AN OVERVIEW OF CRACK ARREST AS IT APPLIES TO REACTOR VESSEL INTEGRITY

T. U. MARSTON, K. E. STAHLKOPF
EPRI, Electric Power Research Institute,
3412 Hillview Avenue, Palo Alto, California 94303, U.S.A.

E. SMITH
University of Manchester, Department of Metallurgy,
Grosvenor Street, Manchester M17HS, United Kingdom

Abstract

The current A.S.M.E. Code procedure for investigating crack arrest in nuclear reactor pressure vessels is based on a static linear elastic fracture mechanics analysis, coupled with the assumption that arrest occurs when the crack tip stress intensification, K_I, equals some critical value, K_{Ia}, the so-called crack arrest toughness. This brief overview paper argues that the conditions for crack arrest in a nuclear pressure vessel when this is subjected to thermal stresses resulting from a hypothetical loss of coolant accident, are appropriate for consideration by the current code method, provided that a suitable value for K_{Ia} can be obtained from laboratory tests; this is possible using current test procedures. It is emphasized that the viability of the relatively simple K_{Ia} approach is critically dependent on the structure's characteristics, and an approach giving detailed consideration to kinetic (dynamic) effects may be necessary for other crack arrest problems.

1. INTRODUCTION

One postulated emergency condition for the pressure vessel of a water-cooled nuclear reactor is a loss-of-coolant accident (LOCA), which might be the result of a large break in a main coolant line to the reactor vessel. The LOCA is followed by operation of the emergency core cooling system (ECCS), when introduction of the relatively cold ECCS water subjects the hot pressure vessel to high thermal stresses in the vicinity of the inner surface. If this surface contains a crack-like defect, the stress intensity at the crack tip increases with time to a maximum, and then decays as the temperature gradient through the wall becomes smaller. With highly irradiation sensitive materials, neutron bombardment can reduce the fracture toughness K_{Ic} at a given temperature, and if the embrittlement is sufficiently severe, K_{Ic} could be low enough that the rising K_I due to the emergency condition will exceed K_{Ic} and the crack will extend. Because the primary objective is to retain a coolable core configuration after an emergency condition, it is essential to guard against the possibility of the crack penetrating the vessel wall.

Flaw evaluation for emergency and faulted conditions is dealt with in Article A-5300 of Section XI of the ASME Boiler and Pressure Vessel Code [1]; this article states that each postulated incident should be considered in the following manner:

(a) Determine the maximum end-of-life fluence profile through the wall thickness at the flaw location.

(b) Determine the temperature and stress profiles through the thickness of the component at the flaw location.

(c) Using the irradiated fracture toughness data, determine the crack arrest (K_{Ia}) and crack initiation (K_{Ic}) fracture toughness profiles through the thickness of the component as a function of the time following the postulated incident.

(d) Calculate the stress intensity factors for various penetration depths of the assumed flaw.

(e) The crack penetration at which the calculated stress intensity factor exceeds the K_{Ic} profile corresponds to the critical size for initiation (a_i), and the penetration at which the stress intensity factor falls below the K_{Ia} curve corresponds to the critical crack size for arrest (a_a). This comparison is illustrated in Figure 1 for both an arrest and a non-arrest situation.

(f) Curves such as Figure 1 should be prepared for a number of selected times following each postulated accident to establish the critical time and the smallest a_i.

The smallest value of a_i determined by the above procedure, and for which the crack penetration (p) is greater than 75% of the wall thickness after all postulated accidents have been considered, represents the minimum critical initiation flaw size for emergency and faulted conditions at the flaw location. The end-of-life flaw must be one-half of the size of the minimum critical flaw size, a_i. The flaw evaluation procedure is explained in detail in reference [2].

In the authors' opinion, the validity of the ASME Code procedure essentially depends on two points:

(1) Are static crack arrest K_{Ia} procedures sufficiently accurate in the nuclear pressure vessel LOCA situation?

(2) Can appropriate K_{Ia} values be measured in laboratory tests?

The K_{Ia} crack arrest procedure is based on a static linear elastic fracture mechanics (LEFM) analysis for the structure. This simplified procedure [3,4] has been questioned in recent years as to its accuracy and, more importantly, as to the conservatism of its predictions. Accordingly, dynamic approaches that are significantly more complicated than the K_{Ia} static approach have been developed (see for example [5]).

It is against this background that the present brief overview paper addresses the problem of crack propagation and arrest with reference to the pressure vessel of a water-cooled reactor subject to a LOCA. Section 2 outlines the problem and Section 3 shows that it can be investigated within the framework of present ASME Code rules. Section 4 shows that K_{Ia} values, for use in the arrest analyses, can be obtained from laboratory tests. It should be emphasized that the authors do not assert that the ASME Code and K_{Ia} procedures can be used satisfactorily for all crack arrest problems, since attention in this paper is merely concentrated on one specific, albeit very important, crack arrest problem where dynamic effects are small.

2. OUTLINE OF PROBLEM

Various theoretical analyses have focused on the possibility of a vessel crack extending during a light water reactor LOCA. To illustrate the general problem, however, the present discussion is based on the theoretical analysis conducted by Cheverton [6] for a reference vessel. The following assumptions were made in modeling the vessel:

- Wall thickness = 216 mm (8.5 in.)
- Inner wall fluence = $4 \times 10^{19} n/cm^2$ $E > 1$ MeV (corresponding to a 40-year operation period).
- High residual copper level (>0.25 wt%, corresponding to severe predicted irradiation embrittlement).
- Pre-irradiation K_{Ic} versus temperature as defined by Westinghouse [7,8] for SA533-B1 steel.
- Vessel not pressurized during the LOCA because of loss of coolant.

As indicated in the Introduction, decreasing fluence and increasing temperature towards the outside wall surface provide a mechanism for the arrest of a running crack that might start to propagate from the highly stressed, and relatively low toughness, material near the inner wall surface. Arrest is assumed to occur when the K_{Ia} value exceeds the K_I value at the crack tip, the K_{Ia} versus temperature behavior for reactor pressure vessel material being defined in Section XI, Appendix A, of the ASME Boiler and Pressure Vessel Code. Although other trend curves are available, the degradation in K_{Ia} due to neutron irradiation has been characterized in Cheverton's subject analysis according to the procedures of Regulatory Guide 1.99 [9]. This guide predicts the K_{IR} (K_{Ia}) versus relative temperature trend for irradiated material by a simple temperature translation of the unirradiated properties, based on the fluence level and residual Cu and P content of the steel. In Cheverton's reference calculational model, the K_{Ic} versus temperature trend for the irradiated material has been obtained in a similar manner by the identical temperature translation.

To illustrate the important features of the propagation and arrest problem, Figure 2 gives K_I as a function of the crack-tip position for a long axial flaw, at a specific time (450 s) after the LOCA; the figure also gives K_{Ic} and K_{Ia} as a function of distance through the wall, again at 450 s after the LOCA. It is immediately seen that an axial crack whose depth-to-wall thickness ratio (a/W) is 0.03 will initiate at 450 s, and will propagate to a relative depth of a/W = 0.35 before it arrests. It is important to appreciate that flaws of different sizes can initiate at different times after the LOCA; Figure 2 represents the conditions only after a time of 450 s into the transient.

Figure 3 shows the stress intensity factor K_I for different crack depths a/W at various times into the transient, while the dashed curve represents the locus of points at which the critical initiation level K_{Ic} is attained. If the initial flaw depth (a/W) is greater than 0.2, K_I decreases with time before it reaches the K_{Ic} value; in other words, K_I attains its maximum early in the transient, and the critical level K_{Ic} is not reached until some time later in the transient. Such cracks will therefore have been warm prestressed [10] and should not extend. Only flaws whose depths (a/W) are less than 0.2 should extend, and this extension will occur within the first 450 seconds of the transient. Figure 4 shows the crack depth for which $K_I = K_{Ia}$ as a function of time into the transient; it is immediately seen that the maximum penetration is to a relative depth of ~0.34, and this will be for a crack that initiates from a flaw of relative depth of ~0.20, after a time of ~450 seconds into the transient. These figures will vary somewhat with the system analyzed.

The preceding arguments lead to the conclusion that although warm prestressing cannot prevent crack initiation from shallow cracks, the amount of crack extension is limited. The central problem regarding crack arrest if therefore to guarantee that a shallow crack is not able to penetrate into the vessel wall, the most likely situation where deep penetration is possible being that for which a/W = 0.2, where the K_{Ia} approach shows that propagation will occur to a relative depth of a/W = 0.34. In other words, it has to be demonstrated that the K_{Ia} approach is indeed appropriate for use in this situation.

3. DEMONSTRATION OF THE VALIDITY OF THE K_{Ia} CRACK ARREST PROCEDURE IN THE LOCA SITUATION

In addressing dynamic crack propagation generally, one starts from the basis that the dynamic crack tip stress intensification K_I^{DYN} is a function of the crack length a, the crack tip velocity a, the structure or specimen geometry, the crack propagation history, and the applied loads or applied displacements. Assuming the dynamic fracture toughness K_{ID} to be a function of crack tip velocity, the crack tip equation of motion is

K_I^{DYN} (a, a, geometry, propagation history, applied loadings) = $K_{ID}(a)$ --- (1)
and the problem's analysis is obviously exceedingly complex.

With the LOCA problem, the crack is propagating normally into the vessel wall and unlike the situation in, for example, the rectangular double cantilever beam (RDCB) test, surfaces parallel to the crack are so remote that as regards the effects of wave reflections, only those from the vessel walls need be considered. Propagation of a crack from a/W = 0.20 to a/W = 0.34 in a vessel 8.5 in. thick, implies a crack jump length of 1.2 in.; however, since the outer surface is 5.6 in. away at the hypothetical arrest point, it is difficult to imagine the outer surface having any effect. Wedge-loaded SEN test specimens provide a better approximation of the LOCA geometrical configuration,and Kalthoff's experimental observations [11] on Araldite B clearly show that wave reflection effects are minimal in such specimens; oscillations in the dynamic stress intensification factor were very small compared to those observed in DCB specimens. These observations support the view that the outer wall surface has little effect in the LOCA situation; furthermore, the observations suggest that wave reflections from the inner wall surface can also be ignored.

If wave reflections do not reach the crack tip, the crack propagation problem simplifies considerably [12-14], the general equation (1) reducing to

$$K_I^{DYN} = f_I(a)K_I^{ST}g(a, \text{geometry}) = K_{ID}(a) \text{ --- } (2)$$

where $f_I(a)$ is a known function of crack tip velocity, K_I^{ST} is the crack tip stress intensification factor determined by static linear elastic fracture mechanics procedures when the crack length is a, and g is a function of crack length and structure or specimen geometry; g can be calculated via a static stress analysis (the product K_I^{ST} g is sometimes referred to as the reflection-less stress intensity factor). For small crack jump lengths, the "correction" factor g is approximately equal to unity, and in the limit of zero crack jump length, $g \to 1$. Equation (2) can then be written as

$$f_I(a)\ K_I^{ST} \sim K_{ID}(a) \text{ --- } (3)$$

and crack arrest occurs when the crack tip stress intensification factor, as determined by standard LEFM procedures, is equal to the value of K_{ID} as $a \to 0$ (this conclusion will be valid provided the K_{ID}-velocity curve does not have a deep minimum). It is in these conditions that the K_{Ia} approach is valid.

Since the crack jump lengths envisaged in the LOCA situation are expected to be of the order only of 1 in. through the vessel wall, this situation would appear to fit the behavior pattern described by relation (3), and the K_{Ia} arrest procedure should be adequate. It may also be adequate for even longer crack jumps, although this point requires further investigation.

4. THE DETERMINATION OF K_{Ia} FROM LABORATORY EXPERIMENTS

The approach described in the preceding section depends on reliable K_{Ia} (the limit of K_{ID} as $a \to 0$) data being available, a point which will now be addressed. In principle, one requires the value of K_{Ia} (i.e., the value of K_I^{ST} at arrest) in a "non-reflecting" situation where there are no wave reflections from surrounding surfaces and where geometrical effects can be ignored, i.e., ideally for a semi-infinite crack arresting in an infinite body. Clearly this is an impossible situation to attain in practice, since all laboratory test specimens have finite boundaries and cracks of finite size. This finiteness, particularly the presence of surfaces parallel to the crack plane, can lead to crack arrest at K_{Ia} values that are less than the value which is appropriate to the non-reflecting situation. This means that laboratory test measurements of K_{Ia} will, in general, be conservative with respect to the pressure vessel application.

Results from the ASTM sponsored SA533-B1 round-robin test program [15] show that K_{Ia} is, in fact, not particularly sensitive to crack-jump length (see Figures 5 and 6). In this program, compact tension specimens of the MRL design [4] and also duplex rectangular double cantilever beam specimens of the Battelle (BMI) design [16] have been tested. Not surprisingly, there is scatter in the experimental data, and this has been attributed [17] to variations in the tendency for ligaments to form during the crack arrest event. As indicated by the Battelle group [17], the presence of this scatter means that any reference toughness curve cannot be an absolute limit, but can only represent a very small, but nevertheless finite probability of K_{Ia} being less than the reference curve value. However, it does seem that tests of the type being conducted within the test program can provide K_{Ia} values which can be used in the arrest analyses.

5. DISCUSSION

It must be strongly emphasized that the present paper's arguments refer to one specific crack propagation and arrest problem, namely, that of crack propagation and arrest in a pressure vessel during a hypothetical LOCA in a water-cooled nuclear reactor. For this particular situation, it has been argued that K_{Ia} arrest procedures, in accord with the ASME Code provisions, should be adequate for assessing the propagation of cracks whose initial depths are less than 20% of the vessel's thickness. As indicated in the paper, deeper cracks will be subject to warm prestressing effects which should prevent them from extending further into the vessel. Even in the unlikely event of the warm prestressing argument being invalid, it is expected that the propagation and arrest of cracks whose lengths are somewhat greater than 0.02 W can still be considered via the K_{Ia} procedure; if support is required for this view, it might be desirable to conduct an appropriate dynamic analysis. For other practical crack propagation and arrest situations, particularly where there are surfaces parallel to the direction of crack propagation, a fully dynamic approach with wave reflection effects taken into account, might indeed be essential.

Arising from this brief overview of the LOCA problem, the areas worthy of future consideration in order to secure the position outlined in this paper are:

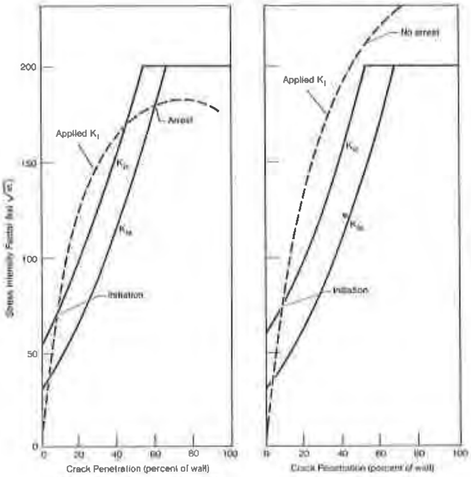
- Propagation of long cracks using an appropriate dynamic approach to confirm that a static analysis is sufficiently accurate; warm prestressing will then not be essential to the safety argument.

- Sensitivity study of the parameters in the model problem discussed in this paper, to see whether this paper's approach can be applied to a wider range of LOCA conditions.

6. CONCLUSIONS

- The K_{Ia} procedure based on the ASME Code provisions should be adequate for discussing the arrest of a crack in a pressure vessel during a hypothetical LOCA in a water-cooled nuclear reactor.

- Appropriate K_{Ia} values for use in the arrest analyses can be obtained from tests of the type being conducted within the ASTM sponsored SA533-B1 round-robin test program.



(a) Example of arrest configuration **(b) Example of non-arrest configuration**

Figure 1 Determination of critical flaw sizes for postulated condition (Reference [1])

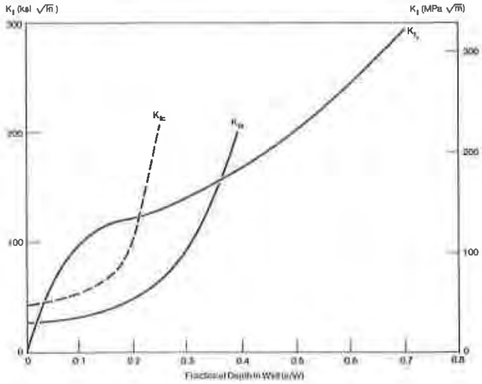


Figure 2 The critical levels for K_{Ic} and arrest K_{Ia} of a crack defined by the intersection of these curves with the K_I curve The curves refer to the behavior of a long axial flaw 450 s after the LOCA

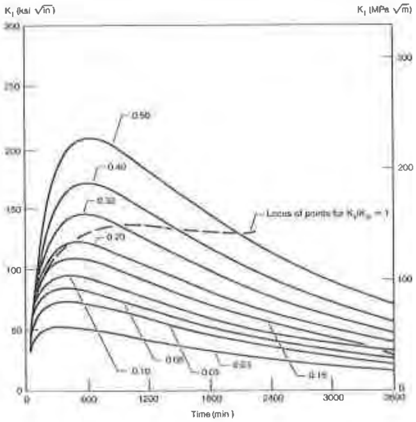


Figure 3 The stress intensity factor K_I versus time for different crack depths a/W. The dashed curve represents the locus of points at which the critical level K_{Ic} for initiation would be attained in the absence of warm prestressing (Reference [6])

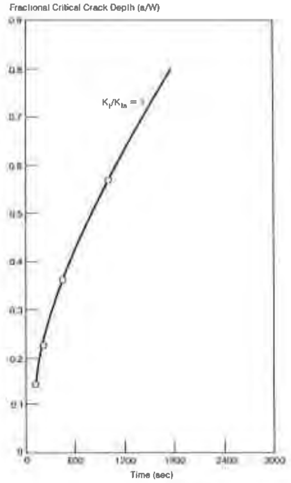


Figure 4 The arrested crack length as a function of time into the transient. (Reference [6])

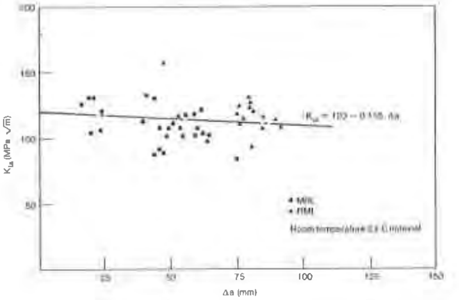


Figure 5 K_{Ia} for various crack jump lengths; results detained in the ASTM cooperative program

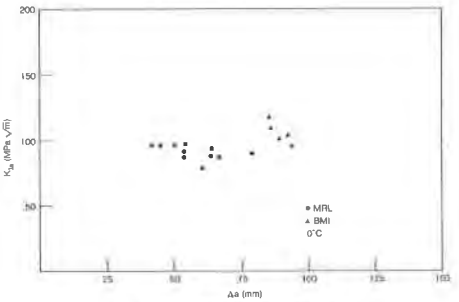


Figure 6 K_{Ia} for various crack jump lengths; results detained in the ASTM cooperative program

REFERENCES

1. ASME Boiler and Pressure Vessel Code, Section XI, Article A-5300, American Society of Mechanical Engineers, 1975.

2. Marston, T. U., Editor, "Flaw Evaluation Procedures - Background and Application of ASME Section XI Appendix A", Report NP-719-SR, Electric Power Research Institute, Palo Alto, CA, August 1978.

3. Krafft, J. M. and Irwin, G. R. in Fracture Toughness Testing and its Application, ASTM STP 381, American Society for Testing and Materials, 1965, p. 114.

4. Crosley, P. B. and Ripling, E. J. in Fast Fracture and Crack Arrest, ASTM STP 627, American Society for Testing and Materials, 1977, p. 203.

5. Hoagland, R. G., Rosenfield, A. R., Gehlen, P. C. and Hahn, G. T. in Fast Fracture and Crack Arrest, ASTM STP 627, American Society for Testing and Materials, 1977, p. 177.

6. Cheverton, R. D. ORNL/NUREG/TM-31, Oak Ridge National Laboratory, September 1976.

7. Shabbits, W. O. WCAP-7623, Westinghouse R&D Center, Pittsburgh, Pennsylvania, December 1970.

8. Shabbits, W. O., Pryle, W. H. and Wessel, E. T. WCAP-7414, Westinghouse R&D Center, Pittsburgh, Pennsylvania, December 1969.

9. Regulatory Guide 1.99, U.S. Nuclear Regulatory Commission, Office of Standards Development, Washington, D.C.

10. Loss, F. J., Gray, R. A. and Hawthorne, J. R. NRL/NUREG Rep. 8165, Naval Research Laboratory, Washington, D.C., September 1977.

11. Kalthoff, J. F. Paper presented at the ASME Pressure Vessel and Piping Conference, Montreal, Canada, June 1978, Proceedings to be published.

12. Rose, L. R. F. Int. Jnl. of Fracture, 12, 1976, p. 829.

13. Melville, P. H. Int. Jnl. of Fracture, 13, 1977, p. 165.

14. Eshelby, J. D. Int. Jnl. Mechs Phys. Solids, 17, 1969, p. 177.

15. Hahn, G. T. and Hoagland, R. G. Paper presented at the ASTM Philadelphia Conference on Crack Propagation and Arrest, November 1978.

16. Hoagland, R. G., Gehlen, P. C., Rosenfield, A. R. and Hahn, G. T. ASME Paper 78-Mat-16, 1978.

17. Hahn, G. T., Hoagland, R. G., Lereim, J., Markworth, A. J. and Rosenfield, A. R. Paper presented at the ASTM Philadelphia Conference on Crack Propagation and Arrest, November 1978.