METHOD FOR LEFM ANALYSIS OF RPV DURING SBLOCA*
S. K. Iskander**

Abstract.

A somewhat simplified two-dimensional linear elastic fracture mechanics model of the beltline of a RPV is presented. The fracture mechanics model used tends to be conservative in the sense that it ignores possible beneficial effects of warm prestressing and cladding.

For LEFM studies that require a large number of analyses on the same geometry but with different loads and material toughnesses, the superposition principle is an accurate and simple method to determine K_I , provided that K_I due to a unit load (called K^* in this paper), acting on an arbitrary point on the crack surface is known. The details of the superposition principle and the procedure used for determining K^* have been presented.

It is believed that the error in the K_I - values so determined is less than 3.5 %. Once these K^* - are determined for a specific geometry, then the determination of K_I for the same geometry can be made accurately and in a manner that permits parametric studies involving thousands of individual analyses.

An example of the use of the simplified model for a parametric analysis is also presented.

1.0 INTRODUCTION

The possible threat to the integrity of pressurized-water reactor (PWR) pressure vessels, when subjected to postulated accidents called "loss-of coolant accidents" (LOCAs) has been recognized for some time /1-4/. LOCAs are characterized by the absence of any significant internal pressure. Only later has the more severe threat to the integrity of the reactor pressure vessel (RPV) of small-break-loss-of-cooling-accidents (SBLOCAs) become recognized. SBLOCAs are characterized by both thermal and pressure loading of the beltline region of the RPV. The thermal loading may cause shallow surface flaws to propagate, and as they get deeper the pressure loading may drive them through the wall. Several SBLOCAs have already occurred /5/, and preliminary studies have indicated that had these transients occurred much later in the life of the vessel, and if appropriate flaws existed, propagation of the flaws might occur /6/.

The concern about SBLOCAs has become the subject of much investigation by both industry and regulatory bodies in the USA /7-9/, and in Europe /10-12/. It was designated by the NRC as Unresolved Safety Issue A-49 in December 1981. Since that time, the NRC staff has issued a report on the matter /13/, and their recommendations are in the review process /14/.

The evaluation of the safety of a RPV requires input from many different disciplines. Systems analysis together with thermal hydraulics is necessary to define the pressure, temperature transients as well as the heat transfer coefficients required. Dosimetry and materials engineering provide the material properties, while non-destructive examination (NDE) methods provide information for example, such as the size of flaws likely to escape detection.

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There are many uncertainties involved in the structural analysis of a RPV. Thus parametric and probabilistic analyses are often performed. Deterministic parametric analyses sometimes involve thousands of individual structural analyses /15/, while the number of analyses in probabilistic studies could be in the millions /16/.

Thus the need for a simple model to be used in such analyses. An important component of such a model is the determination of the stress intensity factor K_I under arbitrary loads. The superposition principle allows the determination of K_I in a very economical manner, provided the so-called unit load response of the structure is known.

This paper discusses a linear elastic fracture mechanics (LEFM) model. Also described is a method for the determination of the unit response. The K_I determined from such unit load response is believed to be quite accurate. Thus the uncertainty associated with the determination of K_I could be neglected. The use of the LEFM model is then illustrated.

2.0 FACTORS INFLUENCING FLAW BEHAVIOUR.

The factors that influence the fracture mechanics (FM) behavior of a flaw in an embrittled RPV during a SBLOCA is shown schematically in Fig. 1, /6/. This shows the temperature, stresses and fracture toughness as a function of the depth in the wall during a particular time in the transient (excluding the effect of cladding). Also included is K_I for long axial flaws of various depths. The steep gradient in K_I results from the steep temperature gradient while that of the toughnesses, both initiation (K_{Ic}) and arrest (K_{Ia}), result from the temperature as well as the fluence attenuation gradients. As a result in this case, both shallow and deep flaws can initiate. However, as the flaw propagates, the steep gradient of K_{Ia} offers the possibility of the crack to arrest.

The interaction between the above factors have also been illustrated in flow chart form Fig. 2, /17/. The SBLOCA gives rise to a temperature and pressure transient. The level of the thermal stresses is augmented by the pressure stresses if any, and for a postulated flaw gives rise to a large stress intensity factor. The fracture toughness of the material on the vessel inner surface is reduced by the low temperature as well as the radiation damage due to the neutron exposure, particularly if the material contains unfavorable levels of Cu and Ni.

3.0 FRACTURE MECHANICS MODEL.

A model that can be used in the study of SBLOCAs is based on two-dimensional (2D) linear elastic fracture mechanics (LEFM). The applicability of LEFM and long flaws implied by the 2D model is discussed below. Cladding can be ignored for the reasons mentioned below. The behaviour of flaws is influenced by a phenomena called warm prestressing (WPS), and this is also briefly discussed.

3.1 Applicability Of LEFM

The only restriction of LEFM is that the size of the plastic zone surrounding the crack tip is small compared to the remaining ligament of the wall. For shallow inner-surface flaws (less than 20 % of wall depth) LEFM is appropriate, as has been demonstrated by the Heavy-Section Steel Technology (HSST) program for thermal-shock loading, /18/ and more recently for pressurized thermal-shock

loading, /19/.

3.2 Infinitely Long Flaws Are Not Excessively Conservative.

A frequently raised concern about the use of infinitely long flaws is that such flaws are unlikely to exist in real pressure vessels, and that they are overly conservative. Certainly finite length flaws are more credible. However, in the absence of cladding and in the presence of a steep toughness gradient, a finite length flaw tends to become a long flaw. Figure 3 (a) and (b) show the "crazed" pattern of cracks that propagated from a single finite length flaw during thermal-shock experiments TSE-5 /20/ and TSE-7 /21/. In Fig. 3(c), the long axial flaw in the PTSE-1 test cylinder bifurcated and grew axially at each end by 120 mm, concurrently with the first crack jump /19/. It is likely that further extension of this flaw was prevented by the restraint of the ends.

Analysis of finite length flaws is more complex, and at present only qualitative-type predictions are possible about the propagation behavior of such flaws. Moreover, for crack depths under consideration in this study, the K_I value at the bottom of a finite length 6/1 semi-elliptic flaw is very close to the K_I of an infinitely long flaw, as indicated in Fig. 4 /22/. It has been shown that the benefits of considering finite length flaws, are considerable under certain conditions. However, above a certain pressure there may be no benefit, depending on the duration of the transient and the limit on crack arrest toughness /23/.

3.3 Effects Of Cladding.

Cladding could be neglected. It has been demonstrated analytically that if both the thermal and stress effects of cladding are excluded, nearly the same potential for crack initiation exists as estimated by the inclusion of the cladding as a discrete region /24/.

3.4 Warm Prestressing.

The behavior of a flaw is influenced by a phenomena known as warm prestressing (WPS) /25/. An essential characteristic of one type of WPS, relevant to SBLOCA FM analysis, is that K_I first increases and then monotonically decreases with time, as shown in Fig. 5. For some postulated SBLOCA transients K_I does not exceed K_{Ic} until $\dot{K}_I < 0$. Under these conditions a flaw will not propagate even if $K_I \gg K_{Ic}$ /18,25/.

Following a period of $\dot{K}_I < 0$, K_I may once again increase. The effect of this load history on the subsequent FM behavior is still under study. In several transients relevant to the SBLOCA analyses, repressurizations have been recorded /13/. Preliminary indications of the pressure and thermal transients from one of these transients is shown in Fig. 6. In PTSE-1, crack initiation occurred when K_I exceeded by about 13 % the maximum K_I value attained during a prior transient /19/. It is also possible that cyclic variations in K_I negate the beneficial effects of WPS by a mechanism similar to that operative during low cycle fatigue.

It is therefore prudent not to rely on WPS as a means of preventing crack initiation. It is a well established phenomena only for monotonically decreasing K_I , which is not possible to ensure under most accident conditons.

3.5 Failure Criterion.

In order to evaluate the behaviour of postulated flaws in a RPV a failure criterion is required. Such a criterion could be whether a propagating flaw would arrest, and if so whether the remaining ligament is plastically stable. However, for the reasons given here, it is suggested that the failure criterion be based on initiation alone.

Implicit in such an approach is the neglect of the possibility of crack arrest. There are several reasons for neglecting crack arrest. Inside cracks initiating in a brittle mode and running deeper into the wall are most likely to encounter material that is on the upper transition or upper shelf region of the material toughness. The behavior of such flaws is still under investigation. Furthermore, previous studies /6,15/ have shown that crack arrest is effective only for rather low-pressure transients. Also, a recent probabilistic FM study /26/ showed that inclusion of crack arrest does not substantially influence the calculated frequency of vessel failure.

3.6 Material Toughness Used.

In LEFM analysis the plane-strain fracture toughness K_{Ic} is needed, and if arrest is to be considered the arrest toughness K_{Ia} also. Both K_{Ic} (and K_{Ia}) vs T-RT are given in Section XI of the ASME code (T is the temperature at the tip of the crack) and RT_{NDT} is the nil-ductility transition reference temperature. If values obtained from surveillance are available, these could also be used. However, at the time many of the older RPVs were constructed there was no requirement for the determination of the beltline RT_{NDT} . For such cases the NRC has defined a method for its calculation /14/, and the method could be used to estimate RT_{NDT} .

4.0 CRITICAL CRACK DEPTH CURVES.

A valuable graphical aid in the description of the behavior of a flaw during a transient event is the "critical crack depth curve" (CCDC) shown schematically in Fig. 7. In these curves, the locus of depths at which $K_I = K_{Ic}$ and $K_I = K_{Ia}$ are plotted against time.

On such a diagram, the locus of crack depths at which K_I reaches a maximum (WPS curve) and curves of constant values of K_I (the dotted curves) could also be drawn. All points to the right of the WPS curve are events that take place during $K_I < 0$, and no initiation can take place during such times as explained above.

There is much information that can be deduced from such curves. The diagram shows whether a crack of a particular depth would initiate, and if so, the time during the transient such initiation would occur. It also shows the smallest depth of a [capable of] initiating for a particular transient. Note that the toughness properties of welded clad material, and particularly the irradiated properties are still under investigation, and thus the behavior of surface cracks which lie wholly within the cladding cannot be described by curves based on the ASME toughness values.

In the curves shown, cracks of about 4 % (or 10 %) would initiate provided that such depths are greater than the thickness of the cladding. The initiated flaw would then run deeper into the vessel, arresting at about 17 % of the wall depth, and then

reinitiate at some later time. The multiple initiation arrest event is depicted by the vertical and dashed lines. Such a crack would penetrate quite deeply into the vessel except for intervention of WPS would prevent initiation at points lying to the right of the "WPS" curve.

The curves of constant K_I enable one to make some estimate of the level of the driving force during the initiation arrest event. This is important since this describes whether e.g. initiation is within the limits of validity of LEFM. Cracks initiating or arresting at values greater than about 200 MPa $\sqrt{m}$ would probably tear and their analysis cannot be properly described by means of LEFM. Arrest at upper shelf temperatures and values is still the subject of much investigation.

5.0 CALCULATION OF K_I

The stress intensity factor K_I can be calculated by means of the superposition principle /27/. This method is illustrated in Fig. 8. The body (a) is meant to represent a cracked structure under some arbitrary loads, thermal or mechanical. In this figure and the next two for purposes of clarity only the upper half of the structure is shown since it is symmetric with respect to the crack face. Due to the assumption of linearity, the structural response of this structure could be considered equal to the sum of responses of two other bodies (b) and (c). The geometry of these structures is identical to the original structure. In (c) the crack is kept closed by the surface tractions that would have existed in the uncracked structure. Thus as far as the stresses in the entire structure (c) are concerned the body acts like an uncracked one. The "crack closure" stresses of (c) are then applied with their sign reversed on the crack surface of structure (b). Since K_I for an uncracked body is zero, then K_I for problem (a) is equal to K_I for problem (b).

The determination of K_I for problem (c) is certainly no less difficult than for problem (a). The tremendous utility of this method stems from its use in the determination of K_I under arbitrary loads. The method is illustrated in Fig. 9. Let the function $G(a',a)$ (whose determination will be explained below), be the K_I for a unit concentrated load acting at a distance a' from the crack tip. G is also a function of the overall geometry implied by the inclusion of the crack depth " a " as an independent variable. Then for a pressure σ acting on the crack surface, the stress intensity factor for the infinitesimal load σda is $G(a',a)\sigma da$ and the K_I is

$$K_I(a) = \int_0^a G(a',a) \sigma da' \quad (1)$$

By means of the superposition principle shown in Fig. 8, K_I can be obtained for a cracked structure subjected to a given load by first calculating the stresses due to the given loads but for an uncracked structure. The integral of the product of these stresses and G over the cracked surface gives K_I , Eq. 1.

There are many such unit load responses published in the literature for specific geometries /28,29,30/, although their format may be slightly different from that given by G in Eq. 1. In case the available response does not correspond exactly to the case under consideration, an estimate of K_I could perhaps be made by approximating the case under study to one of the available solutions. The error involved in such an approximation may be difficult to estimate.

The Thermal Shock Task of the Heavy Section Steel Technology (HSST) Program involved investigations of axially and circumferentially cracked cylinders. There was a need for values of K_I that are as accurate as possible. Furthermore, many parametric analyses were to be performed. In the method developed for that program, the function $G(a',a)$ was obtained by means of the finite element (FE) method. The cylinder is modeled for FE analysis with a large number of small elements around the crack tip. Instead of a unit concentrated load, a unit pressure load is applied successively on each of the elements on the crack surface, Fig 10(a). Let the K_I determined for each of these unit surface pressures be $K^*(a',a)$.

Once such $K^*(a',a)$ are known, then K_I for the same geometry is

$$K_I(a) = \sum K^*(a',a) \sigma_i \quad (2)$$

where

σ_i = average stress over the location of the i th element in the uncracked structure and,

n = number of elements on the crack face.

The K^* s are determined by means of the potential energy release rate method implemented in the FE code FMECH /31/. The error in the determination of K_I has been estimated by comparing the results of FMECH with closed form solutions, and has been found to be less than 3.5 % /32/.

There are advantages to the above procedure over methods that require a polynomial to be fitted to the stress distribution /33/. The errors associated with the use of polynomials are avoided. The difference between K_I determined by Eq. (2) and the direct determination of K_I by the code FMECH is less than 0.5 % /34/. Another advantage is that the discontinuities in the stresses can be accommodated easily. Such discontinuities in stress occur if cladding is included in the analysis as a discrete region.

K^* - values are calculated for about 20 cracks whose depth ranges from about 1 to 95 % of the wall thickness. The number of elements on the crack face, and thus the number of K^* computed, depends upon the crack depth, and is about 10 for the shallow crack and 50 for the deeper ones. The potential energy release rate method requires in principle, two FE analyses, thus the determination of a set of K^* for one crack depth would require two FE analyses for each unit pressure. However, the procedure has been highly optimized. The CPU time on the VAX 11/785 to compute one set of K^* for a single crack depth, is approximately 45 minutes. The FE models have about 5000 degrees of freedom.

6.0 EXAMPLE OF USE OF THE LEFM MODEL

An example of the use of the above model in the LEFM analysis of RPV subjected to SBLOCA transients will now be presented. In the model used no credit was assumed for the possible beneficial effects of either WPS or arrest and cladding was ignored.

The objective of the study was to determine, for a range of transient-related parameters, the minimum pressure required to cause crack initiation at a specific time in the life of a RPV. The time in the life of the vessel for which the calculations were made corresponds to attainment of the limiting nil-ductility transition

reference temperature specified by United States Nuclear Regulatory Commission pressurized thermal-shock-issue-related screening criteria /14/.

A deterministic fracture-mechanics parametric-type analysis of a generic pressurized-water reactor pressure vessel was performed for loading conditions imposed by a specific category of hypothetical ~~BLOCA pressurized thermal shock~~ transients. The parameters included were thermal transients of varying severity, two initial values of RT_{NDT} and two-dimensional circumferential and axial flaws of different depths.

The transients considered were characterized by a constant pressure and an exponential decay of the downcomer coolant temperature. The decay constant, the final temperature of the coolant, and the fluid-film heat-transfer coefficient were the variable parameters. A search was performed to determine the critical pressure corresponding to incipient crack initiation for a range of crack depths up to 20 % of the wall thickness. Full details are in /35/.

The results of that study are summarized in Fig. 11 and in Table 1. These results indicate that the critical pressure is greater than the normal operating pressure, if the coolant final temperature is greater than 150°C.

The fracture mechanics model used in the study tends to be conservative in the sense that it ignores possible beneficial effects of warm prestressing and cladding.

7.0 SUMMARY

A somewhat simplified two-dimensional linear elastic fracture mechanics model of the beltline of a RPV has been presented. The fracture mechanics model used tends to be conservative in the sense that it ignores possible beneficial effects of warm prestressing and cladding.

An important component of the model is the accurate determination of K_I . This is a time consuming process if no general solution to the problem already exists, since the determination of K_I by means of numerical procedures such as the FE method have to be resorted to.

For LEFM studies that require a large number of analyses on the same geometry but with different loads and material toughnesses, the superposition principle is an accurate and simple method to determine K_I , provided that K_I due to a unit load (called K^* in this paper), acting on an arbitrary point on the crack surface is known. The details of the superposition principle and the procedure used for determining K^* have been presented:

It is believed that the error in the K_I - values so determined is less than 3.5 %. Once these K^* - are determined for a specific geometry, then the determination of K_I for the same geometry can be made accurately and in a manner that permits parametric studies involving thousands of individual analyses.

An example of the use of the simplified model for a parametric analysis was also presented.

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Table 1 — Results of parametric analysis. Numbers in the first column refer to the symbols on Fig. 7

Symbol	$T_f, ^\circ\text{C}$	Pressure MPa	n, min^{-1}	$h, \text{W/m}^2 \cdot \text{K}$	Materials	Crack Orientation
1	150	> 20	0.015, 0.045, 0.15, ∞	1000, 6000	1, 2	both
2	50	0	0.045, 0.15, ∞	1000, 6000	1, 2	both
3	50 or 100	> 20	0.015	1000, 6000	1, 2	both
4	100	0	0.15, ∞	6000	1, 2	both
5	↓	1-2	∞	1000	2	circ
6		2-3	∞	1000	1	circ
7		3-4	0.15	1000	2	circ
		3-4	0.045	6000	2	circ
8		4-5	0.15	1000	1	circ
			0.045	6000	1	circ
			0.045	6000	2	axial
9		5-6	$\infty, 0.15$	1000	2	axial
			0.045	6000	1	axial
10		6-7	$\infty, 0.15$	1000	1	axial
11		13-14	0.045	1000	2	axial
12		14-15	0.045	1000	1	axial
			0.045	1000	2	circ
13		16-17	0.045	1000	1	circ

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List of figure captions for paper by Iskander,
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FIG. 1 -- Radial distribution in a vessel wall of parameters relevant to the behavior of flaws /6/.

FIG 2. -- Relationship of factors influencing flaw behavior /17/.

FIG. 3 -- Finite length flaws tend to become long /20,21,19/.

FIG. 4 -- K_1 for shallow finite length flaws is close to K_1 for infinitely long flaws /22/.

FIG. 5 -- The WPS effect - cracks will not initiate while K_1 is decreasing. K values are for one value of a/w .

FIG. 6 -- Pressure and temperature variations during the 1978 accident at Rancho Seco /13/.

FIG. 7 -- Schematic of the critical- crack- depth- curves used in LEFM study of flaw behavior during SBLOCA.

FIG. 8 -- The superposition principle /27/.

FIG. 9 -- Determination of K_1 from the unit response function G .

FIG. 10 -- Definition of K^* .

FIG. 11 -- Results of parametric analysis /35/.

$p = 13.8 \text{ MPa}$
 $T_c = 121 + 167^{0.15t} \text{ } ^\circ\text{C}$
 $h = 1875 \text{ W/m}^2\cdot\text{K}$
 NO CLADDING

Fig. 5

Fig. 6

(a)

(b)

(c)

PROBLEM

EQUIVALENT PROBLEM

$$K_1 = K' + (K''=0)$$

$$K_I = \int_0^a G(a', a) \sigma da'$$

UNIT PRESSURE RESULTING IN $K^*(a'_i, a)$

$$K_i(a) = \sum_{i=1}^n K^*(a'_i, a) \sigma_i$$

Fig. 11