CONSIDERATIONS ON THE PROBLEM OF
AGING OF NUCLEAR FACILITIES

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1. INTRODUCTION

Up to now, the aging phenomena highlighted by the reactor operating experience especially concern:

- embrittlement due to neutron irradiation of the reactor vessel;
- thermal embrittlement of pipe steels in the primary system;
- thermal fatigue of pipes in systems connected to the primary system ("dead channel");
- stress corrosion (SG);
- stress corrosion influenced by irradiation (internal structures of the vessel);
- erosion and corrosion of internal parts of components in safety-related systems (gates of motor-operated valves);
- corrosion of anchoring devices;
- thermal aging of electrical cables;
- thermal aging of control-command components.

The corrective actions planned after incidents due to the aging of components most often involve improvements to the monitoring and maintenance programs.

For periodic visits of plants after 30 years and taking into account the wish to prolong NPP lifetime, this document provided considerations to be assessed in regard with safety requirements to be maintained.

2. GENERAL ASPECTS LINKED WITH AGING

The degradation mechanisms observed in a nuclear plant typically include phenomena that are relating to time and to the magnitude of operating and environmental stresses.

In general, the design incorporated such mechanisms and postponed beyond the planned life cycle of the plant the critical moment when the degradation becomes such that the conditions required for a safe and economically profitable operation of a structure, a system or a component (SSC) are no longer met.

Aging control consists in checking that the initial sizing margins are sufficiently covering the adverse impact of expected or unexpected degradation mechanisms and, if this is not the case, in conducting the operations required for restoring part of these margins. In this context, the life cycle management is based on the identification and assessment of aging-related risks, and on the development and maintenance of physical defense lines and organizational types (see figure 1).
In the Safety Report Series N°15 [1], the IAEA specified general recommendations for the development and the elaboration of a Program of Management of the Life Expectancy of a nuclear power station. Three elements define the Program: the aging of the SSC, the technological obsolescence and the human aspects.

The management of the aging of the materials includes:

- the selection of the SSC which can have a significant impact on the security and the availability of the plants;
- the identification, the understanding and the evaluation of mechanisms and effects of the aging;
- the elaboration of the actions of management of the aging;
- the program intended for the control of the aging.

The management of the technological obsolescence concerns:

- the studies of risk of rough shortages of spare parts for certain equipments;
- the replacement or the modernization of the electric systems or the control commands for which the nominal life expectancy is 40-year-old subordinate.

The human aspects of management of the aging are bound (connected) in:

- the elaboration and the application of a Program of Management of the Life Expectancy, which requires to create a multidisciplinary and qualified team;
- the gratitude of the program as a part of the politics of operating.
3. AGING IMPACT AND IDENTIFICATION

3.1 CURRENT MONITORING OF AGING

The specific features of the aging process concern the sequence of reliability degradation, as well as the type, as a common cause, of failure mode associated with aging of components of the same type. Most of the time, the safety baselines do not specify the target safety margins for each component, considering the sequence and type of the common cause failure due to aging.

The techniques being currently applied to ensure the reliability of components include:

- aging qualification;
- periodic tests;
- preventive maintenance;
- experience feedback analysis and update of the reliability data.

To date, none of these techniques allows characterizing the degradation sequence and the possible impact of aging-related common cause failures.

The criteria and characteristics of the possible aging mechanisms, as well as the aging appearance indicators, are not specified in the above mentioned techniques for most of the safety-related components.

3.2. EVOLUTION OF THE EQUIPMENT FAILURE MODES

In general, the impact of aging on the reliability and availability of a component may be illustrated by the evolution of the failure rate in time. In the "bathtub" curve (Figure 2), three life periods of a component may be identified: youth, normal operation, and aging periods. In order to characterize aging, two parameters are important: the moment when aging starts $T_0$, and the failure rate increase velocity $d\lambda/dt$.

![Figure 2. Failure curve of an equipment – General case](image)
Knowing these two parameters should, in principle, allow predicting the life cycle or the reliability level of the component, and assessing its acceptability with regard to safety.

In reality, the "normal" operation period, for which the failure rate remains constant, is observed only for electrical or electronic components. The mechanical components (simple) undergoing regular stresses start aging from the very beginning of operation (see Figure 3). In the absolute, for these components, the preventive maintenance program aims at identifying the degradation of the safety margins, and implementing corrective actions whenever required.

![Figure 3. Evolution of the failure rate versus the component age – Case of maintenance free simple mechanical components](image)

With regard to the renovation efficiency, three types of maintenance may be defined: "as good as new" maintenance, "as bad as old" maintenance, maintenance with partial restore. The impact of the various maintenance types on the failure rate is illustrated in the Figures 4, 5, and 6.

![Figure 4. Evolution of the failure rate versus the component age – "As good as new" maintenance](image)
Another aspect associated with the preventive maintenance strategy is the relationship between the operating limit, which may be associated with a safety criterion, the acceptability limit of the measured parameters, the degradation velocity, and the stress frequency (strength).

The margin between the acceptability limit and the operating limit should be large enough to ensure a failure free operation until the next maintenance. The selection of the maintenance periodicity depends on the component degradation velocity and, hence, on the strength of stresses undergone during operation.

In most cases, the decision concerning the requirement for replacing or renovating a component is made during preventive maintenance, based on a comparison between a measurement, performed with the value of the acceptability limit, and the operating limit.

If the value of the measured parameter exceeds the acceptability limit, it is necessary to replace the damaged part (case MP3). Otherwise, operation may continue until the next maintenance (cases MP1 and MP2).

Figure 5. Evolution of the failure rate versus the component age – "As bad as old" maintenance

Figure 6. Evolution of the failure rate versus the component age – Partial restore maintenance
These different situations are illustrated in the Figures 7, 8 and 9.

Figure 7. Acceptability limit and maintenance strategy

Figure 8. Operating limit and maintenance strategy

Figure 9. Component degradation velocity and maintenance strategy
As a conclusion, during preventive maintenance operations, only a limited quantity of parts are periodically replaced (seals ...). For more important parts (shafts, radial retainers, etc.), a check of critical parameters is scheduled, but the aging effect is not explicitly involved in the selection of the maintenance strategy.

In the case of complex components, involving various aging mechanisms, various types of stresses, various degradation velocities and renovation levels associated with the different parts, the behavior of the failure rate cannot be presented as a simple function (see Figure 10).

![Figure 10. Failure rate versus the age of complex components](image)

It should be noted that the increase in the failure rate characteristic of the component entering its aging phase, can be observed only from a certain age of the component, and results in degradation modes that may then affect other parts of the component not identified until that time.

Considering the fact that the life cycle of a component is generally defined at the design or manufacturing stage, and varies from 20 to 40 years, it is difficult to directly derive from the current operating experience the trends of the failure rate evolution associated with aging for all types of components.

Consequently, it is necessary to implement specific techniques in order to characterize it.

### 3.3. MANAGEMENT OF LIFETIME OF EQUIPMENT

The analysis of the state of a component concerning its foreseen life expectancy and the forecast of its remaining life expectancy are both essential points of the management of the aging.

For every mechanism of aging (MV) which could lead to the critical failure of a safety related component, it is necessary to verify first of all if this MV was taken into account in the design (choice of materials, frequencies and amplitudes of loads in functioning considered, kinetic of the aging, etc...).
For the cases where the MV was treated during the design, it is advisable to check the MV against the value of the foreseen life expectancy, and to make a forecast of the remaining life expectancy.

It is then necessary to distinguish the couples "MV-safety related component" according to the following 4 categories:

Category 1: MV-components for which the life expectancy specified during the design is equal or superior to the life expectancy of the plant;

Category 2: MV-components for which the specified life expectancy (cycle) is lower than the life expectancy of the plant;

Category 3: MV-components for which the MV was taken into account during the design without specifying the life expectancy at this stage;

Category 4: MV-components for which the MV in question was not taken into account during the design.

For each of these cases, an evaluation of the impact of the aging on the global safety of the plant must be made. This evaluation can be realized on the basis of a gradual approach including, as the case may be, the definition of the remaining life expectancy, the analysis of the problem of obsolescence in the case of an envisaged replacement, the analysis of the management of the maintenance. The appendix presents a proposition of associated approach.

The definition of the remaining life expectancy is issued from an analysis of the functional constraints accumulated during the operation and during the renewal of the component further to the made tasks of maintenance, as well as an understanding of the kinetics of the aging.

At the end of every analysis, three conclusions are possible:

- The remaining life expectancy of the component is equal or superior to the remaining life expectancy of the plant and its value is justified,
- The remaining life expectancy of the component is lower than that of the plant and a replacement or a modification of the component is foreseen,
- The remaining life expectancy of the component is lower than that of the plant or not justifiable and the replacement is not foreseen; as a result compensatory measures and a strengthened program of surveillance must be developed.

Each of these solutions must be accompanied with an evaluation of the impact of the aging on the global safety of the plant.

In the first case, it is necessary to show that the method and the periodicity of surveillance are adapted to the kinetic of the aging and, as a consequence, that the risk bound to the increase of the probability (rate) of failing during the period between the ten-year safety reassessment and the life expectancy foreseen in the initial design of the plant is unimportant.

In the second case, beyond elements mentioned for the first case that remain valid until the replacement of the component, it is advisable to verify that the availability of the systems concerned
as well as the frequency of damage of the core will not be impacted, neither by the effect of the
decrease of the reliability during the youth period which follows the replacement, nor by the
degradation of the reliability of the other components because of the aging.

In the third case (remaining life expectancy lower than that of the plant or not justifiable), the
designer has to show that the risk bound to the increase of the probability (rate) of failing during the
period between the ten-year safety reassessment and the life expectancy foreseen in the initial
design of the plant is unimportant and that the program of surveillance is well adapted to identify
(in case of case occurrence) as quickly as possible the beginning of the degradation of reliability
connected to the aging of components. Should the opposite occurs, it is necessary to foresee the
replacement or the modification of the component.

4. PLANT LIFETIME AND SAFETY OBJECTIVE

The nuclear steam supply system was designed on the basis of a 40-year life cycle (safety report).
With regard to certain safety-related mechanical and electrical components, specific requirements
involving the aging aspect were implemented. In practice, the "nominal life cycle" parameter is not
systematically specified for each component at the design stage. Furthermore, the "aging"
qualification tests were conducted only for certain types of equipment in limited number.

From the regulatory point of view, the French law does not specify any time limit for the operation
of facilities within the scope of the creation authorization decree. Nevertheless, it requires that the
facility remains permanently in compliance with the safety report.

In order to check that such compliance is maintained, the following operations are conducted every
ten years:

- review of the plant units compliance with regard to the safety baseline;
- re-assessment of the baseline, taking account of the changes to the safety rules and of the
  operating experience, then ensuring compliance of the plant units with regard to the re-
  assessed baseline.

In addition, even if the approach applied during the design does not impose any risk objective, it is
aimed at meeting the requirements of paragraph 27 of INSAG-12 [2]: "The target for existing
nuclear power plants consistent with the technical safety objective is a frequency of occurrence of
severe core damage that is below about $10^{-4}$ events per plant operating year. Severe accident
management and mitigation measures could reduce by a factor of at least 10 the probability of
large off-site releases requiring short term off-site response”.

5. IMPACT OF AGING TO SAFETY

5.1. IMPACT TO THE PLANT UNIT SITUATIONS

The overall objective from INSAG 12 should implicitly cover the initiators inside plants as well as
internal and external hazards. It should be obtained regardless of the plant unit age.
But the study of the aging mechanisms of systems, structures and components may highlight difficulties to meet the objective.

From now, various topics for which assessments should be conducted are to be considered. In particular, the potential impact of aging may be noted for:

- the assessment of design basis operating conditions,
- the assessment of beyond design basis conditions,
- the assessment of internal and external hazards,
- the management of severe accidents.

5.1.1 Potential impact on the assessment of design basis operating conditions

A review of the list of initiating events considered as design operating conditions, based on the assessment of operational data and studies of the aging mechanisms for systems, structures and components, might be performed.

This review should include:

1. A re-assessment of the frequencies of initiating events, incorporating the aging effect.

The design incorporates a limited number of events that may occur during the plant unit life cycle (40 years).

With regard to relatively frequent initiators (e.g. transients), for which the operating experience was used to calculate the frequency, the assessment of the frequency dependency with time should be performed.

With regard to initiators for which the frequency was calculated using reliability models, the aging effect should be considered with reliability models depending on the equipment age.

With regard to rare initiators, for which the frequency was calculated using generic data or expert conclusions, the frequency value might be updated through the development of a probabilistic model incorporating the aging mechanisms. With this assumption, additional operational and design data would be required.

2. A review of the pertinence of the classification of the design basis operating conditions considered at the initial design stage of the plant units.

In case of identification of incident or accident initiators for which the frequency calculation would question their belonging to a category of operating conditions, it would then be necessary either to take actions, or to propose specific provisions for processing their occurrence.
5.1.2 Potential impact on beyond design basis conditions

Aging may directly impact the assessment and sufficiency of the provisions selected in order to limit the consequences of a beyond design basis condition. Indeed, these provisions have generally been added during the operation of plant units, and did not benefit of the same design, manufacturing and qualification requirements as the other safety classified equipment.

It is therefore necessary to pay a particular attention to the maintenance of the components reliability in time, in order to ensure that the accident sequences in which they are involved do not undergo a significant increase in frequency.

Furthermore, it cannot be excluded that other events have to be assessed as additional conditions. The vision of the area covered by this impact is not clear until now.

However, in case of identification of a significant evolution in one type of initiators, following an assessment of the aging effects, it might be necessary to re-assess the provisions being implemented in order to limit the consequences.

5.1.3 Potential impact on the assessment of internal and external hazards

It would be useful to consider the assessment of internal and external hazards in terms of classification, timelessness of preventive actions, and pertinence of their processing, especially as a load case. The aging of structures (supporting elements, anchoring devices, and attachments) should undergo specific assessments.

5.1.4 Potential impact on the management of severe accidents

It would be especially useful to analyze the interest of implementing:

- devices that allow limiting the pressure stress of the containment in case of accident, in order to avoid any containment failure,
- devices that allow limiting the occurrence of a severe accident to a fully residual risk. in order to compensate for the lack of freedom for older plant units, in terms of installation of devices for managing severe accidents,

5.2. POTENTIAL IMPACT OF AGING TO SYSTEM PERFORMANCES

Aging of the system components may result in the following:

5.2.1 Modification to the system performances

The degradation of material properties in the primary and secondary systems may require a revision of the safety requirements associated with the emergency systems (e.g. change in temperature of the reactor vessel fragility limit).
5.2.2 Increase in the vulnerability of a system to common cause failures

The impact of aging for a system whose components may become degraded due to aging is especially significant if the system is redundant. Indeed, aging acts as a common cause.

For example, for a system with three redundancy levels, the unavailability ratio after aging start (with \( q_0 \) being the availability before aging start) may be expressed as follows, using a linear model where \( q_0 \) represents the failure probability independent from the age, \( a \) the acceleration rate, and \( t \) the time:

\[
R = \frac{q_0(1+at)}{q_0} = (1 + at)^3
\]

For a non redundant system, this ratio is equal to \((1 + at)\). Thus, the aging effect is all the more important as the systems are highly redundant.

5.2.3 Increase in common cause failures risks

Aging of components implemented on several systems may represent a common cause failure for these systems. The electrical cables, switch cells, circuit-breakers, may be mentioned as examples.

5.2.4 Modification of the list of important equipment and systems in PSA meaning

It should be noted that, due to the variations in the values of reliability parameters, associated with aging for the various types of components, the list of components most contributing to the unavailability of an emergency system may vary with the age of the plant. Thus, the list of important components and systems from the PSA point of view, which is especially used for defining priorities with regard to the improvements to be implemented, should be updated in accordance with the result of the PSA incorporating the aging of plant units.

6. CONTRIBUTION OF A LEVEL 1 PSA INCORPORATING THE COMPONENT AGING

Several studies made for the NRC concerning the aging and the optimization of the maintenance of safety related components use a probability level model 1 taking into account a variable failure rate \([3, 4, 5, 6, 7]\).

They allowed:

- to estimate the influence of the effects of the aging of components on the unavailability of the protection systems;
- To extrapolate curves of unavailability for components at the end of the life expectancy of the power plant;
- To estimate the increase of the core melt frequency induced by the aging of safety related components, the structures and the elements of the seclusion (??);
- To propose an optimization of the intervals between the periodic tests and the preventive maintenance for the active and passive components.
At the level of the systems, the main learnings of a PSA taking into account the aging are the following ones:

- the unavailability of a system is a function of the age of components,

- Important factors relative to components can vary with the age. Furthermore, if the failure rate of a component increases more quickly according to the age than that of the other components, the relative importance of this component increase (see Figure 11),

- the passive components, which are not generally taken into account in the fault trees of the PSA, can increasingly contribute, with the age, to the unavailability of the system.

![Figure 11. Variation of the importance of components face to face of the unavailability of the system of intermediate cooling](image)

Besides, a test case was realized by the IRSN to show the interest of a level 1 PSA taking into account the aging and the program of maintenance (cf. ref. [8]). The test case was limited to the study of the APRP initiators in the operating ranges of Power Operation and Normal Stop on Generators of Vapor (NS/GV). The analysis was made for several types of components included in the level 1 PSA on the 900 MWe PWRs and speaker (???) in safety related systems.

Only the failure mode in the request was held to model the aging for all the considered components. To calculate the unavailability of components and define the model of evolution of their failure rate according to the age, diverse data were used, either from the operating experience of the French PWR when available or from the one of the American PWR (NUREG / CR-5510 [7]).
The core melt frequency and the important factors were estimated for various ages of the plant (0, 32 and 40 years). The results of the test case show that:

- the value of the core melt frequency can increase significantly towards the end of the life expectancy(cycle) of the plant, because of the effects of the aging (see Figure 12);

- This increase of the core melt frequency is not a linear function of the age of the plant. The variation of the value of the core melt frequency depends on rates of aging of every type of component (speed of wear and degradation), as well as of the strategy of the preventive maintenance and the periodic tests. The obtained maximal value is not necessarily linked to the highest age;

- The contribution to the core melt frequency calculated for the various initiators of primary breach varies with the age of the power plant (see Figure 13). One can note the inflection of the probability in the neighborhood of 32 years corresponding to a term before the moment of preventive maintenance of equipments (pumps and sieve) which allows the failure rate to return to its initial value;

- Important factors estimated for the various types of components vary according to time;

- The analysis of the dominating minimal cut sets and the important factors allows to identify components and failure modes for which the strategy of the periodic tests and preventive maintenance is not optimal from the point of view of the risk.

![Figure 12. Increase of core melt frequency (LOCA during 100% power operation and hot shutdown)](image-url)
To conclude, the development of a probabilistic model including aging effects and maintenance operations has a major interest to estimate impact of aging on safety and to manage lifetime of the NPP in operation.

Based on:

- an in-depth design analysis, the operating experience, the periodic test, the maintenance operation, and the associated research results, allowing an improvement of knowledge with regard to the types and characteristics of the SSC aging mechanisms, as well as the effects of such mechanisms on the availability of safety-related systems,
- the development and application of statistical methods for analyzing the operating experience data and for estimating the reliability parameters,
- the development of an accelerated aging test program for the components,

**Figure 13. Contribution to core melt depending of break sizes**

*With: PB (small LOCA), BI (intermediate LOCA), BV (primary steam break), GB (large LOCA)*
a level 1 PSA incorporating the component aging would allow:

- assessing the value of the core melt frequency by the end of the plant unit life cycle;
- studying the variations in the value of the core melt frequency during the third reassessment and the end of the life cycle as a function of the component monitoring and maintenance strategy;
- updating the frequencies of initiators, and analyzing the probability for occurrence of new initiators associated with the SSC aging;
- updating the list of safety-related components depending on their contribution to the core melt frequency during the period from third visit to end of life cycle;
- assessing the impact of passive component and structure aging to the core melt frequency;
- analyzing the efficiency and completeness of monitoring and preventive maintenance programs being applied (test, maintenance);
- analyzing the sensitivity of the core uncovering frequency to the dynamics of the SSC aging process;
- assessing the impact on the safety of the possible absence of spare parts for some types of components.

7. CONCLUSION

The problem of the aging of the structures, of the systems and the components settles to judge the sufficient level of the measures intended for keeping operating plants in the frame or beyond their initially foreseen life expectancy.

The design of nuclear power plant was made on the basis of a life expectancy of 40 years considered in the safety reports. In practice, the parameter "nominal life expectancy" is still not specified at the level of every equipment at the design stage and furthermore, the tests for validation of type "aging" were not made that for a number limited by materials.

On the statutory plan, the French legislation requires that the plant is permanently consistent with the safety report. To verify the achievement of this objective, it is proceeded every ten years to an examination of the consistency of the plants with the repository of safety, then to the re assessment of this repository by taking into account the evaluation of the rules of safety and the operating experience, then to the consistency of the plants with this new repository.

In addition, it is aimed that the paragraph 27 of the INSAG-12 is respected in terms of global objective during all the life expectancy of plants as well as for a possible phase of extended operation.

First of all, it is then necessary to assess the behavior of the equipment or structure which can turn out crippling for the achievement of the objective of the INSAG-12 but also the respect for its other paragraphs by being interested in the containment and in the whole primary circuit including the vessel. Upstream to quite other evaluation, these structures and equipment have to be the object of evaluations. From these evaluations, it can release conclusions relative to a questioning of the
achievement of the objective but also the frequency of the initiating conditions used for designing the plants.

As such, secondly and in a global way, a review of the list of the events initiators of the design basis conditions (conditions of functioning of dimensioning) based on the evaluation of the operational data and the studies of mechanism of aging of the systems, the structures and the components is to be realized.

In the third place, it is necessary to review the assessment of the internal and external hazards in terms of classification, of adequacy of preventive measures and of the adequacy of their treatment notably as load cases.

In the fourth place, it is necessary to review the adequacy of the treatment of the severe accidents for operating plants whose life expectancy would be extended.

Finally, the development of a model PSA model taking into account the effect of the aging and the activities of maintenance presents an interest regarding, on one hand the control of their impact on the plant safety, on the other hand the management of the operating plants life expectancy.
References


Annex

Definition of an aging mechanism (MV), which can lead to critical failure of a safety related component

Is this MV taken into account in the design?

Yes

Is the parameter linked with life duration of the equipment (DVcomp) specified by the designer?

Yes

DVcomp >= DVplant

Action type 1

DVcomp < DVplant

Action type 2

No

DV is not specified

Action type 3

No

MV has not been taken into account during the design

Action type 4
1. Collection of functional constraints and maintenance operations
2. Assessment of the degradation kinetic

Remaining DV estimation for the equipment (DVrest) from periodic visit (10y)

- DVrest – DVplant > 0
- DVrest – DVplant < 0 (or not valuable by lack of data’s)

Possible replacement?

- Yes
  - Action type 2 point A
  - Assessment of the DV management and of the control
  - Reliability follow-up

- No
  - Feasibility of compensatory measures to guarantee availability of the equipment till end of life DV of the plant or plant closure
Action type 2

Possible replacement?

Yes

Problem of obsolete component

Yes

Replacement by similar equipment

DV and reliability specified by the designer

Validation

Reliability control after replacement (youth period)

No

Prolongation of DV till the end of life of the plant DVplant

1. Collection of functional constraints and maintenance operations
2. Assessment of the degradation kinetic

Evaluation of remaining DV at periodic visit (10y)

DVrest – DVplant < 0 (or not valuable by lack of data’s)

Assessment of the reliability till the end of life of the equipment

Eventual program for replacement (???)

No

Feasibility of compensatory measures to guarantee availability of the equipment till its end of life duration of the equipment or plant closure

Yes

Assessment of the remaining DV

Validation of the remaining DV

Assessment of the DV management and of the control

Reliability follow-up

Point A
Action type 3

1. Collection of functional constraints and maintenance operations
2. Assessment of the degradation kinetic

**Aging validation**

- Evaluation of remaining DV at the periodic visit (10y)

- DVrest – DVplant < 0

  - Replacement program

  - No

- DVrest – DVplant > 0

  - Feasibility of compensatory measures to guarantee availability of the equipment till its end of life duration of the equipment or plant closure

  - Assessment of the reliability and of maintenance

  - Reliability follow-up
1. Collection of functional constraints and maintenance operations
2. Assessment of the degradation kinetic

Action type 2

Point A

Yes

Possible replacement

No

DV definition and requirement for the reliability

Aging validation

Assessment of the DV management and control

Reliability follow-up