

THE INTEGRITY OF PWR PRESSURE VESSELS
DURING OVERCOOLING ACCIDENTS*

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ABSTRACT

The reactor pressure vessel in a pressurized water reactor is normally subjected to temperatures and pressures that preclude propagation of sharp, crack-like defects that might exist in the wall of the vessel. However, there is a class of postulated accidents, referred to as overcooling accidents, that can subject the pressure vessel to severe thermal shock while the pressure is substantial. As a result of such accidents vessels containing high concentrations of copper and nickel, which enhance radiation embrittlement, may possess a potential for extensive propagation of preexistent inner surface flaws prior to the vessel's normal end of life.

For the purpose of evaluating this problem a state-of-the-art fracture mechanics model was developed and has been used for conducting parametric analyses and for calculating several recorded PWR transients. Results of the latter analysis indicate that there may be some vessels that have a potential for failure today if subjected to a Rancho Seco (1978) or TMI-2 (1979) type transient. However, the calculational model may be excessively conservative, and this possibility is under investigation.

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Nomenclature

| | |
|------------------------------------|--|
| a | crack depth |
| a/w | fractional crack depth |
| Cu | copper concentration (wt %) |
| E | neutron energy |
| F | fast neutron fluence at tip of flaw ($E \geq 1$ MeV) |
| F_0 | fast neutron fluence at inner surface of vessel |
| h_f | fluid film heat transfer coefficient |
| K_I | mode-I stress intensity factor |
| K_{Ia} | crack arrest toughness |
| K_{Ic} | crack initiation toughness |
| n | thermal decay constant |
| N_f | nickel concentration (wt %) |
| p | primary-system pressure |
| RTNDT | reference nil ductility temperature at crack tip |
| RTNDT ₀ | initial (zero fluence) RTNDT |
| RTNDT _s | RTNDT at inner surface of vessel |
| (RTNDT _s) _A | actual values of RTNDT _s for specific reactor vessels |
| (RTNDT _s) _C | critical value of RTNDT _s corresponding to crack initiation and/or vessel failure (no arrest) |
| Δ RTNDT | change in RTNDT due to radiation damage |
| t | time |
| t_{max} | duration of transient |
| T | temperature at crack tip |
| T_c | temperature of coolant in downcomer |
| T_i | initial temperature of coolant in downcomer and of pressure vessel |

T_f

final (asymptotic) temperature of coolant

w

wall thickness

THE INTEGRITY OF PWR PRESSURE VESSELS DURING OVERCOOLING ACCIDENTS

INTRODUCTION

The reactor pressure vessel in a pressurized water reactor (PWR) is normally subjected to temperatures and pressures that preclude propagation of sharp, crack-like defects (flaws) that might exist in the wall of the vessel. However, there is a class of postulated accidents, referred to as overcooling accidents (OCA's), that allow cool water to come in contact with the inner surface of the vessel wall, resulting in high thermal stresses and a reduction in fracture toughness near the inner surface. This introduces the possibility of propagation of preexistent inner-surface flaws, and this possibility increases with reactor operating time because of the additional reduction in fracture toughness that results from exposure of the vessel material to fast neutrons.

Thermal loading (thermal shock) by itself presumably cannot drive a flaw all the way through the wall; however, if the primary-system pressure is substantial, a potential for vessel failure could exist; that is, a pre-existent flaw, under proper circumstances, could penetrate the vessel wall and provide a large enough opening to prevent flooding of the reactor core. The nuclear industry has been aware of this problem for quite some time,^{1, 2, 3} but the probability of the existence of the requisite conditions for significant flaw propagation seemed very remote. In recent years, however, several PWR OCA initiating events have occurred,^{4, 5, 6} and there has^{also} been a growing awareness that copper and nickel significantly enhance radiation damage in the vessel.^{7, 8} As a result a reevaluation of the integrity of PWR pressure vessels during OCA's has been undertaken.

A complete evaluation of the OCA problem in terms of its threat to pressure vessel integrity requires consideration of a number of factors,

including postulated accident initiating events, reactor system and operator response to these events, specific design features of the reactor vessel and core that affect fluence-rate and coolant-temperature distributions adjacent to the inner surface of the vessel wall, sensitivity of the vessel material to radiation damage, size and orientation of preexistent flaws, and remedial measures. This paper examines primarily the fracture-mechanics-related conditions that could lead to a potential for vessel failure.

THE TENDENCY FOR INNER-SURFACE FLAWS TO PROPAGATE DURING THERMAL-SHOCK LOADING ONLY

The tendency for inner-surface flaws to propagate as a result of thermal-shock loading is illustrated in Fig. 1, which shows the temperature, resultant thermal stress, and fracture toughness distributions through the wall of the vessel (exclusive of cladding) at a particular time during a postulated large-break loss-of-coolant accident (LBLOCA). Also included in the figure for the same time in the transient are the stress intensity factors (K_I) for long axial flaws of different depths and the radial distribution of the fast neutron fluence. As indicated, the positive gradient in temperature and the steep attenuation of the fluence result in positive gradients in the crack initiation toughness (K_{Ic}) and the crack arrest toughness (K_{Ia}), and these positive gradients tend to limit crack propagation. However, K_I for the assumed long axial flaw also increases with flaw depth, except near the back surface, and for the particular case and time analyzed it is evident that both shallow and deep flaws can initiate; that is, $K_I \geq K_{Ic}$ for a broad range of crack depths. As the crack tip moves through the wall it encounters higher toughness material and for this particular case eventually arrests.

If the crack depths corresponding to the initiation and arrest events are plotted as a function of the times in the transient at which the events take place, a set of curves referred to as the critical-crack-depth curves is obtained that indicates the behavior of the flaw during the entire transient. A typical set of critical-crack-depth curves for a LBLOCA is shown in Fig. 2. As indicated by the dashed lines the long axial flaw would propagate in a series of initiation-arrest events and, if a phenomenon referred to as warm prestressing were not effective, would penetrate deep into the wall.

Warm prestressing, as referred to above, is a term used to describe a situation where K_I is decreasing with time^(t) when K_I becomes equal to K_{IC} by virtue of a decrease in temperature. It has been postulated⁹ and demonstrated experimentally^{9,10} that under these conditions a flaw will not propagate; that is, a flaw will not initiate while K_I is decreasing. In Fig. 2 the WPS curve is the locus of points for $K_I = (K_I)_{max}$ ($dK_I/dt = 0$). To the left of the WPS curve $dK_I/dt > 0$ and thus crack initiation can take place; but to the right of the WPS curve $dK_I/dt < 0$, and crack initiation will not take place. For the particular case illustrated in Fig. 2, WPS limits crack propagation to ~40% of the wall thickness.

Even if WPS were not effective, the flaw could not completely penetrate the wall under thermal-shock loading conditions only. This is a result of the substantial decrease in K_I as the crack tip approaches the outer surface (see Fig. 1) and has been demonstrated recently in a thermal-shock experiment.¹¹ However, when pressure is applied in addition to the thermal loading, the possibility of vessel failure (complete penetration of the wall) exists for some assumed conditions.

FRACTURE MECHANICS CALCULATIONAL MODEL

Linear elastic fracture mechanics (LEFM)¹² has been used thus far to analyze the behavior of a flaw during the postulated overcooling accidents. The initial flaw was assumed to be quite long on the vessel surface, to be oriented either in an axial or circumferential direction and to extend radially through the cladding into the base material. The thin layer of stainless steel cladding on the inner surface was included as a discrete region, in which case its effect on temperature and stress and thus K_{Ic} , K_{Ia} , and K_I were accounted for.

Fracture toughness data (K_{Ic} and K_{Ia} vs $T - RTNDT$, where T is the temperature and $RTNDT$ is the reference nil ductility temperature) were taken from ASME Section XI,¹³ and the reduction in toughness due to radiation damage was estimated using equation 1, which was recently tentatively proposed by Randall⁸ as a revision to Reg. Guide 1.99, Rev. 1.¹⁴

$$\Delta RTNDT = f(Cu, Ni, F) \propto (F)^{0.27}, \quad (1)$$

where.

$$2 \times 10^{17} \leq F \leq 6 \times 10^{19} \text{ neutrons/cm}^2$$

$\Delta RTNDT$ = change in $RTNDT$ at tip of flaw due to fast neutron exposure,

Cu, Ni = copper and nickel concentrations, wt %

F = fast neutron fluence ($E \geq 1$ MeV) at tip of flaw

A typical attenuation of the fluence through the wall of the vessel that includes a correction for the effect of displaced atoms (DPA) on radiation damage was also recently proposed by Randall⁸ and is being used in the ORNL studies. The relation is

$$F = F_0 e^{-0.0094a \text{ mm}^{-1}}, \quad (2)$$

where

F = fast neutron fluence at tip of flaw

F_0 = fast neutron fluence at inner surface of vessel

a = depth of flaw

It is of interest to note that the use of Eq. 1 as opposed to Reg Guide 1.99, Rev. 1, and the inclusion of the effects of DPA in the fluence attenuation equation result in relatively greater estimated values of radiation damage ($\Delta RTNDT$) deep in the wall of the vessel.

For some postulated OCA's, following crack initiation the tip of the fast-running crack will encounter upper-shelf-toughness temperatures prior to crack arrest, as illustrated in Fig. 3. Since techniques are not yet well established for evaluating flaw behavior under these conditions, it was assumed that crack arrest would not occur if K_I was above an arbitrary upper-shelf toughness value of $220 \text{ MPa} \sqrt{\text{m}}$ prior to a calculated arrest event.

The procedure used for evaluating the integrity of a pressure vessel was to calculate, using the above model, the threshold or critical values of RTNDT corresponding to incipient initiation (II) of a flaw and incipient failure (IF) of the vessel (extension of the flaw through the wall) and then compare these critical values with the estimated actual values for a particular PWR pressure vessel. To obtain the critical values of RTNDT it is necessary to specify a transient, the fracture-mechanics model, a failure criterion and an initial (zero fluence) value of RTNDT ($RTNDT_0$), although the results are not very sensitive to the latter parameter. To obtain the actual value of RTNDT for a specific plant it is necessary to have a consistent set of values for the fluence, Cu, Ni and $RTNDT_0$ that corresponds to an area of the vessel wall that is most likely to experience propagation

of a flaw; that is, the area in which the worst combination of the four parameters exists.

For convenience the particular values of RTNDT that are compared with each other are the values corresponding to the inner surface of the vessel wall, using material properties for the base material rather than for the cladding. These values of RTNDT are referred to herein as $(RTNDT_s)_c$, the critical value, and $(RTNDT_s)_A$, the actual value.

The critical value of RTNDT is the minimum value, with respect to both time in the transient and crack depth, that results in $K_I = K_{IC}$ and/or crack penetration of the wall (no arrest). Since $K_{IC} = f(T, RTNDT_o, \Delta RTNDT)^{13}$ only, where T is the temperature at the crack tip, it is only necessary to determine these three parameters and K_I to perform the analysis. Values of $\Delta RTNDT$ are calculated from Eq. 3, which was obtained by combining Eqs. 1 and 2.

$$\Delta RTNDT = \Delta RTNDT_s e^{-2.54 \times 10^{-3} a \text{ mm}^{-1}} \quad (3)$$

The complete analysis for obtaining $(RTNDT_s)_c$ was performed with the computer code OCA-II,¹⁵ which accepts as input the downcomer-coolant-temperature and primary-system-pressure transients and automatically searches for $(\Delta RTNDT_s)_c$. For some OCA's, $(\Delta RTNDT_s)_c$ corresponds to incipient initiation followed by crack arrest and no reinitiation, as shown in Fig. 4 assuming WPS to be ineffective. However, increasing $\Delta RTNDT_s$ will eventually result in failure (no arrest), and the corresponding minimum value is $(\Delta RTNDT_s)_c$ for incipient failure. For other OCA's, $(\Delta RTNDT_s)_c$ corresponds to both incipient initiation and incipient failure because, as shown in Fig. 5, there is no arrest following initiation of a shallow flaw.

This latter situation tends to be typical of high-pressure transients and the former of low-pressure transients.

The sets of critical-crack-depth curves in Figs. 4 and 5 include the locus of points for constant values of K_I . This allows one to determine if arrest takes place in accordance with a maximum specified value for K_{Ia} (220 MPa \sqrt{m} for these studies). In Fig. 4 it does and in Fig. 5 it does not.

The existence of two initiation loops (locus of points for $K_I = K_{Ic}$) in Figs. 4 and 5 suggests additional criteria for calculating $(\Delta RTNDT_s)_c$. One is a reasonable range of depths for initial flaws, and the other is the duration of the transient (t_{max}). For the cases depicted by Figs. 4 and 5, specification of a maximum initial fractional flaw size of 0.15 made a difference, because for lower values of $\Delta RTNDT_s$ the small initiation loop (actually just a point for incipient initiation) would disappear, and $(\Delta RTNDT_s)_c$ would be determined by the other initiation loop in accordance with some other criteria such as a greater critical flaw depth.

EVALUATION OF THE FM MODEL

The validity of LEFM for application to thermal-shock problems has been verified in a series of thermal-shock experiments with thick-wall steel cylinders.^{10,11,16} These experiments were designed to exhibit flaw behavior trends calculated to exist during OCA's and thus included initiation and arrest of long axial shallow and deep flaws, a stepwise progression of the flaw deep into the wall, arrest in a rising K_I field ($dK_I/da > 0$) and WPS with $dK_I/dt < 0$. There are still some areas of uncertainty, but in each of these areas the FM model described above is believed to be conservative. The degree of conservatism is not known at this time, but programs are underway to obtain such information. The presumed conservative features_A include ^{in the model}

7a

(1) consideration of long flaws that extend through the cladding, (2) no arrest on the upper shelf, and (3) to some extent a disregard for the beneficial effects of warm prestressing. Long surface flaws have a greater potential than others for penetrating deep into the wall, but the probability of a long flaw existing as an initial flaw and of any length flaw extending through the cladding presumably is very small. One justification

for assuming long flaws was that under thermal-shock loading conditions and in the absence of cladding short flaws tend to extend on the surface to become long flaws.¹⁷ However, it may be that the cladding will prevent short flaws from extending on the surface and if so would limit radial growth of the flaw.¹⁸

If long flaws through the cladding must be considered, there is still the possibility that the tearing resistance of the material will be sufficient to permit arrest on the upper shelf, and it is also possible that WPS effects in addition to the one mentioned earlier will help to limit flaw propagation. For instance, Fig. 6, which compares K_I and K_{IC} for a particular crack depth during a postulated transient involving ^{loss of pressure and then} repressurization, indicates two types of WPS. During normal operation of the reactor, ($t < 0$), the material toughness corresponds to upper shelf conditions and K_I is relatively low, as indicated. The transient starts at time zero, and as it progresses K_I becomes equal to K_{IC} , but only after K_I has begun to decrease with time. Thus, crack initiation would not take place even though K_I becomes substantially greater than K_{IC} . When repressurization finally takes place, K_I increases with time again, but WPS experiments conducted by Loss, Grey and Hawthorne⁹ indicate that because of the particular thermal and loading history that the stationary flaw was exposed to the effective value of K_{IC} would be elevated, perhaps to a value equal to the previous maximum value of K_I . Thus, presumably some repressurization would be possible, but this particular beneficial effect on WPS was not included in the FM model. There is also some hesitancy at this time to take advantage of WPS with $dK_I/dt < 0$ because there is no assurance that dK_I/dt will remain negative.

OCA PARAMETRIC ANALYSIS

To obtain a better understanding of the sensitivity of $(RTNDT_s)_c$ to the many parameters involved in an OCA FM analysis, a parametric study was conducted, assuming an exponential decay of the downcomer coolant temperature and a constant pressure. The temperature transient is expressed as

$$T_c = T_f + (T_i - T_f)e^{-nt} \quad (4)$$

where

T_c = downcomer coolant temperature

T_i = initial temperature of vessel wall and coolant

T_f = final (asymptotic) temperature of coolant

n = decay constant

t = time in transient

The fluid-film heat transfer coefficient, (h_f) , which is a necessary input to OCA-II, was assumed to be independent of time and for most cases was assigned a value that is achieved with the main circulating pumps running ($5680 \text{ W}\cdot\text{m}^{-2}\cdot\text{°C}^{-1}$). In order to determine the sensitivity of $(RTNDT_s)_c$ to h_f a relatively low value corresponding to natural convection cooling (1700) was also used for a few calculations.

A list of pertinent input data for the parametric analysis is included in Table 1, and a summary of results of the analysis is presented in Fig. 7, which shows the relation between $(RTNDT_s)_c$ and pressure (p) for $RTNDT_0 = -7^\circ\text{C}$ and for several values of T_f and n , ignoring the beneficial effects of WPS. The dashed lines in Fig. 7 correspond to both incipient initiation (II) and incipient failure (IF), the latter corresponding to no crack arrest following initiation. The solid line corresponds to II only; however, only a small increase in $RTNDT_s$ is required for failure, except as the pressure approaches

zero. As already mentioned, thermal shock alone will not drive the flaw completely through the wall.

The results in Fig. 7 show that at high pressure and for $n \geq 0.030 \text{ min}^{-1}$, $(RTNDT_s)_c$ is insensitive to the rate at which the coolant temperature decreases; and for the highest pressure considered (17.2 MPa, which is approximately the safety-value setting) it was found that over the range of T_f values considered (66-149°C)

$$(RTNDT_s)_c = 1.10 T_f - 22^\circ\text{C} \quad (5)$$

Equation 5 might be used for obtaining a conservative maximum permissible value of $RTNDT_s$ by specifying a reasonable minimum value of T_f . Suppose such a value of T_f is 120°C. Then the maximum permissible value of $RTNDT_s$ would be $\sim 110^\circ\text{C}$.

The sensitivity of $(RTNDT_s)_c$ to $RTNDT_o$ was found to be rather small ($\sim 3^\circ\text{C}$) over the range of $RTNDT_o$ values considered. Furthermore, the sensitivity to t_{\max} and h_f over the range of 1 to 2 hrs and 1700 to 5680 $\text{W}\cdot\text{m}^{-2}\cdot^\circ\text{C}^{-1}$, respectively, was found to be small except for a few cases involving a sensitivity to t_{\max} as shown in Table 2. For very slow transients ($n = 0.015 \text{ min}^{-1}$), $(RTNDT_s)_c$ decreased significantly with the decrease in t_{\max} . Of course for cases where II takes place prior to 1 hr (see Figs. 4 and 5), changing t_{\max} from 2 to 1 hr would make no difference.

ANALYSIS OF SEVERAL RECORDED PWR OCA'S

Several PWR OCA's have occurred in recent years, and recordings of the pressure and temperature transients have been used as input to fracture-mechanics analyses, using the FM model described herein. The temperature transients were measured upstream of the injection point for the emergency core coolant and thus do not necessarily reflect the temperature of the

coolant in the downcomer. However, in the absence of more accurate data the recorded transients were used so as to obtain some indication of the severity of actual OCA's in terms of pressure vessel integrity.

The accidents analyzed and the results obtained are shown in Table 3. The values of $(RTNDT_s)_c$ correspond to either incipient initiation followed by crack arrest and no reinitiation or to incipient initiation and failure, as indicated. WPS was ignored, and the imposed limits on critical fractional crack depth were 0.025 to 0.15, the lower limit disallowing crack initiation in the cladding. Because copper and nickel concentrations can be very much different in the circumferential and axial welds, $(RTNDT_s)_c$ was calculated for both crack orientations for the plate-type vessels.

Estimates of $(RTNDT_s)_A$ are not yet available for the specific pressure vessels involved. However, a preliminary estimate¹⁴ for nearly all of the existing PWR vessels indicates that there are five vessels with values of $(RTNDT_s)_A$ in the range of 135–149°C. Thus, the analysis indicates that at least one of these five unidentified vessels would have a potential for failure today, if the facility were subjected to a Rancho Seco or TMI-2-type OCA.

SUMMARY

A state-of-the-art fracture-mechanics model has been developed that is based on LEFM, includes recent modifications to the radiation-damage trend curves and the fluence attenuation curve, and is believed to be conservative. The results of an OCA parametric analysis indicate that crack propagation will not take place under the most severe accident conditions if $RTNDT_s < 1.10 T_f - 22^\circ\text{C}$, and it was determined that this relation was not sensitive to $RTNDT_0$, h_f or the assumed duration of the transient over a reasonable range of values.

A fracture-mechanics analysis was also performed for several PWR recorded OCA's, and it was determined, based on preliminary estimates of actual values of $RTNDT_s$ for existing PWR vessels, that a few vessels may have a potential for failure today if subjected to ^{the} 1978 Rancho Seco or TMI-2 type transients.

Presumed conservatisms in the fracture-mechanics model are associated with arrest on the upper shelf, the effects of cladding on surface extension of short flaws and warm prestressing. These areas are being investigated to determine the degree of conservatism and ^{to} see if the model can be modified to remove excessive conservatism, should it exist.

ACKNOWLEDGMENTS

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Table 1. Input data for parametric analysis

| | |
|---|---|
| Vessel dimensions, mm | |
| Outside diameter | 480 |
| Inside diameter | 4370 |
| Cladding thickness | 5.4 |
| Flaw type | Long, axial, inner surface, extending through cladding |
| T_i , °C | 288 |
| T_f , °C | 66, 93, 121, 149 |
| n , min ⁻¹ | 0.015 - ∞ |
| t_{max} , hr | 2, 1 ^a |
| h_f , W·m ⁻² ·°C ⁻¹ | 5680, 1700 ^a |
| p , MPa | 0-17.2 in 1.72 increments |
| RTNDT ₀ , °C | -29, -7, 4 |

^aUsed in a few cases for comparison purposes.

Table 2. Effect of h_f and t_{max} on critical values of $\Delta RTNDT_s$ corresponding to II without WPS

| Case | | | $(\Delta RTNDT_s)_c, ^\circ C$ | | | |
|------------|------------|------|---|--------|--------|--------|
| T_f | n | p | $h_f, W \cdot m^{-2} \cdot ^\circ C^{-1} / t_{max}, hr$ | | | |
| $^\circ C$ | min^{-1} | MPa | 5680/2 | 1700/2 | 5680/1 | 1700/1 |
| 66 | 0.015 | 3.4 | 152 | 157 | 196 | 208 |
| 66 | 0.015 | 17.2 | 101 | 107 | 163 | 173 |
| 66 | 0.15 | 3.4 | 79 | 95 | 79 | 95 |
| 66 | 0.15 | 17.2 | 58 | 61 | 61 | 71 |
| 149 | 0.015 | 3.4 | >220 | >220 | >220 | >220 |
| 149 | 0.015 | 17.2 | 177 | 181 | 216 | >220 |
| 149 | 0.15 | 3.4 | 180 | 194 | 180 | 194 |
| 149 | 0.15 | 17.2 | 151 | 153 | 151 | 157 |

Table 3. Values of $(RTNDT_s)_c$ for several recorded PWR OCA'S

| Plant (date) | $(RTNDT_s)_c$ w/o WPS, °C | |
|-----------------------|---------------------------|---------|
| | flaw orientation | |
| | Long. | Cir. |
| H. B. Robinson (1970) | 321 (F) ^a | 351 (A) |
| H. B. Robinson (1972) | 380 (F) | >480 |
| H. B. Robinson (1975) | 354 (F) | 372 (A) |
| Rancho Seco (1978) | 295 (F) | 329 (A) |
| TMI-2 (1979) | 209 (F) | 256 (F) |
| R. E. Ginna (1982) | — | 378 (F) |

^aA and F in parentheses indicate arrest (with no reinitiation) and failure

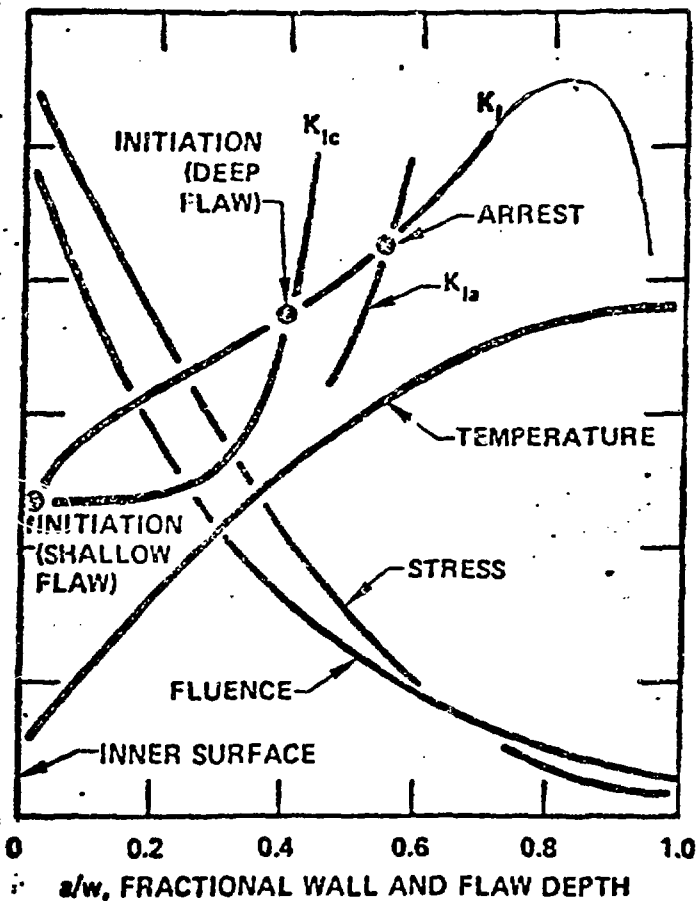


Fig. 1. Radial distributions in a vessel wall of several fracture-mechanics related parameters at a specific time during a PWR LOCA.

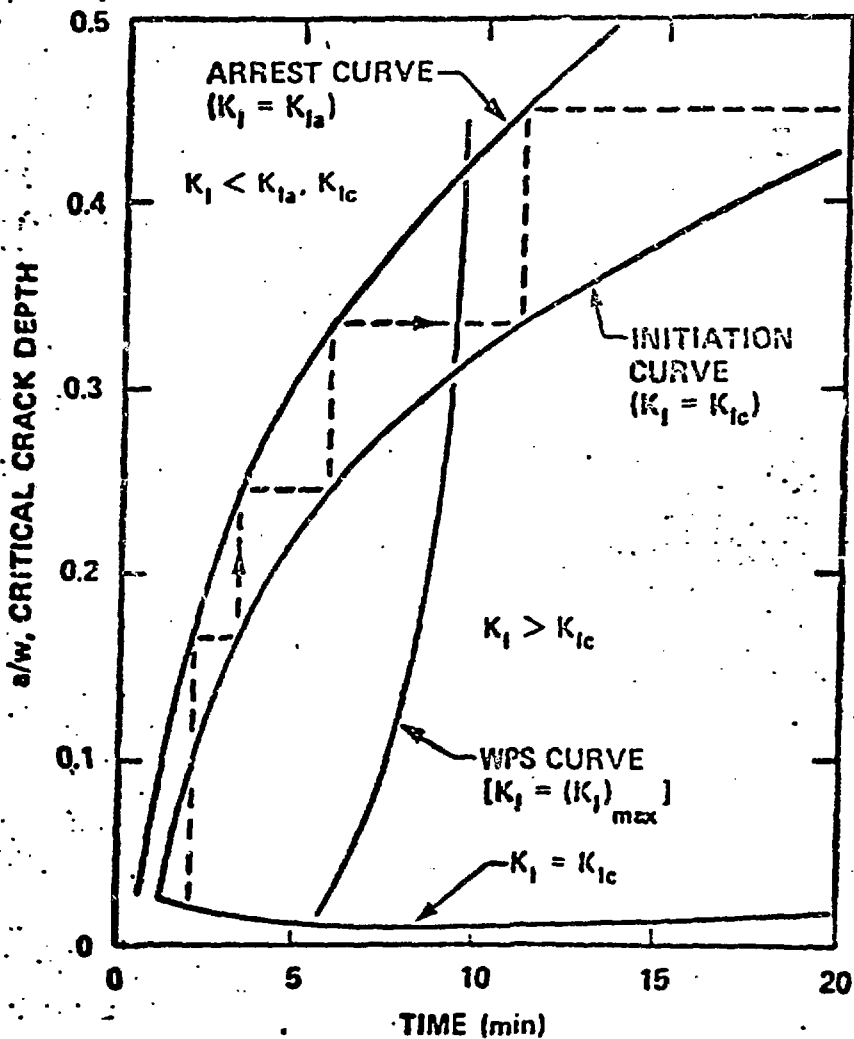


Fig. 2. Critical-crack-depth curves for a PWR LOCA assuming a long axial flaw, high concentrations of copper and nickel, and normal end-of-life fluence.

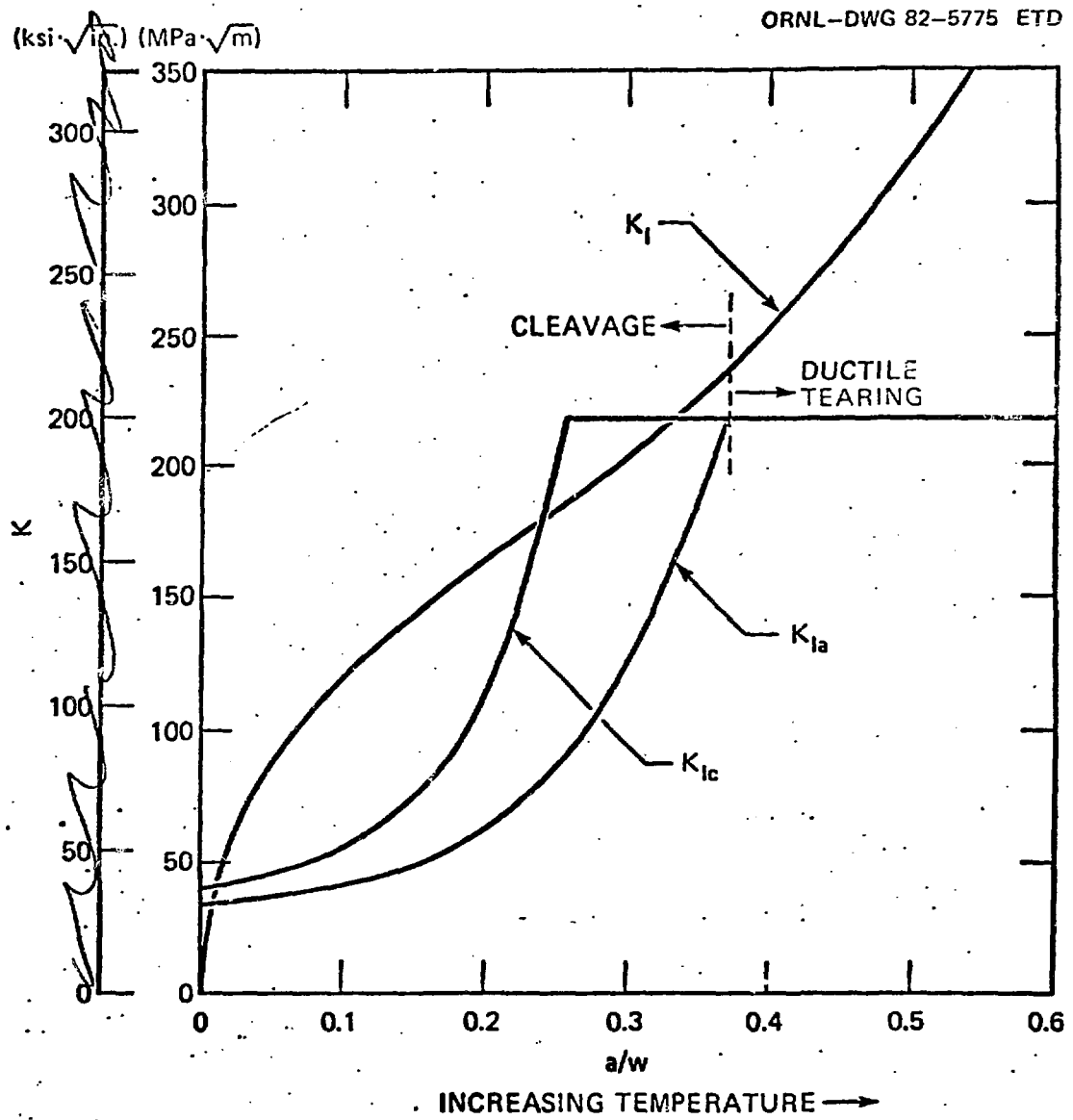
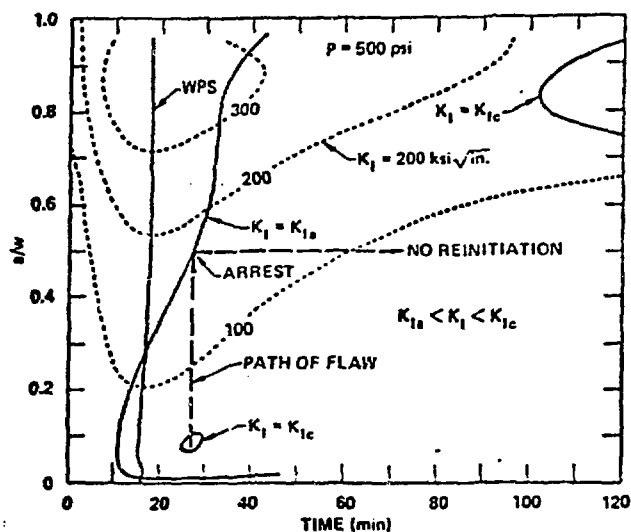
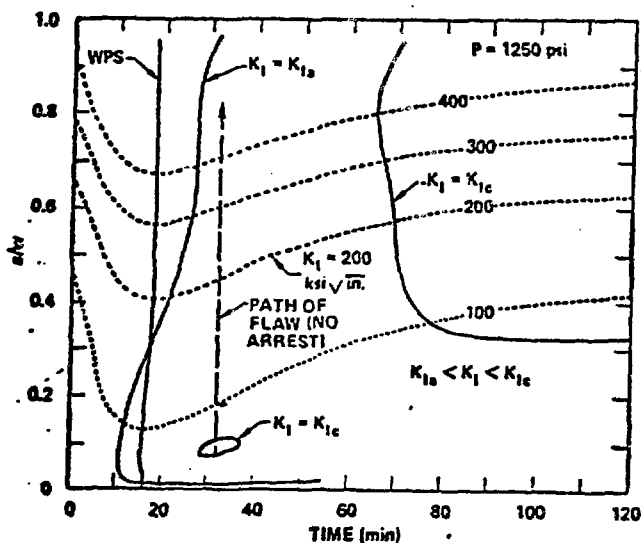


Fig. 3. Plots of K_I , K_{Ic} and K_{IIa} vs fractional crack depth at a specific time in ~~an~~ OCA transient, indicating initiation but no arrest unless on the upper shelf.



F4

Fig. 4. Critical-crack-depth curves for an OCA illustrating incipient initiation followed by arrest and no reinitiation.



F5

Fig. 5. Critical-crack-depth curves for an OCA illustrating incipient initiation and failure (no arrest unless on the upper shelf).

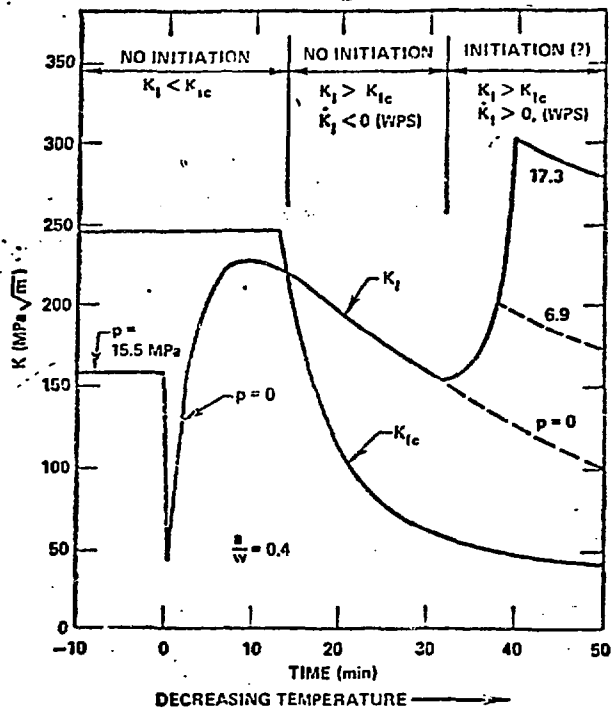


Fig. 6. Illustration of an OCA transient involving repressurization and two types of WPS.

FG

(SI units only)

RTNDT₀ = 20°F

10

200

180

160

140

120

100

80

60

40

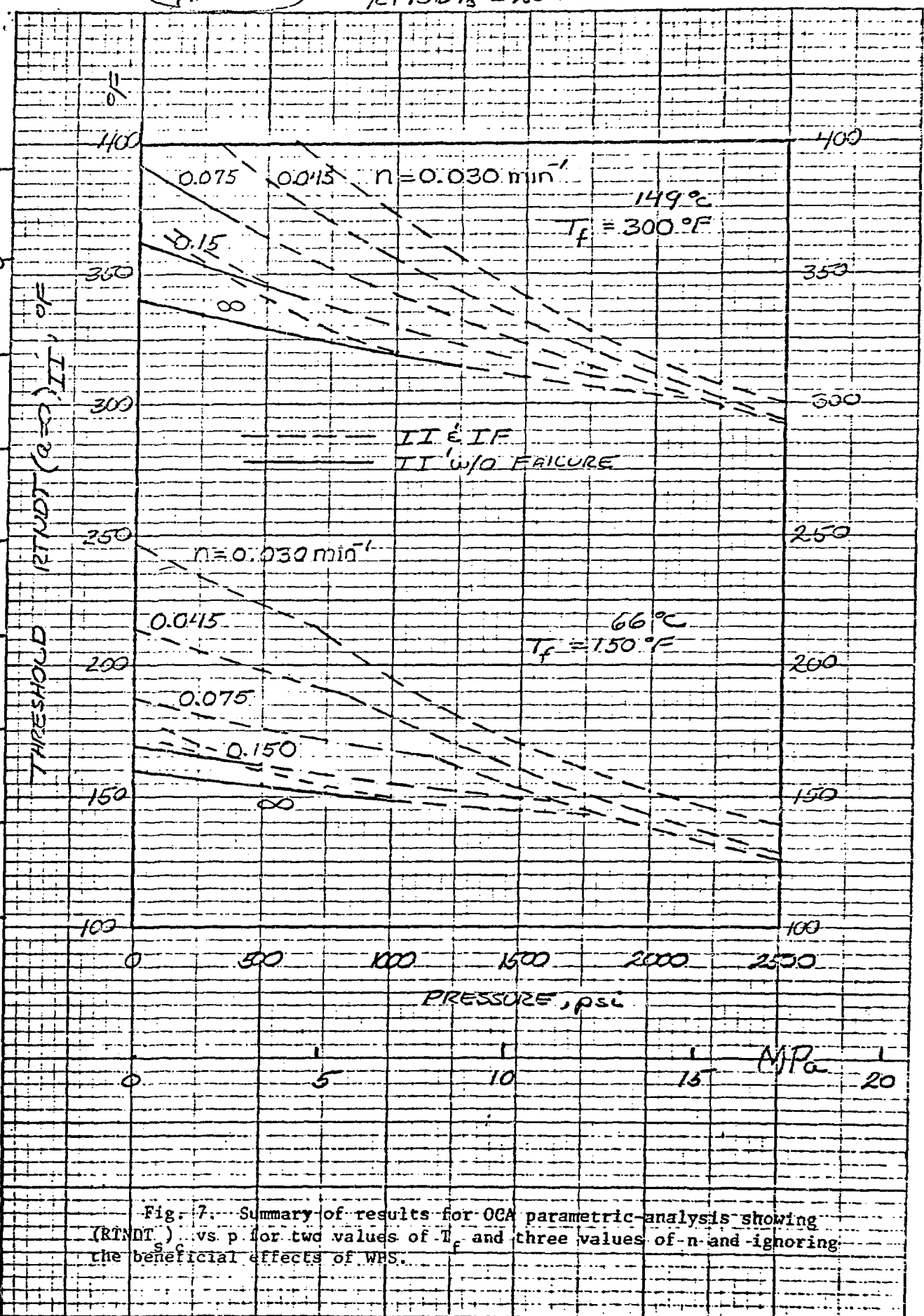


Fig. 7. Summary of results for OCA parametric analysis showing (RTNDT) vs p for two values of T_f and three values of n and ignoring the beneficial effects of WBS.

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