RPV failure probability: evaluation for a set of transients and cracks

Emmanuel P. Ardillon [1)]

1) EDF-R&D, Industrial Risk Management branch

ABSTRACT

This paper deals with the residual risk of fast fracture damage potentially affecting Reactor Pressure Vessels (RPVs) of PWRs. This risk is supposed to result from manufacturing cracks initiation, endeavoured by cumulative neutron irradiation and occurrences of Pressurized Thermal Shocks (PTS). The basic evaluations of this risk of failure concentrate on the calculation of crack initiation probabilities for one given crack and one given transient.

However, the overall risk arises from multiple cracks and transients. A general widespread formula is available to perform this cumulative evaluation. This paper deals mainly with the cumulative risk due to transients, and discusses the relevance of the hidden assumptions required by the general formula. It gives a detailed analysis of the relationship between the RPV state and the transients occurrences process, both aspects that are commonly supposed to be independent. Some suggestions to issue an alternative evaluation are finally given.

CONTEXT

General physical phenomenon

Reactor Pressure Vessels (RPVs) of Pressurized Water Ractors (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 could lead to crack opening for existing 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, when warm pre-stressing is not taken into account.

These transients correspond to particular loading (operating) conditions. These conditions are generally classified as follows [1]: normal and upset conditions, emergency conditions, faulted conditions.

Probabilistic analysis

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 [2]. As a complement to the regulatory deterministic analyses, EDF also has been performing such assessments for fifteen years, as mentioned in [3, 4]. They rely on Probabilistic Fracture Mechanics (PFM), and are one of the major applications of structural reliability methods in the nuclear industry.

The basic evaluation is the so-called conditional failure probability for one given transient, flaw, and RPV age. Failure can be understood as cleavage initiation, or involve other mechanisms like the possibility of crack arrest, depending on the accepted criterion. This evaluation of course relies on a mathematical model of the limit state of the structure submitted to the irradiation damage, including deterministic and random variables, as shown for example in Persoz [3].

However, these basic evaluations have to be aggregated to calculate the global RPV failure annual probability or frequency. This global annual frequency is the aim of the evaluations, as the RPV failure is one major (and direct) core damage initiating event, and a particularly significant input to the calculation of the core damage frequency (CDF) performed in Level 1 PSA. This failure frequency is supposed to be given by the general formula :

$$F_{RPV} = \sum_{i=1}^{N} f_{T_i} * P(RPV\ \ failure / T_i) \qquad \text{(per reactor.year)} \qquad (1)$$

with the notations mentioned in the nomenclature at the end of the paper, and where P(RPV failure / T_i) denotes the probability commonly presented as the conditional RPV failure probability given transient T_i.

Although this general evaluation frame is commonly utilized [5], its practical application can lead to approximations that need to be clearly pointed out. The paper provides some recommendations (currently in progress) to deal correctly with the following issues.

Issues addressed in the paper

First of all, the following aspects related to the (complex) evaluation of the so-called conditional failure probability P(RPV failure / T_i) are out of discussion: failure mode definition (supposed to be cleavage fracture directly induced by crack initiation considered as RPV failure), thermomechanical RPV model, thermal transient description, selection of the indexing temperature $T – RT_{NDT}$, statistical modelling of input variables, probabilistic numerical methods.

At the opposite, this paper will concentrate on typically probabilistic methodological issues involved in the overall risk assessment and its general formulation (Eq. 1). The result are general and do not depend on the above mentioned issues.

In a previous paper [6], one aspect of the cumulative evaluation was treated: a proposal of overall risk evaluation was performed for one given transient applied to a set of cracks corresponding to 2 possible populations: detected cracks with deterministic characteristics and non detectable cracks, with random characteristics (number, location, dimensions). This paper will basically deal with the other aspect of the cumulative evaluation: how to evaluate the risk for one given crack and a set of transients.

Anyway, the overall risk under evaluation is meant for a given RPV at a given age (with the corresponding embrittlement); it is evaluated for the coming operating cycle (one unit period), at its beginning. The ageing (due to embrittlement) on this period is neglected. The treatments apply of course to the PTS that are relevant for the analysis of the RPV crack initiation; however, they are not specific to any transient selection. Moreover, the main symbols and abbreviations are listed and explained in the nomenclature; however, some rare symbols may appear only in the main body of the paper.

TREATMENT OF MULTIPLE TRANSIENTS IN THE PROBABILISTIC ASSESSMENT FOR A GIVEN CRACK

Some comments about the "conditional failure probability"

The basic term of the reference formula (Eq. 1), f_{Ti} . P(RPV failure / T_i) is supposed to reflect the contribution of transient n°i to the overall failure frequency. It consists of two terms, the latter of which is generally considered as a "conditional failure probability". However, for this notion to be relevant and to correspond to the use adopted in probability theory, "T_i" should be an event or possibly a random variable; and in some practical evaluations this is not the fact, the computed probability corresponds to the failure probability during the transient. More precisely, a given transient with a deterministic profile - flow pressure, wall temperature and heat exchange coefficient evolutions vs. time during the transient are supposed to be deterministic – is supposed to occur, and the event for which a probability is evaluated could be described as follows: there exists (at least) one instant during the transient for which the RPV strength is lower than the applied load. As the transient is supposed to be deterministic, the randomness only results from the random variables that characterize the RPV state at the level of a considered crack: RT_{NDT} and its shift ΔRT_{NDT} due to irradiation, flaw dimensions, cumulative fluence… This formulation does not account for the rank of the transient occurrence: is there any difference in terms of failure probability due to the fact that it is the first occurrence? Real conditional probabilities could be for example P(RPV failure / $N_{Ti} = 1$), P(RPV failure / $N_{Ti} = 2$), P(RPV failure / $N_{Ti} \geq 1$)… if we consider the random aspects that may affect the transient itself. And this distinction according to the number of transient occurrences is relevant, as will be shown later; this is also one reason for which the notation of P(RPV failure / T_i) to express a conditional probability would be ambiguous.

Other considerations tend to show also that the notation "P(RPV failure / T_i)" is intrinsically ambiguous: it could mean simply the probability of the RPV failure (in general) given the occurrence of transient T_i. But this event does not only include the failure during transient T_i, but also the failure during all possible transients given the occurrence of T_i. For such an interpretation, the summation of all these terms in (Eq. 1) would lead to count various times the same configurations, which is of course not relevant.

For these reasons, in the remainder of this paper, the term P(RPV failure / T_i) will denote and be rather called "failure probability during the transient T_i", that is in fact during a given transient occurrence. This probability reflects only the RPV state at the crack level, and the transient profile that is deterministic. It has a meaning even if T_i does not occur. Consequently, it will be noted P[fail(T_i)-RPV], to show that this is not a conditional probability, and that the random variables only concern the RPV state $\underline{Z}$. Let us remind that with this definition, P[fail(T_i)-RPV] corresponds in fact to $P(K_{cp} \geq K_{1c})$, where these variables are computed for transient T_i.

However, it will be shown (cf. (Eq. 10)) that this term (multiplied by f_{Ti}) is not necessarily identical to the contribution of transient T_i to the RPV failure probability: this individual contribution corresponds in fact to the following event "There is at least one RPV failure during the unit period, and these failures are due to the occurrence of T_i", it will be noted fail(T_i).

Justification of the reference formula under clarified assumptions

The reference formula (Eq. 1) can be derived from the following assumptions, discussed later:

(A_1) N_{Ti} is not necessarily limited

(A_2) N_{Ti} and $1_{fail(Ti)\text{-}RPV}$ {$\underline{Z}$} are independent variables; true if N_{Ti} and $\underline{Z}$ are independent

(A_3) transient occurrences are mutually independent

Let us give the demonstration of the validity of this formula under the aforementioned assumptions.

Firstly it results from (A_1) and (A_2) that the number of failures during an operating cycle is not limited. It is possible for one RPV to experience various failures, and even due to the same transient. The RPV failure frequency can be expressed as F_{RPV} = E[N(fail)], where fail is defined as the event “There is at least one RPV failure during the unit period”. As failures and transients may not occur simultaneously and do not interact (A_2 and A_3), the whole number of failures is equal to the sum of the failures due to each transient (individual contributions). Therefore :

$$F_{RPV} = E[N(fail)] = \sum_{i=1}^{N} E[N(fail(T_i)] \quad \text{(per unit period)} \tag{2}$$

Under these assumptions, and because of the temporal process leading to possible transient occurrences and RPV failures, the RPV failure frequency is rigorously equal to the sum of the individual failure frequencies due to each particular transient. There remains to evaluate the basic term of the summation.

At this step it is essential to notice that the RPV behavior will be identical at each transient occurrence, since the transient profile is supposed to be deterministic and since the ageing (irradiation embrittlement) is neglected over the coming operating cycle: for one given RPV state $\underline{Z}$, if the failure occurs at the 1^{st} occurrence of T_i, it will occur in the same way at any future occurrence of T_i. This issue is important, since a rapid analysis could lead to consider that the behavior of the vessel at one occurrence of Ti does not provide any information about the behavior at another occurrence, and this is wrong; even in our frame, the behavior is totally correlated (identical). It must be repeated that if you suppose that crack initiation occurs at the first occurrence of T_i, then you have to suppose that it will happen also at any future occurrence of T_i. Thus, for a given RPV state $\underline{Z}$:

$$\begin{aligned} N[fail(T_i)] &= N_{Ti} \text{ if } \underline{Z} \text{ leads to the RPV failure at the first } T_i \text{ occurrence} \\ N[fail(T_i)] &= 0 \text{ otherwise} \end{aligned} \tag{3}$$

Consequently, it results from the definition of the mathematical expectation that:

$$E\{N[fail(T_i)]\} = E\{N_{Ti} \,.\, 1_{fail(Ti)\text{-}RPV} \{\underline{Z}\}\} + 0 \tag{4}$$

And (A_2) yields the following expression:

$$\begin{aligned} E\{N[fail(T_i)]\} &= E[N_{Ti}] \,.\, E[1_{fail(Ti)\text{-}RPV} \{\underline{Z}\}] \\ &= f_{Ti} \,.\, P(\text{RPV failure} / T_i) \end{aligned} \tag{5}$$

And (Eq. 1) is obtained immediately by combining (Eq. 2) and (Eq. 5), which is the expected result.

Assumptions relevant for the RPV case, consequences

The previous paragraph has shown that the validity of the formula that is presented as the reference formula relies on some assumptions. Some sufficient assumptions (but not far from being necessary ones) have been proposed. It has now to be discussed whether these assumptions are relevant in the RPV case or not.

Firstly, it was shown that as a consequence of (A_1) and (A_2), the number of failures during an operating cycle is not limited. This is of course not realistic, since a RPV cannot fail twice [7, 6]. Note that this impossibility arises both from the fact that an RPV failure would be so catastrophic as to prevent the concerned NPP from operating any longer, and also from the fact that in case of fast fracture the RPV could not experience any other damage (the internal pressure becomes very low). One can notice that this structural loss would apply in the same way to other types of structures experiencing a fast fracture damage, it is not particular to RPVs. More generally, some considerations developed in this paper could be fruitful to provide a more rigorous cumulative risk evaluation for other structures.

And this questions firstly (A_1): in the real NPP life, severe transients, corresponding to situations that are not in the range of normal and upset conditions, could happen only once a year, for these transients N_{Ti} has to be inferior or equal to 1. This also questions (A_2), at least for one reason: as a RPV cannot fail twice, a transient that would cause an RPV failure will happen necessarily at most one time. Thus, a correlation exists between the RPV state and the number of occurrences of a given transient: if Z is such that it leads to the failure during the occurrence of T_i, N_{Ti} has to be inferior or equal to 1. Therefore it is possible to answer the question underlined in the first subparagraph: it appears that quantities such as P(RPV failure / N_{Ti} = 1), P(RPV failure / N_{Ti} = 2) can not be identical: (N_{Ti} = 2) implies that the failure does not result from transient Ti, that P[fail(T_i)-RPV] is equal to zero. This is a reason why the notion of "conditional" probability P(RPV failure / T_i) is ambiguous, as aforementioned.

Secondly, it results from these statements that:

$$F_{RPV} = P(\text{RPV failure}) \quad \text{(per reactor . year)}$$

$$\text{For unique occurrence transients: } f_{Ti} = E[N_{Ti}] = P(N_{Ti} \geq 1) = P(N_{Ti} = 1) \quad \text{(per reactor . year)} \tag{6}$$

This is due to the fact that they are unique occurrence events, and in this case occurrence frequency and occurrence probability are identical [6].

Moreover, it will be shown that (A_3) also is questionable, that the occurrence of transients may have an impact on the occurrence of other transients, without any functional analysis.

To summarize this analysis, it becomes clear that the assumptions that can guarantee the validity of (Eq. 1) are not relevant for the RPV. Some relevant assumptions have been indicated; they are the basis of further developments towards an alternative formula.

General frame to derive an alternative formula

As RPV failure frequency and probability are identical on one unit period (here: reactor . year), it is proposed to analyze the probability, a more simple concept in probabilistic analyses.

The RPV failure probability, P(RPV failure), can be expressed as follows (with previous notations):

$$F_{RPV} = P(\text{RPV failure}) = P\{\bigcup_{i=1}^{N}[\,fail(T_i)]\,\} \quad \text{(per reactor . year)} \tag{7}$$

As the failure is (at most) unique, one can notice that the events fail(T_i) are disjoint: the failure will result from one transient, and not from the other ones. Therefore, (Eq. 7) yields immediately:

$$F_{RPV} = P(\text{RPV failure}) = \sum_{i=1}^{N} P[\,fail(T_i)] \quad \text{(per reactor . year)} \tag{8}$$

First attempt to derive an alternative formula

To come back to the common interpretation of the elementary term as a product involving a conditional probability, a first idea could be to write (Eq. 8) as follows:

$$F_{RPV} = P(\text{RPV failure}) = \sum_{i=1}^{N} P[\,fail(T_i)\,/\,(N_{T_i} \geq 1)].P(N_{T_i} \geq 1) \quad \text{(per reactor . year)} \tag{9}$$

This new expression is formally exact, because the events fail(T_i) are included in (N_{Ti} ≥ 1). Its interest is to let the occurrence probability of T_i, P(N_{Ti} ≥ 1), appear explicitly; this probability can be evaluated without difficulties from the given knowledge of f_{Ti}. However, the first term of the product does not immediately appear as the RPV failure probability during transient T_i, P[fail(T_i)-RPV]. For both terms to be identical, the RPV state and the occurrence process should be independent, and we have seen previously that this is a doubtful assumption; this issue will be analyzed more precisely in the following paragraphs. Therefore, the elementary term cannot be evaluated in a simple manner, and this is the main drawback of this expression.

Another attempt to derive a new expression is to let the RPV failure probability during transient T_i, P[fail(T_i)-RPV], appear explicitly. This is, once again, formally exact because the events fail(T_i) are included in [fail(T_i)-RPV]. This yields:

$$F_{RPV} = P(\text{RPV failure}) = \sum_{i=1}^{N} P[\,fail(T_i)\,/\,(\,fail(T_i - RPV))].P[\,fail(T_i - RPV)] \quad \text{(per reactor . year)} \tag{10}$$

For this expression to be fruitful, the first part of the elementary term, P[fail(T_i) / (fail(T_i)-RPV)], should be identical to an occurrence probability of transient T_i. By definition, this conditional probability has to be understood as the probability of the following event: "if the RPV state $\underline{Z}$ can produce the RPV failure during any occurrence of T_i, will such an occurrence take place and will the RPV fail because of this occurrence?". As for (Eq. 9), it appears that for P[fail(T_i) / (fail(T_i)-RPV)] to be identical to an occurrence probability of transient T_i, the RPV state and the occurrence process have to be independent, and this is not the fact: a first dependency results from the fact that in this case the occurrence is necessarily unique, and ($N_{Ti} \geq 1$) should be replaced by ($N_{Ti} = 1$). As for (Eq. 9), this expression does not provide a satisfactory evaluation without further analysis.

Potential impact of correlations between structural state and transient occurrences

To underline that it is necessary to take account of the dependency between the structural state and the transients occurrence process, it can be useful to show on simple examples that such dependences may have a significant impact on the RPV failure probability. The correlations that are taken in this example do not result from the analysis of the transient occurrence process, they do not apply to the RPV case; they have been selected only to illustrate this impact. The example is defined as follows:

- 2 transients T_1 and T_2, with disjoint failure domains (fail(T_1)-Structure $\cap$ fail(T_2)- Structure = $\emptyset$)
- the following (complete) correlation is assumed :
  - the notation for sets « fail(T_i)- Structure » is F_i
  - $F_1 \Rightarrow T_1$ occurs, (which requires that $P(D_1) \leq P_{occ}(T_1)$)
  - $F_2 \Rightarrow T_2$ occurs (which requires that $P(D_2) \leq P_{occ}(T_2)$)

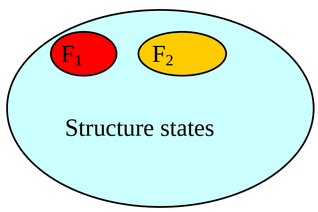

Fig. 1 – Representation of failure sets

Then under these (illustrative) assumptions, it can be seen easily that :

$$F_{Structure} = P(\text{Structure failure}) = P(F_1) + P(F_2) >> P(F_1).P_{occ}(T_1) + P(F_2).P_{occ}(T_2) \quad \text{(per reactor . year)} \qquad (11)$$

The latter part of (Eq. 11) would be the result provided under the assumption of independence; in this case of correlation this result would be a highly non conservative approximation of the real Structure failure probability. As the impact of such dependences may be high, it is therefore necessary to analyze the correlations that can be observed in the reality.

Analysis of dependences between RPV state and transients occurrence process

Let us analyse firstly the consequences of transients occurrences on the knowledge of the RPV state $\underline{Z}$.

If one knows that, at a given instant, some transients already occurred, it means that the RPV resisted to these transients. Therefore it is possible to exclude from the the a priori possible RPV states, those that would have led to the RPV failure. Consequently, for the evaluation of the basic term P(fail(T_i)) of (Eq.8), two disjoint cases may happen:

- No transient has occurred before T_i: then no particular information is available on the RPV state;
- Other transients occurred before T_i: then the corresponding RPV states have to be excluded.

This situation can be illustrated on Figure 2:

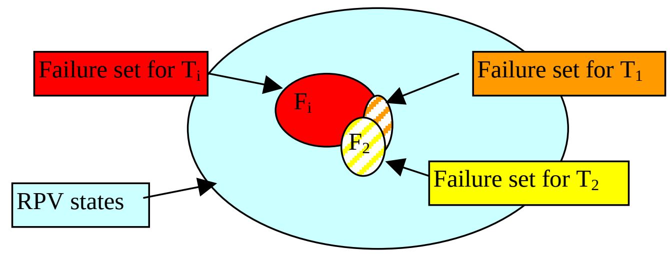

Figure 2 – Representation of impossible RPV states

In the case illustrated on Figure 2, it can be seen that if T_1 and T_2 occur before T_i, (F_1 U F_2) has to be excluded from the a priori possible RPV states.

Conversely, it is possible to identify the consequences of the RPV state $\underline{Z}$ on the of transients occurrences.

For a given RPV state $\underline{Z}_0$, two cases can be identified:

- If no transient can cause RPV failure for $\underline{Z}_0$, then the transients occurrence process is not impacted by the RPV state;
- If some transients may cause an RPV failure for $\underline{Z}_0$, then the 1^{st} occurrence of one of these transients will prevent any further transient occurrence since it will cause an RPV failure; for such transients the occurrence frequency or probability becomes simply 0. Note that this case has to be really pointed out: in such a situation (fortunately never observed), one can say approximately that the most frequent faulty transient for $\underline{Z}_0$ would in general prevent the occurrences of all other faulty transients, or that the less severe faulty transient for $\underline{Z}_0$ would in general prevent the occurrences of all other faulty transients; however these statements are only approximations, since one cannot exclude that other transients than the most frequent one may happen prior to it, and since there is no absolute link between frequency and severity of the transients.

Perspectives

The above considerations are essential to progress towards an alternative evaluation taking advantage of the realistic description of the RPV case, and more precisely of the complex correlations between transient occurrences and RPV states. Some particular assumptions can be used (e.g. unique occurrence transients), and they may simplify significantly the development of an alternative formula. This alternative evaluation is currently under progress; it will have to yield conservative results. This conservatism should be evaluated by comparing simulation results to the theoretical assessment. Moreover, it will be probably necessary to adapt these evaluations to the case where the thermohydraulic variability of transient profiles is considered.

SUGGESTIONS TOWARDS A RISK EVALUATION FOR MULTIPLE TRANSIENTS AND FLAWS

This paper concentrates on the cumulative risk due to transients; however, the evaluation of the overall risk requires to treat also the case of multiple flaws. A corresponding treatment was initiated in [6], providing a complete treatment under the common assumption of the independence of crack failures. However, it was also established in [6] that this assumption is questionable, and an attempt was performed to identify some conditions for which this independence assumption could provide at least conservative results; but these conditions ("positive correlation") proved to be difficult to ensure.

Separate evaluations have been performed for each population of cracks: the detected cracks (with known number and characteristics) and the non detectable cracks, with random characteristics. These two evaluations – that could be aggregated easily – have already been presented and are recalled below:

For detected flaws [6, 8 with a type mistake] :

$$F_{RPV} = P(\text{RPV failure}) = 1 - \prod_{i=1}^{N_{\text{detected cracks}}} \left(1 - P\,(a_i)\right) \quad \text{(per reactor . year)} \tag{12}$$

Where $P(a_i)$ stands for the individual crack failure probability of crack n°i. Note that this term is supposed to reflect the failure probability discussed in the previous paragraph, taking account of both the RPV state vectors $\underline{Z}_i$ at each flaw level, and the transients occurrences.

For non detectable flaws [6]:

$$F_{RPV} = P(\text{RPV failure}) = 1 - e^{-E(N_{non\,detectable\,cracks})\cdot \overline{P}a} \quad \text{(per reactor . year)} \qquad (13)$$

Where $\overline{P(a)}$ stands for the mean failure probability of a non detectable crack; its evaluation is presented in more details in [6], taking account of the random characteristics of the non detectable crack population.

However, these formulas assume that an appropriate evaluation of the individual crack failure probability $P(a_i)$, combining the multiple transient contributions, is available; although it is not provided in this paper, the basic concepts for issuing it have been presented in the previous paragraph.

Moreover, they rely on the crack failure independence assumption and should be replaced by one generalizing the considerations developed for one crack submitted to multiple transients, following the assumptions relevant for the RPV case.

CONCLUSIONS

This paper has dealt with the residual risk of fast fracture damage potentially affecting Reactor Pressure Vessels (RPVs) of PWRs. This risk is supposed to result from manufacturing cracks initiation, endeavoured by cumulative neutron irradiation and occurrences of Pressurized Thermal Shocks (PTS). The basic evaluations of this risk of failure concentrate on the calculation of crack initiation probabilities for one given crack and one given transient.

However, the overall risk arises from multiple cracks and transients. A general widespread formula is available to perform this cumulative evaluation. This paper has focused on the cumulative risk due to transients, and has shown that the hidden assumptions required by the general formula are not valid. This result is based on a detailed analysis of the relationship between the RPV state and the transients occurrences process, both aspects that are commonly supposed to be independent. These considerations are essential to progress towards an alternative evaluation taking advantage of the realistic description of the RPV case, and more precisely of the complex correlations between transient occurrences and RPV states. Some particular assumptions can be used (e.g. unique occurrence transients), and they may simplify significantly the development of an alternative formula. This alternative evaluation is currently under progress; it will have to yield conservative results. This conservatism should be evaluated by comparing simulation results to the theoretical assessment. Moreover, it will be probably necessary to adapt these evaluations to the case where the thermohydraulic variability of transient profiles is considered.

Then some suggestions to issue an alternative evaluation have been given, and possible methods to perform the overall cumulative evaluation, including multiple cracks, have been proposed. However, these methods rely on the crack failure independence assumption and should be replaced by one generalizing the considerations developed for one crack submitted to multiple transients, following the assumptions relevant for the RPV case.

NOMENCLATURE

$1_A(X)$ = indicator function of set A; equal to 1 if $X \in A$, otherwise equal to 0
a = crack height
E(X) = mathematical expectation of the random variable X = the mean value of X
F_{occ} = occurrence frequency; the occurrence frequency of T_i over one unit period equals $E(N_{Ti})$ and is noted f_{Ti}
K_{1c} = fracture toughness
K_{cp} = stress intensity factor, including plastic correction
N = number of transients
N_{Ti} = number of occurrences of transient T_i during a given period (one operating cycle)
PFM = Probabilistic Fracture Mechanics
PSA = Probabilistic Safety Assessment
PTS = Pressurized Thermal Shock
P(A) = Probability of event (set) A
$\overline{P}_a$ = Probability of failure of a non detectable crack
$P(a_i)$ = Probability of crack failure (initiation) of crack n°i
RPV = Reactor Pressure Vessel
RT_{NDT} = nil ductility transition temperature
T_i = transient n°i
$\underline{Z}$ = RPV state vector (coordinates = all the random variables involved in the PFM model for brittle fracture due to cleavage initiation)

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