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OPTIMISATION DE LA MAINTENANCE DES TUYAUTERIES DES CENTRALES NUCLEAIRES

THE MAINTENANCE OPTIMIZATION OF STRUCTURAL COMPONENTS IN NUCLEAR POWER PLANTS

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EDF
Electricité
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SYNTHÈSE :

Electricité de France (EDF) a engagé le développement d'un processus d'optimisation appelé "OMF-Structures" afin d'étendre la méthode "OMF" (Optimisation de la Maintenance par la Fiabilité) aux tuyauteries des centrales nucléaires. Le système d'alimentation auxiliaire des générateurs de vapeur (ASG) d'une centrale nucléaire française de 900 MW a été étudié en vue de définir les principes de la méthode. La note présente ces principes dont la généralisation sera proposée d'ici fin 1997.

La méthode OMF-Structures incorpore certains concepts issus des démarches "Risk-Based Inspections" (RBI) dans un processus général d'optimisation de la maintenance par la fiabilité. La méthode comprend deux phases principales :

- la première phase a pour objectif de sélectionner les modes de défaillance critiques et les composants associés. Cette phase se décompose en deux étapes : l'analyse des conséquences potentielles et l'évaluation des performances de fiabilité des composants. L'analyse des conséquences potentielles utilise à la fois les Etudes Probabilistes de Sûreté (EPS) et des critères déterministes. L'évaluation des performances s'appuie sur des modèles de dégradation permettant de sélectionner les couples {composant, mécanismes de dégradation} pertinents. En fonction de la gravité d'un mode de défaillance, sa probabilité d'occurrence est ensuite évaluée au moyen de modèles de fiabilité des structures ou bayésiens ;

- la deuxième phase consite à définir les programmes de maintenance préventive à appliquer aux composants de tuyauterie critiques. Les tâches et les périodicités associées sont proposées en fonction de la nature des composants, des mécanismes de dégradation pertinents et de leur critique. Pour les modes de défaillance à forts enjeux, une optimisation probabiliste peut être utilisée.

EXECUTIVE SUMMARY :

An optimization process, called "OMF-Structures", is developed by Electricité de France (EDF) in order to extend the current "OMF" Reliability Centered Maintenance to piping structural components. The Auxiliary Feedwater System of a 900 MW French nuclear plant has been studied in order to lay the foundations of the method. This paper presents the currently proposed principles of the process. ~~Its generalization should be proposed by the end of 1997~~.

The principles of the OMF-Structures process include "Risk-Based Inspection" concepts within an RCM process. Two main phases are identified :

- the purpose of the first phase is to select the risk-significant failure modes and associated elements. This phase consists of two major steps : potential consequences evaluation and reliability performance evaluation. ~~For consequence evaluation, both quantitative PSA and deterministic aspects are used. For performance evaluation, degradation models are used to select "sensitive elements" where degradation mechanisms may occur. Depending on the severity of the failure mode, failure rates of piping elements are assessed by using structural reliability or Bayesian reliability models~~;

- the second phase consists of the definition of preventive maintenance programs for piping elements that are associated with risk-significant failure modes. ~~The tasks and frequencies are proposed depending on the nature of the element and the degradation mechanism attributes (attributes, kinetics...). For high risk failure modes, a probabilistic optimization is to be proposed.~~

THE MAINTENANCE OPTIMIZATION OF STRUCTURAL COMPONENTS IN NUCLEAR POWER PLANTS

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INTRODUCTION

Maintenance costs in EDF nuclear power plants account for a significant proportion of the cost price per kilowatt-hour. Maintenance operations are conducted on such a large scale in order to guarantee the desired level of safety, to maintain plant availability and to preserve good operating conditions.

Since 1994, EDF has been generalizing a maintenance optimization process called **" OMF "**. Reliability Centered Maintenance constitutes its general framework, enabling the logical definition of a policy of preventive maintenance on every nuclear plant. The maintenance programs are selected in order to satisfy all safety requirements while keeping competitive costs. " OMF " is also a traceable method which allows for periodic updating of analyses (see Jacquot *et al*, 1995). So far, this method which applies to " active " components (valves, pumps...) is used to optimize the maintenance with respect to the criteria: safety, availability, maintenance costs.

However, this general framework has to be completed to take into account the **maintenance of piping structural components**. The main reasons are the following :

- The lack of operating experience data on structural failures results in not knowing the corresponding failure rates and their time dependence for the piping elements, as this is done for the " active " components (valves, pumps...).
- The consequences of individual structural failures on core damage frequency are often not explicitly taken into account in existing Probabilistic Safety Assessment (PSA).
- Up to now, the optimization of non-critical structural component inspections was only performed at the component level (i.e.: reliability-based rather than risk-based), by using structural reliability tools.

To overcome these limitations, EDF launched the development of an optimization process called " **OMF-Structures** ". In 1996, the Auxiliary Feedwater System (AFW) of a 900 MW French nuclear plant has been studied as representative in order to lay the foundations of a method. This process under development should remain as consistent as possible with the existing " OMF " process. Moreover, it was convenient to adapt some Risk-Based Inspection concepts developed by the ASME (see The Research Task Force on Risk-Based Inspection Guidelines, 1991, 1992, 1995) and Risk-Informed Inservice concepts developed by the EPRI (see Gosselin *et al*, 1996) to include them in the " OMF-Structures " process.

This paper describes the proposed principles for the future " OMF-Structures " process. The first section provides an overview of the whole process. Then, the next sections give more details about the main steps of the process : segment definition and functional analysis, potential consequences evaluation of failure modes, risk evaluation and critical failure mode selection, definition of maintenance programs.

The principles that are exposed in this paper reflect the current progress of the " OMF-Structures " process. This one is still under development and its generalization should be proposed by the end of 1997.

OVERVIEW OF THE EDF " OMF-STRUCTURES " PROCESS

The figure n°1 presents the main steps of the " OMF-Structures " process. This process is still under development. However, its main principles are already established. This process can be split up in two main phases :

- The purpose of the first phase is to identify, select and prioritize the risk-significant failure modes and the associated structural elements,
- The second phase consists in defining preventive maintenance programs for the risk-significant elements.

The different steps of the selection phase are depicted by the figure n°1. They consist in successively sorting failure modes and associated structural elements. The objective is to select the failure modes that are critical with respect to safety, availability or maintenance costs, and to identify the associated structural elements.

In the process, three levels of analysis are considered : **system** level (for the functional analysis), **segment** level (failure modes are defined at segment level and potential consequences of failures are investigated at this level), **structural element** level (causes of failure modes are investigated at the element level).

First, the system is decomposed into piping segments (see block 1.1, fig. 1). For this step, functional aspects and PSA are taken into account (see arrow A, fig. 1). Then, a functional analysis is performed at the system level, and associated segments are investigated for each system function (see block 1.2, fig. 1).

Second, a Failure Mode Effect Analysis (FMEA) is performed for each segment of the system. At this stage of the process, failure modes at segment level and their potential consequences on the plant operation are identified (see block 2, fig. 1). For this purpose, different informations are taken into account : existing PSA, deterministic aspects (emergency operating procedures, technical specifications, regulatory classification of materials), functional analyses and economic experience are used (see arrow B, fig. 1). This step results in selecting the segment failure modes of which consequences are severe with respect to safety, availability or maintenance costs.

Third, a Failure Mode Effect and Criticality Analysis (FMECA) is performed at the structural element level for each previously identified severe failure mode. For this purpose, a decomposition of each severe segment into structural elements has to be done (see block 3.1, fig. 1). Then, for each severe segment failure mode at the segment level, the FMECA identifies all its potential causes as potential degradation mechanisms at the element level. Therefore, the reliability performance of elements have to be evaluated. This step is very specific to structures, because operating experience contains almost no failure and only few observed degradations on pipes. Thus, models are necessary in order to assess reliability performance (see arrow D, fig. 1). Two kinds of models are successively used in order to select risk-significant failure modes at the element level. **Degradation models** allow to identify elements where active degradation mechanisms exist (" sensitive " couples : {element; mechanism}). **Reliability models** are implemented in order to assess the failure rates of elements where a degradation mechanisms has been proved to be active. Depending on the assessed reliability performances of the element and the severity of the segment failure mode to which the element belongs, risk indicators may be evaluated for " sensitive " elements. Finally, depending on the comparison of this risk indicators to a threshold, each segment failure mode is stated **critical** (= risk-significant) or **non-critical** (= non-risk-significant), with respect to safety, availability or maintenance costs.

The maintenance optimization phase defines maintenance tasks and frequencies to be applied to the risk-significant structural elements (see block 4, fig. 1). This phase of the process is of qualitative nature for the great majority of structural elements. The results of degradation and reliability models are used in this step in order to evaluate the kinetics due to active degradation mechanisms (see arrow E, fig. 1). However, it has been shown that a probabilistic quantitative optimization of maintenance tasks and periods should be implemented for " high-risk-contribution " elements.

SEGMENT DEFINITION AND FUNCTIONAL ANALYSIS

The decomposition of the system into piping segments

The Functional Analysis and the FMEA step are all the more easy as the number of segments is small. Therefore, the system is decomposed in the smallest number of piping segments. The AFW pilot-study also established that the severity of consequences of a failure mode should be independent of the point of the segment where the failure occurs. Therefore, the following criteria have been chosen for the decomposition of a system:

- Isolability criterion :
  - ◊ If the system is PSA-modeled, the piping segments must be included in isolable segments for the PSA model (in fact, the piping segments are bounded by active components which ensure an upstream-downstream isolation).
  - ◊ If the system is not PSA-modeled, boundaries of piping segments are defined by operating considerations.
- A pipe segment must contain structural elements of the same regulatory class.
- A pipe segment must be composed of a continuous run of pipe.

The Functional Analysis

The objectives of this step are the identification of the functions of the system and the association of the list of involved piping segments of the system in each function.

This step is similar to the functional analysis that is performed for active components in the standard " OMF " procedure.

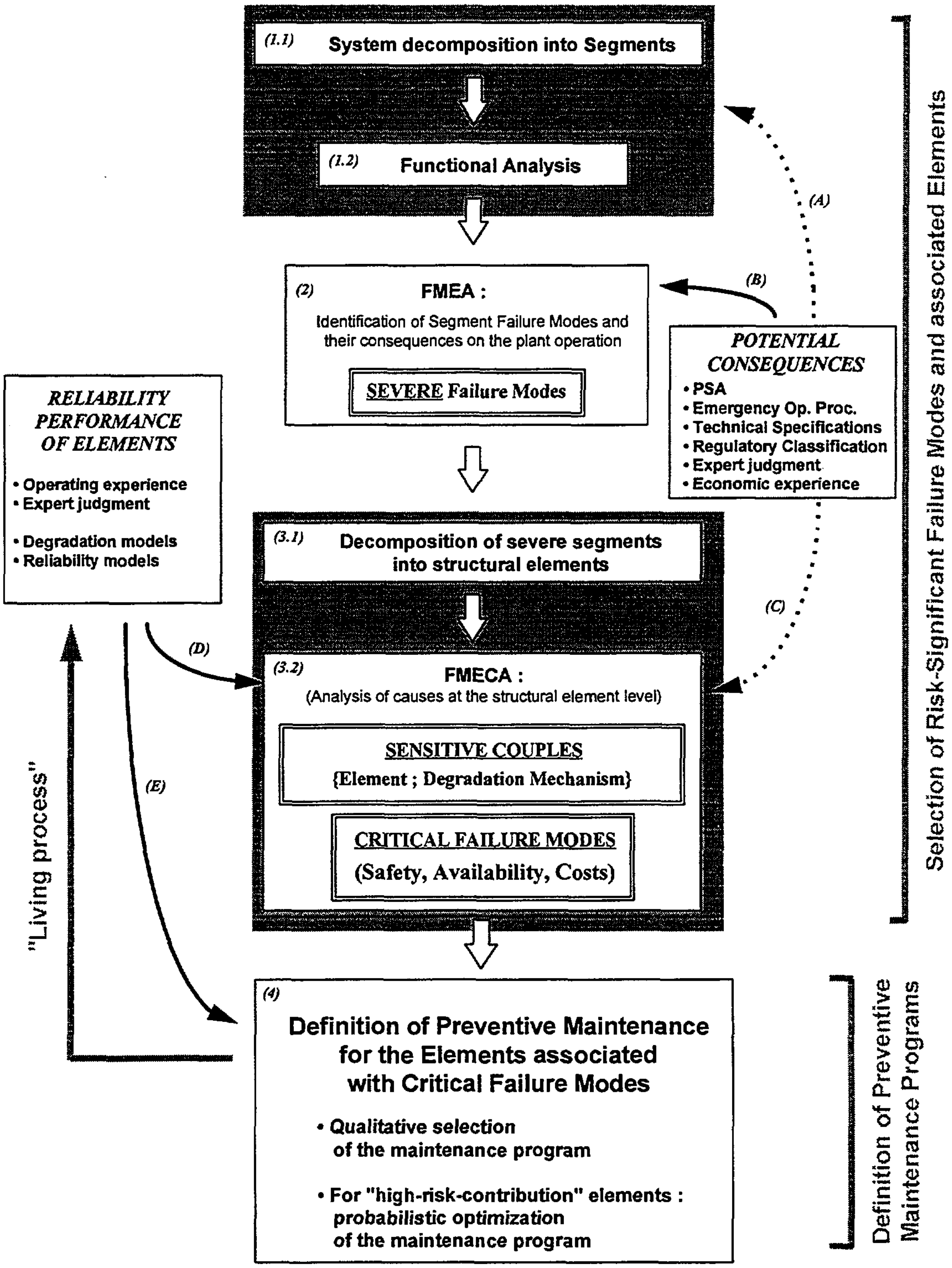

Figure n°1 : Overview of the OMF-Structures process

POTENTIAL CONSEQUENCES EVALUATION OF FAILURE MODES (FMEA)

The objectives of the segment-level Failure Mode Effect Analysis (FMEA) are the following :

1. to **identify the potential failure modes** for each segment of the system,
2. to **evaluate the consequences of each failure** mode on the system functions and on the plant. For this purpose, functional and non functional consequences should be taken into account.
3. To rank each failure mode in a **class of severity**, depending of its consequences.

The severities of consequences are evaluated with regard to three different attributes : safety, availability of the plant, corrective maintenance costs.

Consequences on safety

A process has been defined for evaluating consequences on safety of the segments failure modes. It includes both probabilistic and deterministic aspects.

The **probabilistic criteria** come from the use of Probabilistic Safety Assessment (PSA) models. Level one PSA's are adapted for taking into account the consequences of pipe segment failure modes.

For the " active " components (like valves or pumps...), the standard " OMF " process uses directly the PSA results at the FMEA step in order to identify safety-significant failure modes. This is performed by using two risk indicators : the Fussell-Vesely (FV) and the Risk Achievement Worth (RAW). Both are necessary to characterize the importance of the failure mode with regard to the risk of core damage.

However, the lack of observed failures during the service experience precludes from statistically evaluating failure rates of pipe segments. Therefore, only the RAW can be assessed at this step of the " OMF-Structures " process. Despite it is not sufficient to select safety-significant failure modes, the RAW characterizes the **severity** of the analyzed failures modes with regard to safety. In order to select the safety-significant modes, the FV evaluation and therefore the potential cause analysis through an element-level FMECA are further required (see next section).

For the RAW evaluation, a specific analysis has to be performed in order to identify the initiating events and accidental sequences that are potentially impacted by each piping segment failure mode. As described in Phillips (1993), the RAW can be calculated for piping segments, by running manually the existing " active " components PSA model.

The **deterministic aspects** are considered through the potential initiation of Emergency Operating Procedures (EOP), unavailability governed by Operating Technical Specifications, and regulatory definition of Important to Safety pipe segments (regulatory class 1, 2 or 3).

The figure n°2 (below) gives an overview of the proposed principles for identifying the severity class of failure modes with regard to safety. Three levels of severity are defined :

- **non safety-severe** : to be ranked in this class, a failure mode must not be concerned by any deterministic aspect and either not PSA-modeled or PSA-modeled with RAW < 1,05.
- **very safety-severe** : to be ranked in this class, a failure mode must either directly initiate an EOP or be PSA-modeled with a large RAW, i.e. :
  - ◊ either **RAW > 10,** if the main contribution of the failure mode is due to the loss of a mitigating function,
  - ◊ or **RAW > 2,** if the main contribution of the failure mode to the RAW is due to an initiating event.

  These " very safety-severe " failure modes will be directly declared safety-significant in the FMECA step of the process (see section below), independently of the potential degradation mechanisms evaluation at the structural element level. The assumption (H) justifies this consideration (see section below).
- **safety-severe** : in any other case. Depending on the potential damage evaluation performed in the next step of the process (FMECA), such a failure mode may be declared safety-critical or non-safety-critical.

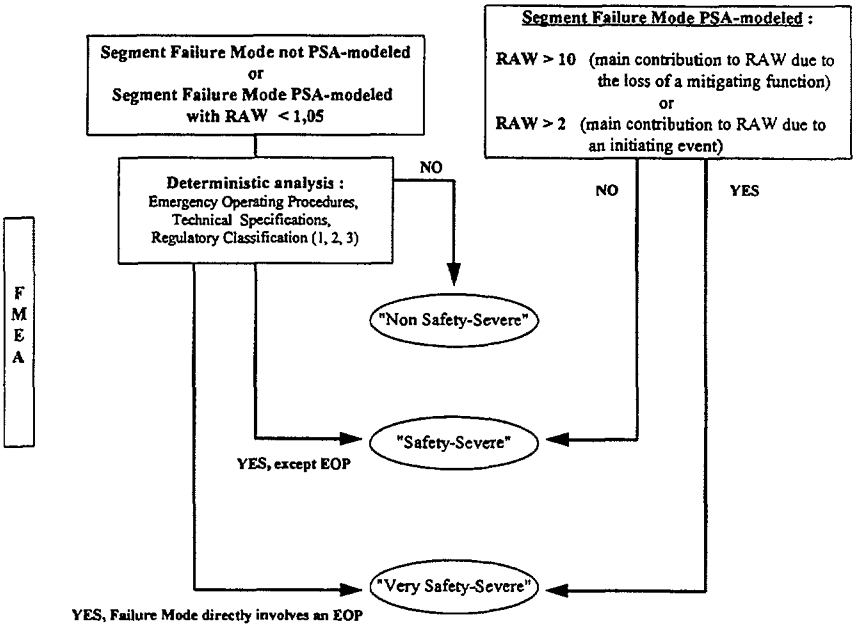

Figure n°2 : Evaluation of consequence severity with respect to safety

Consequences on availability

A failure mode that involves a partial or total drop of the production, an efficiency loss or that delays the connection to the grid is stated " **availability-severe** ". Generally, this type of severity is declared on the basis of operating experience or expert judgment.

Consequences on maintenance costs

Each failure mode whose direct and/or indirect consequences are costly is stated " **cost-severe** ". This kind of severity is generally declared on the basis of the economic operating experience. However, for pipe segments, the lack of failures in the operating experience leads to use especially expert judgment.

This severity can be stated on the basis of quantitative data (how much does cost the repair ?) or on the basis of qualitative data (for example, the failure mode contributes to accelerate aging of a very expensive downstream component).

RISK EVALUATION AND CRITICAL FAILURE MODE SELECTION (FMECA)

Identification of structural elements

Each segment where at least one failure mode was declared severe in the FMEA must be decomposed into structural elements. Structural elements are elbows, welds, straight lengths, tees... For the traceability of the study, one needs to identify exactly all structural elements on a simplified isometric drawing of the segment. In every segment, groups of structural elements are identified (for example : a group for welds, a group of elbows...).

Potential degradation mechanism evaluation

For each segment failure mode which has been declared severe in the FMEA step, the " OMF-Structures " process requires that the piping failure potential also be evaluated. The objective of the FMECA consists of selecting **risk-significant segment failure modes** and **groups of structural elements that contribute to risk.**

For this purpose, the first task of the FMECA is the identification of every potential cause for severe failure modes. The causes are investigated at the structural element group level. At this level, the potential causes for the failure modes are called **degradation mechanisms** (see def. 1). Thus, for each severe segment, the main frame of the FMECA lies in identifying degradation mechanisms that can be active on its structural elements. Depending on the segment severity, quantitative contribution of active degradation mechanisms to the segment failure rate can further be required.

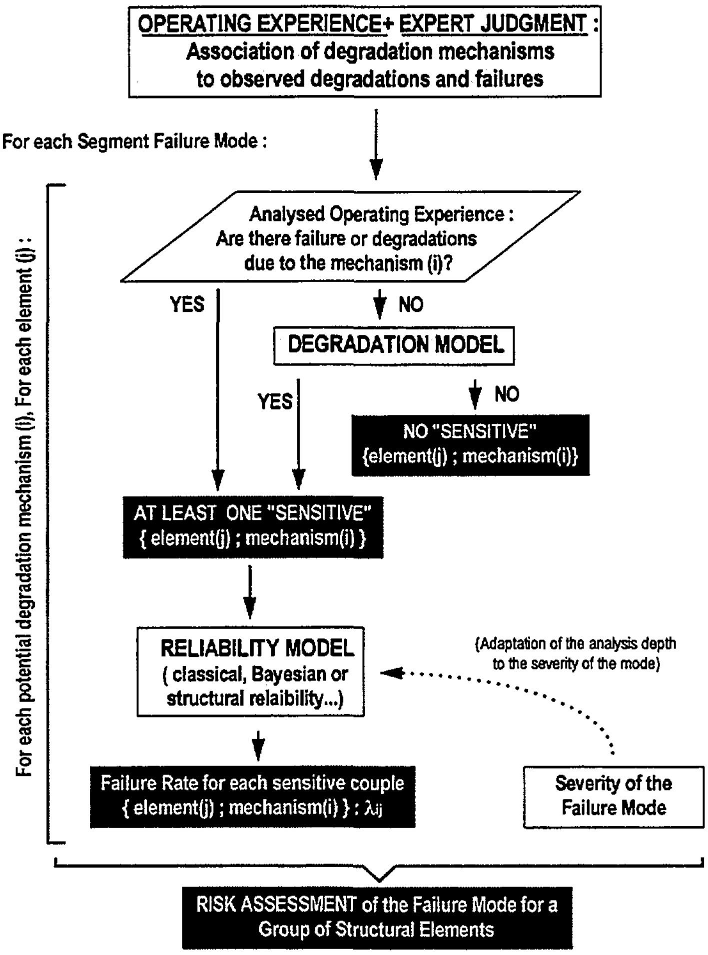

Figure n°3 : Risk assessment in the FMECA step

Definition (1). Arising from a combination of design characteristics, manufacturing practices, operating and environmental conditions, a **degradation mechanism** may occur. It generally results from a physical and/or chemical phenomenon that lead to a generalized or localized degradation of structural elements.

Three classes of degradation mechanisms are defined, depending on their measurable effects on elements :

- Mechanisms that lead to a thickness variation (decrease or increase), for example : flow accelerated corrosion, cavitation-erosion, generalized corrosion (chemical or microbiologically influenced), pitting corrosion.
- Mechanisms that lead to cracks, for example : thermal fatigue, vibration fatigue, stress corrosion cracking.
- Mechanisms that lead to a loss of mechanical characteristics, for example : thermal aging, radiation embrittlement.

Definition (2). A couple {element(j) ; degradation mechanism(i)} is called " **sensitive** " if the degradation mechanism (i) is likely to cause significant degradation and/or failure of the structural element (j) during the power plant life. This couple is called " **non sensitive** " if it can be established that a failure of the element (j) due to the degradation mechanism (i) cannot occur during the power plant life.

The figure n°3 illustrates the proposed FMECA step. The latter uses a combination of the following three evaluation processes for each potential degradation mechanism :

1. **Analysis of the observed inservice degradation and failures by expert judgment** : the objective of this analysis is to associate a list of potential degradation mechanisms to each failure or degradation that has been observed on the piping segment during the service experience. The analysis is performed by experts who have a large experience of structural integrity and understanding of service conditions resulting in degradation of structural elements.

2. **Degradation models** : their purpose is to evaluate the potential for a degradation mechanism on a given structural element. A **couple { element ; degradation mechanism }** will be declared " **non sensitive** " if the degradation model excludes the potential for the degradation mechanism to cause any failure of the element during the power plant life. This couple will be declared " **sensitive** " in the contrary case.

   A degradation model is peculiar to a degradation mechanism and should be generic to be applied to a large number of structural elements.

   Basically, degradation models are deterministic. Their development relies on the following information sources : expert knowledge of the degradation mechanisms, validated numerical tools, database on degradations and failures, validated experimental measurements. In order to be applied to a structural element, the degradation models require, as input, the knowledge of **influence parameters** depending on the design characteristics of the element, its manufacturing practices, operating and environment conditions.

   Except for particular degradation mechanisms (such as vibration fatigue, where an important computational effort is required), degradation models generally consist in a set of conditions depending on the influence parameters. These conditions directly allow to declare a couple {element ; degradation mechanism} sensitive or not sensitive.

3. **Reliability models** : these computational models are used to quantify the failure rate associated to sensitive structural elements with respect to a degradation mechanism. Depending on the severity of the failure mode under consideration, four different levels of reliability models may be implemented :
   - ◊ " Classical reliability tools ", that rely on a statistical analysis of the operating experience failures. Except very particular cases, this kind of model is improper to the piping structural elements, because of the lack of service-based degradations or failures.
   - ◊ " Bayesian reliability tools ", that rely on both elicitation of expert judgment and service-based informations on degradations and failures.
   - ◊ " Simplified structural reliability models " : they require, as input, statistical distributions for a small number of influence parameters and require generally a limited computational effort.
   - ◊ " Complete structural reliability models " : they can require a great accuracy level on a large number of influence parameters and can require an important computational effort. They allow to assess a very accurate time-dependent failure rate that reflect materials and operating uncertainties.

Prior to performing the FMECA, an analysis of the service-based observed failures and degradations must be carried out. Then, for each potential degradation mechanism, " sensitivity " of couples {element(j) ; degradation mechanism(i)} are investigated. If significant failures or degradations were observed during the past **operating experience** and can be associated to the degradation mechanism (i), then the couple {element(j) ; degradation mechanism(i)} is directly stated " sensitive ". If not, a **degradation model** must be applied to structural element (j). Depending on the conclusions of the model, the couple is declared **sensitive** or **non-sensitive.**

Then, a **reliability model** is implemented in order to quantify the failure rate of sensitive couples. The AFW-900 pilot study established that, for such a system, only a small percentage of all couples are sensitive. However, it also established that it would be to cumbersome to implement a " complete structural reliability model " for each sensitive couple. Therefore (see fig. 3), it is proposed to adapt the type of reliability model as a function of the failure mode severity. This consideration is justified as follow : the contribution of a couple {element(j) ; degradation mecha-nism(i)} to the risk is equal to G × Pij(T), where G denotes the severity range of the failure mode and Pij(T) is the failure probability of the element (j) due to the degradation mechanism (i) on the time interval [0,T] : with regard to homogeneity of the assessed risk accuracy, the more severe the failure mode is, the more accurate the reliability model must be.

Thus, depending on the severity of the failure mode, experts will decide to implement :

- for low range severity : no reliability model (in certain cases, the qualitative conclusion of the degradation model can be sufficient) or Bayesian reliability model,
- for middle range severity : simplified structural reliability model,
- for high range severity : complete structural reliability model.

Finally, if a reliability model may be implemented for the sensitive couples {element(j) ; degradation mechanism(i)} associated with a severe failure mode, this one provides a failure rate $\lambda ij(t)$ at the structural element level. The resulting " global " failure rate λ_{MODE} for a group of elements can then be assessed as a function of the λij:(a single sum, if the degradation mechanisms are independant one of another). The corresponding failure probability during [0,T] for a group of elements is given by :

$$P_{MODE}(T) = 1 - \exp\left(- \int_{[0,T]} \lambda_{MODE}(t)dt\right) \qquad (1)$$

Remark (1). The FMECA is performed with respect to an **" reference duration "** : **T**. Thus, failure probabilities and risks are assessed in relation with a time interval [0,T]. It must be noted that the list of selected critical (or risk-significant) failure modes can be strongly dependent on the chosen " reference duration ".

Remark (2). The assessed failure rates $\lambda ij(t)$ are **" potential " failure rates**, assuming that no maintenance is performed on the time interval [0,T]. If $\lambda ij(t)$ is an increasing function of time (as generally assumed), $\lambda_{ij}(T)$ can be considered as an upper-bound of $\lambda ij(t)$ on the " reference duration ".

Selection of critical failure modes and associated elements. The table n°1 (below) resumes the selection of critical failure modes with regard to :

- their severity (result of the segment level FMEA),
- the reliability performance of their structural elements (results of the element level FMECA).

Assumption (H). The failure rate λ_{MODE} of segments where degradation model conclude that there is no sensitive couple {element ; degradation mechanism} is nevertheless assumed to be equal to λ_{mini} : this rate covers the risk for an unknown degradation mechanism to be active or for possible errors in operating information or expert judgment. For conservatism, λ_{mini} could be stated equal to the mean value of the international operating experience failure rates (R. Nyman *et al*, 1995). The RAW thresholds for " very-safety-severe " failure modes have been calculated, using the very conservative value : $\lambda_{mini} = 10^{-7}\ h^{-1}$ for a segment rupture. However, further analyses on that topic are necessary to confirm these thresholds : they are to be developed in 1997.

Type of Severity (FMEA)	No sensitive {Element;Mechanism} for the Failure Mode of the Pipe Segment	At least one sensitive {Element;Mechanism} for the Failure Mode of the Pipe Segment **UNKNOWN λ_{MODE}**	At least one sensitive {Element;Mechanism} for the Failure Mode of the Pipe Segment **ASSESSED λ_{MODE}**
Very Safety-Severe	Safety-Critical	Safety-Critical	Safety-Critical
Safety-Severe	Non Safety-Critical	Safety-Critical	(PSA model) FV ≥ 0,001 => Safety-Critical (PSA model) FV < 0,001 => Not Safety-Critical (No PSA model) $\lambda_{MODE} \geq \lambda_S$ => Safety-Critical (No PSA model) $\lambda_{MODE} < \lambda_S$ => Not Safety-Critical
Availability-Severe	Non Availability-Critical	Availability-Critical	Expected unavailability rate > U_2 => Availability-Critical U_1 < Expected unavailability rate < U_2 => Availability-Critical or not (expert judgment) Expected unavailability rate < U_1 => Not Availability-Critical
Cost-Severe	Non Cost-Critical	Cost-Critical (expert judgment)	Expected annual corrective cost > C_2 => Cost-Critical C_1 < Expected annual corrective cost < C_2 => Cost-Critical or not (expert judgment) Expected annual corrective cost < C_1 => Not Cost-Critical
Non Severe	Non Critical	Non critical	Non critical

TABLE n°1 Selection of Risk-Significant Failure-Modes

A " **very safety-severe " segment failure mode** should be stated safety-critical, taking into account the assumption (H). In this case, the evaluation of potential degradation mechanisms on its structural elements is only performed in order to prepare the definition of maintenance programs on its structural elements.

For a " **safety severe " segment failure mode**, three cases must be considered :

- The analysis of service-based degradation and failures and the degradation models conclude that no degradation mechanism exist as potential cause of the failure mode. Then, the failure mode is declared " non safety critical " for the group of elements.
- The analysis of service-based degradation and failures and the degradation models establish at least one sensitive couple {element ; degradation mechanism}. However, the failure rate λ_{MODE} is unknown either because no reliability model is available, or because it simply does not appear necessary to evaluate λ_{MODE} with regard to the severity range of the failure mode. In this case, the failure mode is directly declared " safety-critical ".
- At least one couple {element ; degradation mechanism} has been declared sensitive with regard to the mode and a global failure rate λ_{MODE} has been assessed by using reliability models :
  - ◊ the failure mode is PSA-modeled : it is declared safety-critical, for a group of elements, if $FV \geq 0{,}001$.
  - ◊ the failure mode is not PSA-modeled : it is declared safety-critical if and only if λ_{MODE} exceeds a threshold λ_S. The threshold λ_S should be defined, depending on whether the failure mode is severe with regard to technical specifications or with regard to the segment regulatory classification.

For an " **availability-severe " failure mode** :

- The analysis of service-based degradation and failures completed by degradation models conclude that no degradation mechanism exist as potential cause of the failure mode : thus, the failure mode is declared " not availability critical ".
- The analysis of service-based degradation and failures completed by degradation models establish at least one sensitive couple {element ; degradation mechanism}. However, the failure rate λ_{MODE} is unknown either because no reliability model is available, or because it simply does not appear necessary to evaluate λ_{MODE} with regard to the severity range of the failure mode. In this case, the failure mode is directly declared " availability-critical ".
- At least one couple {element ; degradation mechanism} has been declared sensitive with regard to the mode and a global failure rate λ_{MODE} has been assessed by using reliability models. The failure mode is declared " availability-critical ", depending on the expected unavailability rate U. Assuming an increasing failure rate, an upper-bound for the expected unavailability rate is: $U_{upper} = \Delta U \times \lambda_{MODE}(T)$, where ΔU denotes the availability duration (hours) resulting from the occurrence of the failure mode and T the " reference duration ".
  - ◊ If $U > U_2$: the failure mode is directly declared availability-critical.
  - ◊ If $U_1 < U < U_2$: the failure mode is declared availability-critical or not, depending on the conclusion of an expert judgment.
  - ◊ If $U < U_1$: the failure mode is not availability-critical.

The thresholds U_1 and U_2 should be compatible with the availability thresholds already used in " OMF " for " active " components.

For a " **cost-severe " failure mode** :

- The analysis of service-based degradation and failures and the degradation models conclude that no degradation mechanism exist as potential cause of the failure mode. Then, the failure mode is declared " not cost-critical ".
- The analysis of service-based degradation and failures and the degradation models establish at least one sensitive couple {element ; degradation mechanism}. However, the failure rate λ_{MODE} is unknown either because no reliability model is available, or because it simply does not appear necessary to evaluate λ_{MODE} with regard to the severity range of the failure mode. In this case, the failure mode is declared either " cost-critical " or not, depending on expert judgment.
- At least one couple {element ; degradation mechanism} has been declared sensitive with regard to the mode and a global failure rate λ_{MODE} has been assessed by using reliability models. The failure mode is declared " cost-critical ", depending on the expected annual corrective cost **C** due to the mode. An upper bound for this expected cost is : $C_{upper} = c \times \lambda_{MODE}(T) \times 8760$, where c denotes the corrective cost resulting from the occurrence of the failure mode and T the " reference duration ".
  - ◊ If $C > C_2$: the failure mode is directly declared cost-critical.
  - ◊ If $C_1 < C < C_2$: the failure mode is declared cost-critical or not, depending on the conclusion of an expert judgment.
  - ◊ If $C < C_1$: the failure mode is not cost-critical.

The thresholds C_1 and C_2 should be compatible with the thresholds on corrective maintenance costs which are already used in " OMF " for " active " components.

Non-severe segment failure modes are also non critical.

DEFINITION OF MAINTENANCE PROGRAMS

The final phase in " OMF-Structures " analysis is the selection of maintenance tasks and their frequency, on the basis of the first phase results. Preventive maintenance tasks are defined on each critical segment, whereas corrective maintenance is generally preferred for non-critical segments

Two analysis levels are proposed, depending on the risk importance of the failure modes under consideration. The first analysis level is especially qualitative and can be applied to a large number of structural elements. The second analysis level is quantitative and is reserved to high-risk structural elements, because it requires advanced probabilistic tools and special effort.

Qualitative process for the task selection

Preventive maintenance programs are defined at the structural element level. Their purpose is to prevent active degradation mechanisms from leading to failures.

For an element belonging to a non-critical segment or an element where no degradation mechanism has been identified, two cases are possible :

1. If there is currently no preventive maintenance on the element, the later is let to corrective maintenance.
2. If preventive maintenance tasks are currently defined on the element, either the tasks are proposed to be suppressed, or they are only kept on a sample of elements where influence parameters are the same.

Maintenance tasks have to be defined on each structural element which has been established to *significantly contribute* to the critical failure modes (FMECA). The degradation mechanism evaluation which has been performed in the FMECA is used for the definition of maintenance tasks.

For critical segment failure modes, the maintenance programs must be defined, by answering the 3 following questions :

1. Which are the elements of the segment where the maintenance tasks must be defined ?
2. What preventive maintenance tasks must be applied ?
3. What is the required frequency for the preventive maintenance tasks ?

Which elements ? For each sensitive couple {element ; degradation mechanism} which significantly contributes to the segment risk, a preventive maintenance task has to be defined. However, if several elements in a pipe segment are affected by the same degradation mechanism, two cases are possible:

- There is no sufficient information to prioritize the affected elements with regard to mechanism kinetics. Then, the task must be applied to every element under consideration.
- The degradation or reliability models allow to prioritize the elements with regard to mechanism kinetics. Then, the task may be applied to the most rapidly affected elements.

What preventive maintenance tasks ? Maintenance tasks are chosen according to a specific selection logic which views all preventive maintenance operations in ascending order of complexity: little upkeep, inservice monitoring, inservice inspection, checks and tests, and scheduled replacement. Today, this final phase is especially based on the expert judgment.

However, a **preventive maintenance task guide** is under development : for a given couple {degradation mechanism ; type of element}, this guide is to propose a list of potentially **efficient** and **applicable** candidate tasks . Then, an expert judgment is required, in order to validate the availability of the candidate tasks, with regard to economical considerations, local access and radiation exposure. This approach is very close to the EPRI process developed by Gosselin *et al* (1996).

What frequency ? A preventive maintenance task must be applied to a structural element in order to strive against a degradation mechanism. For that purpose, a frequency interval is proposed. It is defined on the basis of the following informations :

- The mechanism kinetics. This information generally comes from the degradation and reliability models which have been implemented in the FMECA. The accuracy of kinetics evaluation is also very influent on the choice of maintenance frequency.
- The technical efficiency of the proposed task with regard to the degradation mechanism.
- The contribution of the sensitive couple {structural element ; degradation mechanism} to the failure mode risk importance. The higher this contribution is, the larger the frequency is.
- The current frequency.

A **frequency selection guide** should be developed for that purpose.

Probabilistic optimization. For the sensitive couples {element ; degradation mechanism} which strongly contribute to the risk (i.e. **Risk = G × Pij(T)** is considered significant), a profound analysis using probabilistic tools should be managed. This kind of analysis allows to assess expected risk with regards to safety, availability and costs for several candidate maintenance programs. These expected risks are very useful indicators that facilitate the decision making process to the " best " candidate maintenance program.

Such an optimization has been performed for a weld located in the common segment between the auxiliary feedwater system (AFW) and the main feedwater system (MFW), just upstream of the steam generator. This model produced an evaluation of the risk contribution of the weld as a function of time, and therefore resulted in proposing a new inspection frequency for this weld.

" LIVING " PROCESS

The whole " OMF-Structures " process is a **living process** (see fig. 1). Two levels of updating appear to be necessary.

The objective of the first updating level consists in redefining the maintenance programs, depending on the recent operating experience concerning the efficiency of current programs.

The second updating level involves a much more intensive effort. It consists of :

- updating the list of severe failure modes (FMEA), by taking into account recent economic operating experience and recent evolutions of PSA and operating studies.
- updating the list of sensitive {element ; degradation mechanism} and critical failure modes (FMECA), by taking into account :
  - ◊ the observed degradations and failures during operating experience,
  - ◊ the recent evolutions of the degradation models,
  - ◊ the updating of input parameters of reliability models.

CONCLUSIONS

The principles of the " OMF-Structures " process which were exposed in this paper are consistent with the Reliability Centered Maintenance concepts which are already applied by EDF on a large scale to " active " components, under the acronym " OMF ". The main originalities of the " OMF-Structures " process are the following :

- The use of PSA's, and especially severity and risk criteria are specific to structural elements. The RAW indicator and deterministic aspects are used in the segment-level FMEA and the FV is used in the element-level FMECA.
- The estimation of reliability performance does not only uses the operating experience : they especially use degradation models and reliability models. Therefore, the preventive maintenance of piping structural elements will be defined on the basis of " predictive performances " rather than " recorded performances ".
- The elaboration process of the piping element level FMECA and the required informations (isometric drawings, operating and environment conditions, influence parameters...) significantly differ from the " active " components FMECA : the evaluation for potential degradation mechanisms is specific to piping structures.

In order to generalize and to apply these principles on a large scale, the following points have to be further developed :

- The thresholds λ_{mini} used in the assumption (H), and consequently the thresholds on the RAW for the selection of safety-severe failure modes have to be consolidated by specific analyses.
- Further developments must be carried out in order to establish the criticality thresholds (FV and λ_S for safety, U_1 and U_2 for availability, C_1 and C_2 for costs).
- A degradation model must be developed for each known degradation mechanism. The corresponding pertinence criteria should be as simple as possible, but they should not be too conservative for the process to be selective enough.
- Simplified and complete structural reliability models have to be developed. Moreover, the EDF know-how on structural reliability will allow to define the required refinement and accuracy levels of these models (depending on the severity of analyzed components).
- Preventive maintenance tasks and frequencies guides must be developed, for the qualitative step of maintenance optimization.
- The final version of the " OMF-Structures " process must be simple enough and reliable enough to be implemented within every French nuclear power plant.

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