



Application of LBB concept to LMFR components

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ABSTRACT

The present approach dealing with Leak Before Break (LBB) concept for French Liquid Metal Fast Reactor (LMFR) components is described. This approach tends to improve the defense in depth : it is first verified that the growth of a reference defect is limited and leads to an end-of-life defect which is not through-wall ; then assuming that the defect becomes through-wall for an hypothetical reason, the impossibility of a complete rupture of the component before the leak detection is checked.

INTRODUCTION

The LBB concept was not used at the design level of French LMFR (PHENIX, SUPERPHENIX), but in recent years different studies were performed in order to improve the defense in depth. In the case of the Main Vessel, the LBB approach is used first to verify the absence of risk as regards the core supporting function and then to help the definition of in-service inspection (ISI) program. Application to sodium pipings should prove the impossibility of a guillotine rupture.

This paper presents the different steps of the methodology used for French LMFR sodium or gas components for which creep may be significant or not. The background is issued from European works of DCRC [1] and complementary tasks of the French Comité Tripartite [2].

LBB APPROACH FOR FRENCH LMFR COMPONENTS

The general LBB approach applied to French LMFR components can be summarized in the flow-chart drawn below (figure 1). The different defect dimensions which arise in the LBB procedure are shown in figure 2.

It can be seen that two separate analysis sets are performed :

- * In the one hand, the verification that the end-of-life defect is neither critical nor through-wall (integrity).

* In the other hand, the verification that the detection of the through-wall defect occurs before the component rupture (leak detection).

Figure 1
LBB methodology

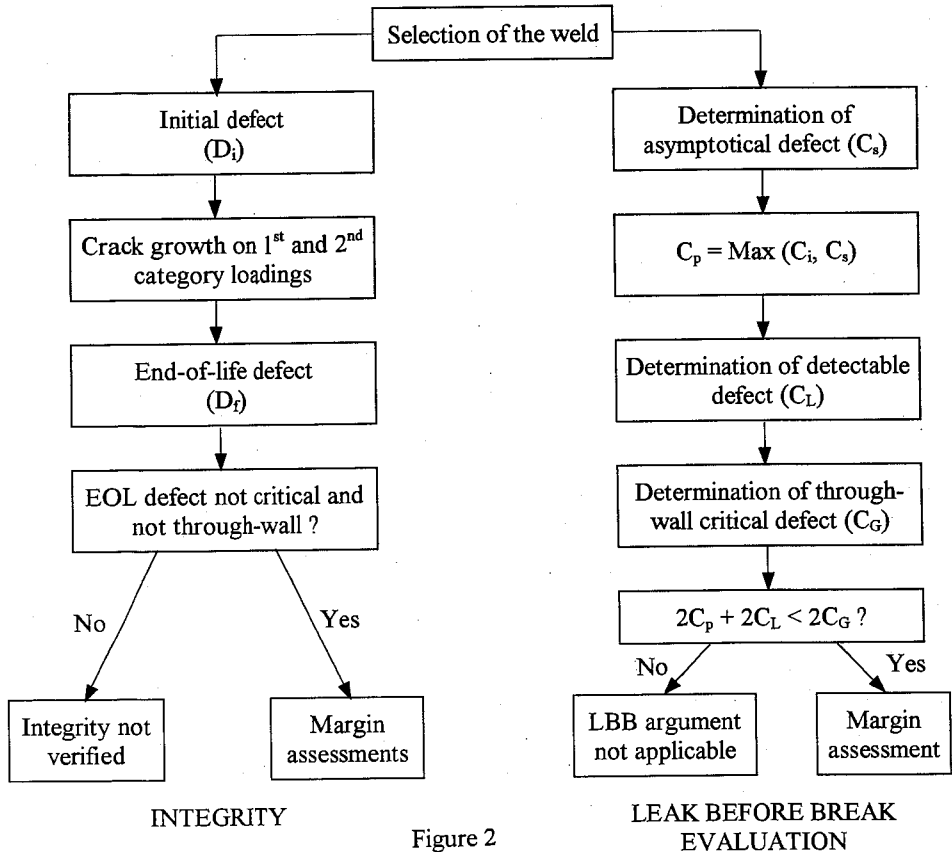
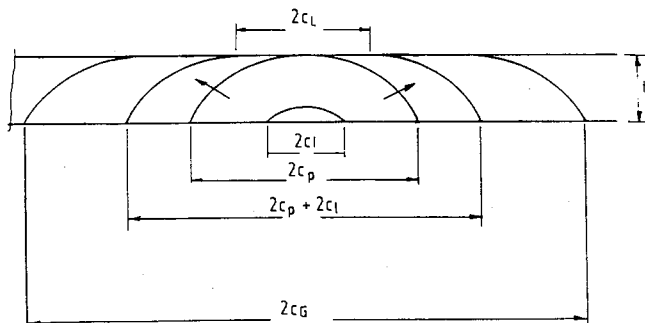


Figure 2
Crack dimensions



Each step of the methodology is detailed below.

INTEGRITY

Selection of the initial defect

The initial defect is always located in weld junctions where a manufacturing defect is the most likely. It is a semi-elliptical defect considered as envelope of all possible defects. It corresponds in general to an electrode deposit, which is very pessimistic when compared to ISI results. The welds selected are those where stresses or stress ranges under level A loadings and stresses under level C and level D loadings are maximum.

Crack growth

An assessment of the crack growth (in depth and in length) is performed considering mechanical and thermal transient loadings belonging to 1st and 2nd category situations. Following, the methodology of A16 document [2], it is assumed that crack growth can be obtained adding the part due to fatigue and the part due to creep without interaction :

$$\delta a = \delta a_f + \delta a_c$$

$$\delta c = \delta c_f + \delta c_c$$

For the fatigue propagation, the PARIS law is used :

$$\frac{da_f}{dN} = C (\Delta K)^n$$

$$\frac{da_f}{dN} : \text{propagation rate (m/cycle)}$$

ΔK : stress intensity factor range (MPa \sqrt{m})

Concerning the creep propagation, for which European R and D is still in progress, the rate is given by a correlation $\left(\frac{da_c}{dt} - C^* \right)$ proposed in reference [3] and which envelopes all tests performed on austenitic steel specimen in France, Great-Britain and Germany :

$$\frac{da_c}{dt} = A (C^*)^q$$

$$\frac{da_c}{dt} : \text{propagation rate (m/h)}$$

C^* : characteristic parameter of fracture mechanics for a flaw submitted to significant creep (MPa.m/h)

C^* is calculated using the simplified method of the so-called R5 rule of CEBG [4] which expresses C^* as :

$$C^* = \sigma_{\text{ref}} \varepsilon_{\text{ref}} \left(\frac{K_I}{\sigma_{\text{ref}}} \right)^2$$

σ_{ref} : reference stress on the remaining ligament

$\dot{\epsilon}_{ref}$: creep strain rate under σ_{ref}

K_I : stress intensity factor (mode I)

For creep-fatigue propagation of semi elliptical surface defects, residual stresses due to welding are generally taken into account as secondary bending stresses whose maximum value is equal to the yield stress $R_{0,002}$ at the operating temperature. The residual stresses are relaxed during the hold time.

Stability analysis of the end-of-life defect

The stability of the end-of-life (surface) defect is assessed using the R6 rule of CEGB based on the (K_R, L_R) diagram [5] :

$$L_R = \frac{C}{C_L} ; K_R = \frac{K}{K_{IC}}$$

C_L : limit load

K_{IC} : toughness ($\text{MPa} \sqrt{\text{m}}$)

For the calculation of L_R , only primary stresses are considered (mechanical loading). In the evaluation of K_R , primary and secondary stresses (with residual stresses) are taken into account :

$$K_R = K_R^P + K_R^S$$

K_R^S is calculated following [6].

Margin assessments for integrity analyses

The complete integrity study needs the evaluation of three margin types with regard to critical or through-wall defect :

$$M_1 = \frac{\text{critical depth}}{\text{end - of - life depth}}$$

M_2 = number of cycles needed to make the defect through-wall/number of design cycles

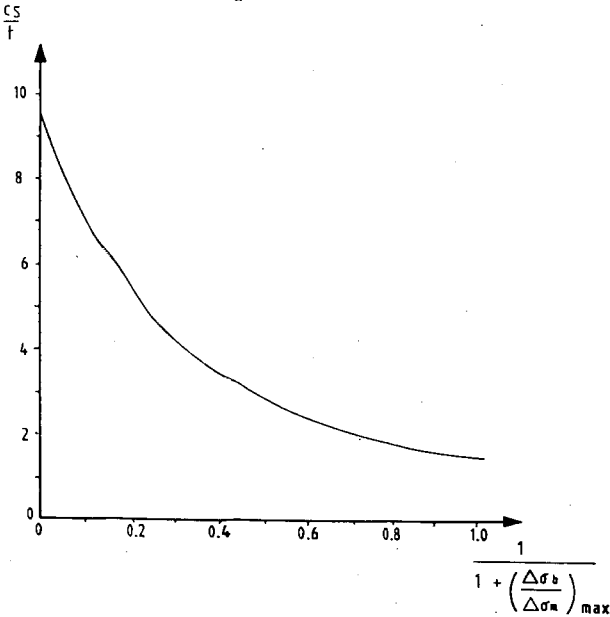
M_3 = loading intensity to obtain a through-wall defect/intensity of design loading (with the same number of cycles)

One must check that these three coefficients are greater than 1.

LEAK BEFORE BREAK EVALUATION

Determination of asymptotical defect (C_S)

The length of the defect when it becomes through-wall depends on the ratio of length propagation upon depth propagation. A master curve deduced from a lot a propagation calculations on plates allows the C_S value to be determined conservatively (figure 3).



For a loading where fatigue predominates, a stress range with a bending component largely greater than membrane component leads to a long through-wall defect, whereas the latter is shorter when membrane stress range is dominant.

Figure 3
Master curve for C_S assessment

When creep propagation is clearly higher than fatigue growth, $\frac{\Delta\sigma_b}{\Delta\sigma_m}$ ratio should be replaced by $\frac{\sigma_b}{\sigma_m}$ (values during hold time). This is an interim procedure which has to be better justified.

Determination of C_p

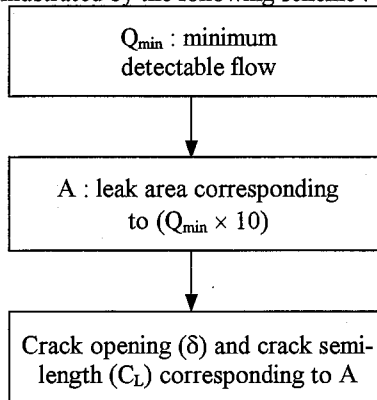
It can occur that the asymptotical length (C_S) is smaller than the initial one (C_i). Then, the LBB criterion has to be applied considering :

$$C_p = \text{Max} (C_i, C_S)$$

Determination of detectable defect (C_L)

The detectable defect size depends on the sensitivity of the detection device. This specific point is not treated in this paper.

It is admitted that a leak (sodium or gas) is surely detected if the leak flow is 10 times higher than the minimum value detectable by the detection device. Then, starting from this value, the determination of C_L , can be illustrated by the following scheme :



The relation between Q_{\min} and A depends on the differential pressure Δp on each side of the component wall :

$$Q_{\min} = \left(\frac{2\Delta p}{\rho \xi} \right)^{1/2} \times A$$

ξ : hydraulic loss coefficient

ρ : fluid density

The relation between δ , C_L and A assumes that the opening area is elliptical, which is rather accurately verified by finite element calculations and experimental tests :

$$A = \frac{\Pi}{2} \cdot C_L \cdot \delta$$

The crack opening δ is related to the crack length C_L . A simple but often pessimistic formula [7] can be used separating the stress normal to the defect plane in membrane and bending components (σ_m , σ_b) :

$$\delta = \frac{4C_L}{E} (\sigma_m - 0.37 \sigma_b)$$

E : Young's modulus

Finite element calculations allow to obtain more realistic δ values for long defects [8].

Determination of through-wall critical defect (C_G)

The loading considered is a combination of Safe Shutdown Earthquake (SSE) and normal operating.

The R6 rule is generally used [5], except when the C_G value obtained by this simplified method is too small. In such cases, finite element assessments of J integral can be performed to increase the critical size. The through-wall defect is always considered as rectangular.

In all cases, the C_G value must be decreased to take into account the defect propagation due to the SSE.

It must be also noted that the critical length can be generally improved if a limited stable tearing (< 10 mm) is allowed. A ductile tearing curve, characteristic of the material, is then needed.

Note

Residual stresses are neglected for determination of C_G [8].

Margin assessment for leak detection

The margin assessment for leak detection is defined as :

$$\alpha = \frac{2C_G}{2(C_p + C_L)}$$

Following recommendations of DCRC report 13, the α value to respect depends on the method used to determine C_G .

CONCLUSION

The complete LBB methodology used for French LMFR has been presented in this paper. Starting from a reference surface defect, the integrity of the component at the end-of-life is first verified and margins with regard to critical depth are assessed.

Then, assuming that the defect becomes through-wall for an hypothetical reason, the impossibility of a catastrophic rupture of the component before leak detection is demonstrated.

Margin between detectable and critical defect sizes is evaluated.

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