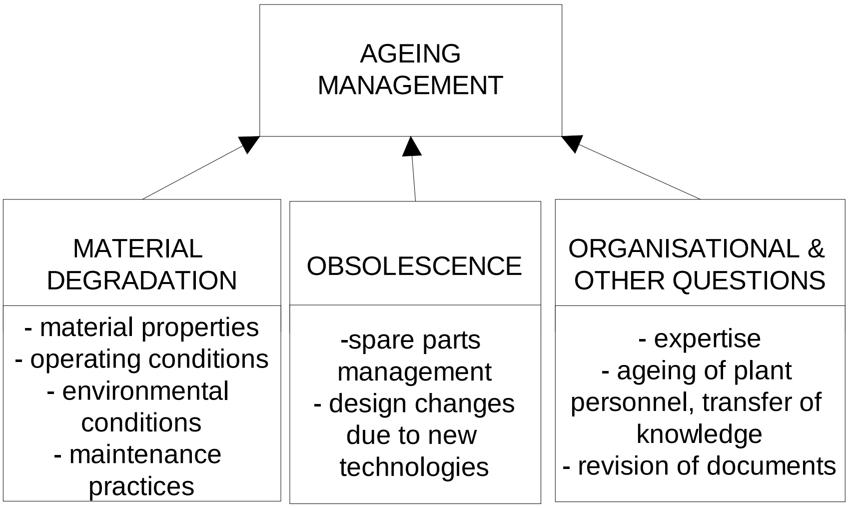

Figure 1. Aspects of ageing management.

The ageing management should be accomplished under a systematic umbrella-type programme that integrates existing programmes relevant to managing ageing. Such an approach is suggested in recently published recommendations by the IAEA on implementation of ageing management programmes (AMP) at nuclear power plants. Examples of relevant programmes to be integrated into the AMP are the following (IAEA 1998):

- Preventive maintenance programme
- In-service inspection, surveillance, testing and monitoring programmes
- Data collection and record management programmes

- Equipment qualification programmes
- Component-specific programmes
- Chemistry programmes
- Operating procedures
- Feedback of operating experience, analysis of significant events and research programmes
- Spare-parts programmes
- Techniques of reliability centred maintenance (RCM) and probabilistic safety analysis (PSA).

The organisation of an ageing management programme is not straightforward because responsibility for the procedures described above is typically distributed amongst several organisations at the plant. Furthermore, authorities and vendors also have an important role in ageing management, although the main responsibility is at the plant. Guidelines for the implementation of an ageing management programme are given in IAEA (1998).

2.3 Plant information management

At every nuclear power plant, design, operating and maintenance information is collected and stored, in order to be used in various decision making situations. Information includes design data, failure and maintenance data (including inspection, condition monitoring and calibration data), operation data (e.g. transients), plant-specific PSA results, etc. This plant-specific operating experience should be used to the largest possible extent and in the most efficient way in ageing follow-up and decision making related to mitigation of the effects of ageing.

Detailed descriptions of good practices for plant information management are given in IAEA Safety series report No. 50-P-3 (IAEA 1991) ‘Data Collection and Record Keeping for the Management of Nuclear Power Plant Ageing’. Some of the key aspects are listed here:

- The information system should provide comprehensive and accurate information about components, including baseline information and operation and maintenance data.

- Data should be entered by maintenance and operations personnel, and the data entry should include an appropriate quality control mechanism.

- Databases distributed throughout the plant should have a common organisation and format.

- The information system should provide adequate tools for data analysis, graphical display and report generation. This could include a detailed classification of age-related ’keywords’ for data retrieval, and trend analysis tools.

Often the existing plant information systems do not meet all the needs of an efficient ageing management procedure. Problem areas have been identified in ageing studies of automation systems ([II], Simola 1991, Simola & Hänninen 1993, Simola & Maskuniitty 1995). The collection of information is not well co-ordinated, e.g. maintenance personnel may have a separate database for calibration data; and lots of information is still stored in paper archives. Furthermore, information on repairs carried out outside the plant are not included in the maintenance database. Failure and component coding and classification may not be suitable for all components and systems, and the coding is too general for detailed analyses. The older systems do not provide the means for displaying, graphically, component failure histories, nor for trending, which is important for quantitative ageing studies.

The quality of record keeping could often be improved ([II]). One way is to motivate the plant personnel to fill up more precisely the failure reports in order to avoid missing or erroneous failure descriptions. A more detailed reporting of, for instance, testing and calibration results would also be beneficial for ageing studies in many cases. Another way is to facilitate the accessibility of data by integration of information sources, as suggested in papers [II] and [VI]. The re-organisation of the collection and storing of information and accounting for ageing management aspects can be done most conveniently at the time of upgrading or replacement of the plant data collection system.

In addition to plant-specific information, the operational feedback from other plants is an important source of information. The data collection is organised on a national level in several countries, for example in Sweden and in France, and there are international organisations such as INPO and WANO.

3. Reliability methods in ageing studies

The management of ageing has to be considered from a wide perspective, aiming at the long-run optimisation of safe and economical plant operation. The specific ageing studies of systems, structures and components should be seen as an integral part of the overall life management programme. Reliability methods are essential in the integration of component-specific ageing and degradation studies with the plant or system level analyses. Furthermore, reliability based approaches together with the use of plant operating experience have an important role in all stages of ageing analyses.

In paper [I], the uses of risk and reliability methods in the various stages of ageing analyses of NPP components, systems and structures are introduced. Figure 2 shows the phases of ageing analyses, introduced also in section 2.1, and the uses of reliability methods applicable in these phases. In the following subsections the uses and applications of these methods are discussed in more detail. The use of probabilistic methods in ageing analyses has also been discussed in (Simola 1992).

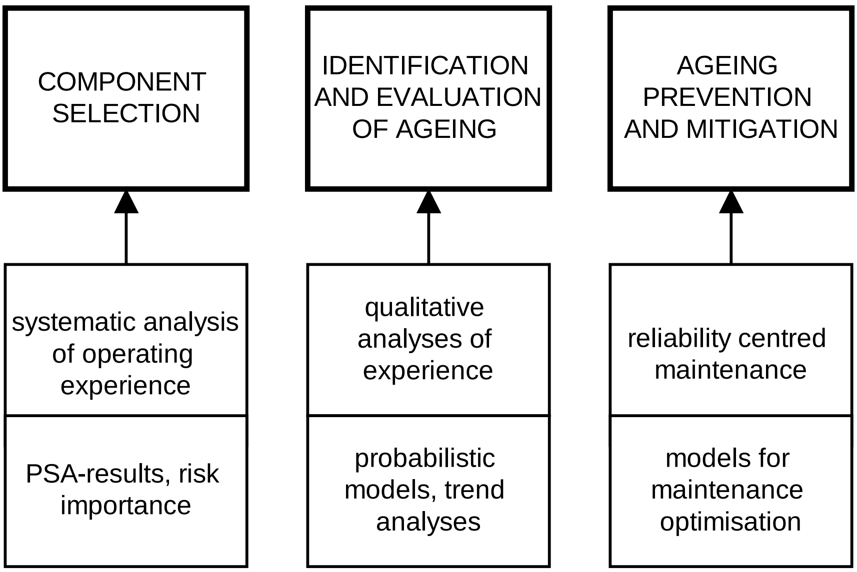

Figure 2. Uses of reliability methods in ageing analyses.

3.1 Identification of age-critical components

The most important structures and components for ageing studies can be selected at plant or system level. In this identification phase, some background knowledge of degradation rates and mechanisms is needed. Besides the expected degradation rate, the importance of the component depends on its safety significance and economic aspects including replacement costs and importance to plant availability. Thus, the prioritisation of components requires a system-level analysis, where results of probabilistic safety analyses can be used.

In the selection of the most important parts of the system, rough analyses of failure records can be used to identify the problem areas. For example, elevated failure rates or increasing trends in failure occurrence may indicate a need for further analyses. In the simplest quantitative analyses, the numbers of failures of components (or component groups) are identified. This information can be used to direct further analyses to potential problem areas.

Paper [II] introduces examples of approaches to studying system ageing and identifying components for detailed ageing studies. These applications are focused on protection automation, but similar procedures are applicable to other systems too. Figure 3 shows the kind of information necessary for the evaluation of ageing and safety importance of components. The component-specific design data and operating experience are essential for the identification of degradation mechanisms. This data has to be completed with information from the operating environment, i.e. mode of operation, maintenance practices and environmental conditions. The safety importance of components can be evaluated by analysing the structure of the system.

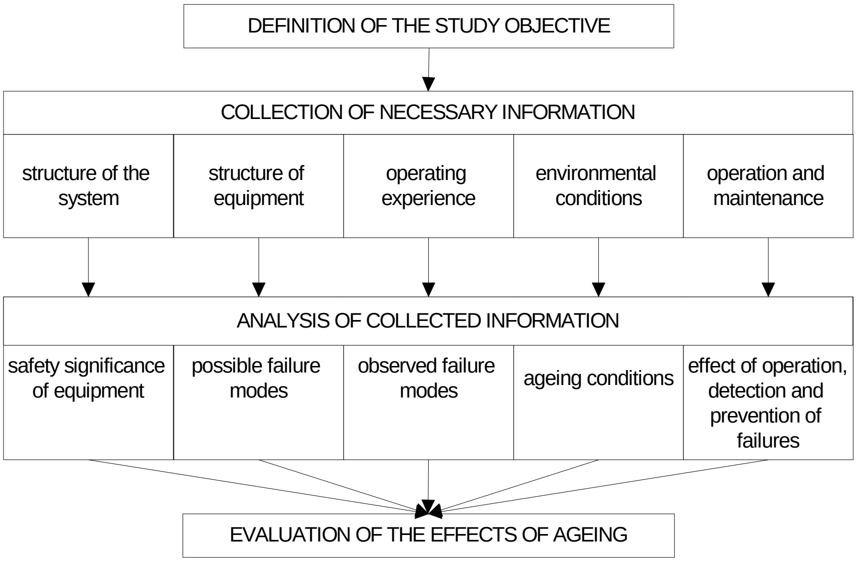

Figure 3. An approach to analysing the ageing and safety importance of components in a system.

The probabilistic safety analysis, PSA, is an efficient systems analysis method which is used to assess risk of operation of nuclear power plants. PSA consists of three levels: level 1 aims at quantifying the probability of core damage, whereas levels 2 and 3 deal with stages beyond core damage, i.e. radioactive releases to the environment and their consequences (see for example NRC 1989). In the level 1 PSA, the failure probabilities of components are evaluated and the accident sequences leading to various core damage states are modelled. The dependability of systems as a function of component reliability is modelled with fault trees, and the evolution of accident sequences from initial disturbances to a core damage state is described with event trees.

Although ageing is not usually considered in the PSA calculations, the safety importance of assumed increases in the components' failure probabilities can be evaluated. Therefore, for instance, if an increase in failure rate of certain components does not have any considerable effect, ageing analysis of such components are known to be of little importance.

The component importance may be evaluated without taking into account the possible ageing effects by applying risk-importance measures, which express the influence of a basic event on the total plant risk. The most commonly used risk-importance measures are risk increase and decrease factors, and fractional contribution (see e.g. Mankamo et al. 1991). The risk increase factor represents the relative increase of the risk given the basic event occurs. Correspondingly, the risk decrease factor describes the relative decrease of risk assuming that the basic event never occurs. The fractional contribution of a basic event to risk, also known as the Fussel-Vesely importance measure, expresses the relative improvement potential when it is assumed that the basic event never occurs. These risk-importance measures can be adapted to give guidance in the component selection, from the system's risk and reliability point of view.

Change in the plant risk due to the assumed increase in failure probability because of component ageing can also be evaluated (see e.g. Davis et al. 1985). In the simplest case, the same ageing rate may be assumed for all components. The different ageing rates of components, however, influence the failure rates and, therefore, also the importance of components. Assumptions about possible increases in failure rate should be based on existing operating experience or expert opinions. Studies on the effects of maintenance programmes and estimated ageing rates of different components on the core melt frequency have been presented, and detailed models and systematic procedures have been developed for incorporating ageing evaluations into a PSA, e.g. in (Vesely 1992).

The usability of PSA for the selection and prioritisation 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. Depending on the objectives of the ageing analysis, it must be possible to evaluate the significance of ageing either at component, system, and core-melt frequency level, or even on the level of accident consequences. This also causes requirements for the PSA analysis tools. Some issues and validation requirements for the use of PSAs have been highlighted in (Vesely & Weidenhamer 1994).

In paper [II], the effect of protection automation failures on plant reliability was studied with a living-PSA code (Niemelä 1991). In this study, the aim was to discover how multiple failures of the system would increase the estimate of the core damage frequency. In the sensitivity analyses, the aspects considered were the severity of consequences, the probability of the accident sequence, and the sensitivity of the accident sequence probability to failures of protection automation. Such an analysis provides information on the importance of increases in failure rates – e.g. due to age-degradation – to the plant safety.

An approach to prioritising components at system level on the basis of both safety significance and operating history is also presented in paper [II]. The analysis was used to select electronic cards from the automation system for further analyses. Because no detailed computerised PSA model was available, the safety importance was studied at system level with a qualitative fault tree analysis. In this case, failure rates were not included, but the minimal cut-sets identified by the fault tree analysis show which parts of the system are most important for the propagation of the electronic signal. This approach is useful when there is no plant-specific living-PSA tool for quantitative sensitivity analyses.

3.2 Identification and evaluation of ageing effects

Ageing can be roughly divided into two categories according to the failure rate of equipment. In the first category, there are typically short-lived mechanical and electrical components, for which the ageing information is usually obtained from failure data. For short-lived and more easily replaceable and repairable components, ageing management means to a large extent ensuring that the maintenance tasks are efficient. Structural components and parts such as cables belong in the second category. For these types of equipment, there is no planned preventive or corrective maintenance, and they are originally designed to reach the end of plant life with an adequate safety margin. However, operating errors or harsh environmental conditions may cause premature degradation, which should be identified prior to failures. For this category, the ageing information is typically in the form of degradation data from condition monitoring. Both qualitative and quantitative analyses are needed in the evaluation of ageing effects on plant safety and availability.

The mathematical interpretation of ageing is that the probability of a failure increases with time, which may be expressed in calendar time, running hours, load cycles, etc. Usually the ageing is dependent on both discrete loads and continuous degradation. Different approaches to modelling ageing phenomena are used depending on the rate of the functional degradation of a component and the availability and quality of failure and condition monitoring data. If a lot of component failure data is available, classical statistical analyses can be performed. Often the amount of failure data available is very limited but information on the degree of component degradation is obtained by surveillance and condition monitoring. In this case, the evaluation of the expected remaining lifetime is based on monitored parameters. The degradation mechanisms usually behaves as a stochastic process and thus probabilistic methods should be applied in the modelling.

In the following, the adaptation of reliability engineering analysis and modelling techniques to the identification and quantification of equipment ageing is described. It is obvious that much equipment has both short-term failure mechanisms and long-term structural degradation. However, for simplicity these two categories of ageing are treated separately here. Furthermore, it is assumed that for components, the available information is failure data, and for structures, mainly degradation data from condition monitoring.

3.2.1 Short-term ageing

The identification and evaluation of component ageing in its operating environment is mainly based on the operating experience including both failure and maintenance information. Qualitative analyses are used to differentiate ageing-related failures from other failures that are due to such problems as maintenance errors, wrong operation or unexpected events. The most elementary form of a qualitative analysis is the study of failure reports. Even a single failure report may reveal an ageing problem. On the other hand, a qualitative study of a sudden increase in failure occurrence may reveal a common cause of maintenance error that is not an age-related phenomenon. Thus, it is important that conclusions are not drawn solely on the basis of quantitative analyses. The participation of plant maintenance personnel in qualitative analyses is important.

More detailed qualitative analyses should be carried out by systematically analysing the failure records. One approach is presented in paper [III], where motor-operated valve failure and maintenance data are analysed with an approach based on the failure modes and effects analysis (FMEA) (IEC 812 1985). FMEA is commonly used in reliability engineering in the design phase to identify possible failure modes and their impact, but [III] introduces the adaptation of the method to the analysis of operating experience data. In addition, maintenance records are analysed with a similar approach.

Another qualitative analysis approach based on the FMEA was introduced in a study of protection automation (Simola & Hänninen 1993, [II]). In this simplified approach, possible failure mechanisms, particularly those involving ageing, were identified together with plant maintenance personnel. These analyses were then compared with the actual failures described in the failure records. In this way – by analysing the possible causes and consequences on the one hand and by exploring the records of events on the other hand, the significance of ageing can be evaluated.

The plant failure classifications are usually not directly applicable for component-specific analyses, where very detailed qualitative analyses are needed to identify the problem areas properly. For instance, in paper [III], a more detailed classification was developed for valve failures. Analyses of root causes of failures are sometimes difficult or impossible to do because of the sparse or missing information in failure reports, but the maintenance personnel can often provide further details for the analyst on a specific event.

Besides the qualitative studies described above quantitative analyses are also needed. It is important to identify increasing trends in failure occurrence, which are warning signals of possible age-related problems, and to evaluate the rate of ageing. Quantitative analyses can be used both for a crude identification of deviations from an assumed constant failure rate, and for more detailed studies aimed at optimising test, maintenance or replacement intervals.

The quantitative analyses can be based either on the modelling of the physical degradation process or on the statistical analyses of failure data. The degradation models are generally based on complicated mixtures of several physical phenomena, and they are not discussed further here. In the following text, we shall concentrate on the case where the ageing process is estimated statistically from failure data. Knowledge about the mode of operation, and repair and testing policies are needed for the selection of suitable models.

The time-dependence of failure occurrence is expressed by the hazard rate, i.e. the probability of failure given the component has been in operation for a certain time. An increasing hazard rate indicates component ageing (Barlow & Proschan 1975). In addition to the time dependence of the baseline hazard rate, in the ageing modelling of repairable components, assumptions are made concerning the effect of preventive maintenance and repairs on the component failure rate. The basic alternatives are ’as-good-as-new’ where it is assumed that the repair restores the component to a state corresponding to a new one, and ’as-bad-as-old’, where, after repair, the component is considered to be in the same state as it was just before the failure.

Although there are lots of theoretical models for the identification of increasing trends and for the prediction of future behaviour of a component or a group of components, some problems only appear in practice. In most cases, there is very little data on a single component and, typically, data from several components of the same type are pooled. In theory, pooling is justified only for components which can be regarded as forming a homogeneous group, because the most commonly used trend models assume that the pooled inter-event times are realisations of same stochastic process (Paulsen et al. 1996). Often in practice the pooled data consists of failure data from components in different environmental conditions, of different ages, with varying maintenance histories, and even with quite different designs. Such pooling can be justified when the aim is to monitor an overall trend, but the disadvantage of pooling is the loss of information. The larger and more heterogeneous the component group is, the more possible it is that some interesting phenomena remain hidden in the pooled data. E.g. increasing and decreasing trends of some sub-groups may compensate for each other in such a presentation of the data. Thus, it is worthwhile analysing the data also in smaller groups chosen by suitable criteria, as recommended in paper [I].

In paper [III], statistical analyses of the data were performed, including trend analyses. In this case, failure data of 104 motor-operated valves were pooled, but mechanical and electromechanical failures were treated separately. The trends were analysed by estimating the parameters of the Weibull process from failure data. In paper [IV], a trend model based on Bayesian statistical methods was developed and applied to the same valve failure data. In the model it is assumed that the failure rate is constant during an observation cycle, e.g. between two outages, and that the ageing appears as a change in failure rates of successive cycles. In this context, indicators for ageing were also introduced. These indicators were based on posterior properties of model parameters.

So-called stand-by components are operated only on demand, and their operability is verified in periodic tests. The ageing of such stand-by components can be expressed in terms of probability of failure in the test situation. The increase in numbers of failures in tests may result from degradation of components between tests, e.g. due to corrosion, vibration, or dirt. An important cause of degradation can also be the test itself, as in the case of diesel generators. Furthermore, the repair may not be perfect and thus the repaired component does not correspond to a new one. When the probability of success in test is modelled by the binomial distribution, the change in value of the parameter of the binomial model can be used as an indicator of ageing. In paper [IV], a Bayesian model is introduced to analyse the development of failure occurrence in successive periodic tests.

3.2.2 Long-term ageing

Ageing analyses of structural components are aimed at identifying the degradation mechanisms and the increase in failure probability due to ageing, ensuring the structural integrity and predicting the remaining lifetime of structural components. The structural degradation can be evaluated with probabilistic fracture mechanistic (PFM) models. The advantage of such probabilistic modelling is the possibility of modelling clearly the uncertainties related to the material degradation processes, and thus being able to perform sensitivity analyses of the factors affecting this process. Software for degradation modelling has been developed, for example, to estimate crack-growth rates and failure probabilities of pressure vessels (Cheverton & Ball 1984, Simonen et al. 1986, Dickson 1993), steam generators (Pitner et al. 1993) and piping (Harris et al. 1986, Brückner-Foit 1987, Nilsson et al. 1990, Kastner et al. 1990) in NPPs. For a literature survey, see e.g. Simola & Koski (1997) and the references therein.

The level of details and the extent of probabilistic crack-growth models vary a lot. The simplest models consider the growth process of a single existing flaw. In more extensive models, in addition to the crack growth, also flaw initiation, in-service inspections, etc. are modelled, and several welds can be considered simultaneously. The most common approach is that the model is based on some physical laws or empirically identified relationships between the crack growth and material properties, stresses, loadings, and other environmental factors. Then some of the parameters affecting the growth rate are assumed to be random variables.

Often the models that are built on the empirically identified relationships between various factors affecting the degradation process are very complex. The benefit of this complexity can be questioned, especially if some important factors affecting the failure probability include uncertainties that dominate the results. In such cases, the detailed calculations are useless, if the purpose is to obtain estimates for failure probability. The benefit of models based on empirical relationships between the degradation process and influencing factors is the possibility of performing sensitivity analyses of these various elements affecting the failure probability. For ageing management purposes it is of interest, for example,. to evaluate how changes in operating conditions can affect the failure probability of the structure.

Uncertainties in the results of the analyses depend on the amount and quality of data. Sometimes data has been collected from different sources, and the suitability of the data for a specific purpose can be questioned. In order to improve the quality of the data, systematic collection and treatment procedures of damage and ageing-degradation data should be created. When data is sparse or missing, it is of particular importance to properly model and express the uncertainties related to this fact.

In structural reliability and degradation models, the operating conditions should be well known, e.g. water chemistry, loadings and stresses. Unexpected ruptures are due to unusual material properties or environmental conditions. Thus, not only an understanding of the effects of various factors on degradation are needed, but knowledge of actual environmental conditions is essential for ageing management.

Paper [V] describes an attempt to relate the plant transient history to crack profiles, in order to improve the understanding of inter-granular stress-corrosion cracking (IGSCC) growth rates. IGSCC is an environmentally-assisted crack-growth mechanism, which is caused by the combined effects of stresses, material properties and environmental conditions. The water chemistry, especially the oxygen concentration, has a significant effect on the crack-growth rate. The transients may promote IGSCC through stress variations and changes in reactor water chemistry. The removed piping was analysed, and, based on the assumption that branching in the crack growth could have been initiated in cold shut downs of the plant, the relationship between branchings and transient occurrences were analysed. In paper [V], the use of probabilistic models and the follow up of transient history are suggested.

The degree of degradation in a structure is evaluated by performing non-destructive inspections. The proper quantification of degradation, e.g. a flaw size, requires knowledge on uncertainties in measurement results. The reliability of flaw detection and the sizing accuracy depend on several factors, e.g. characteristics of the defect and its location, the type of material inspected, inspection procedure and equipment, and human factors. In paper [VII], the modelling of non-destructive inspection reliability is discussed and models for accounting for uncertainties are introduced. The paper proposes new models for describing the uncertainty both in flaw detection and sizing. In the proposed models the measured flaw characteristics (depth, length) are assumed to be simple functions of the true characteristics and random noise corresponding to measurement errors.

Besides the structural components, another important subject for long-term ageing is cabling, more precisely the organic insulation materials of electrical cables (see e.g. IAEA 1997 and NEA 1999). Safety-related cables should perform their functions in accident conditions even when they are approaching the end of their designed lifetime. The dominant causes of ageing in polymeric components are temperature and radiation. The safety-related cables have undergone qualification where accelerated ageing is followed by a simulation of a design basis event. Mathematical models are used to make inferences about component lifetimes in normal service conditions based on results obtained under accelerated testing. However, realistic accelerated ageing of cable materials is complicated by many factors, such as dose-rate effects, and synergy between thermal and radiation ageing which may lead to non-conservative results of accelerated tests. The ageing of cables should therefore be monitored during the plant lifetime, and the validity of accelerated testing models should be checked.

3.3 Mitigation of ageing effects

In the last phase of ageing analyses, decisions on management of ageing should be made on the basis of identified degradation mechanisms and their severity. The basic management methods are controlling and slowing down ageing, and replacement of components. Tests, inspections and condition monitoring are means for controlling component performance. The slowing down of the ageing process can be done either by optimising the maintenance procedures, or reducing the operating or environmental loads.

Risk and reliability methods applicable in ageing mitigation are mainly related to improvement of maintenance practices and making decisions on replacements, taking into account operating experience, results of risk analyses, and other factors. As the selection of the appropriate ageing mitigation methods is a complex process where, often conflicting, objectives have to be considered, analytical approaches to decision making are needed.

The same simplification is made here as was made in connection with identification and evaluation of ageing effects, i.e. the separate consideration of ageing mitigation for short-term and long-term ageing.

3.3.1 Management of short-term ageing

In the case of short-term ageing, the management usually consists of reviewing current maintenance practices taking into account such factors as spares availability, obsolescence, and replacement. Often the maintenance schedules are based on manufacturer's recommendations or decisions taken early in the design phase. Experience may show that these maintenance programmes are unbalanced, and both their economy and reliability could be improved by enhancing maintenance practices e.g. by introducing new monitoring methods, and optimising test and maintenance intervals.

The optimisation of maintenance intervals should be based on historical information on failures and maintenance actions. Furthermore, the unavailability of components due to maintenance should be accounted for in the modelling. Although the unavailability of a single component in a redundant system does not cause system unavailability, in the case of safety-critical components the increase in plant risk during an overhaul must be considered in the analyses.

Lots of theoretical models have been developed in the field of maintenance optimisation, but a literature survey on applications of these models (Dekker 1996) indicates that there are not many real-life applications in maintenance management. Problems have been identified to arise from lack of data, and from the gap between models and practice. The lack of data can be in some extent compensated by using expert opinions. The use of expert judgement, i.e. opinions of the maintenance staff in estimating the residual life of components, is suggested in (Øien 1998) and (Procaccia et al. 1997). The available operating feedback and expert judgements can be combined using a Bayesian approach (Pulkkinen & Pyy 1996).

One principal concept in ageing and maintenance management is the concentration of effort on reduction of the failure probabilities of the most important components. Reliability centred maintenance (RCM) is a method for establishing a scheduled preventive maintenance programme resulting in improved component reliability and minimised costs (see e.g. EPRI 1989). The RCM approach intends to optimise the use of maintenance resources by identifying the most critical components with respect to safety, availability, or maintenance costs, and selecting for these components the most appropriate maintenance procedures with the aid of decision logic. An ageing management approach, where PSA results are integrated into RCM are discussed by Duthie et al. (1998).

Paper [VI] shows how a systematic methodology such as reliability centred maintenance (RCM), can be applied to evaluate and improve the current maintenance programmes. The experience-based reliability centred maintenance methodology introduced in paper [VI] utilises the accumulated operating experience of failures and maintenance. The paper suggests the use of a decision analytical approach both in the selection of components for analyses of maintenance effectiveness and in the selection of optimal maintenance tasks and intervals. In this application, the criteria for selection of components for further analyses were reactor safety, functional reliability, repair and preventive maintenance costs, and radiation exposure in the workspace. A detailed re-assessment of the maintenance action programme was directed at the selected items. These detailed analyses are the basis for deciding whether to prolong or shorten maintenance and test intervals, or whether to introduce new condition monitoring methods.

Apart from the above discussed improvements in maintenance practices, sometimes the ageing process can be managed simply by reducing environmental or operational loads. In paper [II], an example of ageing management by improving environmental conditions is given. The analysis of relay operating experience revealed the probable cause of increased failure occurrences, and the ageing could be managed or slowed down by improving ventilation.

3.3.2 Management of long-term ageing

For structural components, the basic ageing management approach is to control ageing by inspections to identify the degree of degradation. The control of environmental conditions is also applicable in some cases – e.g. improvement of water chemistry to slow down IGSCC. The reliability of inspection and condition monitoring results can be improved both by introducing new techniques, and improving the data analyses.

The structural ageing is managed at the plant by performing in-service inspections and condition monitoring. The results of such measurements are imperfect, and thus the proper interpretation of the results requires understanding and accounting for measurement uncertainties. Incorporation of probabilistic modelling in condition monitoring is presented in (Morilhat 1998) with an application to fatigue measurement. In paper [VII], the modelling of non-destructive inspection reliability is discussed and a Bayesian model is introduced for considering measurement uncertainties in updating the flaw size distribution.

The optimisation of in-service inspection intervals can be seen as a method for ageing management. In a risk-informed inspection methodology (see e.g. NRC

1992), the inspection intervals and techniques are determined on the basis of the expected degradation mechanisms, the risk importance of the structural component (e.g. piping segment), effectiveness of inspections, and other aspects, such as accessibility and costs. The results of plant-specific PSAs are used to rank systems and structures according to their risk importance. The application of this methodology requires a system approach combining expertise on plant risk analyses, structural reliability analyses and expert opinions on, for instance, degradation mechanisms. Furthermore, the modelling of in-service inspection reliability is needed, as discussed in paper [VII].

When replacement decisions are made on the basis of both economic and safety aspects, information is needed on the residual life of the component. In some cases, trend analyses may be used to predict the remaining lifetime of components, but in general there are no reliable methodologies for this purpose. Decisions for in-time replacement will therefore have to be taken on the grounds of condition monitoring or failure data, on the results of pre-ageing tests, and, to a large extent on judgement. Model development for optimisation of maintenance policies is discussed by Pulkkinen (1994).

In the ageing management of cables, the main concerns are to verify that the predicted environmental causes of stress and their effects on cable condition have not been underestimated. It is recommended that initial qualification is supplemented by ongoing qualification procedures and environmental monitoring (IAEA 1997). Environmental monitoring of both temperature and radiation dose is needed to evaluate the actual ageing rate of cables. Follow-up of cable ageing can be organised by placing cable deposits in representative locations inside the containment and taking samples from these real-time aged cables for testing. Comparison of slowly aged cable samples with results from earlier accelerated tests increases knowledge of applicability of accelerated testing results, and helps to reduce the uncertainty related to the use of high acceleration factors.

4. Conclusions

Increasing attention to the issues related to plant ageing is required in order to both maintain the required safety margins and maximise long-term profitability of the power production. Often 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 analyses. The safety significance of ageing has to be analysed at the plant level, which calls for systems analysis approaches.

This thesis promotes the use of reliability methods and a systems analysis approach in nuclear power plant ageing management. The wide range of applications of reliability methods to all stages of ageing studies are demonstrated by both practical case studies and model development. Approaches for analysing system ageing with prioritisation of components for in-depth studies are introduced and applied to automation systems. Methods for detailed analyses of failure and maintenance data are presented with application to motor-operated valves, and the use of such operating experience together with decision analysis methods in the optimisation of maintenance tasks is discussed. The importance of probabilistic approaches to structural ageing studies is also highlighted. Statistical reliability models and indicators based on Bayesian statistics are proposed for analyses of failure data and inspection results.

The life management of a nuclear power plant, considered from a broad perspective, is a challenging optimisation and decision making problem. Already the decision for selecting the appropriate ageing mitigation method for a set of components is a complex process with conflicting objectives. Furthermore, ageing studies need multidisciplinary analyses where the expertise of engineers, system analysts, material degradation and structural integrity experts, and from human and organisational research should be combined. This is often a very difficult task and may require a specific type of organisation to succeed. These problems can be partly solved by introducing a specific ageing management programme at the power plant.

The work in this thesis has been related to nuclear safety research. However, many of the methods and approaches presented here are applicable also outside the nuclear industry, e.g. in conventional power generation and other industrial fields such as process plants, where the life-extension questions are also addressed. For example, a systematic approach to the management of the lifetime of process plants has been proposed in (Suokas et al. 1998). The main differences in the positions of the nuclear and non-nuclear industries are due to a differing concern about possible risks. In the nuclear industry, the detailed safety regulations naturally imply a specific emphasis on safety-related decision making. A limiting factor for the applicability of some reliability methods in other fields may be the quality and quantity of collected operating experience.

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