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Safety Margins in Mechanical Integrity Assessments for Passive NPP Components

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1 ABSTRACT

One particular concern of both regulators and operators related to NPP lifetime is to keep a sufficient safety level as a function of time. This requirement is sometimes considered to be equivalent as keeping safety margins constant. However, the notion of safety margins has an important variety of meanings.

This paper investigates various existing meanings encountered in different contexts: NULIFE discussions, structural engineering and more precisely the context of structural integrity assessments in the French nuclear industry. In that context, “safety margin” is a generic term that applies to every kind of analytical margin supposed to enhance the structural safety. The potential requirement to keep safety margins constant does not apply to every type of margin: even the safety factor may in some cases be turned into equivalent sets of factors. Finally, what is important is that the safety level has to remain unchanged; this reliability level should be evaluated through a reliability index, rather than through an overall safety factor.

Therefore, the appraisal of the safety level should at least include probabilistic highlights. A current example of such an attempt is given in this paper, with a proposal of an adapted deterministic method for RPV integrity assessments.

2 INTRODUCTION

NULIFE (NUclear plant LIFE prediction) is a European excellence network in EC’s 6th Framework Program. It was launched in 2006 and comprises 44 members (in 2008), basically nuclear utilities and research institutes working in the area of nuclear engineering. EDF is one of the 11 contractors of NULIFE, is a member of its governing board and is strongly implied in its development. 4 Expert Groups gather the specialists of NULIFE member organizations working in the knowledge areas that are necessary to NULIFE activities.

NULIFE aims at promoting harmonized methods to evaluate and manage the lifetime of NPPs, particularly the lifetime of materials and passive components. In this regard, the issues related to safety and risk assessment methodologies are an important concern; they become increasingly significant with the ageing of NPP components and with the industrial objectives of lifetime extension. They are investigated in the framework of NULIFE expert group n°4 called “Safety and Risk”, in which at least 15 member organizations participate.

One particular concern of both regulators and operators related to lifetime is the evolution of safety margins versus time for the components subject to ageing phenomena: the requirement of the regulator is to keep a sufficient safety level as a function of time, during the whole component lifetime, and this requirement is a prerequisite for any possibility of lifetime extension. This notion of sufficient safety level is country-dependent: in some countries (like in the USA), a slight increase of risk (CDF or LERF) can be accepted under certain conditions, whereas in other countries (like France), the safety level is supposed to increase regularly. This requirement is sometimes considered to be equivalent as keeping safety margins constant. However, the notion of safety margins has an important variety of meanings. Therefore, it is necessary to identify more precisely what these meanings are and what safety margins are affected by this requirement.

This paper presents the various meanings of "safety margin" that have been identified at EDF for the safety margins in the framework of the integrity assessment of mechanical components. The margins considered are basically those appearing in the mechanical integrity analysis of passive components of NPPs. Then, an understanding of the requirement to keep the same safety margins is given: what is important is that the safety level has to remain unchanged, and the appraisal of the safety level should at least include probabilistic highlights. Finally, a current example of such methodological evolution including probabilistic considerations is given on the case of the reactor pressure vessel: a possible adaptation of the French RPV integrity assessment deterministic method is presented.

3 SAFETY MARGINS: A CONCEPT WITH MULTIPLE MEANINGS

Discussions performed in the framework of the Expert Group n°4 "Safety and Risk" of NULIFE have suggested that the notion of "safety margins" has an important variety of senses.

In many cases the safety margin is understood as the difference (margin) between the regulatory limit (acceptance criterion) and the real failure of the system considered. This margin corresponds obviously to an epistemic uncertainty, that can be reduced through sufficient increase of knowledge. Therefore, this margin cannot be supposed to increase as a function of time, since knowledge is likely to increase gradually. Consequently, it is not possible to require this margin to increase with time, this requirement would seem paradoxical. However, it can never be reduced to zero, since reality (real failures) never can be described perfectly by physical, mathematical and numerical modelling which always constitutes an idealized representation of the reality. And this representation is one source of conservatism.

For failure modes of mechanical metallic components of NPPs, some examples of such a situation can be easily given:

- When plastic collapse is considered, it is usual to resort to an acceptance criterion where the applied stress has to be inferior not to the ultimate stress σ_u, but to a conventional stress that is inferior to σ_u (e.g. the yield strength σ_Y);
- When brittle fracture by cleavage is considered, it is usual to consider crack initiation as equivalent to rupture; however, it is known that in some cases the crack propagation may stop in the wall thickness before resulting in a through-wall crack, this is the phenomenon of crack arrest; note that the vision of this paper is not to state that crack arrest is acceptable or not, complex technical debates occur in other frameworks;
- In the same way, when ductile tearing is considered, it is usual to represent rupture by crack instability, although the crack propagation may stop in the wall thickness before resulting in a through-wall crack.

Two specific industrial contexts are now examined in the sequel, for which safety margins have been used for a long time and are well-defined.

3.1 Safety margins in the field of structural engineering

The area of structural engineering is a well-established and reputable knowledge field. The concept of safety margins have been used there for centuries. Some elements of this description were given in Ardillon et al. (2006).

For many centuries, the method used to build structures was only based on experience feedback. Since metallic buildings were invented (XIX^e century), it has been relying on the ratio of the maximum stress the material can tolerate to the maximum stress actually experienced by the material over the anticipated life of the structure. This ratio must be sufficient for the structure to be considered safe. This ratio is called the **safety factor,** commonly denoted as the **(safety) margin**. It is the basis of deterministic safety assessments. In such traditional deterministic analyses, safety factors are generally considered as highly important, since they provide a visible testimony that there is a care for the structural safety.

Safety factors are therefore applied in all industrial branches:

- Civil engineering and building works (bridges, tunnels, etc…), offshore engineering and metal constructions;
- Transport: rail, air, road and sea;
- Heavy industry: mining, steelmaking, petrochemicals, nuclear, etc.
- High-tech industries: space, armaments, etc.

This is one of the most common senses of the term “safety margin”. It can be seen that this ratio is a particular kind of **acceptance criterion**, used in the context of **structural integrity**: the design of the structure is accepted only if it meets this ratio.

More generally, the current codes supposed to ensure the safe operating of industrial facilities (e.g. nuclear power plants) mostly resort to deterministic criteria relying on safety margins, the form of which is close to the aforementioned ratio.

As it can be seen, the issue at stake in estimating safety margins is to guarantee the safety of the constructions concerned, or more specifically the various types of safety that can be envisaged, depending on the level concerned:

- safety of the personnel working in the facilities;
- safety of the surrounding populations;
- safety of future populations;
- non-failure of the equipment during its planned service life (availability and satisfactory performance),
- preservation of the environment.

This corresponds to the general sense given to safety as it appears in ISO (1987): the structural safety “means the capacity of a structure to resist all the actions, and also certain specified accidental phenomena, which it will have to withstand during construction and anticipated use (ultimate limit states related)”. Note that, in this general sense, the term of safety has not the same meaning as in the notion of “nuclear safety”: the safety here is what is meant in the common sense, it is a result, whereas nuclear safety is a set of measures to guarantee a satisfactory level of safety (in the 1st sense) to the different populations.

3.2 Various meanings for safety margins (mechanical integrity of structures)

A significant work has been performed at EDF in the context of **mechanical integrity of structures (passive components)** to address the issue of safety margins: this issue was addressed at EDF in the late 90’s when a new regulatory framework (the “Operation Decree”) was issued to define (among other things) new safety coefficients to be applied in flaw evaluations regarding fast fracture damage. The different regulatory documents related to the prevention of this damage and their relationships are presented in the appendix.

3.2.1 Description of the integrity assessment framework (case of Fracture Mechanics)

Firstly, some precisions can be given about the codes supposed to prevent fast fracture damage. They rely on mathematical models of the physical phenomenon considered (e.g. ductile tearing initiation or unstable propagation).

These models are, in our case, composed of analytical equations involving input variables. These analytical equations are in fact codified approximations (simplified methods). The equation constituting the model can generally be expressed as the comparison of a term characterizing the load that has to be inferior to a term characterizing the structural strength. The difference of the two terms (“Resistance term – Load term”) is the limit state function. The equality of the two terms corresponds to the limit state. The case where the load term is inferior to the resistance term constitutes the **acceptance criterion** (in our case the **flaw acceptance criterion**), it corresponds to the “safe set”; the opposite case corresponds to the “failure set”.

The input variables of these models are typically: flaw size (in the case of Fracture Mechanics), geometrical dimensions, applied loads (stresses), material mechanical properties (yield strength, crack driving force…). The load evaluations may require finite element calculations. For the flaw evaluation, these variables are taken equal to characteristic (reference) values, supposed to be representative and pessimistic values of the parameters (e.g. a low resistance capacity, a high load). They constitute a supplementary level of safety margins: they are implicit margins. Moreover, partial safety factors may be applied to these values; they are always superior to 1 in the conventional practice, and may reach high values (2 or more). They are considered as explicit margins. The combination of the two types of margin corresponds to a certain failure probability (risk level); this probability is of course dependent on the structure considered.

You can find below a typical example of an acceptance criterion combining different types of margins based on a fracture mechanics model:

$$J\left(\gamma_\sigma \sigma ; a ; \sigma_0\right) \le \frac{J_{0,2}}{\gamma_{J_{0,2}}} \qquad (1)$$

J represents the J-integral (crack driving force), $J_{0,2}$ the fracture toughness, a the crack depth, σ the applied stress (proportional to loading), σ_0 the yield stress. γ_σ and $\gamma_{J0,2}$ are the safety coefficients applied to stress and fracture toughness.

More precisely, the values of the input parameters of eqn (1) are characteristic values (denoted with k-indices) usually employed in the mechanical analysis. These values are selected as usual values in the pessimistic part of the distribution. Some of them have an explicit statistical meaning: for instance the characteristic value of J_{02} is a certain fractile codified in [RSEM 97] (currently the 16% fractile for pipes). For others, the probabilistic calculations will require assumptions.

Implicit margins may also be present in the model definition, that is supposed to be a conservative approximation of the "real" physical state. These margins are generally difficult to quantify.

3.2.2 Meanings of "safety margins"

Based on this example, several meanings of "safety margins" appeared. In that context, the term of safety margin is generic and applies to every kind of analytical margin supposed to enhance the structural safety. The definitions proposed below try to represent the meaning currently accepted by the EDF specialists in charge of this issue. They are reported from Ardillon (2000). Only a few basic terms are proposed in this section. Note also that the definition work has been carried out in French basically and that here some terms are translated from French to English. Although these definitions were issued for the case of fast fracture, they can be considered as general.

Table 1 – Meanings of "safety margin"

Term	**Definition**
Characteristic value	Same as reference value, but includes a probabilistic meaning (definition as a distribution fractile for example)
Explicit margin	Same as safety coefficient
Implicit margin	Same as reference value
Margin	Same as safety margin
Overall safety factor	Ratio between a parameter characterizing the material strength and a parameter characterizing the effect of actions (loading)
Reference value	Value of an analysis parameter that is used in the margin equation before application of safety coefficient. It is generally a pessimistic value representing the parameter in the analysis.
Reserve factor	Difference between the threshold value of the criterion and the value derived from the calculation carried out with the problem data including their safety coefficients
Safety coefficient	❶(Sense 1) Same as Overall safety factor ❷(Sense 2) = partial safety coefficient = minimum coefficient to be applied to the characteristic values
Safety factor	Same as safety coefficient
Safety margin	❶(Sense 1) Same as overall safety factor ❷(Sense 2) Equation arising from the physical model, with the same form as ❶ but that can be applied to whatever variable value. In this sense, the margin can be a random variable. Equivalent to the limit state function ❸(Sense 3) Same as partial safety coefficient

Term	Definition
	❹(Sense 4) Same as reserve factor

It can be seen in the previous table that the notion of “Reserve factor” can be considered as one possible way of understanding a “safety margin”. For example, the reserve factor can be the difference between the limit crack size accepted by the criterion and the measured size of the detected crack. For the flaw to be accepted and the NPP operation to be continued (before an appropriate maintenance operation), this difference has to be positive. It is clearly depending on the size of the detected crack.

4 REQUIREMENTS ABOUT SAFETY MARGINS

To our understanding, the requirements to keep the same safety margins during all the plant components life do not apply to the reserve factor (also called “extra margin” sometimes). This reserve factor may decrease with ageing as far as the acceptance criterion is fulfilled.

They may apply to the margins supposed to guarantee the safety level (i.e. mainly the regulatory safety coefficients, and to a certain extent the characteristic values and mathematical models in which they are involved).

But, as mentioned in Ardillon (2003), even these regulatory coefficients should be considered as a formal reference (this is clearly mentioned in the Memorandum of application (1999) of the “Operation” Decree (1999)), valid on specific cases, and other equivalent sets of factors may be adopted, provided that some knowledge about the uncertainties on the input parameters of the integrity analysis is available. In case of better knowledge of the uncertainties resulting in reduction of epistemic uncertainty, the safety factors may be reduced, but the same safety level is preserved. And the way to perform this equivalence of safety factors is of course to resort to probabilistic methods, that provide a rational and rigorous treatment of the uncertainties and explicitly refer to safety (reliability levels).

Note that this equivalence can also be performed on the “characteristic” values, especially if the safety factor has to remain unchanged for non technical reasons. This is what is suggested in the adapted deterministic method proposed for French RPVs, described in the sequel.

Finally, what is important is that the safety level has to remain unchanged; and as mentioned in Ardillon (2000, 2006), it is well-known that safety factors (and especially overall safety factors) do not provide a consistent evaluation of the safety (reliability) level ensured by their application. This reliability level should be evaluated through a reliability index (or, equivalently, a failure probability), rather than through an overall safety factor, as the latter does not provide a sufficiently uniform reliability level.

Therefore we think that the appraisal of the safety level should at least include probabilistic highlights; the adapted deterministic method for RPVs presented below is an attempt to include such highlights.

5 RPV INTEGRITY ASSESSMENT: AN EXAMPLE OF POSSIBLE ADAPTATION OF THE DETERMINISTIC METHOD

5.1 General physical phenomenon

Reactor Pressure Vessels (RPVs) of Pressurized Water Reactors (PWRs) are subjected to cumulative neutron irradiation exposure over their operating life, resulting in increasing embrittlement (i.e. reduced ductility and fracture toughness) of the RPV steel wall zones close to the reactor core, and thus potential cleavage or brittle fracture in these zones. The degree of RPV steel embrittlement is quantified by the shift of the nil-ductility transition temperature RT_{NDT}, that is a function of the chemical composition of the steel, the neutron irradiation exposure and the initial unirradiated transition temperature RT_{NDT} of the ferritic steel constituting the base metal.

In PWRs, transients can occur that result in severe overcooling (thermal shock) of the RPV concurrent with or followed by high repressurization. The pressure and the stress gradients originated from the thermal shock can lead to crack opening for existing manufacturing flaws located on or near the inner wall surface, all the more since the low temperature during the transient can reach the brittle/ductile transition zone of the steel, where the fracture toughness is significantly reduced.

These possible transients (Pressurized Thermal Shocks) correspond to particular loading (operating) conditions. As mentioned in Ardillon & al. (2003), these conditions are generally classified as follows: normal and upset conditions, emergency conditions, faulted conditions.

Two populations of cracks related to in service inspections are considered: detected cracks, with known dimensions and location, and non detected cracks, whose characteristics are not known. The term "non detected cracks" denotes the cracks for which detection can not be guaranteed in every case due to the limits of NDE performances; however, the French experience feedback of RPV examinations shows that such cracks (the depth of which is inferior to a given threshold) are sometimes detected. The probabilistic knowledge about this population of "non detected cracks'' comes from other inspections (destructive and non destructive examinations) during the manufacturing of the vessel and nozzles.

5.2 Description of the current deterministic integrity assessment method

The current integrity assessment rule can be described as follows:

$$K_{CP}(C_S.L) \leq K_{1C} \quad (2)$$

where K_{cp} stands for the stress intensity factor calculated at the crack front for the load L considered multiplied by the regulatory safety coefficient C_s valid for the category of this load L. A codified method enables to compute the elastic stress intensity factor and then to apply a plastic correction to it. K_{1C} is the material fracture toughness at the crack front, issued from the codified curve given for instance in the RSE-M (2005).

5.3 Appraisal of the conservatism of the deterministic method

The current deterministic treatment of this population leads to overly conservative assumptions, that may endanger the objectives of lifetime extension adopted by EDF. Without probabilistic analysis, it is not possible to quantify exactly this level of conservatism; however, it is possible to imagine that this level should be high by noticing that the number of parameters involved in the analysis and taken equal to a reference pessimistic value is high, and that the individual conservatism of each reference value is generally significant. Let us mention that:

- The codified curve fracture toughness K_{1C} corresponds approximately to a minus 2 standard-deviation curve;
- The RT_{NDT} shift also corresponds to a 2 standard-deviation value;
- The dimensions of the so-called "generic" crack, that is supposed to cover the population of "non detected cracks", are superior to those of all the non detected cracks;
- This generic crack is located at the most conservative point of the irradiated vessel shell ring: maximum irradiation (hot spot), maximal thermal shock (under inlet nozzle);
- The thickness of the clad is taken equal to its minimum value, although examinations have detected significantly higher values;
- The amplitude of the thermal shock due to water injection is maximized: the water temperature considered has never occurred during the corresponding measurement campaign.

Moreover, these pessimistic values are combined with a high safety factor. The only way to have a rational estimation of the risk level is to perform a probabilistic analysis.

5.4 Probabilistic analyses

RPV brittle fracture (considered as failure) probability assessments have been performed for many years in various countries. Since the mid-1970s, several probabilistic fracture mechanics computer codes have been developed in the United States and used by the U.S. Nuclear Regulatory Commission (NRC), as recently the FAVOR code (cf. Dickson (1995)): the PTS regulatory evaluations rely on the probabilistic assessments performed by FAVOR. As a complement to the regulatory deterministic analyses, EDF also has been performing such assessments for more than fifteen years, as mentioned in Turato & al. (2003). They rely on Probabilistic Fracture Mechanics (PFM) and are one of the major applications of structural reliability methods in the nuclear industry.

5.5 Description of the potential alternative method

Due to the difficulty to identify precisely the conservatism of the current approach and to the knowledge improvements related to data uncertainties, an alternative, semi-probabilistic approach, has been developed. It takes advantage of the better statistical knowledge of the input variables like fracture toughness, RT_{NDT}

shift, fluence and especially the non detected crack population. In the deterministic analysis, this population is represented by one single crack ("generic crack") with the most pessimistic location and dimensions. Some assumptions are performed about the distribution of these parameters. It is therefore possible to compare at a given age the RPV reliability of the so-called generic crack, and the reliability of the population of non detected cracks, which is much better with the realistic assumptions considered. Consequently, it is also possible to calculate the age at which the two reliabilities are equivalent. This gives the possible RPV lifetime extension. A preliminary presentation of this method has been given by Meister (2006).

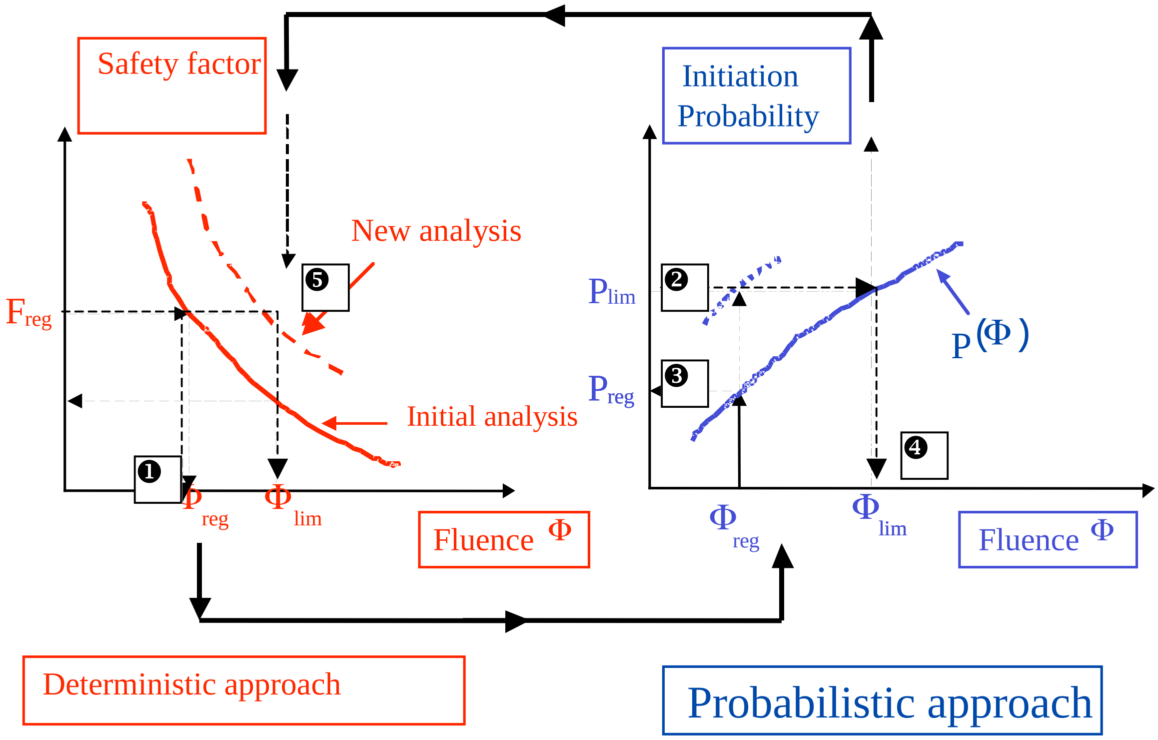

Figure 1. Schematic description of the adapted deterministic method.

The steps of the method appear at figure 1 above. They are as follows:

1. Step 1: for a given transient, evaluation of Φ_{reg}, the maximum acceptable fluence level derived from the regulatory deterministic analysis using the regulatory safety factor F_{reg} applied to the generic crack; equivalently, gives the maximum acceptable age of the RPV;
2. Step 2: at this age derived from Φ_{reg}, evaluation of the corresponding failure probability P_{lim} (initiation probability) of the generic crack; P_{lim} corresponds to the residual failure risk derived from the current deterministic regulatory analysis; this risk is implicitly accepted by the regulator;
3. Step 3: at this age derived from Φ_{reg}, evaluation of the failure probability P_{reg} (initiation probability) of the population of the non detected cracks; the difference between P_{lim} and P_{reg} is due to the probabilistic knowledge about this population;
4. Step 4: calculation of Φ_{lim} (and the equivalent RPV age), the fluence level at which the failure probability of the non detected cracks population becomes identical to P_{lim}; the difference between the ages corresponding to Φ_{lim} and Φ_{reg} gives the lifetime extension derived from this semi-probabilistic analysis;
5. Step 5: estimation of a new set of parameters of the deterministic analysis, for which the maximum acceptable fluence level derived from this adapted deterministic analysis using the regulatory safety factor F_{reg} applied to the generic crack, is equal to Φ_{lim} (and not to Φ_{reg} like in step 1); this is the adapted deterministic method.

This proposed adaptation of the currently applied deterministic integrity assessment method gives the possibility:

- to take advantage of the better statistical knowledge of the uncertain input quantities to perform rational failure risk (probability) evaluations;

- to respect the formal requirements of the regulation (the safety factor F_{reg} remains unchanged) by adapting some parameters of the deterministic analysis (characteristic values); these implicit margins may change in that case; this adapted selection is now based on risk considerations rather than on an accumulation of margins with no rigorous justification.

6 CONCLUSION

One particular concern of both regulators and operators related to NPP lifetime is to keep a sufficient safety level as a function of time. This requirement is sometimes considered to be equivalent as keeping safety margins constant. However, the notion of safety margins has an important variety of meanings.

This paper has presented such meanings encountered in different contexts: NULIFE discussions, structural engineering, and more precisely the context of structural integrity assessments in the French nuclear industry. In that context, "safety margin" is a generic term that applies to every kind of analytical margin supposed to enhance the structural safety. The potential requirement to keep safety margins constant does not apply to every type of margin: even the safety factor may in some cases be turned into equivalent sets of factors. Finally, what is important is that the safety level has to remain unchanged; this reliability level should be evaluated through a reliability index (or, equivalently, a failure probability), rather than through an overall safety factor, as the latter does not provide a sufficiently uniform reliability level.

Therefore, we think that the appraisal of the safety level should at least include probabilistic highlights; the adapted deterministic method for RPVs presented in the paper is a current attempt to include such highlights.

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