METHODOLOGY FOR THE CONTROL OF EQUIPMENT AGEING IN NUCLEAR POWER PLANTS

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SUMMARY

This paper presents a methodology for the control of equipment ageing as it applies to CANDU 600 nuclear power plants. The methodology that has been developed is based mainly on the approach proposed in *Nuclear Plant Ageing Research (NPAR)*, a program implemented by the *Nuclear Regulatory Commission (NRC*). It includes twelve steps covering the selection of the equipment, the understanding and the management of ageing. The methodology complies with the new Canadian nuclear regulations as well as recommendations made by world wide nuclear industry. It has been validated through application to three types of mechanical equipment, with results that are deemed significant.

Keywords: Maintenance, Ageing, Reliability Centred Maintenance (RCM)

1 Introduction

CANDU 600 nuclear power plants have an estimated life of 30 years. Several owners are presently considering the possibility of extending that life by 20 to 30 additional years. One of the criteria for that decision is the expected life of the main equipment, the replacement or failure of which would constitute a very high cost to justify the investment. In that context, it is necessary to fully understand the ageing phenomena for that equipment.

This paper proposes a methodology for the control of equipment as a function of its ageing. It takes under consideration the requirements of the Canadian nuclear regulations [1] and the recommendations made by world wide nuclear industry [2]. Also, it has been developed to be readily integrated into the existing station processes without requiring major changes. It has been validated by application to three types of mechanical equipment.

2 Defining the Issue

Control of equipment ageing is an area that is still relatively recent. It has begun drawing attention mainly over the last thirty years, with the ageing of equipment in the oil, chemical and nuclear industries. Significant progress has been made in recent years. It is recognized that ageing is a process that affects all technologies, which calls for systematic inspections and assessments, in order to maintain the safety of the facilities. The problem lies in determining how to prevent, or at least mitigate, the ageing of the critical equipment used in those industries.

3 Literature Review and Ageing Definition

There are two distinct generic approaches that have been observed in the control of ageing. The first one has, as its objective, the definition of an approach aimed at identifying and characterizing the effects of ageing [3]. The second is a decision making process, which has been developed for the nuclear industry, in order to optimize its operations [4]. However, those approaches define only the general principles and therefore cannot be applied directly.

Also, a multitude of references cover data and information required to understand and manage equipment ageing in the nuclear field (experience in the industry, ageing data, a history of the performance of the specific equipment and the maintenance programs applied in nuclear power plants [5,6]).

Finally, there are several definitions of ageing. Looking at the industrial sector, and particularly in the nuclear area, the *Nuclear Plant Aging Research program (*NPAR) [3] defines ageing as « showing the effects of time or use in the physical characteristics of a system, structure or component ». From another perspective, the *Electric Power Research Institute* (EPRI) [7] and the *US Department of Energy* (DOE) [8] define it as « a general process in which characteristics of a system, a structure or a component gradually change, with time or use ». Upon analysis, those documents define ageing as a phenomenon of accumulation, visible or invisible, of the effects of wear, of use and of the load on a piece of equipment which, if they are not properly managed, will adversely affect its characteristics as a function of elapsed time, utilisation or operating environment.

4 Control of Ageing

A structural ageing control program includes the following elements [9,10]:

- The selection of equipment for which ageing is a significant concern,
- An understanding of the causes of its ageing, and
- An ageing management program.

4.1 Selection of the Equipment

In general, equipment which draw particular attention are those that have a significant impact on safety or generation. Selection of the equipment may be based on various methods, including weighting, a deterministic method, a risk-based method or a hybrid approach combining more than one of those methods.

4.2 Understanding Ageing

The factors that can cause ageing are:

- The natural internal process (chemical or physical),
- External constraints and environments,
- Operating wear,
- Excessive testing,
- Improper installation, operation or maintenance.

Those factors may act independently or in a synergistic fashion to degrade the equipment. This degradation, which is a function of time, should be one of the main concerns during design.

A good understanding of ageing starts with thorough knowledge of the equipment, for example its design, fabrication, installation, functional testing, unavailability, as well as its maintenance program. Ageing is very sensitive to overloading and changes in state. Extended use, even at nominal power, is only a minor contributor. Degradation persists even at shutdown, which emphasizes the influence of time and environment. Sometimes, the latter factors can even cause ageing comparable to that due to time and use.

Equipment wears out at a certain rate depending on the materials used, the stresses that are applied, the operating environment. The stresses and the environment act together on the materials causing degradation over time. Thus, many mechanisms may potentially contribute to the deterioration of the equipment. Often, deterioration appears to be so slow that one would not expect it to affect the equipment during its design life.

The potential effects of those mechanisms may vary greatly from one equipment to another. An ageing mechanism is deemed significant when it can act without the possibility of detection or mitigation. In such a case, the affected equipment will eventually lose its capacity to perform its intended function.

Based on the results of ageing studies, the ageing mechanisms that are most often observed are the following:

- Corrosion,
- Erosion,
- Fatigue,
- Erosion-corrosion,
- Radiation induced embrittlement,
- Wear,
- Contraction or creep,
- Chemical and biological degradation.

Those mechanisms may show up randomly or after some actuations, or with time over a number of years (ageing).

4.3 Management of Ageing

When all factors that cause degradation in a piece of equipment are known, they can be managed in order to maintain its intrinsic reliability, so that it can properly fulfill its function. To that end, there are many actions that can be taken, for example monitoring programs, preventive or corrective maintenance programs.

A maintenance program includes several important and relevant elements to manage ageing. This requires a good understanding of the tasks to be performed. Depending on the objective, those programs may take various forms, such as corrective maintenance, preventive maintenance, predictive maintenance or reliability centred maintenance (RCM). Streamlined versions of those programs, inspections, tests, monitoring and good industry practices are also extensively applied.

A good maintenance program includes several of the above components in order to take into account the technical nature and the potential consequences of the degradation process that the program is intended to manage. This is particular true in the nuclear, aeronautical, oil and chemical industries, where one cannot afford to wait for a catastrophic accident to take place.

In fact, the maintenance program is the vehicle whereby ageing is detected, monitored and managed. It is the key element of an ageing control program. The recording of data generated by the monitoring programs should be used in the maintenance programs to verify the extent of ageing and plan preventive and corrective maintenance tasks to manage ageing. Adequate monitoring of ageing will permit timely repairs, replacement or maintenance activities, which will minimize the cost of those activities.

5 Purpose and Methodology

The purpose of this paper is to present results of research works aimed to develop a methodology for the control of ageing of equipment for nuclear power plants. Figure 1 illustrates the methodology developed to control equipment as a function of its ageing. The methodology is broken down into twelve steps.

5.1 Ranking and Selection of the Equipment

The methodology starts with the ranking of the equipment by order of importance. In general, this type of analysis should be performed on equipment that show evident signs of ageing or that do not inhibit such signs, but have a significant impact on safety or production. This is one of regulatory requirements of the Canadian nuclear regulations [1] and one of the practices recommended by the nuclear industry [2]. The Canadian Standards Association, has developed guidelines to help the operators of nuclear power plants define a list of safety related equipment [11].

5.2 Functional Analysis

The purpose of a functional analysis is to collect all relevant information that could be necessary to analyse the failure modes and their effects (FMEA). In this analysis, the objective is to define the function and boundaries of the equipment, its structure, operating conditions, operating factors, the environment in which it is operated, its general operation and its materials tree, by collecting information on its components.

5.3 Determining the Modes of Failure and Performing a FMEA

The equipment failure modes and the information generated by the functional analysis serve as inputs for performing an FMEA. The FMEA is completed by a critical analysis of failure modes. The latter may be performed in three different ways:

- With the assistance of the engineering department, maintenance department, manufacturer or experts (as required),
- By using a generic FMEA from a database [12], or
- By developing a hybrid method.

Each of those methods has advantages and disadvantages. The idea is to use the one that best fulfills the needs. Based on the FMECA, it is possible to define the maintenance tasks that will adequately address the identified degradation mechanisms.

5.4 Identification of Ageing Mechanisms

This step serves to determine, among the degradation mechanisms that have been identified, those that are related to the ageing phenomenon and that may potentially be observed on analyzed type of equipment. It identifies those mechanisms based on both external operating experience reports (data bases), and expert judgment. In this context, the data used has been obtained from the EPRI Preventive Maintenance (PM) Database [5][1]. Each mechanism is assessed based on practices and

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[1] The EPRI PM Database was created in 1998 and updated in 2004, which identifies best practices concerning preventive maintenance and the implementation of RCM on more than 74 types of systems, structures and components, coming from several dozens of US nuclear power plants over a 20 year operating period. The project was steered by a panel composed of EPRI experts, staff from US nuclear power plants, and equipment manufacturers. The database contains the preventive maintenance tasks and recommended frequency for a variety of operating conditions, as well as the technical justification for those recommendations.

on equipment conditions specific to the site where it is located (operating conditions, environment, operating factor, etc.).

5.5 Determining Whether the Existing Programs Are Adequate to Mitigate or Slow Down Ageing

This step identifies all the tasks or maintenance programs that are applied on equipment. It includes the preventive maintenance programs, tests, equipment rotation, periodic inspections and inspection rounds, as a function of operating factors. This is a requirement of Canadian nuclear regulations [1] and one of the best practices recommended by the nuclear industry [2].

5.6 Update of Existing Programs

When some ageing mechanisms are not adequately addressed by existing programs, then they have to be modified or adjusted, either by modifying one of the existing tasks or by developing new tasks. The main objective is to not only manage the effects of ageing mechanisms, but also to ensure the monitoring of each of the mechanisms that are not covered or for which the coverage is not adequate. It is not necessary to address the ageing mechanisms that have no significant effect. However, those having a predominant effect shall be included.

5.7 Determining Whether the Equipment Shows Signs of Ageing

This step identifies all the work orders recorded in the operating history of the equipment since first operation. This will show all the failures (modifications, replacement of components, etc.) that have affected the equipment. This step then goes on to compare the degradation mechanisms that have caused those failures to the degradations mechanisms that had been identified. The comparison is carried out in close collaboration with maintenance and operating personnel who have thorough knowledge of the equipment. When a degradation mechanism can be related to ageing, the equipment is then considered as showing signs of ageing.

5.8 Determining Whether it is Possible to Mitigate the Effects of Ageing

Based on internal and external operating experience and expert judgment, this step verifies whether it is possible to mitigate the effects of ageing. Some of the actions that could be taken include:

- Modification of operating conditions,
- Modification of utilisation rate (duty cycle), or
- Revision of the preventive maintenance program (number of tasks, their contents, frequency, etc.), of testing, rotation, inspection rounds or periodic inspections.

5.9 Determining Whether the Residual Life of the Equipment is Sufficient

When equipment is affected by ageing and it is possible to mitigate its effects, then it is necessary to check where it is located on the bathtub curve, based on expert judgment or other methods [13]. A judgment is then made of the residual life compared to the required life.

5.10 Determining a Course of Action Based on the Critical Nature of the Equipment and its Degree of Ageing

If the equipment shows signs of ageing and it is not possible to mitigate its effects, or if it has reached the end of its useful life, a course of action must then be considered to determine the exact time when it should be replaced. Depending on the degree of ageing and on the impact on safety or production, one of the following decisions may be considered:

- Immediate replacement (if the required components are available),

- Earliest replacement possible (when the required components become available), or
- Replacement at the next planned outage or when the equipment fails (if the equipment has no impact on safety or production).

5.11 Carry out Refurbishment, Repair, Replacement of Component(s)

In the case where equipment has not reached the end of its useful life, it is advantageous to extend its operation, the following courses of action may be considered:

- Refurbishment or rehabilitation,
- Repair,
- Return to as good as new condition,
- In the case of complex equipment, replacement of one or several components, or
- Take no action if applicable (the deficiency affects neither safety nor production).

5.12 Degradation of the Performance of the Equipment or OPEX Available

A complete impact assessment of the decisions that have been taken and/or the modifications that have been performed is implemented and monitoring based on internal and external operating experience (OPEX) is necessary.

6 Validation of the Methodology and Results Obtained

The applicability of the method that has been developed was validated on three types of equipment: two pneumatic isolating valves, two control valves and the diesel motor (pump).

6.1 Pneumatic Isolating Valves

The two pneumatic isolating valves that were considered are located on the water piping of the emerging core cooling system. They are normally closed and on standby. They are operated only during mandatory testing.

6.1.1 Maintenance, Inspection and Testing Programs

No prevention maintenance is performed on those valves. An inspection round is performed at the beginning of each shift to identify air or water leaks or abnormal noises. There are 5 testing procedures that require operation of the valves, for a total of 139 cycles per year.

The EPRI PM Database lists 55 ageing mechanisms for this type of valves and their components. It proposes an optimum maintenance program involving 17 tasks.

6.1.2 Deficiencies and Failures

Since the commissioning (22 years), only 15 work orders have been raised on this equipment. Three deficiencies were identified on those valves, of which two are considered failures. None of those failures can be attributed to ageing, as no ageing mechanism has yet been observed on this equipment.

6.1.3 Recommendations

The valves have exhibited good performance and have shown no sign of ageing. In spite of that situation, it is recommended:

- To optimize the number of "open/close" cycles, as that number causes wear in the valve and its components.

- To carry out a "FlowScanner"[2] every 5 years in order to determine the internal operating condition of the components.

6.2 Control Valves

The two control valves are located on the secondary side. Their function is to maintain the water level in the steam generators as a function of reactor power.

6.2.1 Maintenance, Inspection and Testing Programs

Preventive maintenance on those valves consists in checking for air leaks on all the tubing. A visual and aural inspection is performed at the beginning of each shift. Its purpose is to identify air or water leaks or abnormal noises.

« FlowScanner » have been carried out since 1996. This signature allows not only to observe several components of the valve (such as the setting of the emergency air supply relay), but also to validate the functionality of the emergency air supply.

The EPRI PM Database lists 71 ageing mechanisms for this type of valves and their components. It proposes an optimum maintenance program involving 28 tasks.

6.2.2 Deficiencies and Failures

Since the start of operation (22 years), 133 work orders were raised concerning those valves. There were 48 deficiencies reported, of which 43 are considered failures. Those deficiencies fall mainly in the following three failure modes: drift, external leakage, and air leaks. Approximately forty of those failures constitute evidence of ageing as listed in the EPRI Database.

6.2.3 Recommendations

Those valves show evident signs of ageing. The existing ageing control programs (inspection, maintenance, "FlowScanner") have been reviewed. The main recommendations are:

- Review the calibration setting for the close and open limit switches,
- Carry out a more extensive study of the possibility of changing the period between "FlowScanners" from 1 ½ to 3 years. According to the EPRI PM Database, this recommendation should have no significant impact on the failure rate of the equipment.

6.3 Diesel Motor (Pump)

The methodology was also applied to the motor of a diesel driven pump that has been in service for 18 years. On 26 November 2000, the motor suffered catastrophic failure through a mechanical breakdown during a test. It should be noted that two identical diesel driven pumps have been in service during that same period.

6.3.1 Maintenance, Inspection and Testing Programs

Those diesel driven pumps are standby equipment. Six preventive maintenance activities were performed on the motors, but no periodic inspection. Two test procedures were performed. There was a visual and aural inspection at the beginning of each workshift to identify air or water leaks or abnormal noises.

The EPRI PM Database lists 96 ageing mechanisms for the motor and its components. It proposes an optimum maintenance program (testing and preventive maintenance program (PMP) involving 15 tasks.

[2] More commonly known as valve signatures.

6.3.2 Deficiencies and Failures

Over 18 years, 108 work orders were raised concerning the motor alone. 51 deficiencies were identified, of which 11 constituted failures. Those failures fall mainly in the following categories: drift, leaks of the exhaust gas, of the oil, coolant and fuel. Approximately twenty of those failures constituted signs of ageing that are listed in the EPRI Database.

6.3.3 Recommendation

The diesel motor showed signs of ageing. The preventive maintenance program did not seem to have been able to control ageing effectively. With a better designed program, it might have been possible to limit the onset of the ageing mechanisms. However, the signs of ageing that were observed were not precursors of catastrophic failure.

6.4 Limits and Advantages of the Methodology

The methodology can be easily applied to equipment where the operating history contains a large number of work orders. It can be used to analyze failures that occur most often and relate them to ageing mechanisms. In that context, the decision making process is simple, that is whether or not the equipment is ageing and whether or not it should be replaced.

It is difficult to apply the methodology to equipment where the operating history does not contain a sufficient number of work orders or where there is no maintenance history. When the number of works orders is low, this means that the failure rate of the equipment is also low. Consequently, the signs of ageing are less evident. In that context, it is preferable to spend time on equipment that has suffered many failures and possibly exhibits signs of ageing.

The benefits of applying this methodology depend on many factors, among which an access to a reference database for maintenance, expert judgment and operating experience. The way of how the methodology can be applied without those elements should be further examined.

The cost-benefit ratio of applying this methodology may sometimes be arguable, because costs may be significant. Applicability criteria based on costs and benefits should still be determined.

7 Conclusion

This research was aimed at developing an ageing control methodology for nuclear power plant equipment. The approach that was developed makes limited use of the RCM technique and is broken down into 12 steps. It establishes links to both the requirements of Canadian Nuclear Regulation S-98 [1], and the generic Equipment Reliability Process AP-913 of INPO/WANO [2]. Its applicability has been validated on mechanical equipment, namely isolating valves, control valves and the diesel motor (pump). The application of this methodology should be favored when dealing with equipment having an impact on safety or production on which one possesses a well documented operating history.

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Figure 1 : Methodology for the Control of Equipment Ageing