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Application of the EDF/FRAMATOME industrial variation of the BEREMIN model to APAL transients

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ABSTRACT

This paper presents a parametric application of an industrial variation of the BEREMIN criterion for brittle fracture risk evalution. The selected configuration for that application was provided by the APAL European project.
After a short description of the proposed criterion, the numerical application is presented and discussed. It is shown that the criterion provides an important benefit regarding the RPV justification. Additionally, it is shown that the transient classification or definition for the assessment is not modifed by the criterion: worst loading situations remain the ones corresponding to the severest thermal transients.

ACRONYMS

CT	Compact Tension specimen
FEM	Finite Element Modelling
FMA	Fracture Mechanics Assessment
LOCA	Loss Of Coolant Accident
PTS	Pressurized Thermal Shock
PWR	Pressurized Water Reactor
RPV	Reactor Pressure Vessel
SIF	stress Intensity Factor
WPS	Warm Pre-Stressing

INTRODUCTION

A huge work is actually going on in France regarding Long Term Operation (LTO) of historical PWRs. For the Reactor Pressure Vessel (RPV), which is part of the core of those LTO developments, a strong effort is being done for developing less severe Fracture Mechanics Assessment (FMA) criteria than the actual deterministic criterion based on the global approach (toughness curve indexed by RT_{NDT} reference temperature associated to the K_J loading parameter calculation). Within this framework, a common EDF/FRAMATOME effort is going-on for developing an industrial variation of the BEREMIN model.

In parallel to this French work, a significant international effort was performed within the APAL European project for developing/supporting the probabilistic assessment of the RPV. One of the main issues emerging for the APAL results concerns the transient classification, which appears to be strongly depending on the criteria assumptions (that is including the WPS – or not [1]). This constitutes a difficulty, particularly for thermo-hydraulics which aims at defining the most severe loading conditions for the FMA.
Based on those observations, it was decided to evaluate the impact of the industrial variation of the BEREMIN model on the transient classification, compared to the classical conventional criterion, with or

without WPS consideration. For that purpose, a few relevant transients were selected and transmitted by the APAL project to the French team for assessment through the industrial BEREMIN model.

Before providing the results of this industrial BEREMIN application, the first part of the paper describes shortly the main bases of the criterion.
In a second part, the data under consideration (RPV and defect geometry, material data, transient consideration) as well as the specific model developed for APAL applications are presented: The BEREMIN model being of local approach type, such a model is heavy, and must follow specific recommendations which are shortly described.
In a third and final part, the obtained results are presented and discussed.

SHORT DESCRIPTION OF THE INDUSTRIAL VARIATION OF THE BEREMIN MODEL

Weibull stress definition

This section provides a short description of the so-called industrial variation of the BEREMIN model. More detailed information is provided in [2].
It is widely recognised that brittle fracture mechanism is activated by plastic strain then governed by the largest principal stress. For reactor pressure vessel low alloy steel, and in presence of a crack like defect, the failure begins at particles, inclusions or brittle areas of various sizes, distributed at random in the material. Thus, in addition to the stress level induced by the imposed loading, the volume submitted to a large tensile stress is also of significance: the greater the volume in which cleavage can occur, the greater the probability of failure.
Based on those observations, the BEREMIN model [3] provides an expression of the probability of cleavage integrated in the process region, the plastic zone in a first approximation, where the cleavage could occur at a microstructural singularity. In the original formulation of the criterion, for a monotonically increasing loading, the failure probability at the tip of a loaded crack takes the following form:

$$Pr = 1 - exp\left\{-\int_{V_p}\left(\frac{\sigma_1}{\sigma_u}\right)^m.\frac{dV}{V_0}\right\}$$

In the following, we consider a formulation with a threshold stress. By introducing the so-called Weibull stress (σ_W), the failure probability becomes:

$$Pr = 1 - exp\left\{-\left(\frac{\sigma_W}{\sigma_u}\right)^m\right\}, \quad with: \sigma_W = \left[\int_{V_p}(\sigma_1 - \sigma_{th})^m.\frac{dV}{V_0}\right]^{\frac{1}{m}}$$

This Weibull stress constitutes the pertinent loading parameter for quantifying the fracture risk in the brittle fracture domain.
McMeeking and Parks [4] have shown further that in Small Scale Yielding (SSY) conditions, the stress field at the crack tip is homothetic relatively to the parameter $r.\sigma_y/J$ (r being the distance to the crack tip and σ_y the material yield stress), provided that the stress triaxiality is fixed. Thus, it can be shown that the Weibull stress can be separated in two dimensions:

- In the plan perpendicular to the crack front. In SSY conditions, this dimension is directly linked to the loading parameter J or K_J.
- Along the crack front, this dimension being directly linked to the specimen thickness B.

$$\sigma_W = \sigma_y.\left[\frac{B}{V_0}.\left(\frac{J}{\sigma_y}\right)^2.\Omega_{th}\right]^{\frac{1}{m}},$$

Where Ω_{th} is a dimensionless function which depends on the stress ratio σ_{th}/σ_y and the stress triaxiality. This formulation is consistent with the crack length correction considered in the Master-Curve

formulation [5]: for the same probability of failure (i.e., the same Weibull stress), the specimen thickness B acts as J^2 or K_J^4.

The Weibull stress density

If the specimen thickness dependence of the Weibull stress was largely verified through testing over different specimen thicknesses, it remains an approximation which is valid for small specimen, but potentially excessive for large ones. This point was highlighted by Rathbun *et al.* in [8] through an extensive test series on specimen of different sizes: the authors showed, at the T_0 reference temperature of the material, a saturation of the length correction for B~130 mm. Considering that the number of possible weak links increases with decreasing temperature, this saturation might depend on the temperature within the brittle to ductile transition.

Another important point regarding the industrial framework is that the ferritic components under consideration are very large and thick, whereas postulated defects for evaluating the defect tolerance are on inner surface (or close to the surface) semi-elliptical cracks. For such defects, the local loading (J or K_J) and the stress field vary significantly along the crack front. Consequently, the summation along the crack front cannot be a simple product with the crack front length. In such a case, the Weibull stress should be written as:

$$\sigma_W = \sigma_y . \left\{ \int_L \left[\frac{J(z)}{\sigma_y} \right]^2 . \Omega_{th}(z) . \frac{dz}{V_0} \right\}^{\frac{1}{m}},$$

where z represents the abscissa along the crack front and L the total length (with L = B for a CT specimen). The important point to notice is that, in the general case, the stress triaxiality is also varying significantly along the crack front, this last parameter affecting the dimensionless sum Ω_{th}. Introducing a 2D Weibull stress density corresponding to the integration in the plan perpendicular to the crack front, it comes that:

$$\sigma_W{}^m = \int_L \sigma_{W-2D}(z)^m . dz\,, \qquad \text{with: } \sigma_W^{2D}(z)^m = \sigma_y{}^m . \left[\frac{J(z)}{\sigma_y} \right]^2 . \frac{\Omega_{th}(z)}{V_0}$$

This so-called 2D Weibull stress density is fully consistent with the Weibull stress density $\tilde{\sigma}_W$ introduced by Gao and Dodds in [6], or the Ψ function proposed by Gao *et al.* in [7]:

As mentioned by Gao *et al.* in [7], this 2D Weibull stress density or Weibull stress density might vary significantly along the crack front because of constraint loss. Moreover, the paper [7] illustrates the good correlation between the maximum of the Ψ function along the crack front and the actual cleavage initiation spot, thus illustrating the relevance of the proposed local Weibull stress.

Criterion proposition

The important point to mentionned here is that, in the French regulatory framework, the brittle fracture risk must be deterministically excluded. For that purpose, in the conventional approach, the local loading parameter is compared to an envelope toughness curve defined as a function of the temperature. The criterion is simply:

$$K_J(t) < K_{JC}(T)$$

In this formulation, $K_J(t)$ represents the maximum K_J along the crack front of the postulated defect within the industrial configuration, at the time t of the loading, and $K_{JC}(T)$ represents the material toughness curve. The envelope nature of the toughness curve relies on a large dataset of laboratory specimen testing.

The main gaps of this criterion are that it does not consider the material yield stress evolution with temperature nor the stress triaxiality at the crack tip: the toughness curve is associated to isothermal fracture tests on CT specimen (highly constraint specimen).

For overcoming these main gaps, the proposition made here is to rely on the Weibull stress density, which was shown to be the pertinent loading parameter of the BEREMIN model for quantifying the brittle fracture risk. For that purpose, the principle of the proposition is to compare the Weibull stress density σ_w^{2D} vs. K_J evolutions of the industrial configuration to the one of the reference CT specimens (see fig. 1). Based on that comparison, an equivalent $K_{J\text{-}CT}$ (the K_J on reference CT specimen providing the same σ_W^{2D}) can be proposed, this $K_{J\text{-}CT}$ being directly comparable to the material envelop toughness curve.

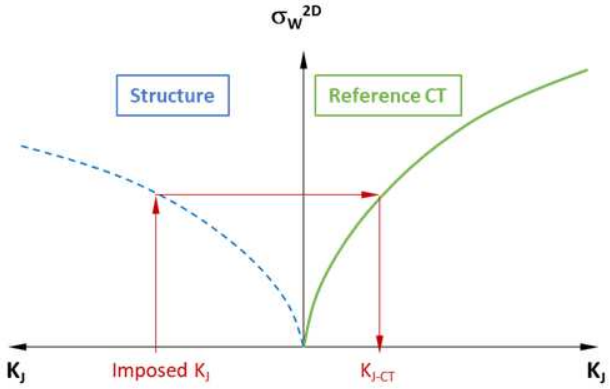

Figure 1: Definition of the $K_{J\text{-}CT}$ parameter

Regarding the regulatory deterministic requirement, it has to be postulated that the weakest link is located at the maximum loaded point of the crack front. Therefore, this comparison should be made at the maximum loaded point of the crack front.
Additionally, since the temperature may vary significantly through the thickness for PTS situation, the parameter $K_{J\text{-}CT}$ must be determined all along the crack front, as a function of the temperature. Such approach is consistent with the philosophy of the conventional global approach which considers the $K_J(T)$ along the crack front to the material toughness curve.

At this step, it is important to mention that, due to the variation of the stress triaxiality along the crack front, the maximum loaded point in terms of σ_W^{2D} or $K_{J\text{-}CT}$ does not correspond systematically to the maximum loaded point in terms of J. Again, the relevance of the choice of the Weibull stress density for quantifying the risk of cleavage fracture is supported by the adequacy between the maximum of this function along the crack front and the actual cleavage initiation spots (from [7], [8] and in-house complementary analyses).
The main advantage of such approach is that it relies on a pertinent parameter for evaluating the brittle fracture risk: the Weibull stress density. By comparing the industrial configuration to the reference CT specimen, it allows to remain at the deterministic level required by the regulation.
At the opposite, the main disadvantage is that it requires a refined modelling since, in a general case, the triaxiality can vary significantly along the crack front and the $\Omega_{th}(z)$ function is not explicitly known in any case. The Weibull stress density is then to be determined through a direct numerical integration in planes perpendicular to the crack front.

APAL TRANSIENT DATA UNDER CONSIDERATION

Geometrical and material data

The geometrical configuration under consideration corresponds to a RPV cladded cylindrical shell of a KONVOI plant. It is defined by an inner diameter Φ_i = 4870 mm, a base metal thickness t = 243 mm and a cladding thickness r = 6 mm.

The physical and mechanical data characterizing the base metal low allow steel and the cladding austenitic stainless steel are provided in table 1 as a function of the temperature.

The BEREMIN model relying on an elastic-plastic Finite Element Modelling (FEM), those data are completed by simplified stress-strain curves. Those curves are assumed bi-linear, with an hardening modulus H = 17.1 GPa for the low alloy steel and 24.4 GPa for the austenitic stainless steel.
Finally, the postulated defect for the FMA is a through-clad inner surface semi-elliptical defect defined by its depth in the base metal a = 10 mm and a total length 2.c = 60 mm.
For margin evaluations, the considered RT_{NDT} is 75°C.

T (°C)	*Low alloy steel base metal*					*Stainless steel cladding*				
	E (GPa)	K (W/m/K)	Cp (J/kg/K)	α (°C^{-1})	σ_y (MPa)	E (GPa)	K (W/m/K)	Cp (J/kg/K)	α (°C^{-1})	σ_y (MPa)
20	206	44.4	450	10.3E-6	450	200	16	500	15E-6	320
100	199	44.4	490	11.1E-6	431	194	16	500	16E-6	320
200	190	43.2	520	12.1E-6	412	186	17	540	17E-6	320
300	181	41.8	560	12.9E-6	392	179	17	540	19E-6	320
350	172	39.4	610	13.5E-6		172	18	590	21E-6	320

Table 1: Material data (assuming ρ = 7800 kg/m^3)

Thermal transient data
Transients under consideration are different variations of a LOCA-50 cm² PTS event. Three of those transients were selected within a set of 59 transients generated by the RELAP5 software in APAL project. They were selected based on their impact on the fracture mechanics criterion:

- TR1 is the severest transient with the standard global approach criterion (without considering WPS benefit).
- TR2 is the severest transient considering the WPS benefit.
- TR3 is a variation of the TR1 transient with slightly different parameters.

The figure 2 gives a representation of the thermo-mechanical answer of TR1 and TR2 transients in the K_J vs. T space together with the complete set of transient evolutions. As illustrated by this figure, TR1 and TR2 are significantly deferent in shape with an important unloading-reloading phase for TR2.

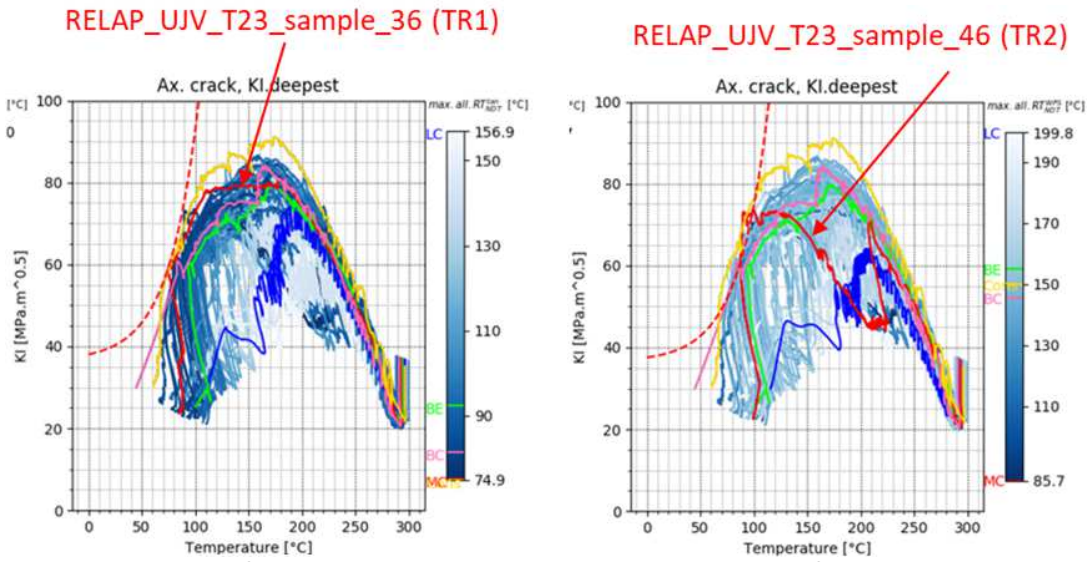

Figure 2: Illustration of two selected transients within the complete set of data generated by APAL

The data provided by the APAL project are detailed description of the internal pressure, the fluid inner surface temperature and the heat exchange coefficient (one point ~5s of the transient). For simplification purpose (and modelling time consideration), those data were simplified by only considering a limited number of characteristic points in time. An example of such simplification is provided in figure 3 for TR2, where the orange curve represents the complete evolutions and the black point the selected points.

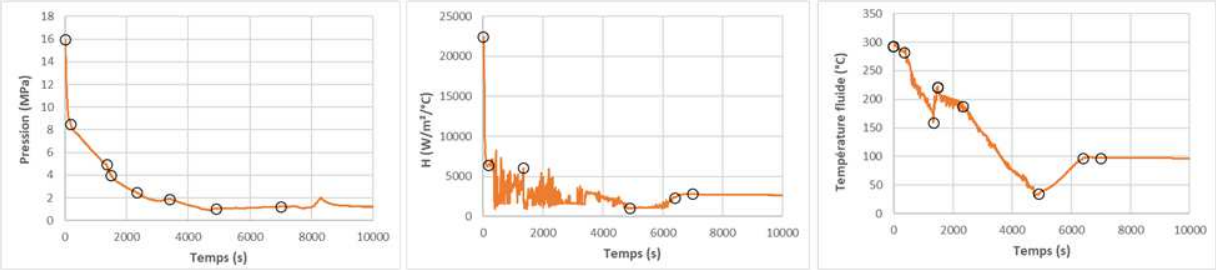

Figure 3: Simplification of the thermal transient loading data (example for TR2)

Due to that simplification, the thermo-mechanical responses calculated here are not strictly identical to the responses calculated by the APAL partners (which are based on 2D elastic crack free modelling completed by SIF compendia applications).

RESULTS AND DISCUSSION

Model description

The BEREMIN model relying on a direct FEM of the stresses and strains at the crack tip, it requires a full 3D elastic-plastic model. Regarding the 2D variation of the criterion proposed here for industrial applications, this implies the following:

- The main principle of the criterion is to compare the Weibull stress density between the structural configuration and the reference CT specimen (see fig. 1). For such comparison, the two models are obviously to be strictly equivalent:
    - In terms of material behaviour,
    - BEREMIN fracture parameters (m and σ_{th}),
    - Meshing perpendicular the crack front (particularly element shape and size),
    - Modelling and post-processing options (large strains or not, integration at the crack tip),
- The BEREMIN characteristic distance being of the order of 50 µm, this implies developing a specific mesh with integration plans distributed all along the crack front (see fig. 4):
    - The mesh size within those planes being the same than for the reference CT specimen,
    - The most loaded point being not known *a priori*, the planes must be defined all along the crack front.

In the following, the results are obtained based on the following modelling options:

- BEREMIN parameters m = 3 and σ_{th} = 1300 MPa,
- Square shape elements in integration planes perpendicular to the crack tip of 50 µm² size,
- Small strain and displacement modelling option.

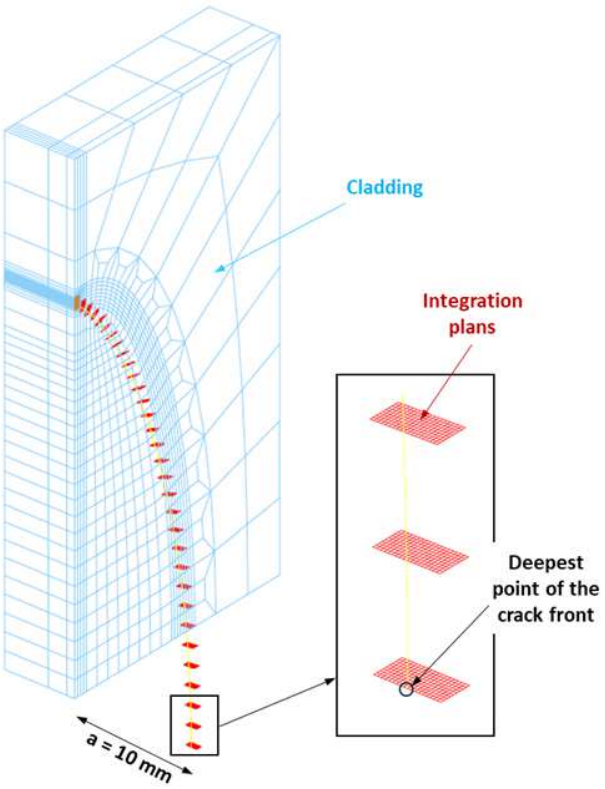

Figure 4: Mesh definition along the investigated through-clad inner surface crack front (the cladding is represented here in blue)

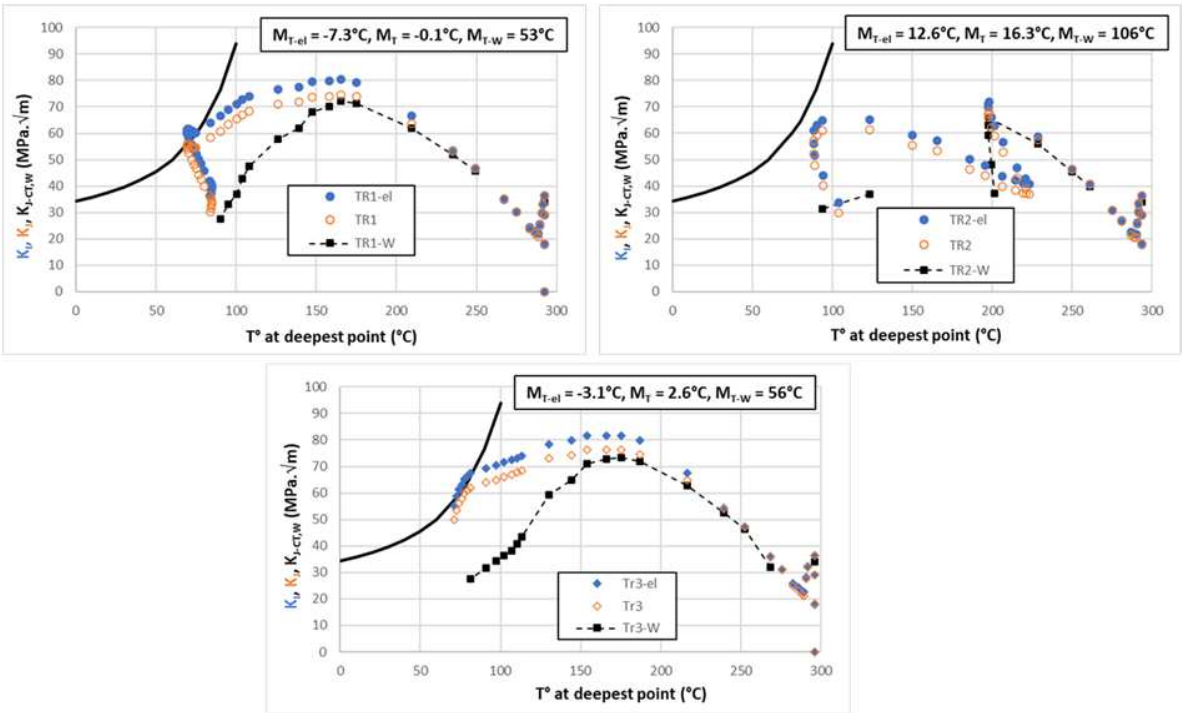

Figure 5: Application of the criteria for the 3 selected transients

Main modelling results

Two modelling were done for each transient for comparison purpose:

- A purely elastic model providing a K_I solution. This modelling is directly comparable to the APAL partners results,
- An elastic-plastic modelling providing an elastic-plastic K_J solution and stress evolutions for the Weibull stress density determination (and thus $K_{J\text{-}CT}$).

Those results are compared to the material toughness curve in figure 5 for the 3 transients. The comparison is done here for the deepest point of the crack front which is the most loaded point for both the global and local criteria. The margin M_T indicated in the legend of those figures corresponds to the minimum horizontal distance between the material toughness curve and the loading curve (a negative value indicating that the transient does not satisfy the regulatory criterion).

The comparison of those results shows that:

- Elastic and elastic-plastic modelling are providing similar results, K_J parameter being slightly lower than K_I. This result is normal for a through clad defect and associated to the fact that, for a thermal transient leading to through thickness thermal strains, stresses are partially of secondary nature and relaxed by plasticity.
- The solution provided by the industrial variation of the BEREMIN model is significantly lower (and thus the margins much larger). This can be explained by two factors:
    - In the increasing phase of the transient, the difference between K_J and $K_{J\text{-}CT}$ is moderate and associated to the lower constraint of the through-clad defect compared to the CT specimen.
    - In the decreasing phase, $K_{J\text{-}CT}$ reduction is strongly higher than the one of K_J. This can be associated to the fact that, during this unloading phase, the stresses at the crack tip are decreasing following an elastic behaviour. The Weibull stress density (and the brittle fracture risk) strongly depending on the stress level, the margin is enhanced in this unloading phase. The global approach cannot capture such reduction.
- TR1 and TR3 are very similar in shape. Those transients which are dominating in terms of thermal shock remain dominant with the proposed variation of the BEREMIN criterion.
- TR2 with a less severe thermal shock provides a larger M_T. Additionally, it can be noted that the second loading phase of this transient is not significant regarding the brittle fracture risk, which is not the case for the global approach criterion.
- For each transient, the main gain provided by the proposed criterion appears during the decreasing part of the loading.

The figure 6 gives another representation of the results confirming the previous interpretations. On this graph, $K_{J\text{-}CT}$ is expressed as a function of the SIF K_I at the deepest point of the crack tip, showing that:

- At the beginning of the transient, the two parameters are proportionnal,
- Then, $K_{J\text{-}CT}$ decreasses compared to K_I (starting arround 60 MPa.$\sqrt{m}$). This is due to the plasticity at the crack tip and the associated loss of constraint,
- As observed on figure 5, during the unloading phase, $K_{J\text{-}CT}$ reduction is sharper than K_I redution.

But the important point to mention on this representation is that the 3 transients are equivalent in shape, which means that the benefit procured by the industrial BEREMIN criterion is linked to the defect geometry (constraint effect) and material behavior (plasticity) and not the thermal transient shape.

Another important point regarding the transient classification is that the minimum margin is observed at the top of the first loading phase. This means that the worst loading situations remains the ones with the severest thermal shock as it is usually postulated in the FMA. This means that the transitient definition for assessment is not affected by the criterion.

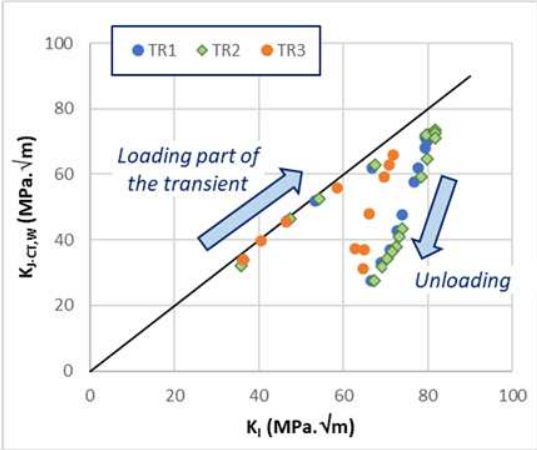

Figure 6: K_J vs. $K_{J\text{-}CT}$ evolutions for the 3 transients

SYNTHESIS AND CONCLUSION

This paper deals with a parametric application of the industrial BEREMIN model variation to a set of thermo-mechanical transients provided by the European APAL project. The selected configuration for this application, also provided by APAL, is the one of a cladded cyclindrical vessel with a through clad defect of 10 mm depth in the low alloy steel base metal.

After a short presentation of the industrial criterion, the paper presents the detail of the investigated configuration then the numerical results.
The first important of those results is that the proposed industrial BEREMIN variation provides, for the three investigated transients, a significant benefit in terms of margin. The margin in terms of allowable RT_{NDT} increasses by 50°C at minimum for the 3 transients. For the loading configurations investigated here, this gain mainly appears during the unloading phase of the transient where a sharpe reduction of the loading parameter $K_{J\text{-}CT}$ (reduction associated to the elastic unloading of the stresses at the crack tip).

The second one, relative to the thermal transient classification, is that the formulated criterion is in line with a standard FMA which considers that the severest loading situations are corresponding to the severest thermal shocks without considering the WPS effect. The criterion relying on the stress-field at the crack tip, it appears quasi-equivalent to a conventional elastic analysis relying on the SIF K_I or K_J. The consequence is that it does not affect the transient ranking, which is not the case when including WPS considerations.
Finally, regarding safety and the regulatory context, the important points are that the proposed criterion reflects the stress field evolution at the crack tip (and consequently the brittle fracture risk which is directly linked to the stress level) within the deterministic frame requested by the regulation.

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