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The Impact of Nondestructive Examination Unreliability on Pressure Vessel Fracture Predictions

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Operated by
Battelle Memorial Institute

Prepared for
U.S. Nuclear Regulatory
Commission

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ABSTRACT

This report reviews the significant variables of flaw depth, length, location and orientation required for fracture mechanics evaluations of pressure vessel integrity. Results of calculations are presented which emphasize pressurized thermal shock (PTS) and the significance of flaws located at or near the inside surface of the vessel. For PTS conditions, previous studies have shown that vessel failure probability is relatively insensitive to flaw depth. In this study the impact of flaw length is also evaluated, indicating the importance of fully characterizing all flaw dimensions by NDE. Results of other evaluations are presented, showing the importance of accurately locating flaws by NDE. The influence of vessel cladding is emphasized, with the relative significance of flaws through the clad and at various depths below the clad being addressed.

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INTRODUCTION

This report describes predictions of crack growth in pressure vessels performed as part of a program, "Integration of NDE Reliability and Fracture Mechanics," sponsored by the U.S. Nuclear Regulatory Commission. This work was performed at the Pacific Northwest Laboratory, which is operated by Battelle Memorial Institute for the U.S. Department of Energy. Data generated in the program are intended to provide a basis to formulate revisions to ASME Section XI Boiler and Pressure Vessel Code and regulatory requirements needed to assure low failure probabilities. The primary objective has been to determine the reliability of ultrasonic inservice inspection (ISI) as performed on commercial, light water reactor primary systems. This report concerns a second objective, which is to determine the impact of NDE (nondestructive evaluation) unreliability on system safety and to determine the level of inspection reliability required to assure a suitably low failure probability.

Preservice and inservice inspections are important factors in ensuring the safety of reactor pressure vessels. The objective of these inspections is to detect crack-like flaws that could grow when stresses are imposed on a vessel during reactor operation. Although flaws can occur at any location within the wall of a vessel, the detection of near-surface defects has become the primary focus of inservice inspections of reactor vessels (Taylor et al. 1983; Pedersen et al. 1982). Such defects have been termed "PTS type flaws", in reference to the concern for the rupture of reactor vessels during pressurized thermal shock (PTS) events. In this regard risk assessments have shown that PTS is perhaps the main potential contribution to risk from vessel failure. This report discusses the characteristics of PTS events and the role that inservice inspection can play in minimizing the probability of vessel failure from such events.

Vessel failure in a PTS scenario requires the simultaneous occurrence of all of the following factors (Cheverton, Iskander and Whitman 1983):

- tensile thermal stresses from the rapid cooling (e.g., 100°C per hour) of the inside surface of the vessel with prevailing internal pressures at a significant fraction of the normal operating pressure (e.g., 10 MPa or greater)
- a significant loss of fracture toughness near the vessel inner wall due to irradiation damage - this loss of toughness is a result of an upward shift in the ductile-brittle transition temperature of the ferritic steel of the vessel wall (e.g., RT_{NDT} in excess of 100°C). The current concern for embrittlement is greatest for welds in the beltline region of vessels, particularly for welds with high copper contents (e.g., 0.35 weight percent copper).

- the existence of a crack-like flaw in the highly stressed and embrittled region of the vessel wall.

Unless all three conditions coexist, the risk of vessel failure is minimal. Therefore, one would like to demonstrate with a high degree of confidence by inservice inspection that the critical regions of the vessel have no flaws. If no flaws exist, vessel failure is unlikely, even if embrittlement and rapid cooling occur. Unfortunately, the requirements for nondestructive examination (NDE) are demanding because evaluations have shown that flaws as small as 6 mm in depth can propagate through the vessel wall during the rapid cooling conditions of PTS type events.

In evaluations of risks from PTS, the existence of flaws in given vessels has been postulated although there is no evidence of such flaws in these vessels. A lack of sufficient confidence in NDE reliability has been the basis for postulating the presence of such flaws. In contrast, PTS type overcooling events have actually occurred on a number of occasions with an estimated frequency of one such event per 100 years of reactor operation (Dircks 1982). In addition, the irradiation embrittlement of vessel welds has been extensively studied. A comprehensive data base and methods for predicting embrittlement characteristics currently exist.

The traditional methods used in the United States for vessel inspection have not been designed to detect near-surface flaws. Efforts to apply improved NDE methods are now underway, particularly for those vessels that have the highest estimated levels of irradiation embrittlement. Consequently, the possibility of detecting defects during routine inservice inspection has increased for those vessels subjected to these enhanced levels of NDE. As the detection probability for near-surface flaws is increased, there is a corresponding need to accurately measure the size, location and orientation of the flaws that may be detected. At the inner surface of a vessel, such measurements are difficult because of the presence of weld deposited cladding of stainless steel (Woodridge, Allen and Denby 1982; Doctor 1983). The surface roughness of this cladding and the ultrasonic characteristics of the clad material itself are important factors. Efforts to date have been to improve detection of flaws in the ferritic vessel material just beneath the cladding. The presence of cracks in the clad itself or the possible continuation of underclad cracks into the clad metal is largely unevaluated with current field practice. For this reason, fracture mechanics calculations for postulated cracks have conservatively assumed that underclad cracks extend through the entire thickness of the clad to the very inner surface of the vessel.

The objective of the calculations described in this report is to apply fracture mechanics analyses to illustrate the relative consequences of cracks beneath and within the clad inside surface region of reactor vessels. The results show how errors in measuring the size, location and orientation can impact the subsequent fracture mechanics evaluation of these flaws. The results also show that conservative assumptions about flaw characteristics due to inadequate NDE measurements can lead to severe penalties in evaluation of the risks associated with flaws. Finally, the results of the analyses presented here are intended to encourage efforts to develop improved NDE methods so that the flaws of greatest significance to vessel integrity will be reliably detected and more accurately characterized.

FRACTURE MECHANICS APPROACH

All calculations presented in this report are based on the simplified methods of linear elastic fracture mechanics. This is consistent with the methodology used in other evaluations of PTS (Iskander, Cheverton and Ball 1981; Sauter, Cheverton and Iskander 1983; Smith 1983). Nevertheless, consideration of actual vessel geometry (e.g., presence of clad) and realistic flaw characteristics (finite length and depth) presents a challenge even to available linear elastic methods. Work at Oak Ridge National Laboratory[a] and elsewhere[b] has been directed toward improved solutions for crack-tip stress intensity factors and crack growth criteria that apply to flaws that are relevant to PTS concerns.

The approach taken in this study is to apply available fracture mechanics solutions whenever possible. Nevertheless, many flaw geometries of interest--in particular for underclad cracks--have not yet been treated in published solutions. In these cases, the superposition of "handbook" solutions for crack-tip stress intensity factors was used. The limitations of such approximations are recognized, and care was taken not to extrapolate results beyond the range where numerical errors would invalidate the trends and conclusions important to the objectives of this work. This section reviews the methods used in calculating crack-tip stress intensity factors, but does not attempt to fully document the methods or to evaluate their accuracy.

HEAT TRANSFER AND STRESS SOLUTIONS

The state of stress in the wall of an uncracked reactor vessel can be readily and accurately calculated with any number of well-known and documented computer codes. The first step is to calculate the temperature distribution through the vessel wall for the assumed time-dependent temperature of the coolant adjacent to the vessel wall. Then, a thermal stress solution is calculated for these through-wall temperature distributions and combined with stresses due to internal pressure.

(a) See Sauter, Cheverton and Iskander (1983); Smith (1983); Bass et al. (1982); and Bass and Bryson (1983).

(b) See Labbens, Pellissier-Tanon and Heliot (1976); Heliot, Labbens and Pellissier-Tanon (1978).

For surface flaws of finite length, the computer code VISA (Stevens et al. 1983) was applied for the heat transfer analyses, the stress calculations, and the subsequent calculations of crack-tip stress intensity factors. However, the VISA code does not consider the effect of cladding on heat transfer and thermal stresses. For these cases, the finite element computer program ANSYS (Swanson Analysis Systems, Inc. 1979) was applied. The cylincrical geometry of the vessel was modeled, with separate regions defined for the differing clad and base metal characteristics which affect the heat transfer and stress response. Both the VISA and ANSYS codes treated the effect of the surface heat transfer coefficient between the fluid and the inside surface of the vessel wall.

FINITE LENGTH SURFACE FLAWS

The computer code VISA utilizes an influence function approach to calculate stress intensity factors for "long" flaws at the ID surface of the vessel. The actual cylindrical geometry of the vessel is treated, along with the nonlinear variation of stress through the vessel wall. Flaws of finite length (e.g., semi-elliptical surface flaws) are not treated. For these cases, the solutions for the long flaws were corrected for finite length effects using an approach similar to that given in Appendix A, Section XI of the ASME Code (American Society of Mechanical Engineers 1983).

A compilation of solutions by Yukawa (1982) provided a basis for correction factors corresponding to situations of a uniform stress and a linear gradient of stress through the vessel wall. The factor for uniform membrane stress was applied to the pressure-induced stress intensity factor from VISA. The linear gradient factor was applied to the stress intensity factor due to thermal stresses. Results for this approximate method were compared to more exact results for a 6:1 length-to-depth flaw based on influence functions for the 6:1 flaw. The agreement was within 10 percent, which was adequate for the purpose of this study.

SUBSURFACE FLAWS

All subsurface flaw solutions, as well as consideration of clad effects, assumed long flaws. Furthermore, the cylindrical geometry of the vessel was approximated by a flat plate of equal thickness in calculations of stress intensity factors following the approach used in Appendix A, ASME Code Section XI. However, as previously stated, the stress analysis was based on the actual cylindrical geometry of the vessel.

The flat plate approximation limits the approach to flaws whose depth is a small fraction of the vessel wall. For depth fractions greater than 0.25 the errors in the solution are probably excessive. All data presented in this report are for flaws less than this depth. For the flaws of concern to PTS events, this range of solution validity is more than sufficient.

For consideration of clad effects and subsurface flaws, stress intensity factor results from Tada, Paris and Irwin (1983) were systematically applied. A computer program was written to combine their solutions and to compare crack-tip stress intensity factors with fracture toughness values.

Fracture toughness values were calculated from the reference curves in ASME Section XI (1983). The irradiated values of ductile brittle transition temperatures (RT_{NDT}) were calculated using the equations in Regulatory Guide 1.99 (U.S. NRC 1977). For subsurface flaws, results were generated for each of the two crack tips. One tip was at the point of maximum flaw depth and the other tip was at a location adjacent to the inside surface of the vessel. In all cases the tip nearest to the surface was critical, having the greater stress intensity factor and lower fracture toughness.

Details of the stress intensity factor calculations will not be described here. However, some of the features of the calculations were as follows:

- For cases where the flaw extended through the cladding to the ID surface, the solution for a point load on the crack surface was used as an influence function. Thus the stress distribution on the plane of the crack location was accurately treated. The only approximation was that of replacing the cylindrical vessel geometry with a flat plate.

- Surface proximity effects were treated for subsurface flaws. The effects of unequal ligament dimensions were treated accurately for the mean stress on the plane of the crack. Proximity effects were also treated for the variation of the actual stress state from this mean stress level using a point load solution as an influence function. However, the ligament widths were taken to be equal at a value equal to the minimum ligament width (distance from inside surface of vessel to innermost crack tip).

PRESSURIZED THERMAL SHOCK TRANSIENT

Fracture mechanics analyses were performed for a typical PTS accident and for a level of vessel embrittlement of concern to pressurized thermal shock risk. The specific parameters were selected to extend the scope of calculations in Sauter, Cheverton and Iskander (1983). The PNL study substantially increases the range of postulated flaws over that considered by Sauter and colleagues, with respect to greater variations in flaw dimensions, location and orientation.

VESSEL CHARACTERISTICS

Table 1 lists the parameters describing the vessel; Table 2 gives material properties used in the calculations. Both cladding and base metal properties are listed. The higher coefficient of thermal expansion for the stainless steel cladding relative to the base metal is an important factor. During

TABLE 1. Analysis Model Used for Calculations

Parameters	Values
Vessel dimensions	
Outside diameter	4800 mm
Inside diameter	4369 mm
Cladding thickness	6.1 mm
Copper concentration	0.35 wt%
Heat transfer coefficient	5700 $w/(m^2 K)$
Flaw type	Long, axial, inner surface
Flaw depth, fraction of wall (a/w)	0.0 to 0.25
K_{Ic} and K_{Ia}	ASME Code Section XI
RT_{NDT}	Regulatory Guide 1.99
Fracture mechanics analysis	Linear-elastic fracture mechanics

TABLE 2. Material Properties Used in Calculations

Properties	Base Metal	Cladding
Thermal conductivity, W/(m K) Btu/(h ft °F)	41.5 (24)	17 (9.8)
Specific heat capacity, J/kg K) Btu/(lb °F)	502 (0.12)	439 (0.105)
Density, kg/m^3 (lb/ft^3)	7833 (489)	7929 (495)
Coefficient of thermal expansion, K^{-1} ($°F^{-1}$)	14.4×10^{-6} (8×10^{-6})	18×10^{-6} (10×10^{-6})
Elastic Modulus, GPa (ksi)	193 (28×10^3)	193 (28×10^3)
Poisson's ratio	0.3	0.3

rapid cooling of the inside surface of the vessel, the cladding contracts at a higher rate than the underlying base metal. This induces enhanced tensile stresses in the cladding. These enhanced thermal stresses elevate the crack-tip stress intensity factors for flaws located in both the cladding and the base metal near the inside surface of the vessel.

Copper is the primary element in accelerating radiation-induced embrittlement in vessel welds. In the example of Table 1 the copper concentration of 0.35 percent was selected as an upper bound for copper in actual vessels. In addition, the RT_{NDT} predictions of Regulatory Guide 1.99 (U.S. NRC 1977) were also selected as an upper bound on the observed shift in ductile-brittle transition temperature.

The neutron fluence at the inner surface of the vessel wall was 2.0×10^{19} n/m^2. Attenuation of this fluence followed the law $f = f_o \exp(-ax)$, where f_o is the inner surface fluence, x is the depth below the surface (inches) and the constant a has the value of 0.33 $in.^{-1}$.

In all calculations, the vessel and cladding were assumed to be free of residual stresses at the reactor operating temperature (290°C). Because the irradiated toughness of cladding materials is not well known, the toughness of the cladding was conservatively assumed to be the same as the high copper base metal.

RANCHO SECO TRANSIENT

Figure 1 shows the pressure and temperature history for the 1978 Rancho Seco accident. This history is typical of a severe overcooling transient that has actually occurred in an operating reactor. Similar transients could occur in other pressurized water reactors in the future. In the Rancho Seco transient an instrumentation and control system failure led to an excessive cooldown rate for the vessel. The level of embrittlement in the Rancho Seco vessel was relatively low; thus, the overcooling presented little hazard to the vessel. Safety and regulatory requirements must assure that an embrittled and flawed vessel will not rupture, should it be subjected to such a cooling transient.

The curves of Figure 1 describe a "smoothed" version of the actual Rancho Seco transient. The cooling rate is sufficient to produce substantial levels of tensile thermal stress at the inside surface of the vessel, which are additive to the tensile stresses due to the sustained internal pressure. In an embrittled vessel, the temperature of the cooled inner surface of the vessel may drop into the low toughness temperature range if the inner surface of the vessel is severely irradiated. Thus, detection of flaws at the inner surface of the vessel is particularly important. Flaws at less severely stressed and embrittled portions of the vessel (mid-wall and outside portion of the wall) are of much less significance.

FLAWS OF INTEREST

Figure 2 depicts the types of cracks or flaws that are considered in the current fracture mechanics calculations. These flaws can be described as:

- axial surface flaws - The length of the flaw as well as its depth was considered to be a variable parameter. Most fracture mechanics evaluations of PTS events have focused on axial surface flaws but have emphasized very long flaws. In the PNL study, both long and short flaws were considered. The surface flaws were taken to extend through the entire thickness of the cladding and into the base metal.

- axial subsurface flaws - These flaws were considered to have variable depth, and to be located at various depths within the vessel wall. In some cases the flaw was entirely in the base metal, while in other cases the flaw was partly or entirely in the cladding. Many of the subsurface flaws depicted in Figure 2 were close to the vessel inner surface. These flaws would have been evaluated as surface flaws if the rules of ASME Section XI had been followed in the current calculations. However, for this study the surface proximity effects were treated in a realistic manner rather than by the conservative procedures of the ASME Code.

- flaws parallel to vessel surface - In this case the plane of the flaw was parallel, rather than normal, to the vessel surface. Thus, the flaw was not aligned with the high tensile hoop stresses in the vessel wall. This type of flaw has received little attention in evaluations of vessel integrity. However, such flaws might be detected during inservice inspection. Results of this study quantify the relative lack of significance of flaws that are parallel to the vessel surface.

RESULTS OF CALCULATIONS

Calculated stress intensity factors are presented in this section. All results are presented in the format of applied crack-tip stress intensity factor (K_I) as a fraction of the corresponding value of fracture toughness for initiation of crack growth (K_{Ic}). For surface flaws both K_I and K_{Ic} are presented for the point of maximum flaw depth rather than for the point at which the flaw intersects the inside surface of the vessel. The fracture toughness values include the fact that the toughness increases with depth into the wall of the vessel. This increase occurs because the metal temperature increases with depth. In addition, the vessel material becomes less embrittled with increasing depth due to attenuation of neutron fluence.

The actual values of the ratio K_I/K_{Ic} presented in this section are not particularly significant. Rather, attention should be directed to the relative impact of different flaw characteristics on this ratio. A ratio of K_I/K_{Ic} = 1.0 implies that flaw growth occurs and that catastrophic vessel rupture will occur if the growing crack is not arrested. However, the current

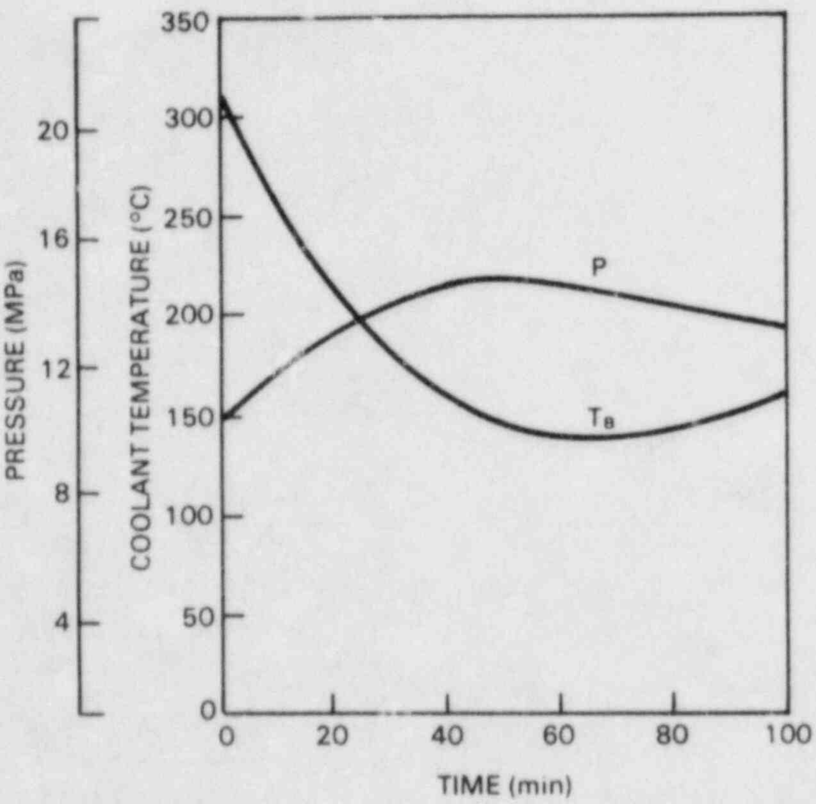

FIGURE 1. Temperature and Pressure Transients for Rancho Seco Accident (1978)

calculations have assumed a combination of worst-case conditions such as high copper content, upper bound shift in RT_{NDT}, and a severe, but low probability, PTS transient. Thus, the relatively high values of K_I/K_{Ic} imply a relatively low safety margin against vessel failure and relatively high probability of vessel failure for the given transient.

The usual emphasis in fracture mechanics evaluations has been on flaw depth and how it impacts inspection requirements. The results presented here reinforce the importance of flaw depth as a measure of flaw significance. However, the other flaw parameters (e.g., length, location and orientation) are also shown to be of great importance in determining the significance of a given flaw. In each case, the impact of uncertainties, errors and conservatisms in measuring these other parameters is related to equivalent errors in measuring the more familiar parameter of flaw depth.

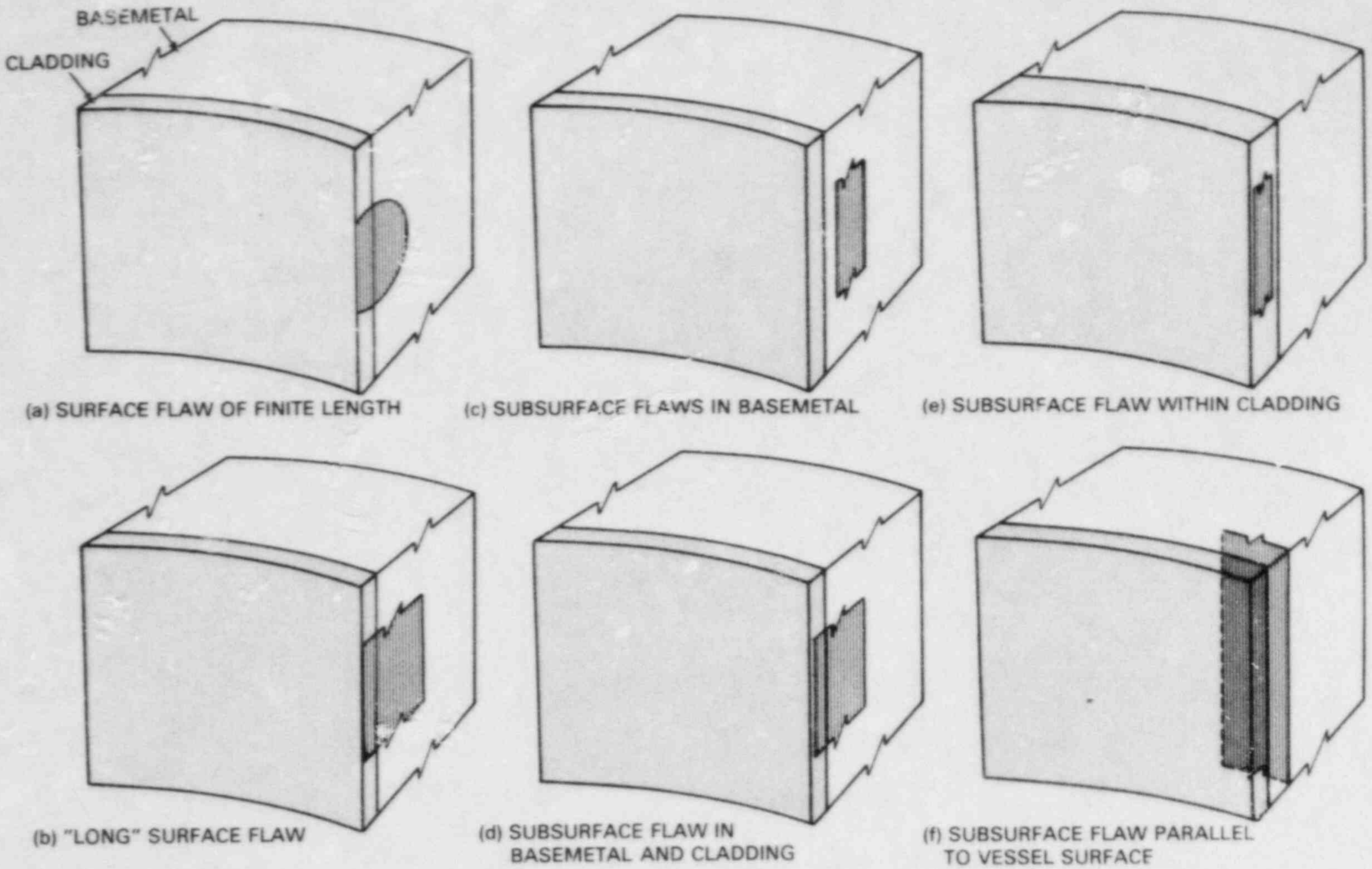

FIGURE 2. Flaws of Interest to Inservice Inspection and Pressure Vessel Integrity

EFFECT OF FLAW SHAPE

Figure 3 shows the variation of the ratio K_I/K_{Ic} for surface flaws as a function of both flaw depth and flaw length. Each curve corresponds to a given ratio of flaw length to flaw depth. All flaws have a semi-elliptical shape and extend through the cladding to the inside surface of the vessel. In these calculations the stress due to the different thermal expansion coefficient of the clad relative to the base metal was neglected. Also, the initiation of flaw growth was taken to be governed solely by conditions at the point of maximum flaw depth. It was assumed that the clad toughness was sufficiently high to prevent the initiation of lengthwise flaw growth at the vessel inside surface. However, the lengthwise flaw growth following initiation was assumed to be sufficient to maintain the aspect ratio of the flaw.

The range of variation of K_I/K_{Ic} with flaw length is about the same as the range of variation with flaw depth. This clearly shows the importance of characterizing flaw length. There are also benefits to be gained with NDE methods that have an increased detection capability for longer flaws. Furthermore, the treatment of all flaws as long in fracture mechanics evaluations may be overly conservative if NDE methods can accurately measure flaw length.

The impact of flaw length is dramatic if one compares the critical depth for a 2:1 (short) flaw with a 30:1 (long) flaw. A long flaw exceeds the critical K_I/K_{Ic} limit for a depth of less than 6 mm. In contrast, a very short flaw can be 10 times as deep or 25 percent of the wall and still not be as severe as a long flaw of only 6 mm depth.

EFFECT OF FLAW LOCATION

It has been customary in fracture mechanics evaluations to treat PTS type flaws as extending through the cladding to the inside surface of the vessel. In the calculations shown in Figure 4, the flaws have been treated as truly subsurface flaws that may or may not extend partly into the clad. The surface of the vessel was realistically taken at the actual inner surface of the cladding, rather than at the clad to base metal interface as is the practice in ASME code evaluations. Although in these calculations the flaws have been treated as long cracks, the effect of flaw location for finite length flaws should be similar to that seen in Figure 4.

Each curve in Figure 4 corresponds to a flaw with a given depthwise dimension, with each curve indicating how the ratio K_I/K_{Ic} decreases as the flaw is located at increasing depths within the wall of the vessel. A striking trend is the rapid increase in K_I/K_{Ic} as the flaws approach the inner surface of the vessel and begin to penetrate the cladding. This effect is due to the high tensile thermal stresses in the cladding relative to the corresponding thermal stresses in the base metal. In these calculations the cladding toughness was taken as equal to the base metal toughness. Therefore, the curves of Figure 4 indicate that cracks will grow further into the cladding more readily than they will grow deeper into the base metal.

Figure 4 also shows the relative severity of truly underclad cracks as a function of their location within the vessel wall. A crack just under the cladding is seen to be two or more times as severe (as measured by K_I/K_{Ic}) as the same size of crack at the quarter wall location.

Figure 4 also indicates requirements for flaw sizing. For flaws at the quarter wall location one can tolerate nearly four times the uncertainty in flaw sizing than that which is required for flaws near the cladding/base metal interface. However, flaws at this depth (exceeding 25 to 50 mm below the inside surface) are not likely to be detected by the UT methods currently applied in the U.S. for near-surface examination (Pade 1983). Methods used elsewhere (e.g., German practice) are capable of detecting flaws at such depths.

The results shown in Figure 4 suggest that the scope of improved inservice inspection should be expanded to examine depths up to and beyond the quarter wall location. Flaws at these depths, if of sufficient size, can impact vessel integrity under PTS conditions. Nevertheless, priority should continue to be given to detecting the near-surface flaws. These near-surface flaws have smaller critical sizes and thus are much more likely to occur in practice. Flaw size distributions indicate that the critical size of near-surface flaws is about ten times more likely to exist in practice than the larger size of critical flaws for the quarter wall location (Stevens et al. 1983).

FLAW EXTENSION INTO CLADDING

Figure 5 addresses the issue of underclad cracks extending into the cladding material. Current NDE methods as practiced in the field are not suited to detect or measure cracking in cladding. In particular, cracks solely in the cladding that do not extend through the cladding to the inside surface of the vessel are unlikely to be detected during inservice inspection by ultrasonic methods. Eddy current methods would be more suited to detecting cracks in cladding (Pigeon 1983). The results presented in Figure 5 emphasize two significant points:

1. Improved NDE methods could justify the elimination of conservative assumptions in fracture mechanics analyses. Reliable NDE measurements would be needed to show that detected cracks do not extend into the cladding.

2. Data that demonstrates a high level of the fracture toughness properties for weld deposited cladding would show that relatively deep underclad cracks can be tolerated (say 10 to 20 percent of the vessel wall). In effect, a very tough cladding material will prevent crack growth into the cladding and will reduce stress intensity factors for flaws within the vessel wall.

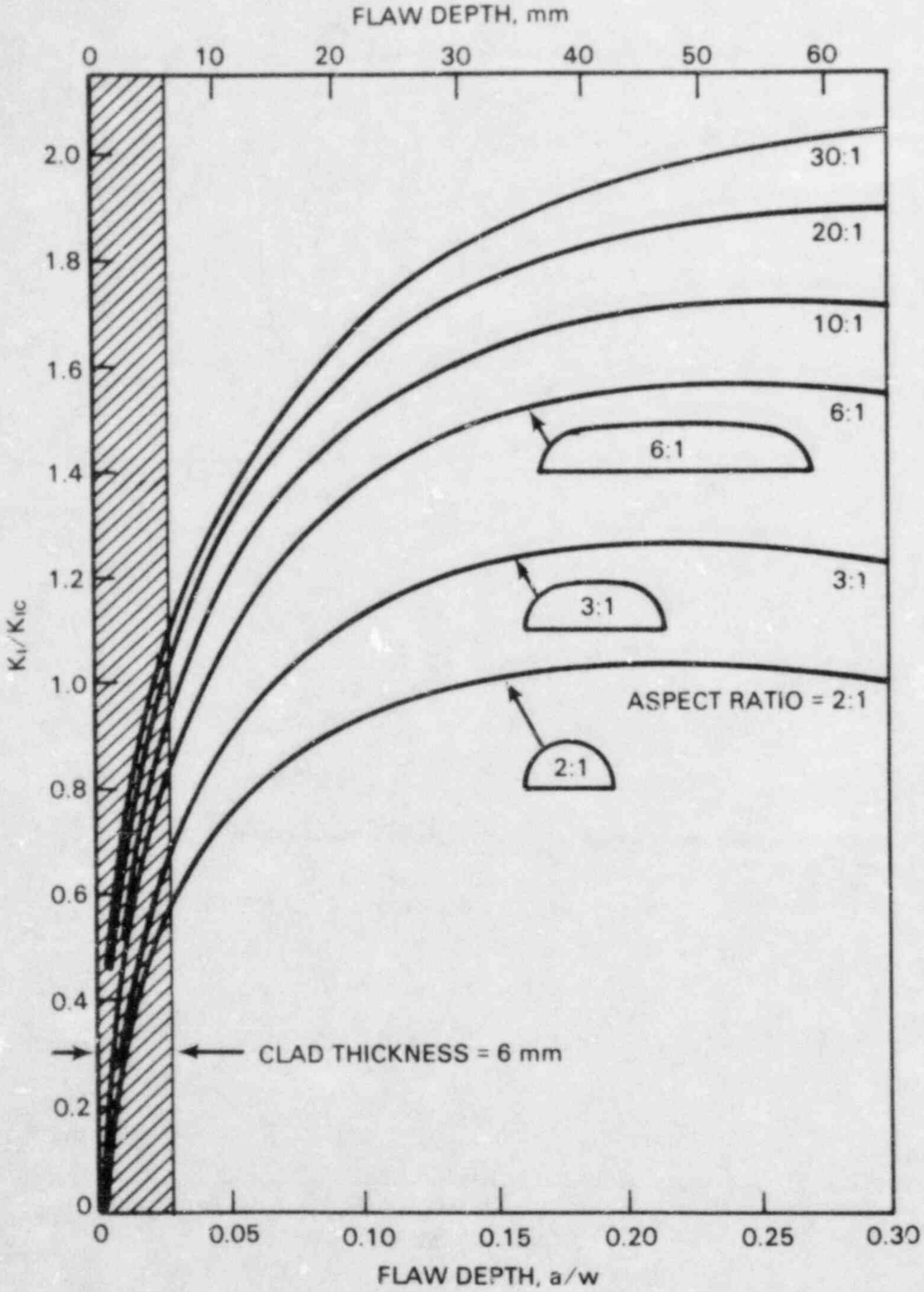

FIGURE 3. Effect of Surface Length on Fracture Evaluation

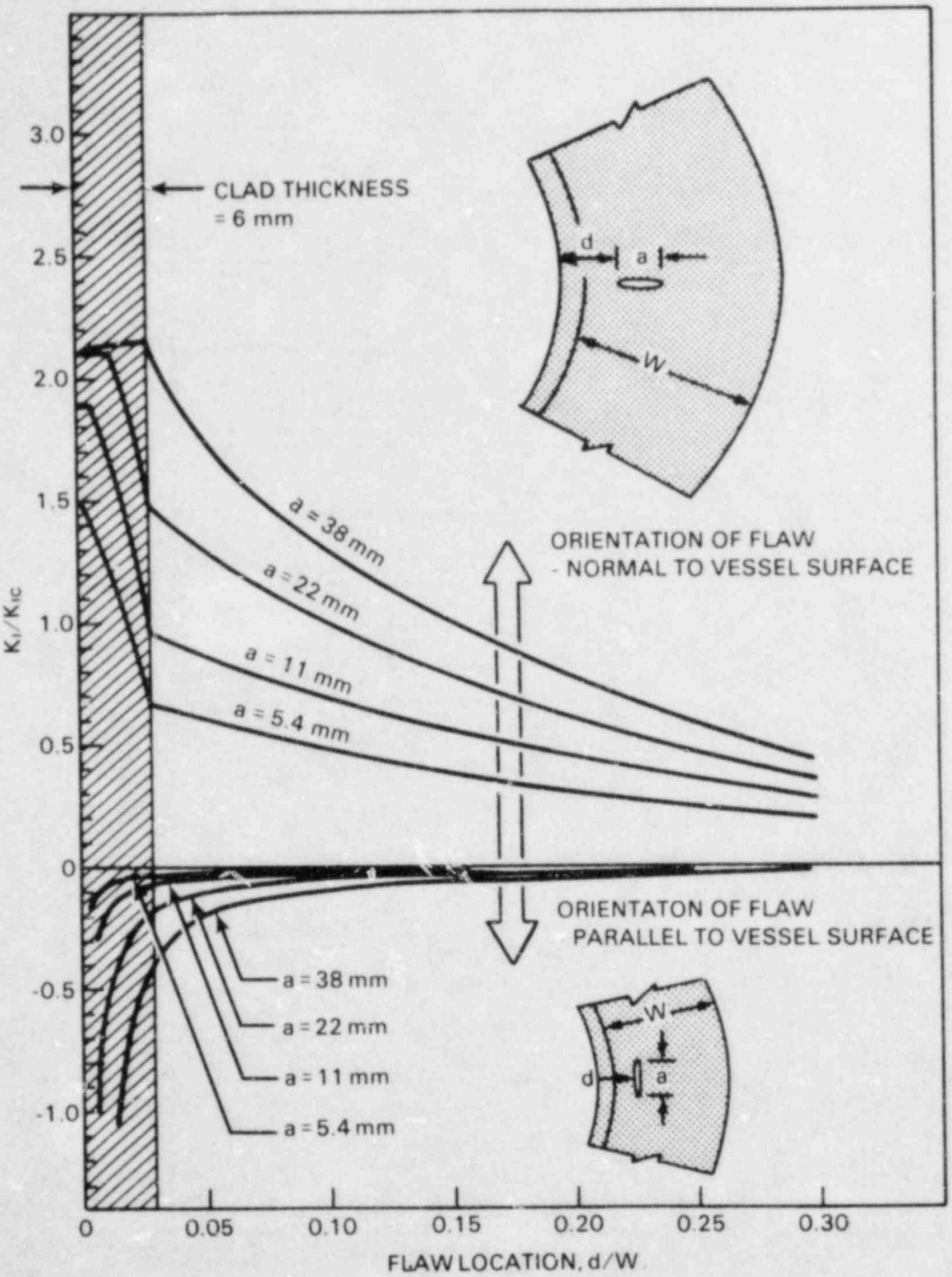

FIGURE 4. Effect of Subsurface Flaw Location and Orientation on Fracture Evaluation

Figure 5 shows three cases that correspond to different assumptions regarding penetration and propagation of cracks into cladding. Cases 1 through 3 represent an increasing level of cladding effectiveness in preventing the initiation and growth of flaws.

Case 1

This most pessimistic situation assumes that any cracks detected under the cladding also extend through the entire cladding to the inside surface of the vessel. Clearly, this case gives the highest values of K_I/K_{Ic} in Figure 5. For the severe vessel embrittlement and the severe cooling transient for the PNL analyses, the calculations actually predict that any crack entirely through the cladding will be of critical depth, even if it does not initially extend into the base metal.

Case 2

In Case 2, the crack does not initially extend into the cladding, but the cladding is assumed to be no tougher than the embrittled base metal. Figure 5 indicates a marked difference in severity of the subsurface Case 2 crack compared to the Case 1 through cladding crack. Reliable NDE for cracks in the cladding would justify a fracture mechanics analysis based on the Case 2 rather than the Case 1 assumptions. However, the state-of-the-art in NDE technology would probably require assuming that any detected underclad cracks extend through the clad. Figure 5 indicates that the penalty of this assumption is very severe.

Case 3

In this case, the fracture mechanics model assumes that cracks will not grow into the cladding because the cladding material is assumed to be very tough. For crack depths up to about 6 mm, the value of K_I/K_{Ic} is about the same at the two (inner and outer) tips of the crack. However, if the flaw depth exceeds 10 percent of the vessel wall thickness, the value of K_I/K_{Ic} at the cladding/base metal interface is substantially higher than the value at the crack-tip deeper into the vessel wall. Currently data on the toughness of irradiated cladding materials are insufficient to justify use of the Case 3 assumptions for fracture mechanics evaluations. Nevertheless, the trends of the Case 3 curve indicate a potential conservatism in current evaluations of pressure vessel failure due to PTS events.

EFFECT OF FLAW ORIENTATION

Fracture mechanics evaluations of flaws in vessels generally assume that the plane of the flaw is normal to the surface of the vessel. This is a worst-case assumption. Flaws oriented parallel to the surface of the vessel are generally excluded from concern. However, it is likely that many such flaws exist and could be detected during inservice inspection. Conclusive NDE measurements will have a major and favorable impact on the conclusions of fracture mechanics evaluations if the NDE data clearly show that a detected flaw has an orientation parallel to the vessel surface.

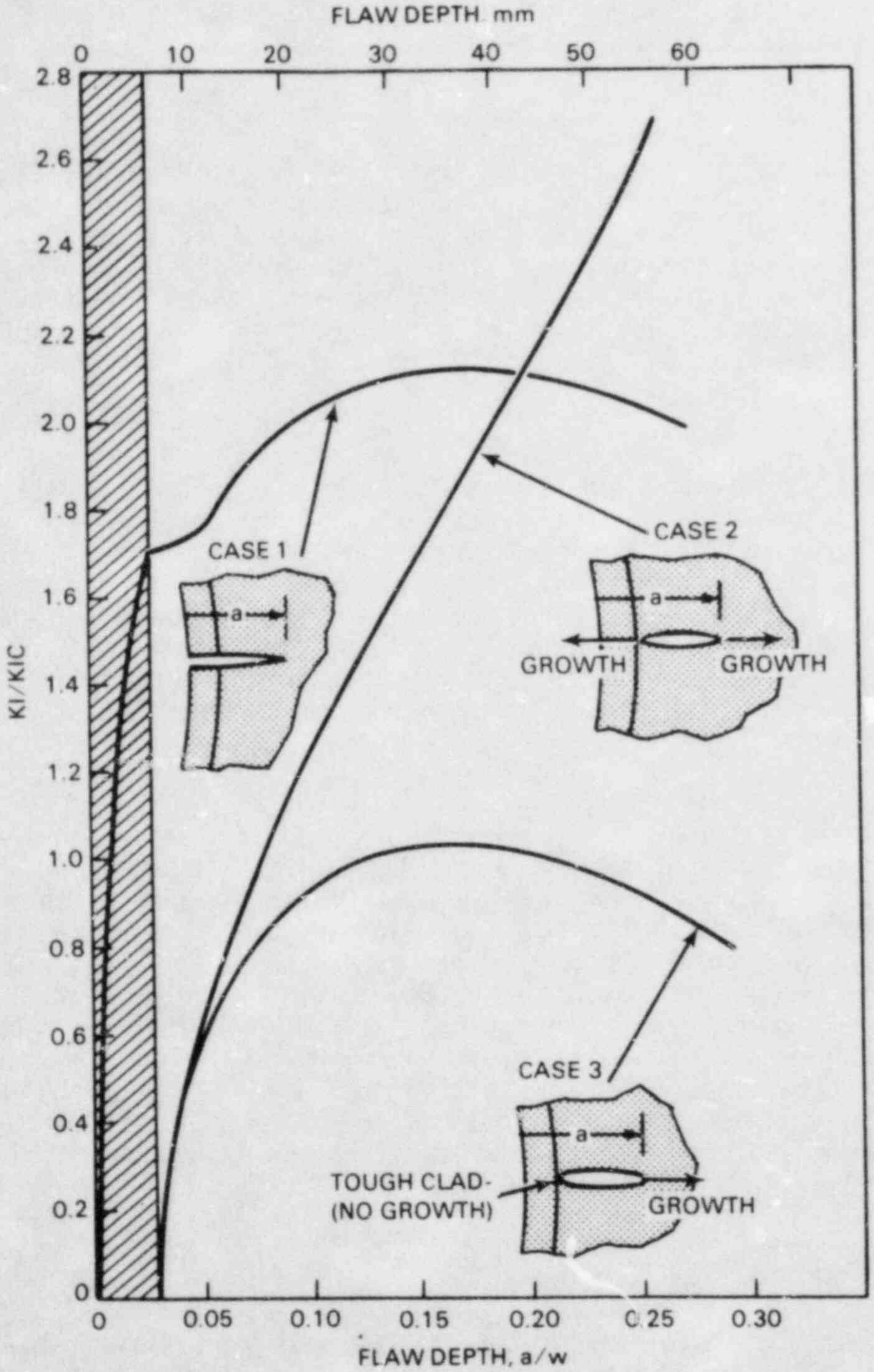

FIGURE 5. Effect of Cladding on Fracture Evaluation

Figure 4 shows fracture mechanics results for flaws that are parallel to the vessel surface. The lower set of curves for the parallel orientation are in sharp contrast to the upper set of curves, which apply to flaws with orientations normal to the vessel surface. The predicted values of crack-tip stress intensity factors are not only significantly lower for the flaws with the parallel orientation, but the calculated stress intensity factors are actually negative. This means that stresses during the PTS accident will tend to close such cracks and that there is no possibility that these cracks will grow in size. Notable in Figure 4 is the substantial closing action (i.e., $K_I/K_{Ic} << 0$) for flaws located within a clad thickness from the vessel inside surface. The effect is particularly large when the distance between the flaw and inside surface becomes small compared to the flaw size ($d/a << 1$ in Figure 4). For these flaws, the compressive radial stress from internal pressure acting on the inside surface of the vessel tends to close the cracks. The tensile radial stresses from thermal stress effects are relatively insignificant to this pressure-induced stress.

CONCLUSIONS

Fracture mechanics calculations can be applied to evaluate the impact of errors in measuring the size, location and orientation of flaws. Such evaluations can also guide the development of improved NDE methods that can be designed to detect the flaws of greatest significance to pressure vessel integrity. The calculations presented in this report support the following conclusions:

1. The importance of flaw depth measurements, as emphasized in current NDE practice, is reinforced by the results of fracture mechanics analyses.

2. It is also important to measure the length and location of flaws because these parameters can be as critical as depth in estimates of flaw severity.

3. Cracks with orientations parallel to the surface of the vessel are benign. It is thus important that NDE measurements provide a reliable characterization of flaw orientation so that the significance of detected flaws can be correctly evaluated.

4. Cladding has a significant effect on crack propagation. Flaws solely or partially in vessel cladding may be more significant than underclad cracks in the base metal of a vessel. It is important that NDE measurements reliably detect and size cracks in cladding to assure that fracture mechanics evaluations are based on realistic assumptions and inputs.

5. The most critical subsurface flaws are those near the clad/base metal interface. Priority should continue to be given to detecting and sizing such flaws.

6. Flaws located up to a quarter wall thickness from the vessel inside surface can also impact the integrity of vessels under thermal shock conditions. Such deeper flaws should not be neglected during inservice inspection. Improvements are required in existing practice to assure the detection and sizing of such deeper flaws. Further analyses should be performed to better define the region of examination and required detection capability. These analyses should consider a broader range of vessel embrittlement conditions and thermal shock transients.

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This report reviews the significant variables of flaw depth, length, location and orientation required for fracture mechanics evaluations of pressure vessel integrity. Results of calculations are presented which emphasize pressurized thermal shock (PTS) and the significance of flaws located at or near the inside surface of the vessel. For PTS conditions, previous studies have shown that vessel failure probability is relatively insensitive to flaw depth. In this study the impact of flaw length is also evaluated, indicating the importance of fully characterizing all flaw dimensions by NDE. Results of other evaluations are presented, showing the importance of accurately locating flaws by NDE. The influence of vessel cladding is emphasized, with the relative significance of flaws through the clad and at various depths below the clad being addressed.

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