Section 10

Case Studies in Fracture and Fatigue

Case Studies in Fracture Mechanics

- Some actual failures and some made up examples

- Some missing data is assumed or estimated

- Examples follow the FM triangle logic

Examples

- Comet aircraft failures
- Steel retaining ring failure
- Offshore Structure Component
- Pressurized thermal shock

Comet Aircraft Failures

- Use fracture mechanics properties to look at the role of critical defect size
- Based on actual failures with some properties assumed from literature

British Comet

Comet aircraft

- The De Havilland Comet was the first commercial jet aircraft - 1949
- It had some noted failures related to fatigue and fracture

Comet failures

- The comet webpage lists 20 failures
- Some were pilot error, some sabotage and some equipment failure
- One example of equipment failure is cracks coming from the window hole in the fuselage

Example FM calculation for the Comet window

- Material 7000 series Al alloy

- Yield strength = 65 ksi

  Fracture toughness, K_{Ic} = 25 to 30 ksi-in^{½}

- Let the design stress be 30% of yield,

  19.5 ksi

Critical defect size

- K_{Ic} = 30 ksi-in^{½}

- F = 1.0

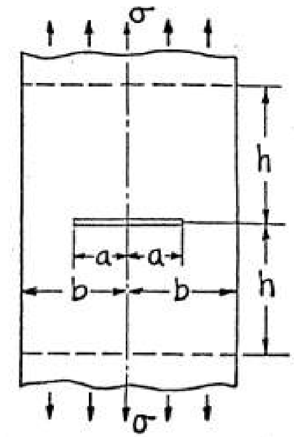
- a = 0.75 in, 2a = 1.5 in

- This is fairly large, however , the fuselage saw this

THE CENTER CRACKED TEST SPECIMEN

A. Stress Intensity Factor

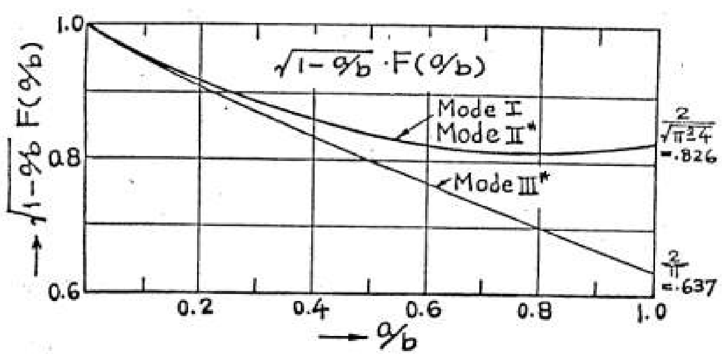
$$K_I = \sigma\sqrt{\pi a}\, F(a/b)$$



Numerical Values at F(a/b)

(Isida 1962, 1965 a, b, 1973)

Isida's 36 term power series of $(a/b)^2$ (Laurent series expansion of complex stress potential, 1973) gives practically exact values of F(a/b) up to a/b = 0.9. Numerical values of F(a/b) are shown in the table.



a/b	F(a/b)
0.0	1.0000
0.1	1.0060
0.2	1.0246
0.3	1.0577
0.4	1.1094
0.5	1.1867
0.6	1.3033
0.7	1.4882
0.8	1.8160
0.9	2.5776
1.0	$\frac{2}{\sqrt{\pi^2-4}}/\sqrt{1-a/b}$ **

Actual FM

- Cracks came from both sides of the window corner

- If the window is 8 in. across, a small crack from the corners would appear as 2a > 8in

Generator Retaining Ring Failures

- Combination of material and environmental interactions
- Qualitative look at failure; exact quantitative details were not developed


Generator retaining ring

Failed retaining ring

- A retaining ring failed in a peaking generator causing a hydrogen explosion
- Since other units had similar rings, there was concern about all such units
- Retaining rings are high strength, highly stressed generator components
- Material was 4340 Q&T steel

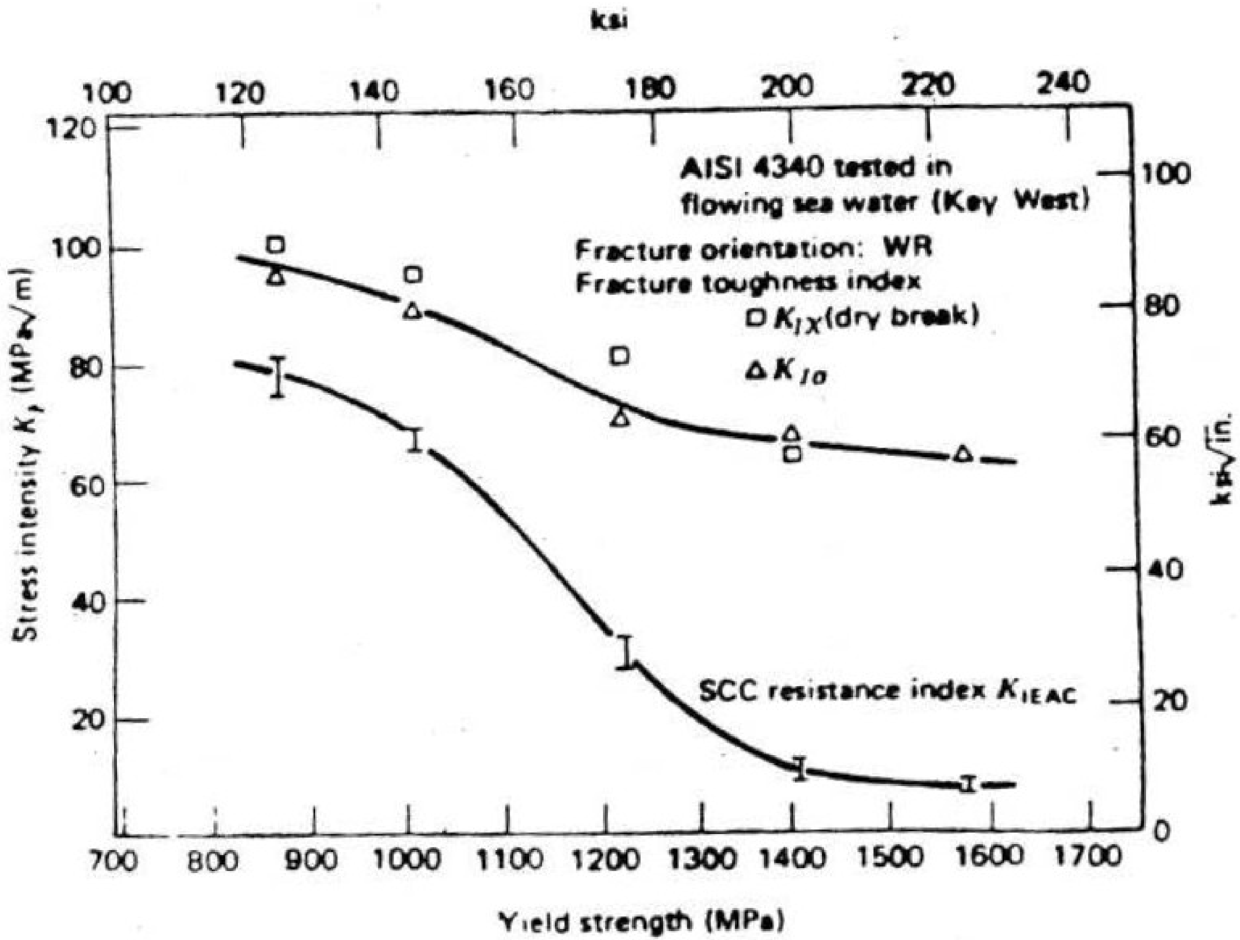
Properties of the 4340 material

- Yield strength – 180 ksi
- Ultimate tensile strength – 190 ksi
- K_{Ic} = 160 ksi-in½
- K_{Iscc} = 30 ksi-in½

- K_{Iscc} is a threshold for subcritical crack growth in an H_2 gas environment

Material strength problem

- The 4340 steel had a minimum yield strength, 150 ksi, but no maximum
- The strength specification was based on plastic burst
- In an attempt to supply the best material, very high strength steel was provided, 150 ksi



- Effect of yield strength on K_{Ic} and K_{IEAC} (in water) in 4340 steel.

H_2 cooling gas

- H_2 was used a s the cooling gas, the only alternative He was too expensive
- To do the best job, the gas was kept very clean and pure

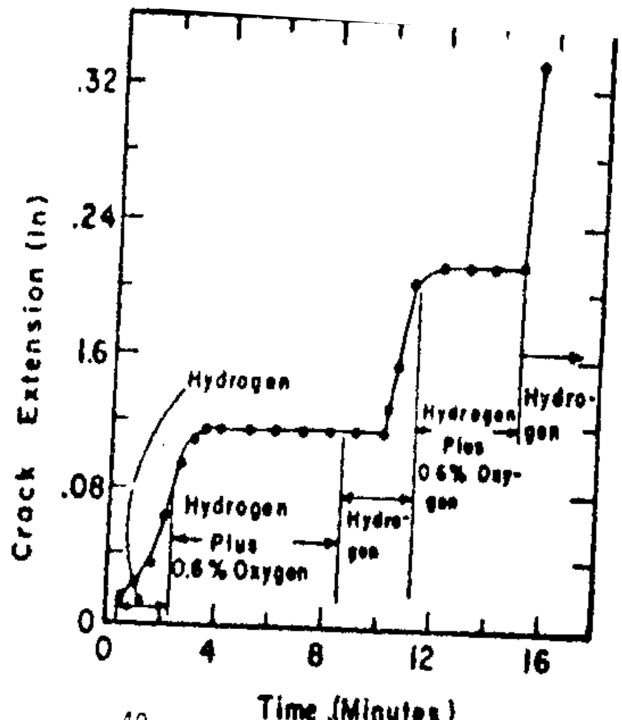


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Fig. - Hydrogen-oxygen mixtures and subcritical crack growth, d-11 steel, 230 ksi yield.

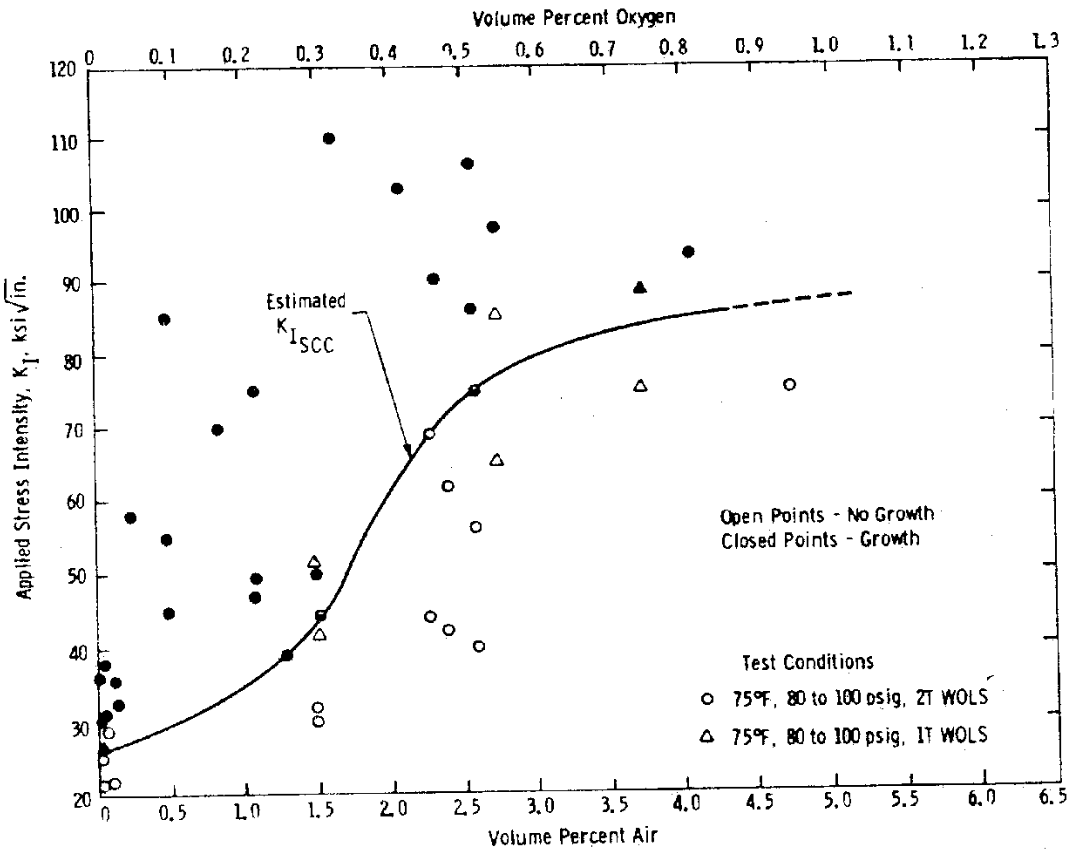


Fig. 49 - Effect of gas chemistry on hydrogen induced static crack growth in 180 ksi yield strength 4340 steel.

Fixes to the problem

- Pick a lower yield strength material, in the area of 150 ksi
- Do not try to keep the H_2 gas pure, let air or moisture leak into the gas
- Watch the sharp corners to lower stress concentration

Offshore Rig Problem (ORP)

- Simulated problem combining several aspects of LEFM

- Used in UT fracture mechanics course

ORP Problem Statement - Input

- A structural member has a 25x100 mm cross-section
- There is a constant tensile stress of 200 MPa
- Ocean waves give a bending stress of
  ± 50 MPa outer fiber stress at 7 cycles per minute
- NDE can find a flaw of 1 mm depth

ORP Problem Statement – Questions

1. Choose the best material to survive a 10 year inspection period

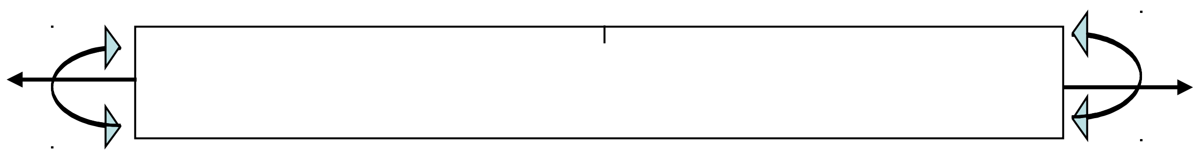
2. Choose the best material to survive a hurricane that does on change the tensile stress but increases the bending stress by five times (± 250 MPa, maintaining a 7 CPM frequency)

Material Choices; A, B, C

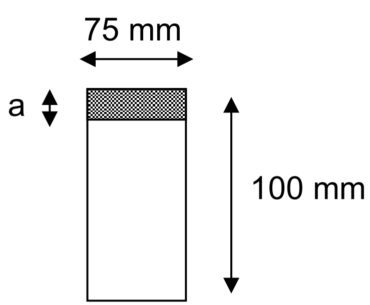
Property (sea water)	Material A	Material B	Material C
Yield Strength	300 MPa	600	1000
UTS	550 MPa	850	1100
K_{Ic}	200 MPa-in$^{1/2}$	120	80
da/dN (m/cyc)	$5.0\text{x}10^{-12}\Delta K^3$	$5.0\text{x}10^{-12}\Delta K^3$	$5.0\text{x}10^{-12}\Delta K^3$
K_{IEAC}	180 MPa-in$^{1/2}$	80	50
ΔK_{TH}	7.0 MPa-in$^{1/2}$	6.0	5.0
da/dt (above K_{IEAC})	1x10^{-4} mm/hr	1x10^{-3}	1x10^{-2}

Sketches of loading and Cross-section

- Member loading



- Cross-section



Part 1 - 10 year inspection problem

1. Consider final failure – crack lengths for K or net section stress failures
2. Initial length
3. Growth to failure – cycles, times
4. Can any material last 10 years?

Cycles and times

- Cycles; Hrs at 7 CPM
  - 1 day – 10,080 cycles; 24 hrs
  - 1 year – 3,679,000 cycles; 8760 hrs
  - 10 years – 36,790,000 cycles; 87,600

K solutions

- Combine SENT (2.10) and SENB (2.13)
- Stress is 200 MPa tension + 50 MPa bend
- K solutions:

$$K = \sigma \sqrt{\pi a} F(a/W)$$

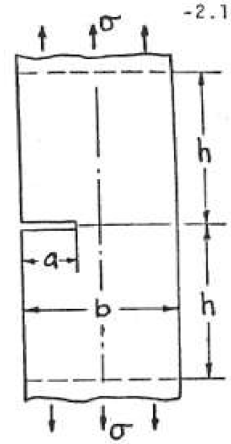
- F(a/W) is F(a/b) from either 2.10 tension F_T or 2.13 bend, F_B.

Example K calculation

- Initial crack size

  a = 1 mm = 0.001 m (inspection limit)
- a/W = 1/100 = 0.01
- $F_T = 1.122 = F_B$.
- $K_T = 200(.001\pi)^{1/2}(1.122) = 12.58$ MPa-m$^{1/2}$
- $K_B = 50\ (.001\pi)^{1/2}(1.122) = 3.14$ MPa-m$^{1/2}$
- K = 12.58 + 3.14 = 15.72 MPa-m$^{1/2}$

THE SINGLE EDGE NOTCH TEST SPECIMEN

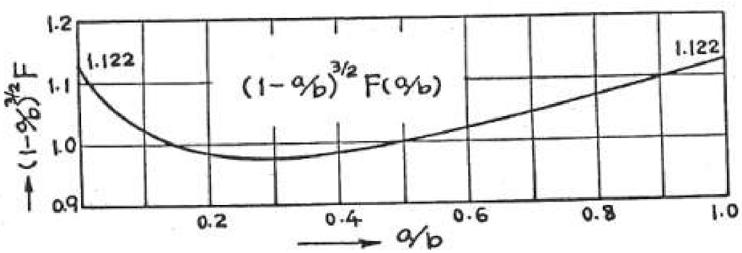


A. Stress Intensity Factor

$$K_I = \sigma\sqrt{\pi a}\, F(a/b)$$

Numerical Values of F(a/b)

The curve in the following figure was drawn based on the results having better than 0.5% accuracy.



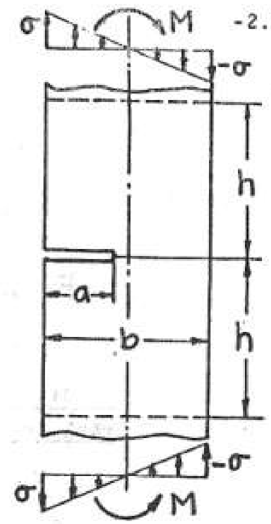
Methods and References

1. Boundary Collocation Method (h/b > 0.8): Gross 1964
2. Mapping Function Method (h/b = 1.53): Bowie 1965
3. Green's Function Method (h/b>1.5): Emery 1969, 1971
4. Weight Function Method: Bueckner 1970, 1971
5. Asymptotic Approximation: Benthem 1972
6. Finite Element Method (h/b=2.75, 1.0): Yamamoto 1972

Note

1. Load is applied along the center line of the strip at the crack location(or Uniform Pressure on crack surfa
2. The effect of h/b is practically negligible for h/b≥1.0

THE PURE BENDING SPECIMEN



A. Stress Intensity Factor

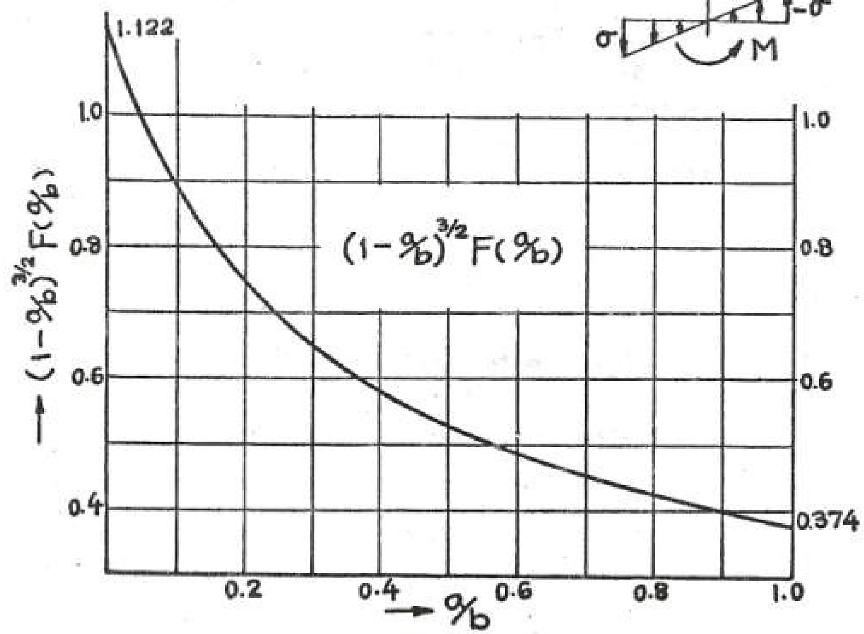
$$\sigma = \frac{6M}{b^2}$$

$$K_I = \sigma\sqrt{\pi a}\, F(a/b)$$

Numerical Values of F(a/b)

The curve in the following figure was drawn based on the results having better than 0.5% accuracy.

Used also: for 4 point bending.



Methods and References

1. Singular Integral Equation, Bueckner 1960
2. Boundary Collocation Method ($h/b \geq 2$), Gross 1965
3. Weight Function Method, Bueckner 1970, 1971
4. Green's Function Method ($h/b \geq 1.5$), Emery 1969
5. Asymptotic Approximation, Benthem 1972

Other K values

- $a = 20$ mm = .02 m
- $a/W = 0.2$
- $F_T = 0.98/(1 - 0.2)^{3/2} = 1.37$
- $F_B = 0.75/(1 – 0.2)^{3/2} = 1.05$
- $K_T = 68.7$
- $K_B = 13.2$
- $K = 81.9$

Net Section Stress

- Tension: $\sigma_{net} = P/A_{net} = \sigma x A/A_{net} =$ $200x(100x25)/(100-20)x25 = 250$ MPa

- Bend: $\sigma = Mc/I$; $M = \sigma I/c$ $(I = bh^3/12)$

  $\sigma_{net} = \sigma I c_{net}/I_{net} c$

  $= 50(100^3 x25/12)x80/(80^3 x25/12)100 = 78$ MPa

- Combined $\sigma_{net} = 250 + 78 = 328$

Table of K and Stress Values

a, mm	K, MPa–m$^{1/2}$	σ_{net}, MPa
1	15.7	$\sim$ 250
2	22.3	256
10	51.4	284
15	66.8	304
20	81.9	328
25	99.2	350
30	119	387
40	173	472

Determine Final Crack Lengths

- Material A: K_{Ic} = 200, a > 40 mm
  σ_{ys} = 350, a = 25 mm,
  a_f = 25 mm, plastic overload

- Material B: a_f = 30 mm, K_{Ic}

- Material C: a_f = 19 mm, K_{Ic}

Crack length to cause SCC K_{IEAC}

- Material A: $K_{IEAC} = 180$, $a > 40$ mm
  No problem, plastic failure first

- Material B: $K_{IEAC} = 80$, $a = 19$ mm

- Material C: $K_{IEAC} = 50$, $a = 9$ mm

Time to Fail SCC

- Material B: Δa = 11 mm, $\Delta t = \Delta a / da/at$
  $= 11mm/1x10^{-3}$ = 11,000 hr = 1.25 yr

 (not enough life)

- Material C: Δa = 10 mm, $\Delta t = 10\ mm/1x10^{-2}$
  = 1000 hr = 1.4 mo.

(not enough life)

Fatigue Crack Growth

- Material A has the longest Δa from a = 1 mm to a = 30 mm
- Integration has a variable F from bending stress only, F_B = 1.122 is about constant; (it actually decreases some)
- Assume that a constant F = 1.122 gives a reasonable estimate of life

Predicting life from da/dN vs ΔK

1. $da/dN = C(\Delta K)^n$

2. $K = \sigma\sqrt{\pi a}\, F$

3. $da/dN = C(\Delta\sigma\sqrt{\pi a}\, F)^n$

4. $dN = da/C(\Delta\sigma\sqrt{\pi a}\, F)^n$

5.

$$N = \int_{a_o}^{a_f} \frac{da}{C\,(\Delta\sigma\sqrt{\pi a}\, F)^n}$$

6. This is easier if F is constant or a simple function

Material A Fatigue Life

- Crack growth rate equation (MPa and m/cyc)

$$\frac{da}{dN} = 5x10^{-12}\Delta K^{3}$$

- Stress range ± 50 = 100 MPa

- K expression, $K = 100\sqrt{\pi a}1.122$

Fatigue Life Calculation

$$\frac{da}{dN} = 5x10^{-12}(100\sqrt{\pi a}1.122)^3 = 3.93x10^{-5}a^{3/2}$$

$$N_f = \int_{.001}^{.03} \frac{da}{3.93x10^{-5}a^{3/2}} = \frac{1}{3.93x10^{-5}}\left[\frac{a^{-0.5}}{-0.5}\right]_{.001}^{.03} = 1.315x10^6$$

Fatigue Life

- Material A: From the table 1 year is 3.7×10^6 cycles

- A life of 1.3×10^6 cycles is $1.3/3.7 = .4$ year (Life is much too short, playing with F_B is not worthwhile)

- The only chance is no crack growth

No Crack Growth

- At a_o = 1 mm, K_{max} was 22.3 MPa-m$^{1/2}$, at σ_{max} = 250 MPa

- However for $\Delta\sigma$ = 100 MPa, from the bend stress, $\Delta K = 100(.001\pi)^{1/2}1.122$

  $= 6.29$ MPa-m$^{1/2}$

Final Analysis of Part 1

- For no crack growth, ΔK must be below ΔK_{TH}
- This means $\Delta K = 6.29 < \Delta K_{TH}$
- The only material that meets this is Material A, $\Delta K_{TH} = 7.0$
- Choose Material A

Part 2 Hurricane

- Assume original properties, initial service to make the analysis feasible

- If $\Delta\sigma$ = 250, the stress range = - 50 to 450 MPa

Short K and Stress Table

a, mm	K, MPa – m$^{1/2}$	σ_{net}, MPa
1	28	> 450
6	62	
8	78	512
10	88	530
15	112	581
20	134	640

Critical Crack sizes

- Material A yielded with no crack, discard
- Material B has a_f = 17 mm, K_{Ic} or stress about the same
- Material C has a_f just over 8 mm
- Look at Material B life with a from 1 to 17 mm

Crack Growth Life

$$\frac{da}{dN} = 5x10^{-12}(450\sqrt{\pi a}1.122)^3 = 3.58x10^{-3}a^{3/2}$$

$$N_f = \int_{.001}^{.03} \frac{da}{3.58x10^{-3}a^{3/2}} = \frac{1}{3.58x10^{-3}}\left[\frac{a^{-0.5}}{-0.5}\right]_{.001}^{.03} = 1.55x10^4$$

Life Analysis

- Cracks will grow, all ΔK are above ΔK_{TH}
- Cycles per day are 10,080; Material B has about 15,500 cycles (34 hrs)
- Material C with a growing from 1 to 8 mm could have about half of that life, 17 hrs
- Choose Material B

Comments

- Although this requires a detailed analysis, many simplifying assumptions were made
- Strategy: start simple and conservative. If this works, it is okay. If it does not work, go back and do more detailed, less conservative analysis.
- Once you understand the process, use sortware aids

Pressurized Thermal Shock

- A simulated nuclear reactor accident where cooling water is sprayed on a pressure vessel to prevent core meltdown

WHAT IS REACTOR VESSEL PRESSURIZED THERMAL SHOCK ?

- PTS is — An event that results in a rapid and severe cooldown in the primary coolant system coincident with a high or increasing primary system pressure

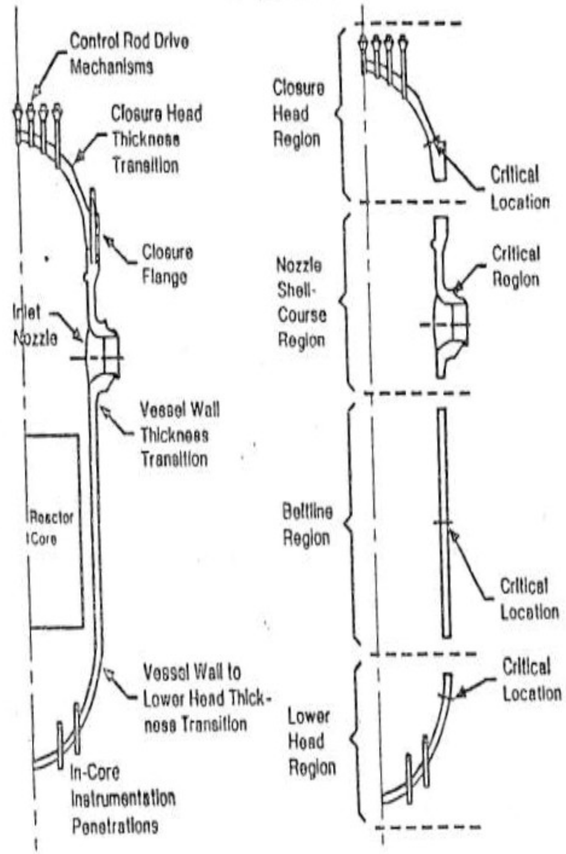
- A PTS concern arises —

  1) If a PTS transient occurs on the beltline region of a reactor vessel,

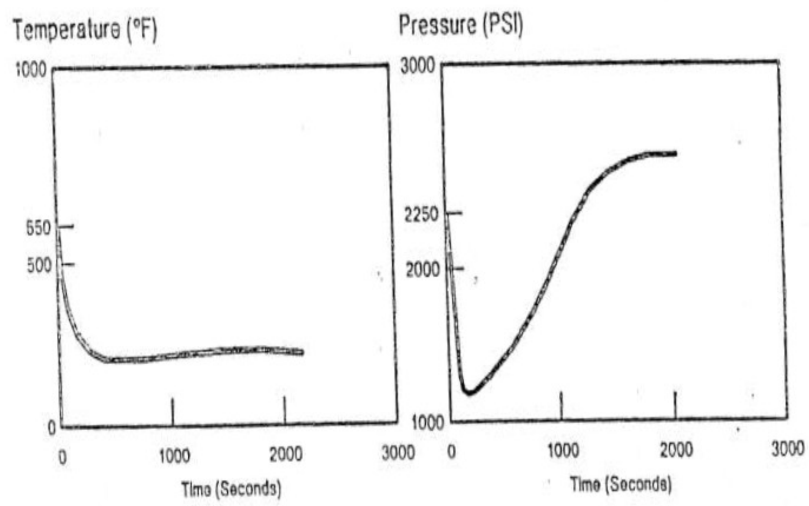
  2) If the beltline region has a reduced fracture resistance because of neutron irradiation, and

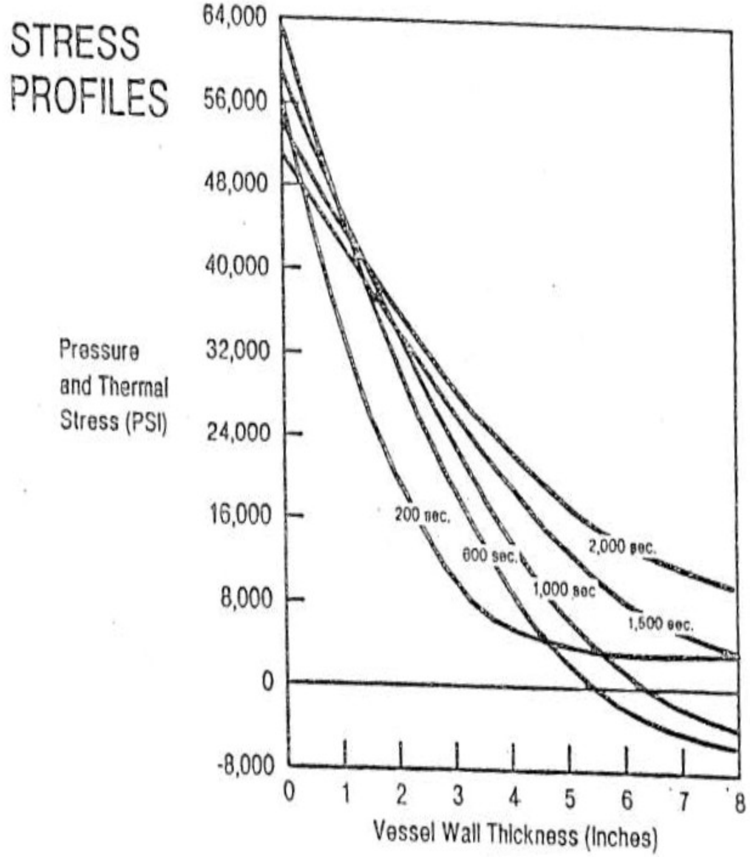
  3) If a flaw exists near the inner surface of the vessel wall

REACTOR VESSEL CRITICAL LOCATIONS



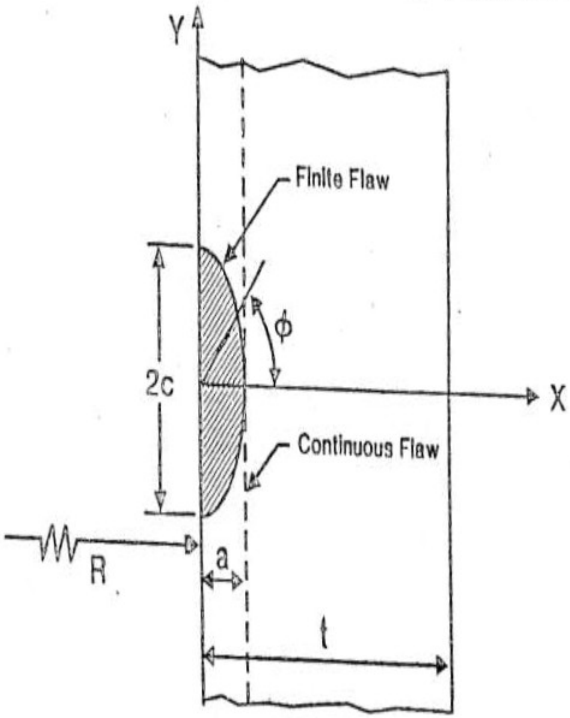
REACTOR COOLANT PRESSURE AND TEMPERATURE TRANSIENTS FOR A REPRESENTATIVE SEVERE THERMAL TRANSIENT



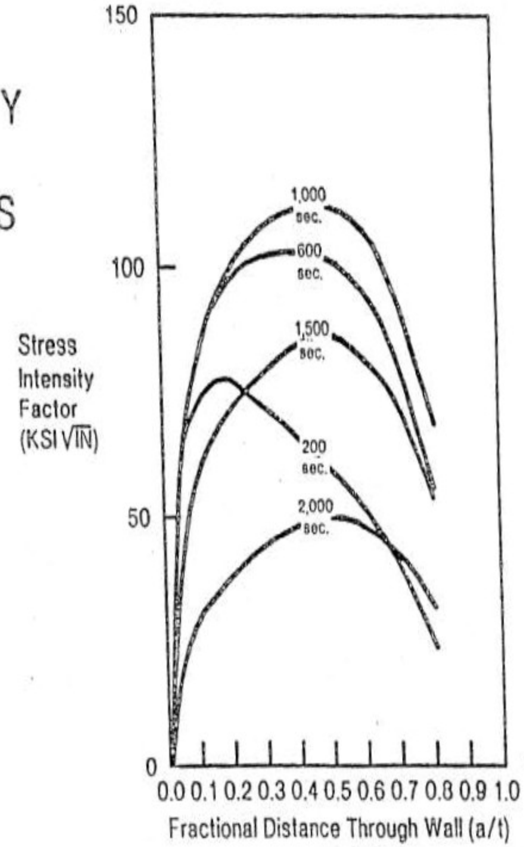


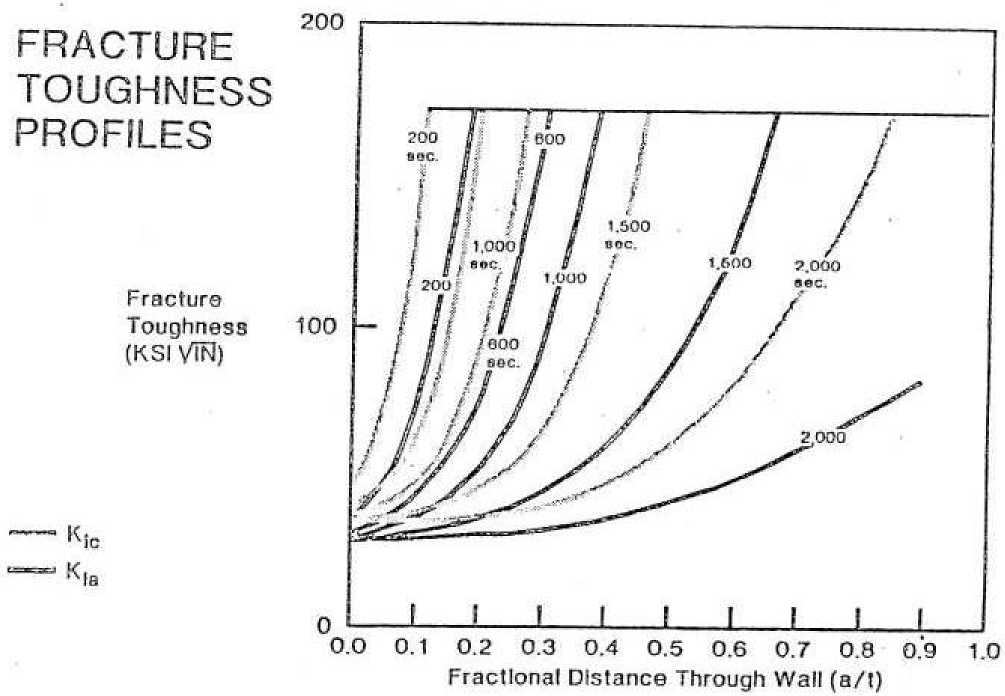
STRESS
PROFILES
Pressure
and Thermal
Stress (PSI)
64,000
56,000
48,000
40,000
32,000
24,000
16,000
8,000
0
-8,000
0
1
2
3
4
5
6
7
8
Vessel Wall Thickness (Inches)
200 sec.
600 sec.
1,000 sec
1,500 sec.
2,000 sec.

FLAW SHAPES FOR FRACTURE MECHANICS ANALYSIS



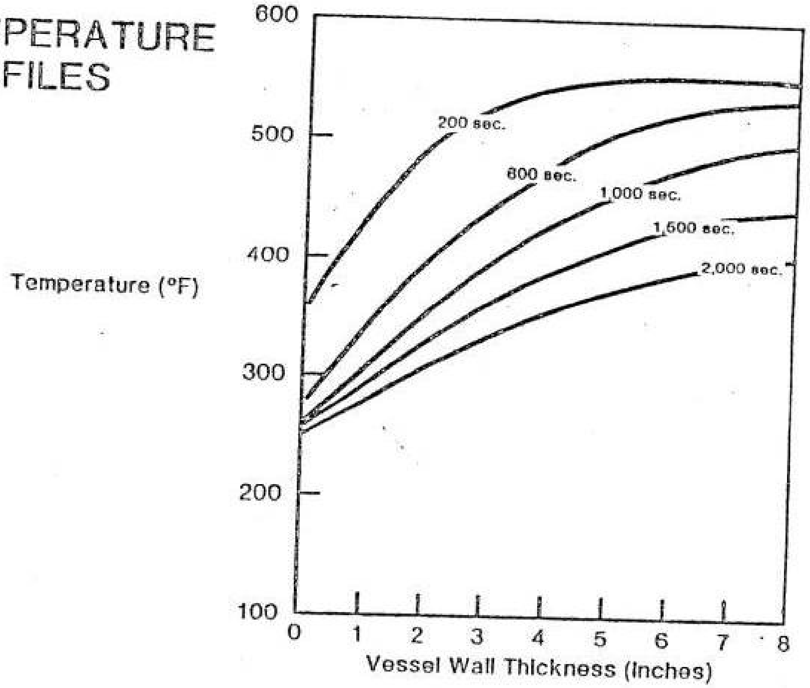
STRESS INTENSITY FACTOR PROFILES



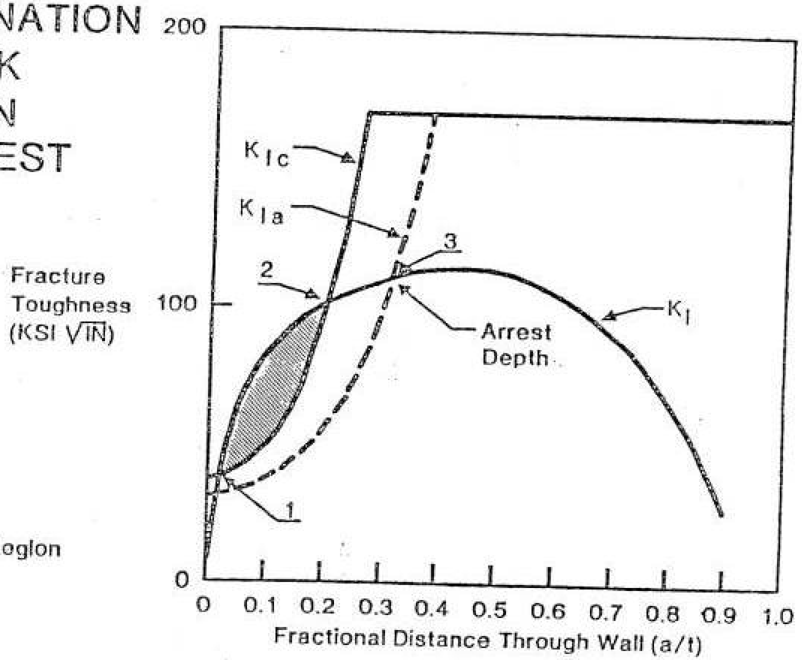


FRACTURE TOUGHNESS PROFILES
200
100
0
Fracture Toughness (KSI √IN)
200 sec.
600
1,000 sec.
200
1,000
1,500 sec.
600 sec.
1,500
2,000 sec.
2,000
K_{Ic}
K_{Ia}
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Fractional Distance Through Wall (a/t)

TEMPERATURE PROFILES



DETERMINATION OF CRACK INITIATION AND ARREST



Initiation Region