ANALYTICAL PWR VESSEL INTEGRITY ASSESSMENT BY TEARING INSTABILITY THEORY

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ABSTRACT

Analytical failure predictions for a PWR vessel from Linear Elastic and Elastic-Plastic Fracture Mechanics have been compared. Results were related to internal pressure and wall thickness strain gradient. The conservatism of linear elasticity via K_{IC} when compared to elasto-plasticity by means of the Ductile Tearing Instability Theory was quantified. The overriding effect of testpiece size on both approaches as well as of side-grooving on elasto-plasticity were shown. The healthy conservatism of the J_{50} criterion for design and service was demonstrated and the J-R curve linear extrapolation on J-T space as well. The ductile crack extensions undergone by the nuclear component were calculated according to several elastic-plastic criteria. On these bases, some considerations about leak-before-break were made. Finally, the logarithmic fit for J-R curves was proposed.

KEYWORDS

J-R curve, leak-before-break, PWR vessel failure, safe design and service, structural integrity, tearing instability.

INTRODUCTION

The undue conservatism in the instability evaluation of structural components under upper-shelf conditions via Linear Elastic Fracture Mechanics (LEFM) criteria as compared to Elastic-Plastic Fracture Mechanics (EPFM) methodologies is widely recognized. Nevertheless this quantification has never been properly appreciated. Specifically, the linear elastic criterion, K_{IC} for cleavage triggering, is always applied on PWR assessment. Not willing to underestimate its importance in pressurized thermal shock studies, it seems interesting to estimate the predictions of instability according to K_{IC} when the system operates under fully ductility response and then compare them quantitatively to those more realistic from Elastic-Plastic Tearing Instability Theory (J-T diagrams). In this work, such analytical comparison is accomplished for a PWR vessel considering eight different cracks types. The results are helpful for hydrotesting purposes.

MATERIAL, SPECIMENS TEST AND STRUCTURAL COMPONENT

A 130 mm thick nuclear forged plate steel, grade A508-3A, was tested in the as-received condition. This material exhibited a yield strength, S_Y, of 384 MPa, a ultimate tensile strength, S_U, of 519 MPa when tested at 175°C. One and two inch-thick proportional-compact specimens for K and J toughness testing were extracted from the central portion of the plate in the ST orientation. The cylindrical PWR vessel, with mean radius, R, of 950 mm and wall thickness, t, of 130 mm is shown in scheme in Fig.1. The vessel is supposed to have four elliptical embedded cracks (with nil excentricity) and four semi-elliptical cracks in the outside surface wall (each one individually considered) which are fully submitted to the hoop stresses. The component is internally pressurized at 175°C.

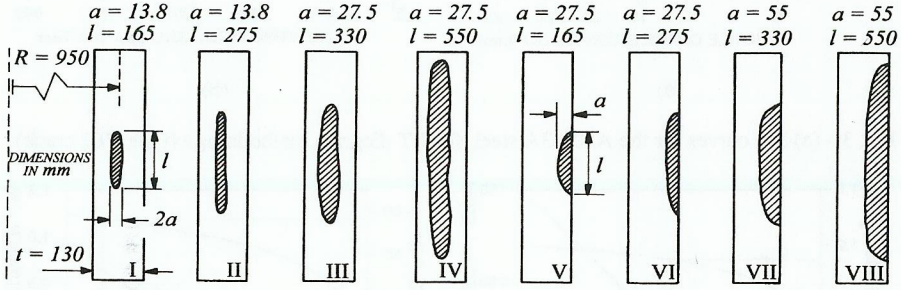


Fig.1 - Eight axial cracks in the belt-line of a intermediate size PWR vessel.

EXPERIMENTAL AND ANALYTICAL PROCEDURES

Linear Elastic Fracture Mechanics (LEFM)

K_{IC} tests were carried out according to ASTM-399 standard (1995) at temperatures from -196°C to -60°C in order to achieve maximum valid K_{IC} results for both specimen sizes. The stress intensity K factor for a surface crack with depth a ($2a$ for internal cracks) axially sited in the belt-line of a cylindrical isothermically pressurized vessel is given by the ASME code (1992):

$$K_{IM} = S_M . M_M \sqrt{\frac{\pi . a}{Q}} \tag{1}$$

where K_{IM} points out the mode I loading, S_M is the nominal hoop membrane stress and M_M and Q are crack shape factors. In elastic regime, K is related to J-integral by:

$$J = \frac{K_I^2}{E'}, \quad where \quad E' \begin{cases} E & (plane-stress) \\ E/1-\nu^2 & (plane-strain) \end{cases} \tag{2}$$

E and ν are material constants. From (1) in (2) and introducing the yield strength (S_Y):

$$J_{APP} = \frac{S_Y^2 . a}{E'} . \left\{ \frac{S_M^2 . \pi}{S_Y^2} \right\} \left[\frac{M_M^2}{Q} \right] \tag{3}$$

where the symbols { } and [ ] are respectively stress and geometric correction terms. J_{APP} is implicitally related to the internal pressure, P, in Eq.3 by means of S_M. The strain gradient vessel wall-through, with respect to P and S_M, was obtained from thick-walled components theory and Ramberg-Osgood law. The J_{APP} x P x e_M diagrams were constructed, where e_M is the maximum, $e_{M(MAX)}$, and minimum, $e_{M(MIN)}$, nominal hoop strain, and after introducing the converted J_{MAT} values of material cracking resistance in terms of J-integral (Eq.2), the predictions for the vessel failure by elasticity theory upon K_{IC} criterion were achieved.

Elastic Plastic Fracture Mechanics (EPFM)

J-R curves were obtained at 175°C for 8% and 21% side-grooved specimens using the recently developed linear normalization technique (Reese and Schwalbe, 1993) in accordance with ASTM-E1152 standard (1995). The J-R data points were adjusted by both power law and logarithmic fits. Following J-T diagrams methodology (Paris and Johnson, 1983), where T is the tearing modulus, and deriving J-R curves, the J-T_{MAT} curves were obtained, where T_{MAT} is the increase rate on the material cracking resistance. The loading curves for the cracked structure, J-T_{APP}, where T_{APP} is the increase rate on the crack driving force, were achieved by:

$$\frac{J_{APP}}{T_{APP}} = \frac{S_Y^2 . a}{E} \tag{4}$$

At the intersection of J-T_{MAT} and J-T_{APP} curves, that is, when T_{MAT} equals T_{APP}:

$$\frac{d\,J_{MAT}}{d\Delta a} . \frac{E}{S_Y^2} = T_{MAT} = T_{APP} = \frac{d\,J_{APP}}{d\,a} . \frac{E}{S_Y^2} \tag{5}$$

the J values for the vessel instability (J_{inst}) were determined. The so called J_{50} values, suggested as a good approximation of J_{inst}, were obtained from a loading curve given by J/T_{MAT} = 50 lbf/in = 8.8 kJ/m^2. The J_i values of ductile tearing initiation (ASTM-E813 standard, 1995) were determined from 0.2 mm off-set criterion. The instability predictions according to J_{50} and J_{inst} were settled as intervals with the upper and lower limits related to respectively to J-T_{MAT} curves fitted by power law and linear extrapolation based on ω criterion of Deformation-J (ω = 5 for CT[S]). The J_{APP} values (Eq.3) on plastic range were calculated by considering an intermediate condition between plane stress and plane strain for the stress correction, while the geometrical solutions were supplied by the ASME code (1992). Just as for the LEFM analysis, J_{APP} x P x e_M diagrams were traced and also the vessel failure predictions, in terms of internal pressure and strain gradient, were determined for all elastic-plastic criteria and crack types.

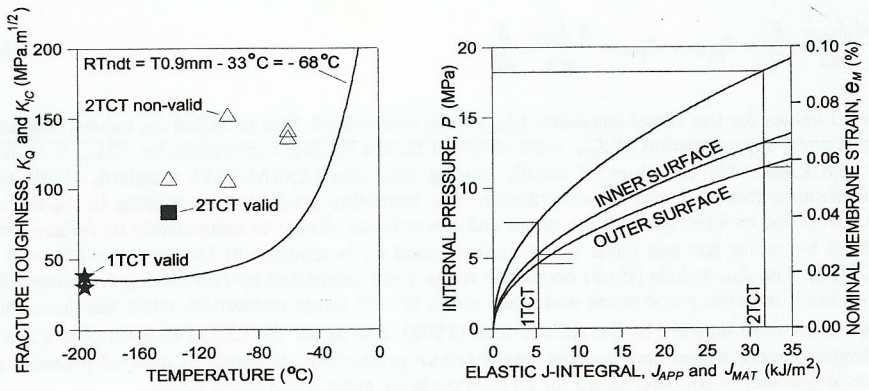
RESULTS AND DISCUSSION

Figure 2(a) presents the results of fracture toughness testing, K, when one valid result was obtained from 2TCT specimens and two from 1TCT ones. A K_{IC} curve was drawn according to

ASME code (1992) for the reference temperature (RTndt, for a Charpy specimen lateral expansion of 0.9 mm) of the A508-3A steel. This curve is shown to be conservative when compared to the 2TCT specimen valid result and slightly unconservative with respect to the less massive 1TCT specimens results. Figure 2(b) shows the graphical procedure on obtaining the critical values of the vessel failure upon K_{IC}.

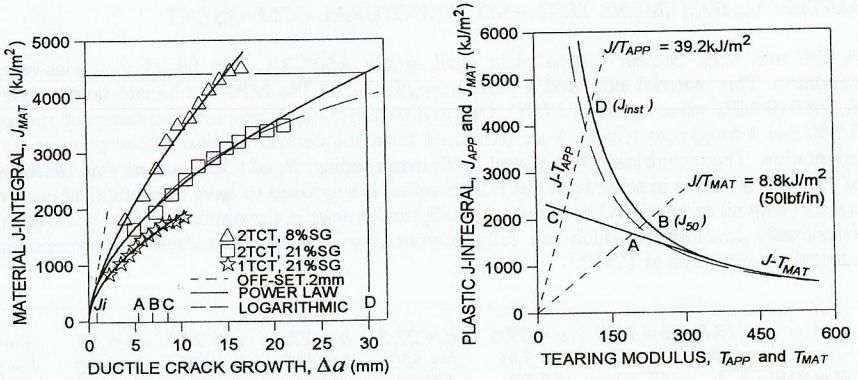
Figure 3(a) presents the J-R curves for 1T and 2TCT side-grooved specimens. In both approaches, LEFM and EPFM, the massive specimens 2TCT provided the most realistic (and liberal) results, since the specimen width was almost identical to the vessel wall thickness, allowing simulation of axial cracks growing on radial direction. So, their results were used for instability analysis. In addition, 21% side-grooving of J specimens gross thickness produced almost perfectly straight crack fronts (slightly inverted tunneling) and very small thickness changes, as expected to occur in PWR vessels due to highly constrained yielding. This way, 2TCT 21% SG specimen results were applied to EPFM analysis. In Fig. 3(a) it is also observed the best pliability of the logarithmic (against power law) fit adjusting the J-R data points for high crack extension levels, where J-saturation takes place and the ductile instability is of main concern. In Fig. 3(b), in the J-T space for crack stability analysis, the J-T_{MAT} curves (dotted line for J-R logarithmic fit) of material tearing resistance relatively to 2TCT 21% SG specimen, and the J-T_{APP} curves (straight lines) of J_{50} criterion and mechanical loading (pressurization) considering type VIII crack are plotted. J_{50} and J_{inst} values (upper limits) are indicated for the J-T_{MAT} curve derived from J-R power law fit.

The extended stress correction factor and the Ramberg-Osgood law for the A508-3A steel at 175°C are presented in Fig. 4(a). Figure 4(b) shows the graphical procedure to determine failure conditions according to elastic-plastic criteria. All the failure predictions upon both LEFM and EPFM methodologies are presented in Table I. Back to the Fig. 3(a) and based on the J-R curve referred to 2TCT 21% SG testpiece it was possible to achieve the ductile crack growth levels (Δa) before the vessel failure upon EPFM criteria, as specified in Table II.



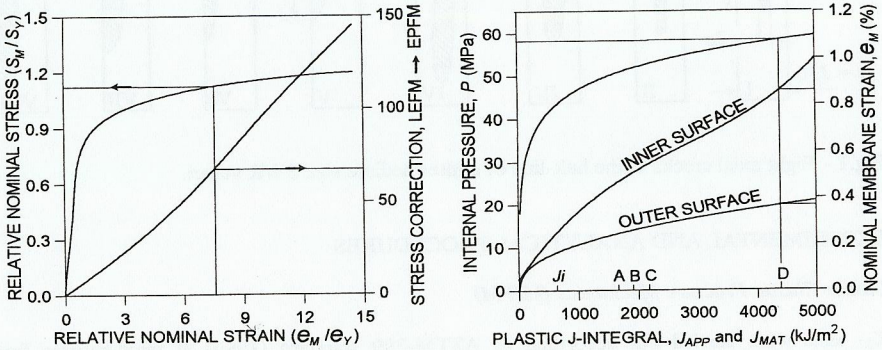
(a) (b)

Fig. 2 - (a) Fracture toughness, K, results (valid K_{IC}, non-valid K_Q) for the A508-3A steel; (b) Pressure and strain failure predictions upon K_{IC} criterion (considering the presence of the type VIII crack).



(a) (b)

Fig. 3 - (a) J-R curves for the A508-3A steel; (b) J-T diagram methodology (type VIII crack).



(a) (b)

Fig. 4 - (a) Ramberg-Osgood law and the elastic-plastic stress factor for the A508-3A steel; (b) Pressure and strain failure predictions for the pressure vessel based on EPFM (type VIII crack).

Table I - PWR vessel failure predictions following LEFM and EPFM analyses.

CRACK TYPE	CRITERION	P (MPa)	$e_{M(MAX)}$ (%)	$e_{M(MIN)}$ (%)
I	K_{IC}	55.4	0.80	0.30
	J_i	57.5	1.19	0.35
	J_{50}	63.7-65.7	2.42-3.02	0.68-0.84
	J_{inst}	63.9-65.8	2.50-3.15	0.70-0.89

Table I (*cont.*)

CRACK TYPE	CRITERION	P (MPa)	$e_{M(MAX)}$ (%)	$e_{M(MIN)}$ (%)
II	K_{IC}	54.2	0.69	0.27
	J_i	57.1	1.16	0.34
	J_{50}	63.5-65.5	2.38-2.96	0.65-0.82
	J_{inst}	63.8-65.7	2.43-3.05	0.69-0.87
III	K_{IC}	36.0	0.14	0.12
	J_i	51.5	0.61	0.26
	J_{50}	58.3-59.4	1.35-1.52	0.47-0.51
	J_{inst}	59.7-62.6	1.56-2.18	0.52-0.65
IV	K_{IC}	35.3	0.13	0.11
	J_i	51.3	0.60	0.25
	J_{50}	58.2-59.3	1.30-1.47	0.46-0.50
	J_{inst}	59.5-62.5	1.51-2.12	0.51-0.64
V	K_{IC}	37.4	0.14	0.12
	J_i	52.9	0.65	0.27
	J_{50}	59.7-60.5	1.49-1.65	0.49-0.54
	J_{inst}	61.1-63.4	1.73-2.39	0.56-0.68
VI	K_{IC}	34.0	0.12	0.105
	J_i	50.9	0.55	0.23
	J_{50}	57.6-58.7	1.21-1.35	0.42-0.46
	J_{inst}	59.2-61.7	1.42-1.97	0.47-0.61
VII	K_{IC}	22.6	0.09	0.07
	J_i	46.0	0.32	0.21
	J_{50}	52.9-54.0	0.66-0.74	0.31-0.33
	J_{inst}	54.8-60.3	0.80-1.35	0.34-0.46
VIII	K_{IC}	18.5	0.065	0.06
	J_i	43.6	0.22	0.17
	J_{50}	50.7-51.8	0.48-0.51	0.25-0.27
	J_{inst}	52.7-58.5	0.55-0.87	0.28-0.37

Table II - Ductile crack growth (in millimeters, and for each one crack fronts) preceding the failure of the pressure vessel according to elastic-plastic analysis for the eight crack types.

CRITERION	I	II	III	IV	V	VI	VII	VIII
J_i	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
J_{50}	4.3-6.9	4.3-6.9	5.3-6.9	5.3-6.9	5.3-6.9	5.3-6.9	5.3-6.9	5.3-6.9
J_{inst}	4.8-7.6	4.8-7.6	7.2-15	7.2-15	7.2-15	7.2-15	8.5-30	8.5-30

Considering the conditions used in this study, the data presented shows that EPFM always produces the most liberal and realistic results over LEFM, regardless of the adopted failure criterion.

In EPFM analysis the predictions from the crack initiation criterion Ji are very conservative (besides allowing as much as 0.9 mm of crack extension) when compared to those from J_{50} and, of course, from J_{inst}. J_{50} predictions are excellent when compared to J_{inst} results, which define the ductile instability event. Despite the very high ratios J_{inst} / J_{50}, their failure predictions (in terms of pressure and strains) are often close due to basically the low strain-hardening capacity exhibited by the A508-3A steel at 175°C, as evidenced by the low ratio S_U / S_Y of this material. J_{50} has produced just slightly conservative failure predictions, particularly for the surface cracks with modest dimensions and specially for the internal cracks, even the largest ones. On these bases, the relevance of J_{50} as a safe design and service criterion is ratified for internally pressurized nuclear components.

As can be seen, the failure predictions ranges in terms of ductile crack growth (Δa), as well as of pressure (P) and strains (e_M), related to the J_{inst} criterion are too extensive as a consequence of the poor strain-hardening features of the material, which, in turn, is directly reflected on J-R curve shape. This way, J_{50} reafirms its advantage over J_{inst} as a design and assessment criterion.

The linear extrapolation of J-T_{MAT} data from the ω criterion for Deformation-J controlling crack growth, has provided very good J values instability estimates, as compared to those obtained from the non-linear extrapolation through the power law fit, particularly for the smallest surface cracks and once again for the internal ones.

From the data it can be assured that surface cracks are much more critical than embedded ones having the same depth and length.

Also, it is shown that crack depth has much more influence on failure predictions, for both LEFM and EPFM, than does the crack length. In fact, the later has produced only small effects over the results.

For the least critical cracks, the smallest internal ones, the trend on approaching between LEFM and EPFM failure predictions was noticed. In these cases large plasticity effects are expected, which are quite beyond the LEFM premises. Therefore, its predictions should be considered absolutely inconsistent.

As can be noted from the expected ductile crack growth levels before the vessel instability, leak-before-break is prone to occur for the most critical cracks (the deeper ones), while for the other cracks ductile instability can be stablished without any prior notice.

Finally it can be observed that logarithmic fit of J-R curves produces conservative failure predictions when plotted in a J-T format (J-T_{MAT} curve), and in this sense it is thought to be the optimum adjustment practice instead of power law.

CONCLUSIONS

1 - Under upper-shelf conditions, the EPFM approach always produces more realistic (and liberal) failure predictions than does the LEFM (this one as imposed by ASME code), regardless the adopted failure criterion. In addition, less massive specimens always produce more conservative results, for both LEFM and EPFM, proving the safeness of periodical structural integrity assessments of PWR plants by using small scale testpieces.

2 - Crack initiation J_i failure predictions are highly conservative. J_{50} has produced excellent, slightly conservative, approximations of the conditions in which the real failure of the component is verified as defined by J_{inst}. Consequently, J_{50} is here ratified as an accurate criterion for safe design and service in nuclear power components industry. Ductile crack growth, internal pressure and wall strain are trustworthy parameters on instability predictions

provided J_{50} is the selected design and service criterion.
3 - Non-linear extrapolation on J-T space, adjusting J-T_{MAT} data with a power law curve, led to much closer results to those acquired from the linear extrapolation following $\omega = 5$.
4 - The approximations between J_{50} and J_{inst} results and from the linear and non-linear extrapolation of J-T_{MAT} data are much finer for less deep cracks (more likely to occur between periodical plant inspection programs), specially for the embedded ones.
5 - Surface cracks are much more critical than the internal ones having the same depth and length.
6 - Instability results are highly affected by crack depth changes but just slightly by changes on its length (l); crack length has no effect over the instability results for small embedded cracks.
7 - Ductile crack extension related to initiation J (J_i), as graphically determined, was approximately 0.9 mm instead the expected 0.2 mm; the reason for such discrepancy was the expressible steepness of J-R curve in the vicinity of its intersection with the 0.2 mm off-set line.
8 - Logarithmic fit is more effective than power law on adjusting J-R curve data points for large crack extension (where saturation-J is developed), producing conservative failure predictions through J-T diagram methodology.
9 - LEFM is inappropriate when dealing with small embedded cracks analysis under upper-shelf conditions.
10 - The larger the crack is, the greater the probability of leak-before-ductile instability. In this sense deeper cracks (in principle the most critical ones) are subject to crack arrest events as well as visual detection of the failure threshold, while the shallow ones may grow catastrophically without any prior notice..
11 - 20% side-grooving of J specimen gross thickness in both 1T and 2T specimen sizes is the ideal level for producing straight crack fronts, since 21% side-grooving always produced slightly inverted tunneling.

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