Lecture 15

Nonlinear Application Models

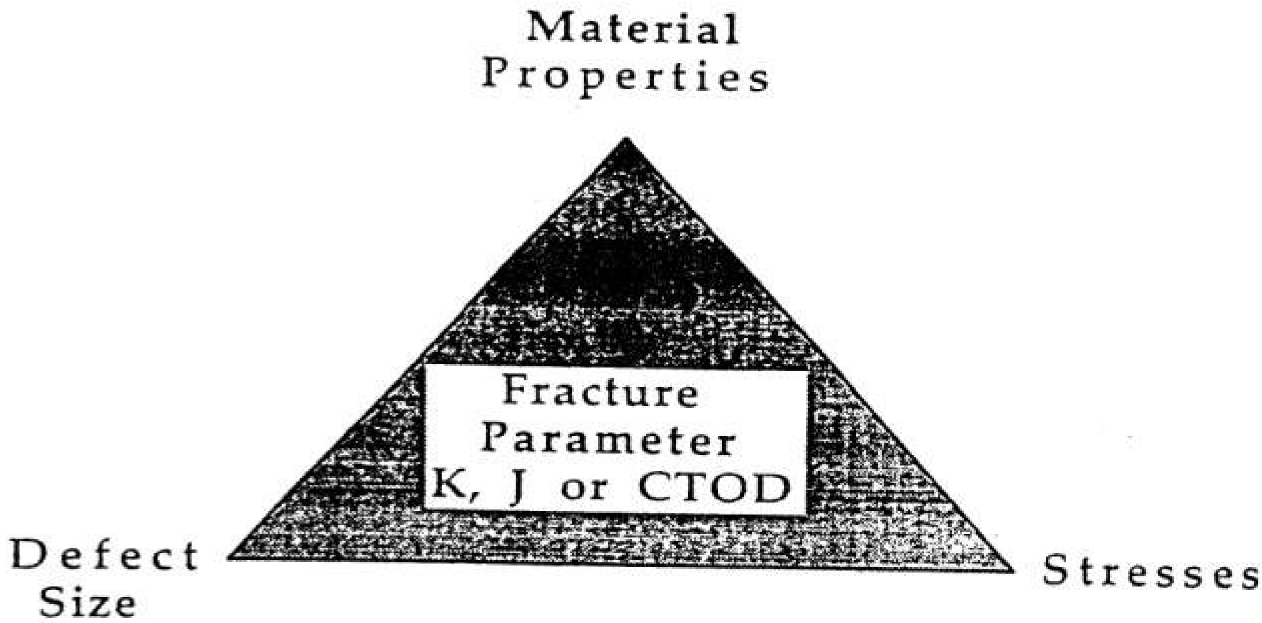
Application Procedure

1. Consider conditions by corner
   - Stress
   - Defects
   - Material behavior

2. Determine type of safety required
   - Safe life
   - Fail safe
   - Leak before break
   - Failure analyses diagrams

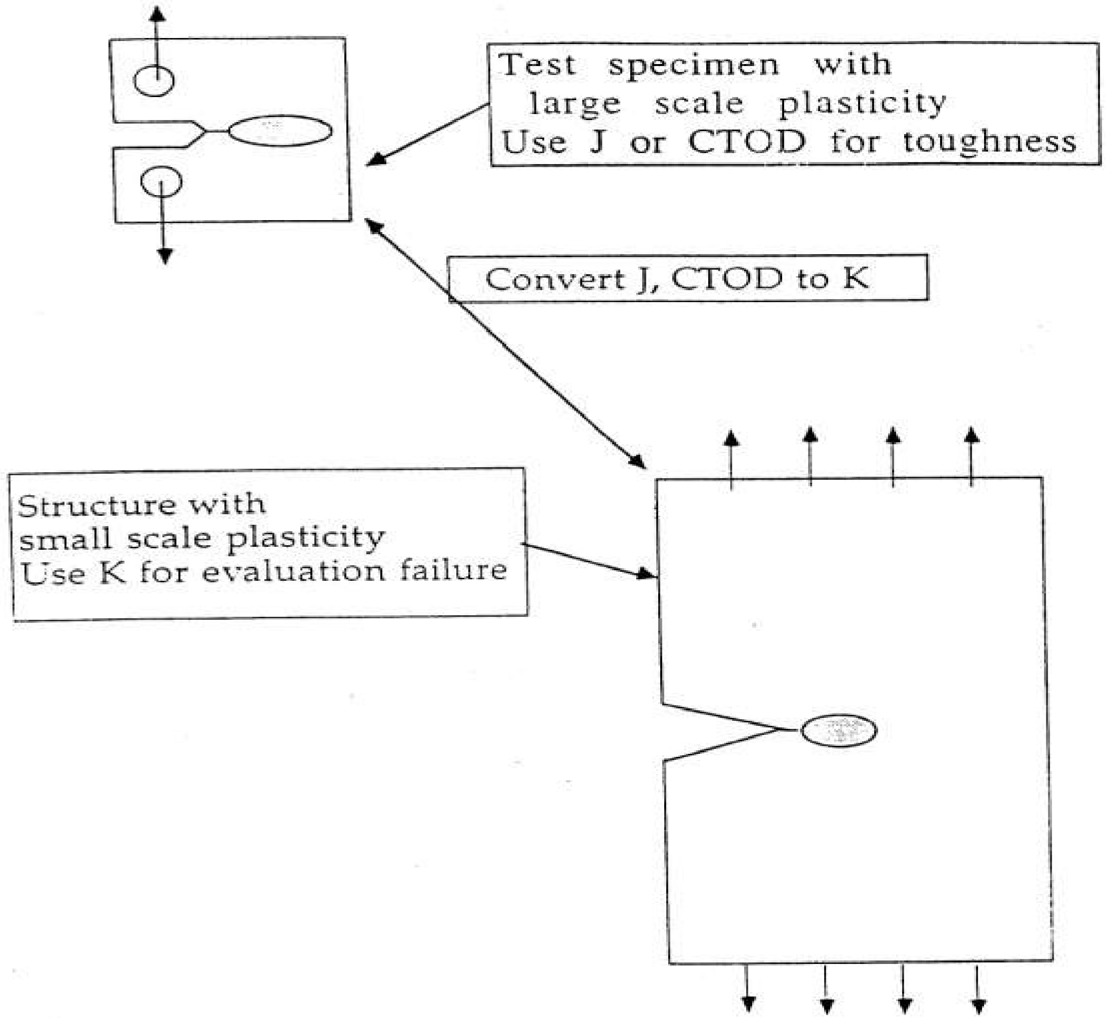
3. Gather information

4. Do required analysis



Fracture Mechanics Triangle

Areas of Information
Related By Fracture Parameter



Original Application for Ductile Fracture

Fracture Mechanics Used in Fractography

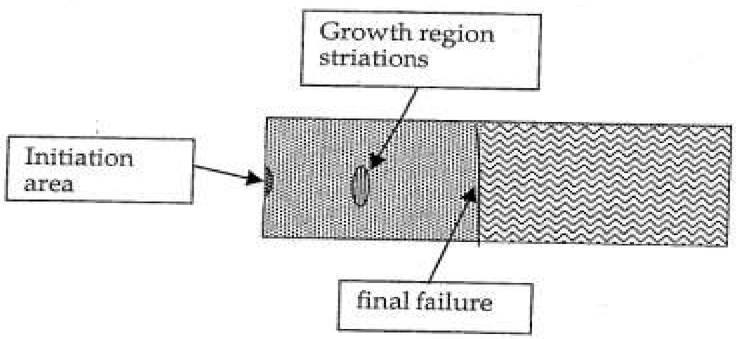
1. Use fracture surface as a guide to the behavior of the component

2. Stages in failure

   i) Crack initiation (or pre-existing crack)

   ii) Crack Propagation, fatigue crack growth, stress corrosion cracking

   iii) Final Failure



3. Examples of calculations of behavior

   i) Initiation, S-N or, ε-N

   ii) Growth, da/dN vs ΔK

   iii) Failure, K_{Ic}

Application Methodologies

1 Crack drive based

- J/K based
- CTOD design curve

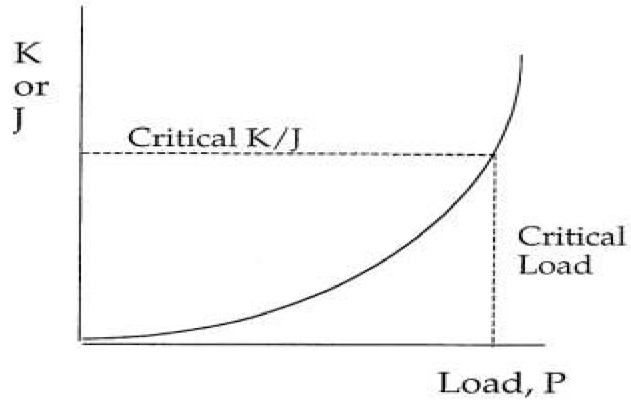
2 Failure analyses curves

- R-6, DPFAD
- PD 6493, BS 7910
- API 579

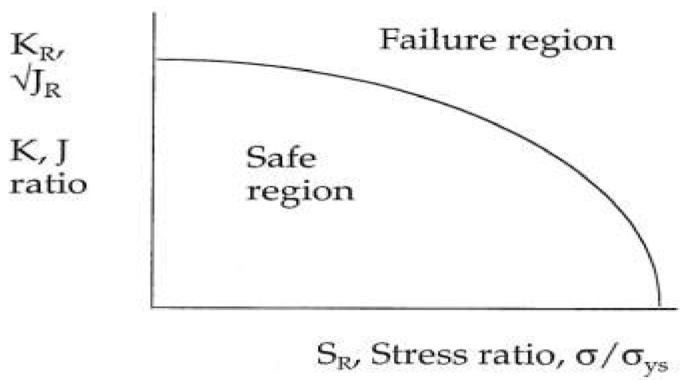
3 Example, pressurized thermal shock

4 European Methodologies, FITNET, SINTAP

Crack drive vs failure analysis diagram



Example crack drive curve



Example Failure Analysis Diagram

Uses of the handbook for application:

Since $v = v(P, a)$ and
$J = J(P, a)$

1. Calculate P at J_{Ic}

2 Calculate J - T applied

3. Other methods discussed later

More general methodology:

1. Calibration functions:

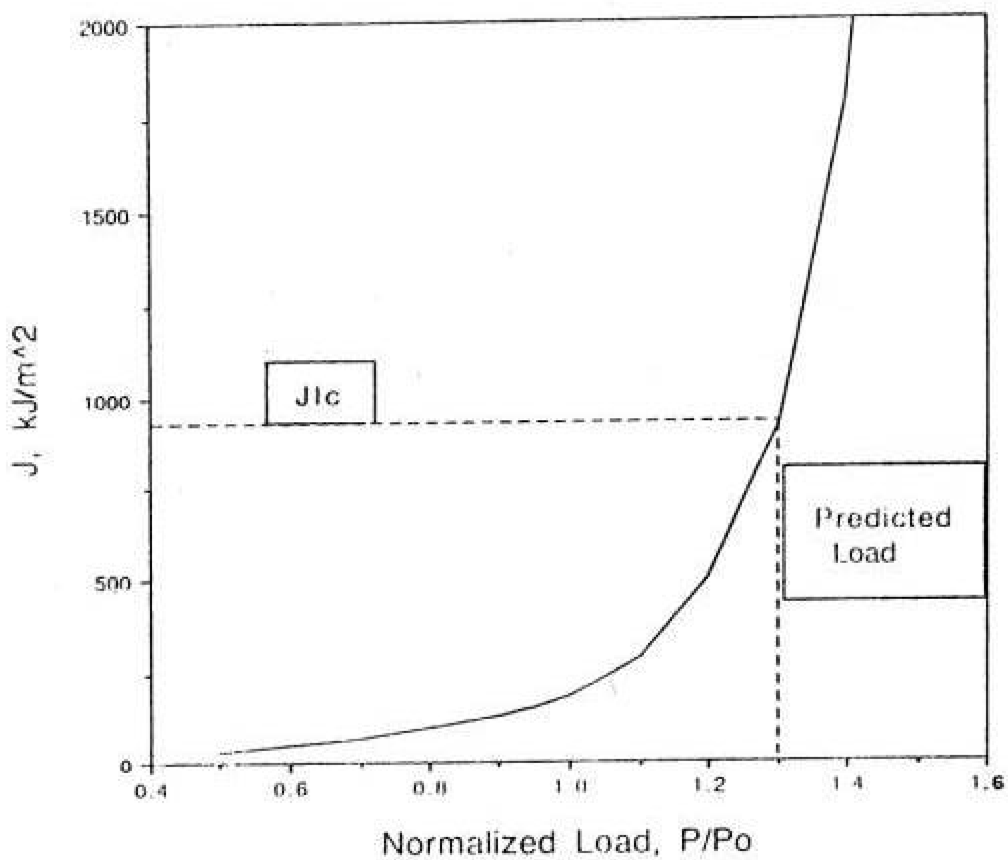
$$P = G(a/W)\, H(v_{pl}/W)$$

$$J = J(a/W, v_{pl}/W)$$

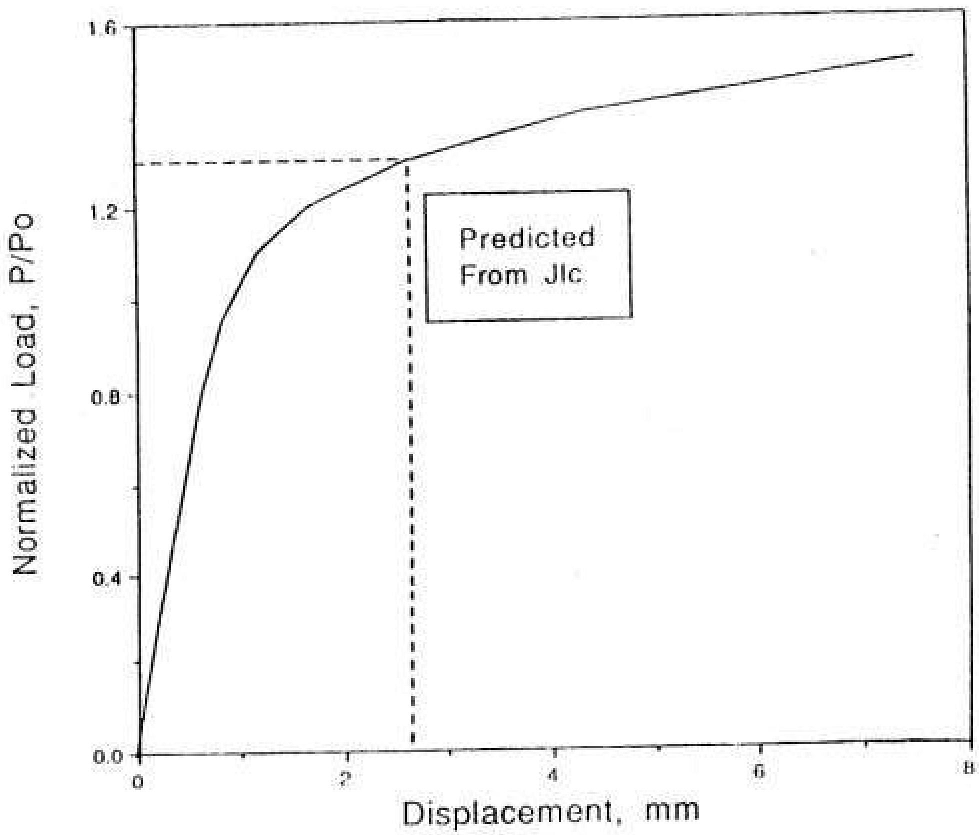
This is the deformation response to loading

2. Fracture toughness:

J vs Δa R curve



J Predicted as a Function of Load from the Handbook



Load versus Displacement
Prediction from the Handbook

J_{Ic} application

1. From Workshop problem, $J_{Ic} = 1400$ in-lb/in^2

What is P_{cr} from handbook solution

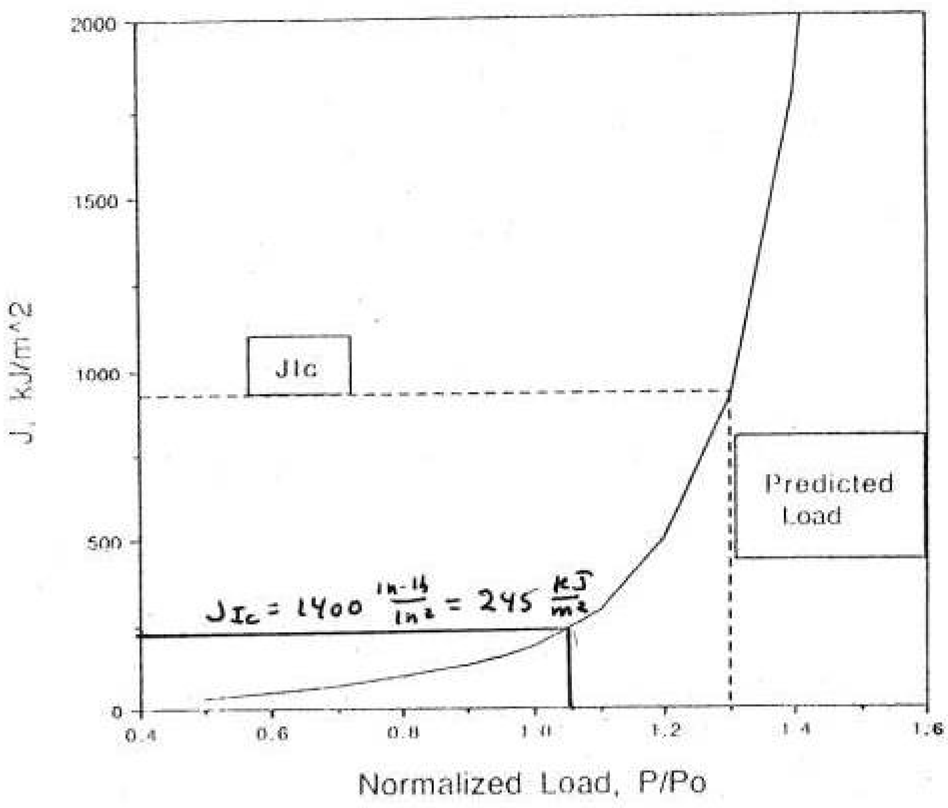
(assume $P_o = 300$ kips)

Use the graph from the notes, but it is in kJ/m^2

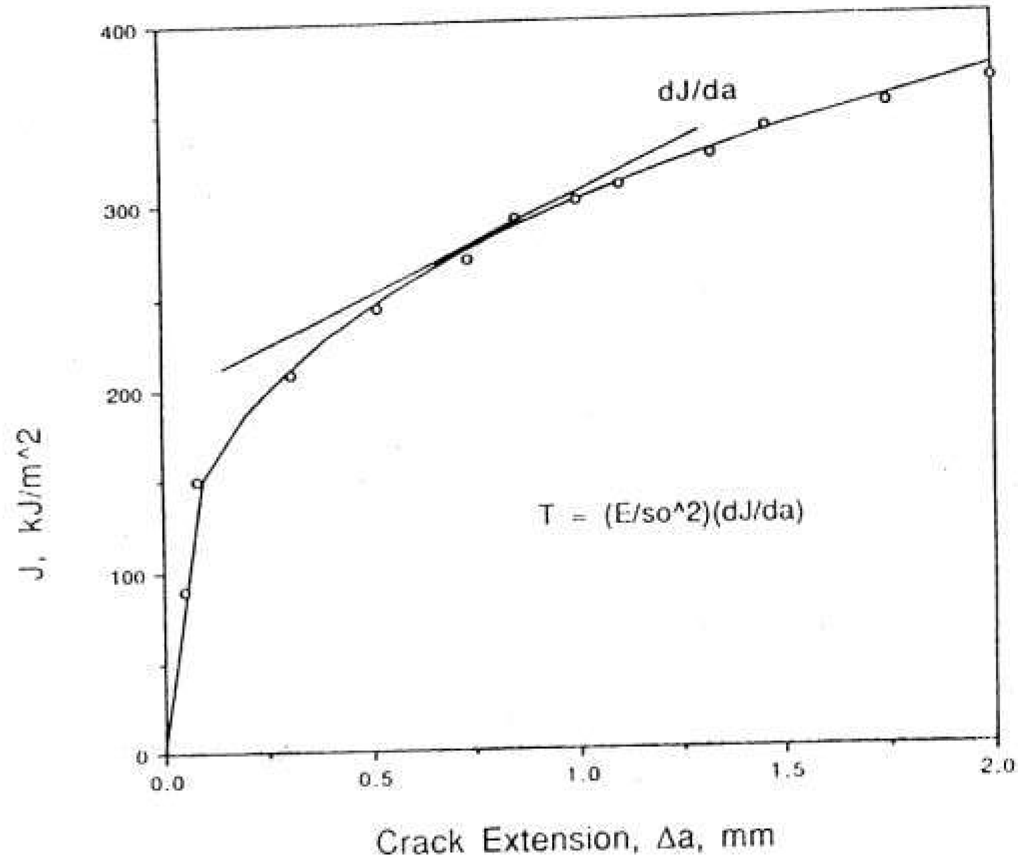
1400 in-lb/in^2 x(.175) = 245 kJ/m^2

Graph, for J = 245, $P/P_o = 1.05$

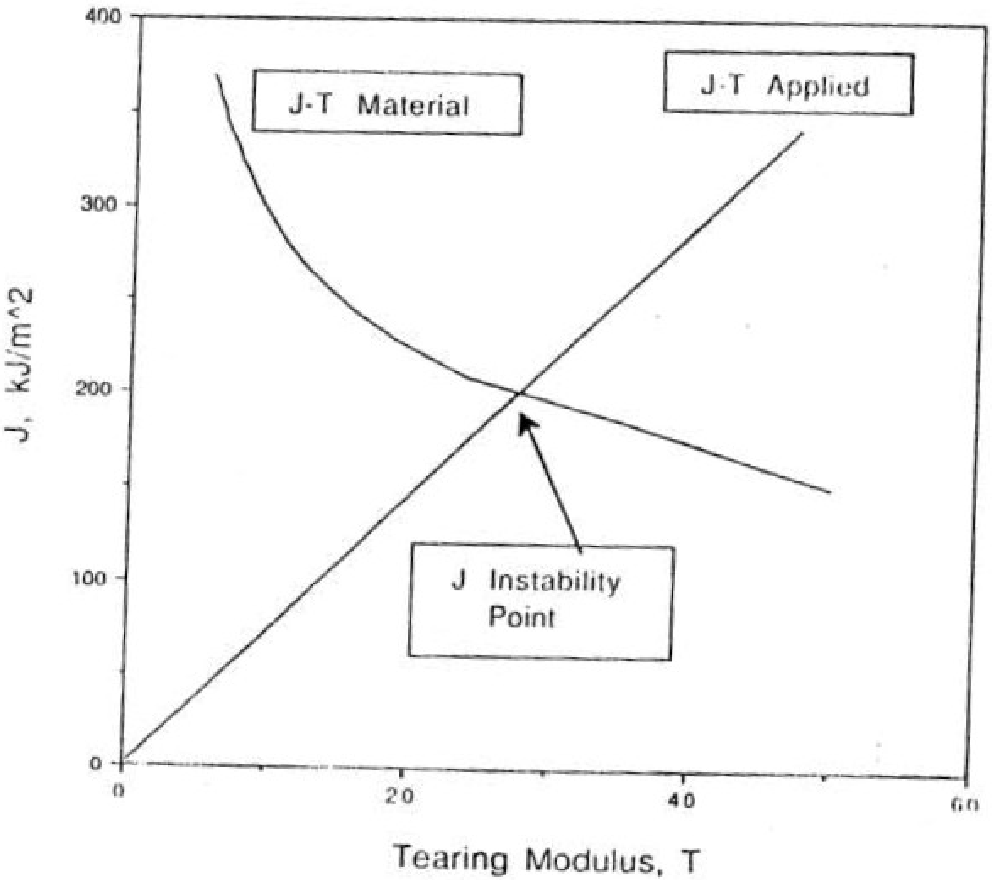
$P_{cr} = 1.05(300) = 315$ kips



J Predicted as a Function of Load from the Handbook



J-R Curve with Tearing Modulus



J-T Diagram Showing J Instability Point

CTOD Design Curve – strain calculation

$$\varepsilon = [k_t(\sigma_m + \sigma_b) + Q]/E$$

where,

$\varepsilon/\varepsilon_o$ = strain ratio, horizontal axis

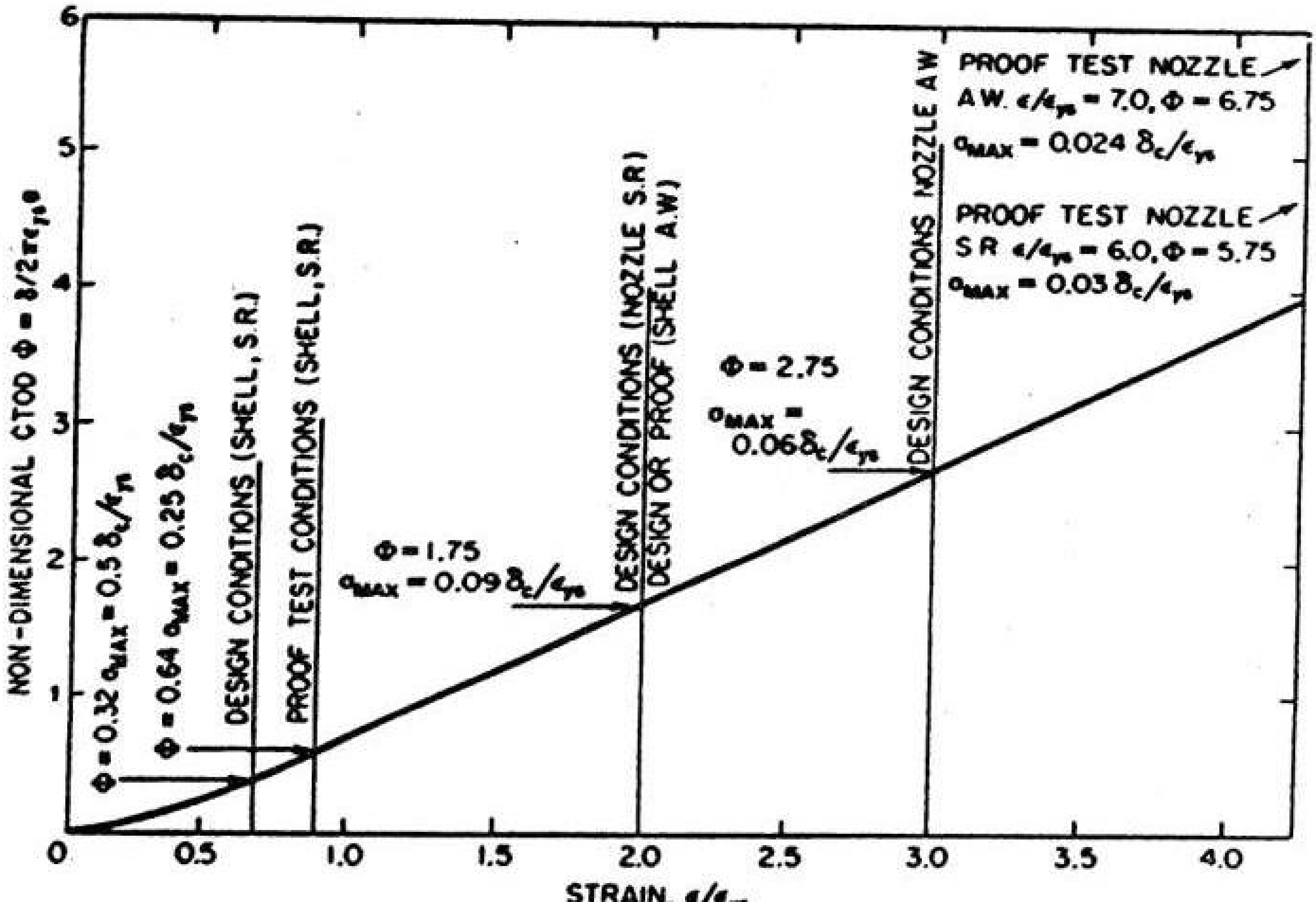
k_t = stress concentration factor

σ_m = primary membrane stress

σ_b = primary bend stress

Q = secondary stress, residual, thermal

$$\varepsilon/\varepsilon_o = \varepsilon/(\sigma_{ys}/E)$$



(a) DESIGN CURVE FOR CTOD, STRAIN, AND CRACK SIZE RELATIONSHIP AS PROPOSED BY BURDEKIN AND DAWES

Application Methodologies

1 Crack drive based
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Dugdale Model

1. A strip of yielded material is assumed in front of the crack tip

2. This leads to a K solution

$$K_D = \sigma_{ys}[(8a/\pi)\{\ln \sec(\pi\sigma/2\sigma_{ys})\}]^{1/2}$$

3. The Dugdale analysis forms the basis for the R-6 diagram used for failure analysis diagram approaches

R-6 Failure Analysis Diagram

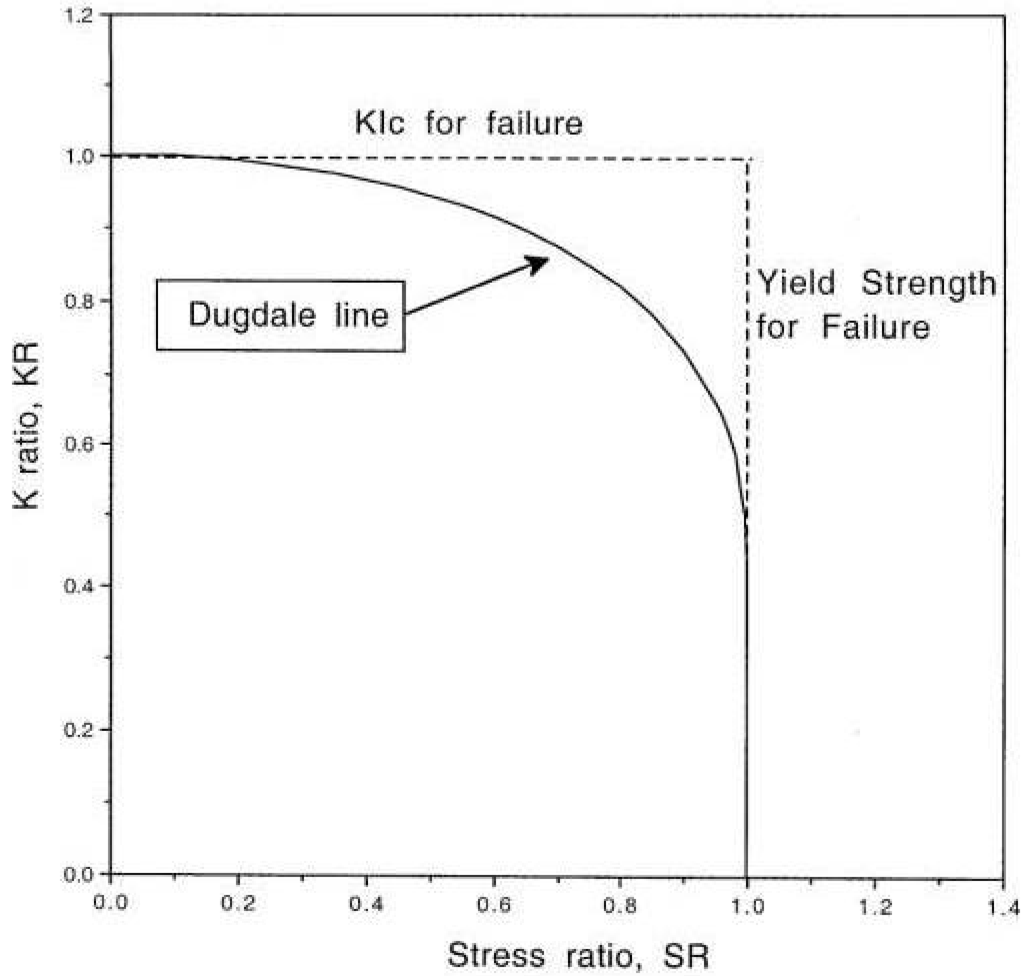
1. K_R versus S_R

2. S_R is strength ratio, σ/σ_{ys}

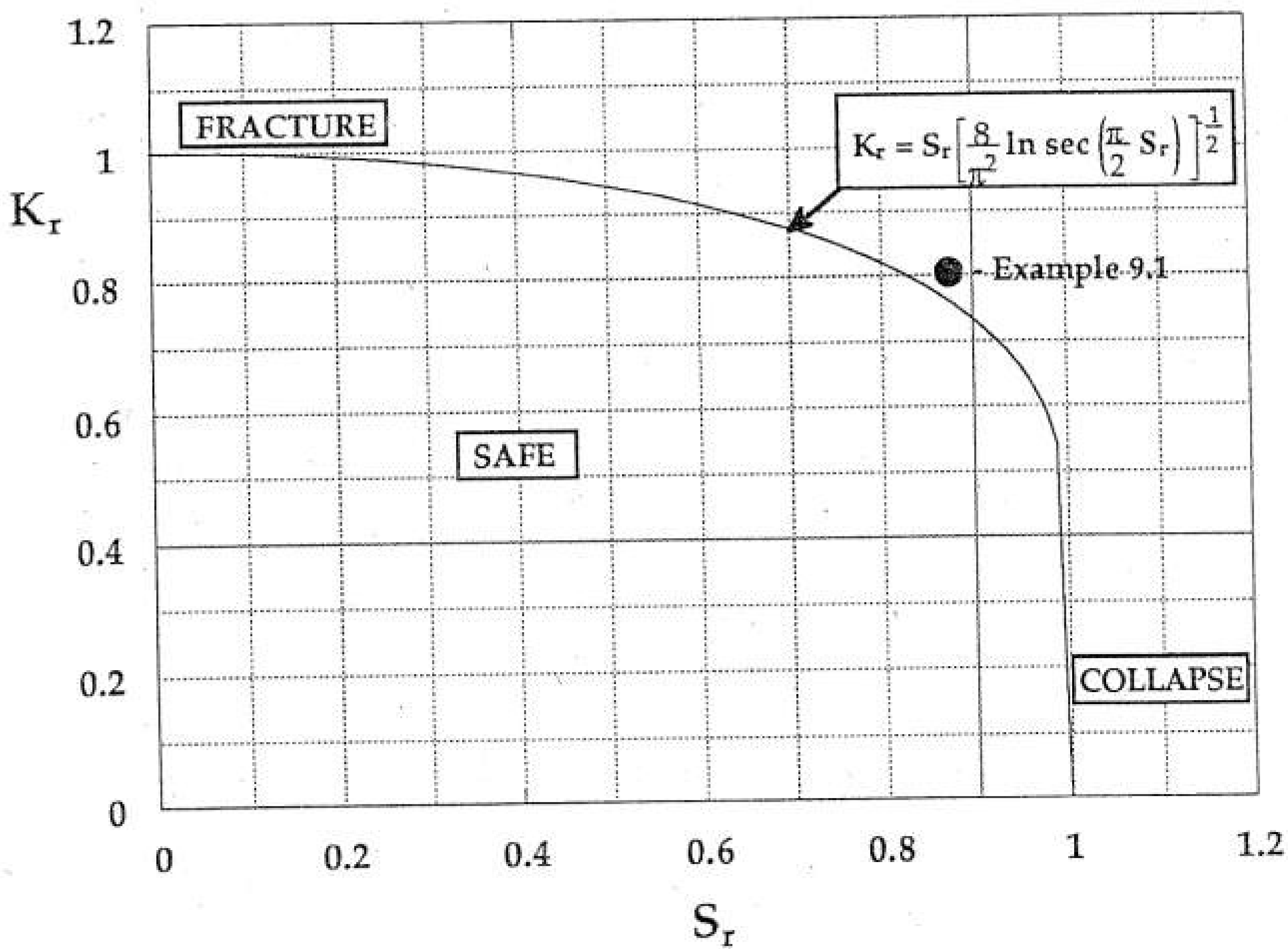
3. K_R is K ratio
   - K_{CCT}/K_D for curve
   - K_{appl}/K_{Ic} for point

4. Inside point

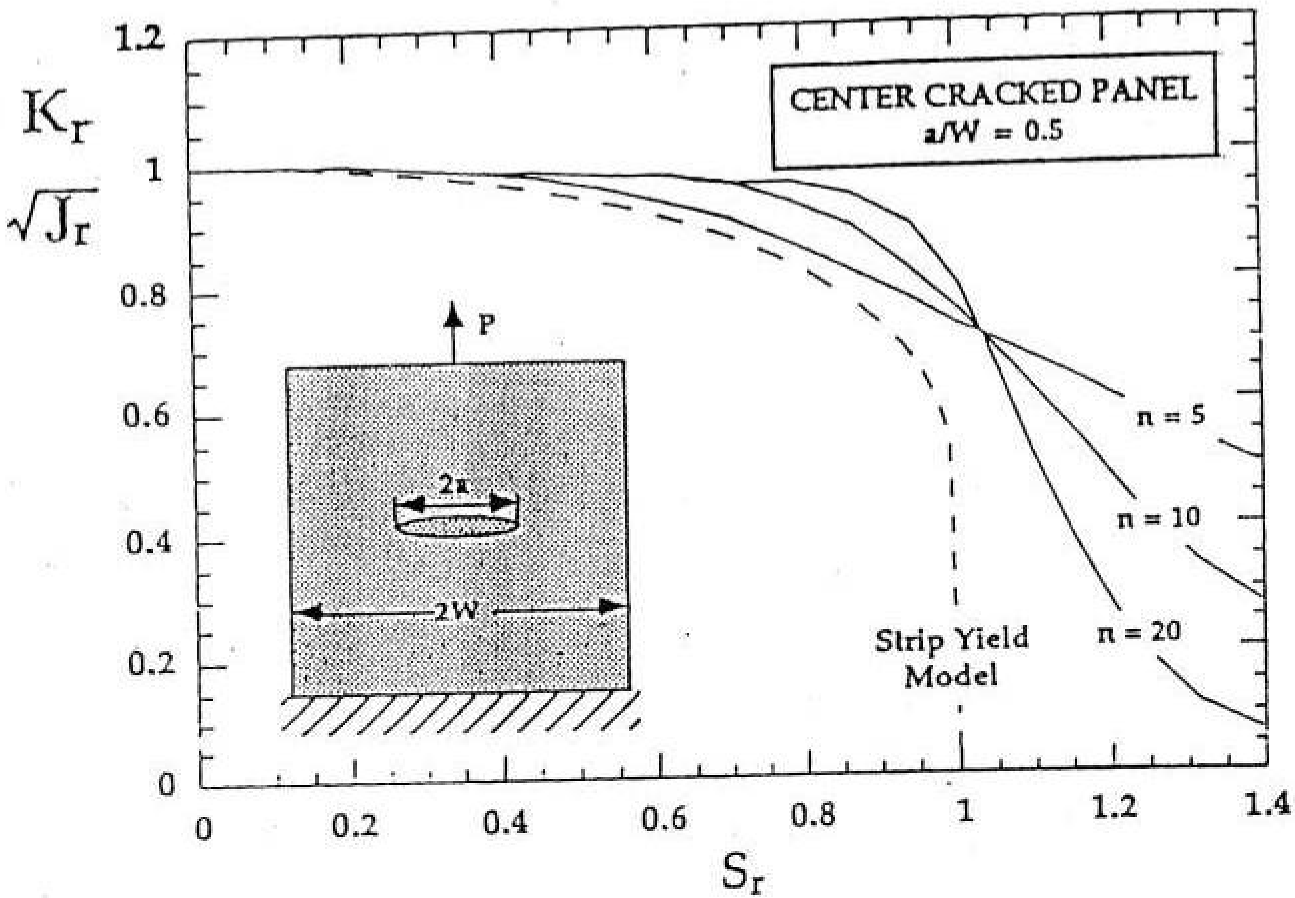
   $1/K_{Ic} < 1/K_D$, then $K_D < K_{Ic}$



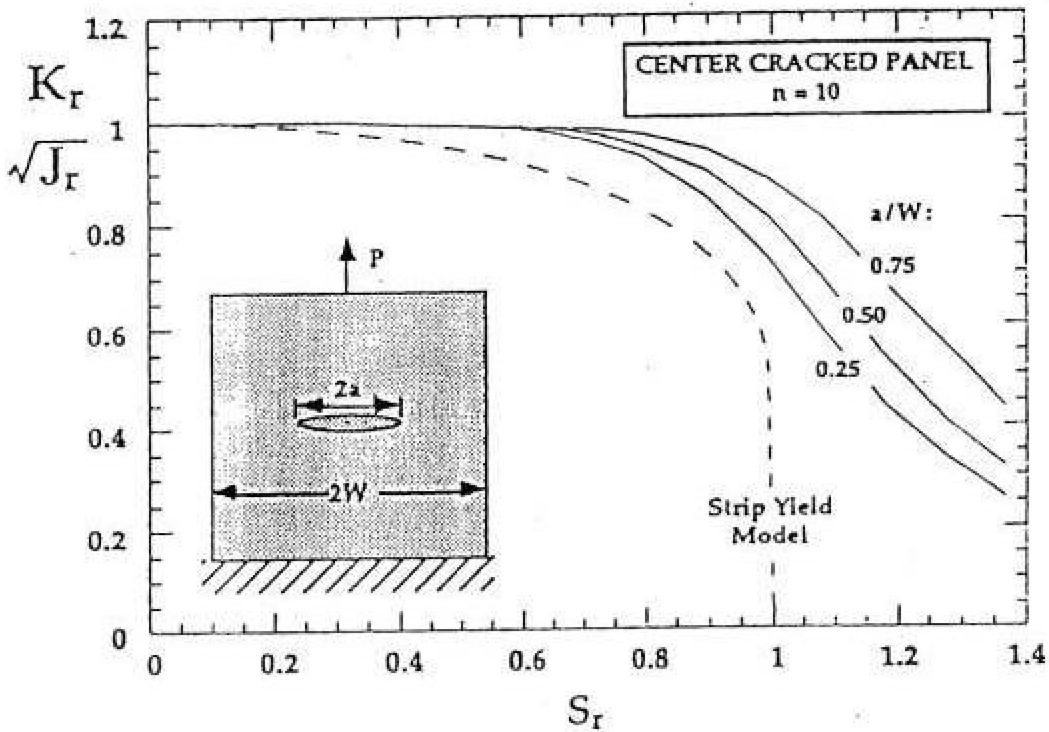
R-6 Failure Analysis Diagram



The strip yield failure assessment diagram [23,24].



CENTER CRACKED PANEL
a/W = 0.5
1.2
1
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
P
2a
2W
Strip Yield
Model
n = 5
n = 10
n = 20



Deformation Plasticity Failure Analysis Diagram, DPFAD, for a Range of a/W Ratios, Center Cracked Panel

Example for R-6

1. Applied Stress = 60 ksi

   Yield Strength = 100 ksi

   $K_{Ic} = 120 \text{ ksi}\sqrt{\text{in}}$

2. $S_R = 60/100 = 0.6$

3. If CCT model with $2a = 1$ in

   $K = \sigma\sqrt{\pi a} = 60\sqrt{\pi(0.5)} = 75.1$

   $K_R = 75.1/120 = 0.626$

   Point inside diagram, safe

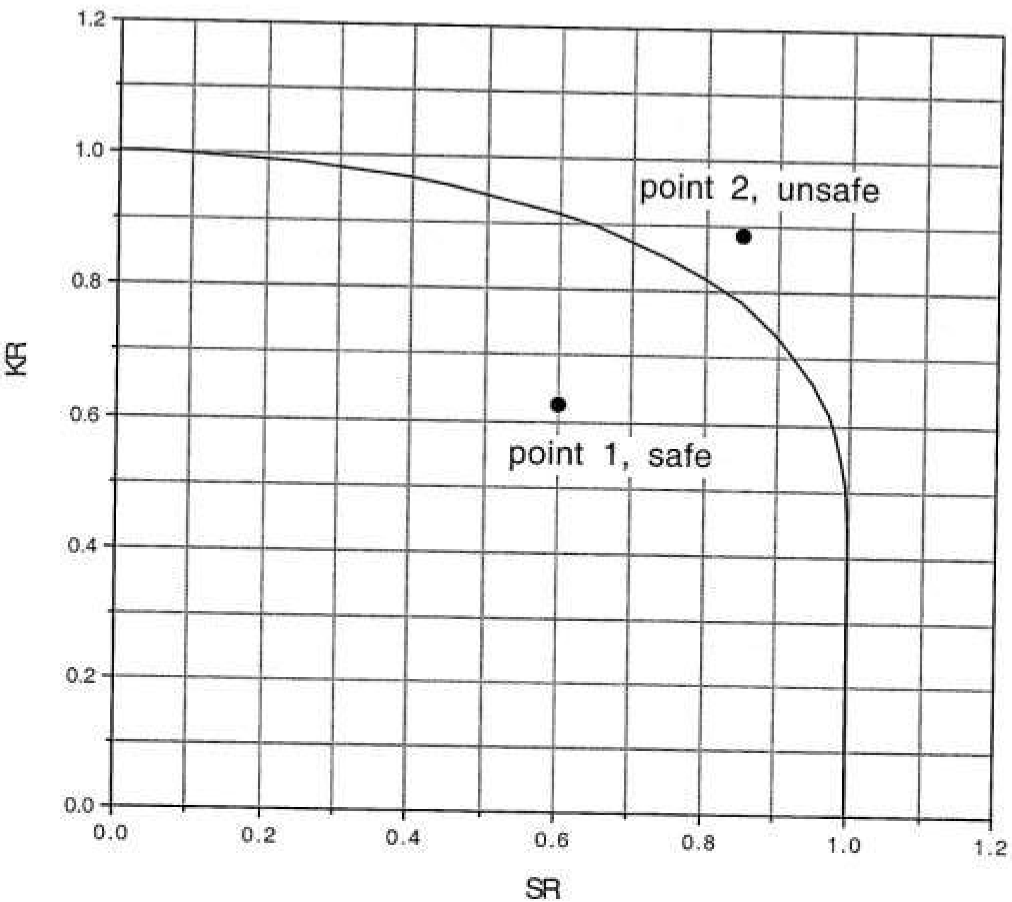
4. Raise applied stress to 85 ksi

   $S_R = 0.85$

   $K = 106.5$

   $K_R = 0.888$

   Point outside diagram, unsafe



R-6 Failure Analysis Diagram, with trial points

Flaw Acceptance Methodology
PD: 6493 (now BSI 7910)

A. Three levels of assessment

Level 1: Keep K below 0.707 K_{Ic} or
stress below 0.8 σ_{ys}

Level 2: R-6 method

Level 3: Replace R-6 curve with material specific

B. Start with level 1 if okay stop, if not, precede to level 2, etc. Method can be applied with little expertise in fracture mehcanics

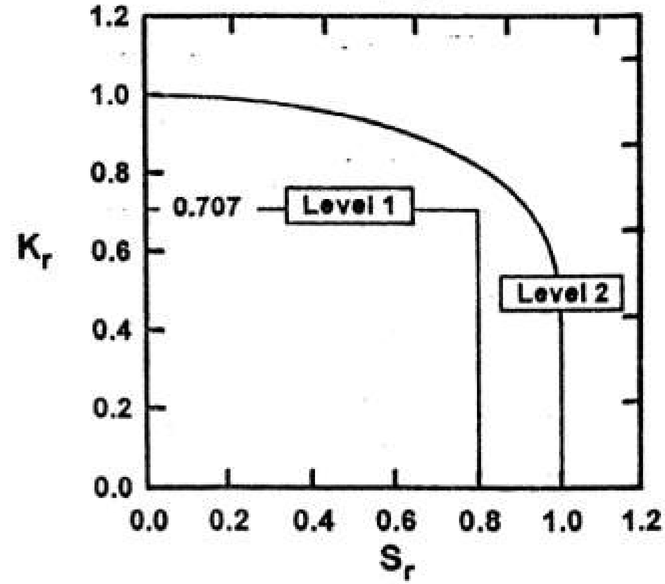
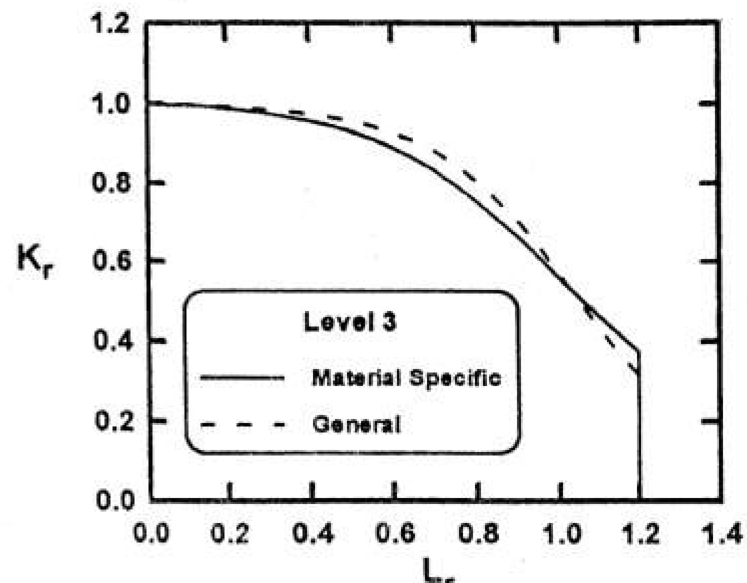


Fig. 17. PD 6493 FAD's, Levels 1 and 2.



ASME Boiler and Pressure Vessel Code – Use of FM

1. Section III, Appendix G –
   - Use of K_{Ic} and K_{IR} curves

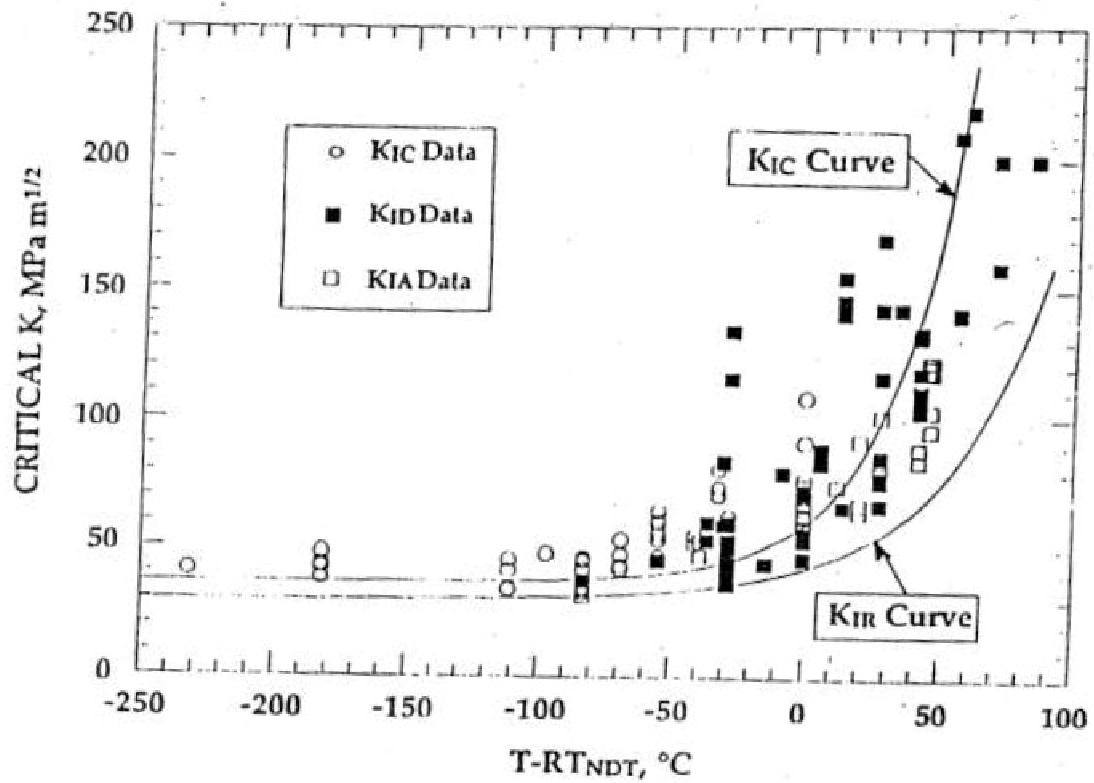
2. Section IX – Rules for in-service inspection of nuclear power plant components
   - K_{Ic} and K_{Ia}
   - da/dN vs ΔK reference curves

ASME Section Boiler and Pressure Vessel Codes

Reference Curves

$$K_{IC} = 36.5 + 3.084 \exp[0.036(T - RT_{NDT} + 56)]$$

$$K_{IR} = 29.5 + 1.344 \exp[0.026(T - RT_{NDT} + 89)]$$



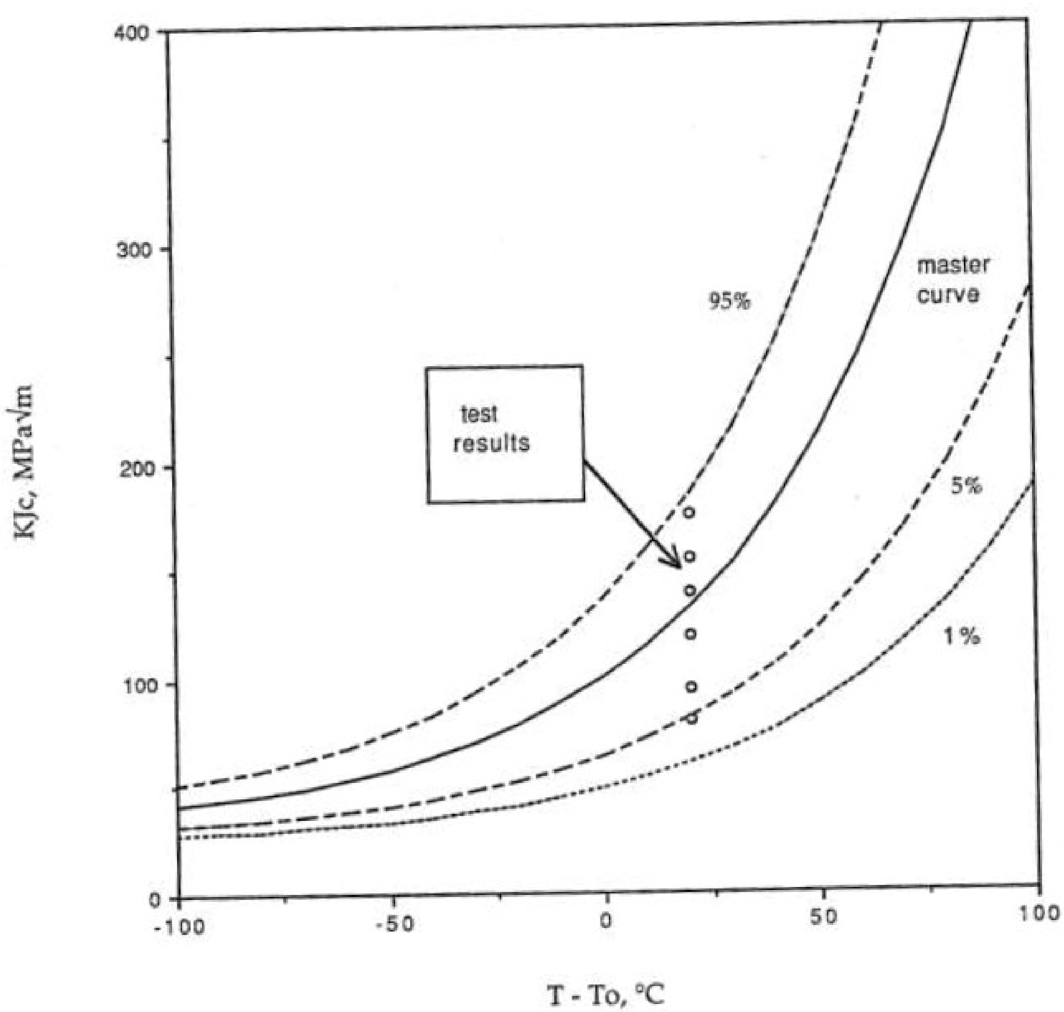
KIC and KIR Curves From ASME Section XI

T_o as an ASME Reference Curve

1. Use T_o instead of RT_{NDT} as the reference temperature

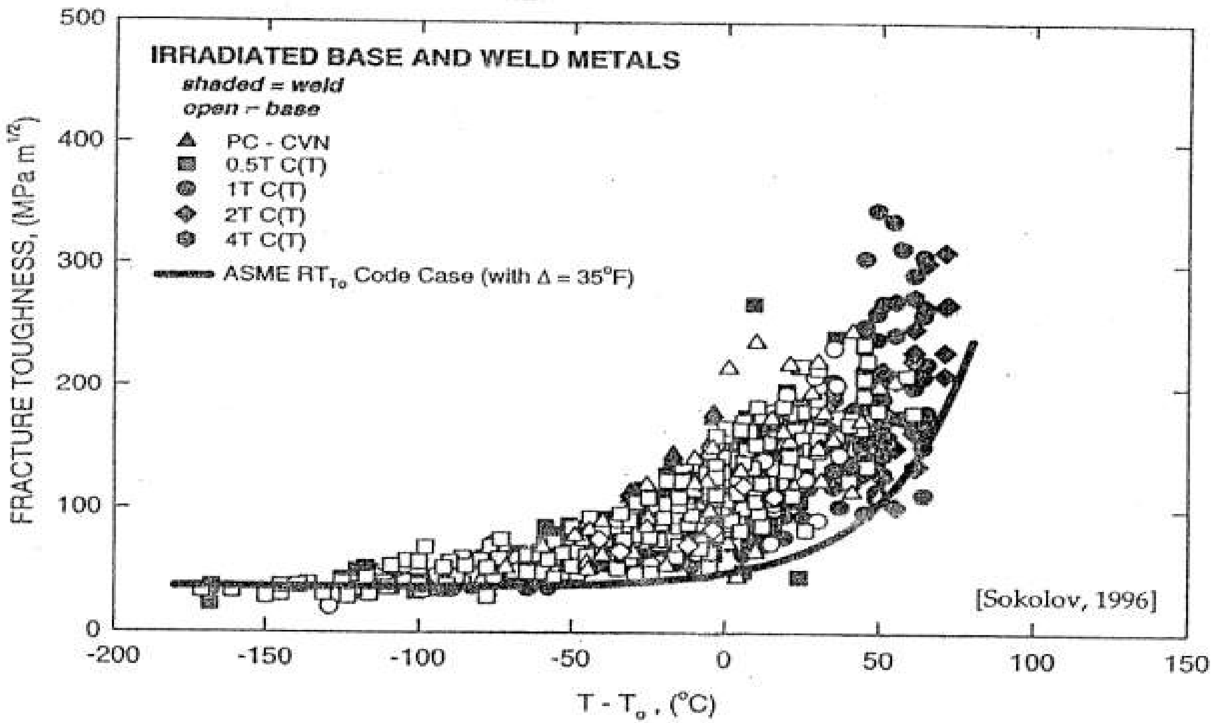
2. The K_{IR} is a lower bound, the master curve is a median

3. Shift the master curve by 35 °F to recover the lower bound concept



Master Curve with Tolerance Bounds

T_o for ASME Transition toughness data



Use T_o with a ΔT shift to get a lower bound for the ASME toughness data to replace T - RT_{NDT}

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European Application Methodologies

1. FITNET - FITNET is a 4-year European thematic network with the objective of developing and extending the use of fitness-for-service procedures throughout Europe. (www.euro**fitnet**.org/)
2. SINTAP – **S**tructural **INT**egrity **A**ssessment **P**rocedures for European Industry (www.eurofitnet.org/**sintap**_index.html

API 579-1/ASME FFS-1

- Fitness for Service Standard for pressure containing equipment in the refining and petrochemical industries
- API standard first issued in 2000
- Influenced by BSI 7910?
- Designed to be cookbook in nature?

NASGRO

- Fracture Mechanics and Fatigue Crack Growth Analysis Software
- analyze fatigue crack growth and fracture
- Perform assessments of structural life
- Process and store fatigue crack growth properties
- Analyze fatigue crack formation (initiation)

NASGRO

- NASGRO was originally developed at the NASA Johnson Space Center to perform fracture control analysis on NASA space systems. A growing interest in NASGRO among a variety of industrial users motivated NASA to develop a new partnership with industry. In July of 2000, NASA and Southwest Research Institute® (SwRI®) signed a Space Act Agreement under which SwRI formed and manages a consortium to provide guidance and support for future NASGRO development and user services. The NASGRO Consortium is now in its third three-year cycle (2007-2010).

Other FM Software

- AFGROW - The official home page of the AFGROW Fracture Mechanics program. This site contains all of the information one needs to use AFGROW effectively.

- NASGROW - Analyze fatigue crack growth and fracture, Perform assessments of structural life, Process and store fatigue crack growth properties, Analyze fatigue crack formation(initiation), and Compute stresses. Airframe Guide for Certification of Part 23 Airplanes.

- CRACKS2000 - CRACKS2000 is a state-of-the-art crack growth analysis software system based on linear elastic fracture mechanics technology.

Other (cont)

- RAPID - Repair Assessment Procedure and Integrated Design. Effect of structural repairs on aircraft structural integrity is one of the critical issues that needs to be properly addressed to assure the aircraft continuing airworthiness and operational safety
- .
- FRANC2DL - FRANC2D/L is a highly interactive finite element program for the small deformation analysis of two-dimensional structures. As such, it is useful for engineering calculations or for instruction in finite element and fracture courses.

- FRANC3D AND OSM - FRANC3D is a work-station based FRacture ANalysis Code for simulating arbitrary non-planar 3D crack growth that has been under development since 1987. OSM (Object Solid Modeler) is a pre-processor to FRANC3D for building the initial geometric modeled.

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

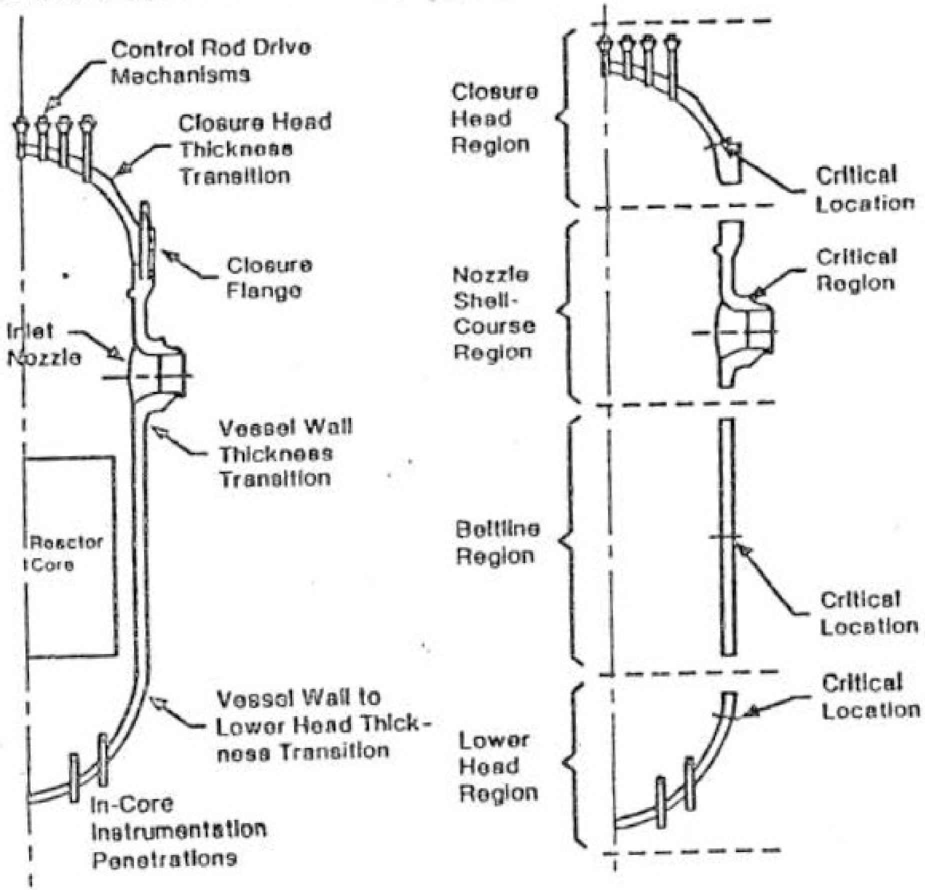
- A PTS concern arises —

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

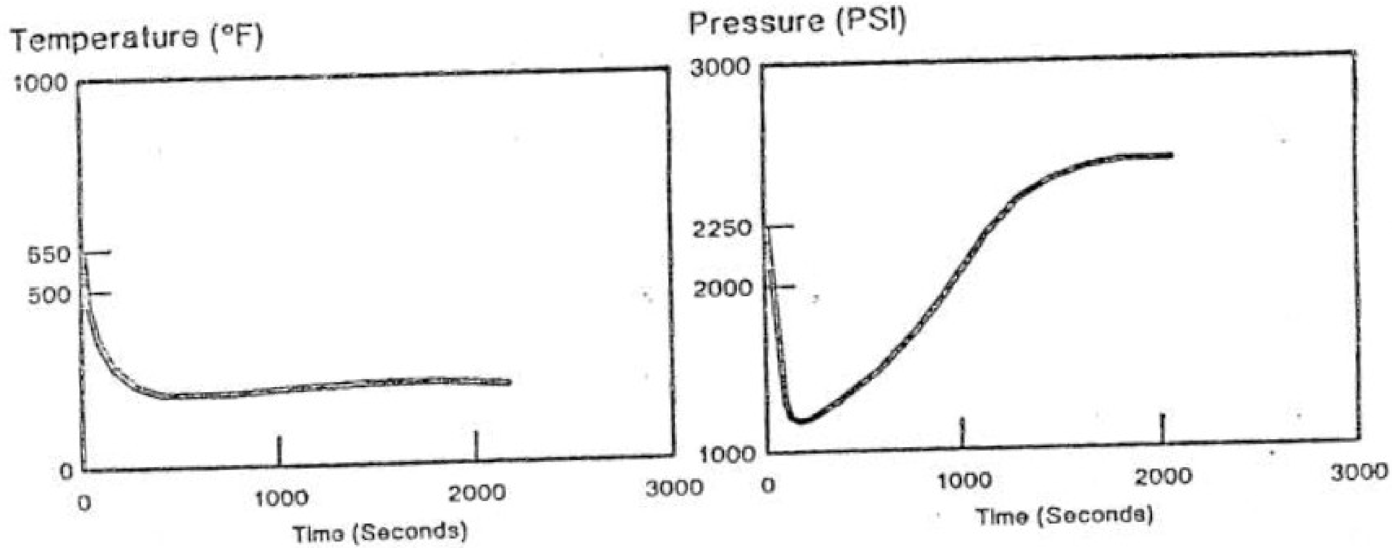
  2) If the beltline region has a reduced fracture resistance because of neutron irradiation, and

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

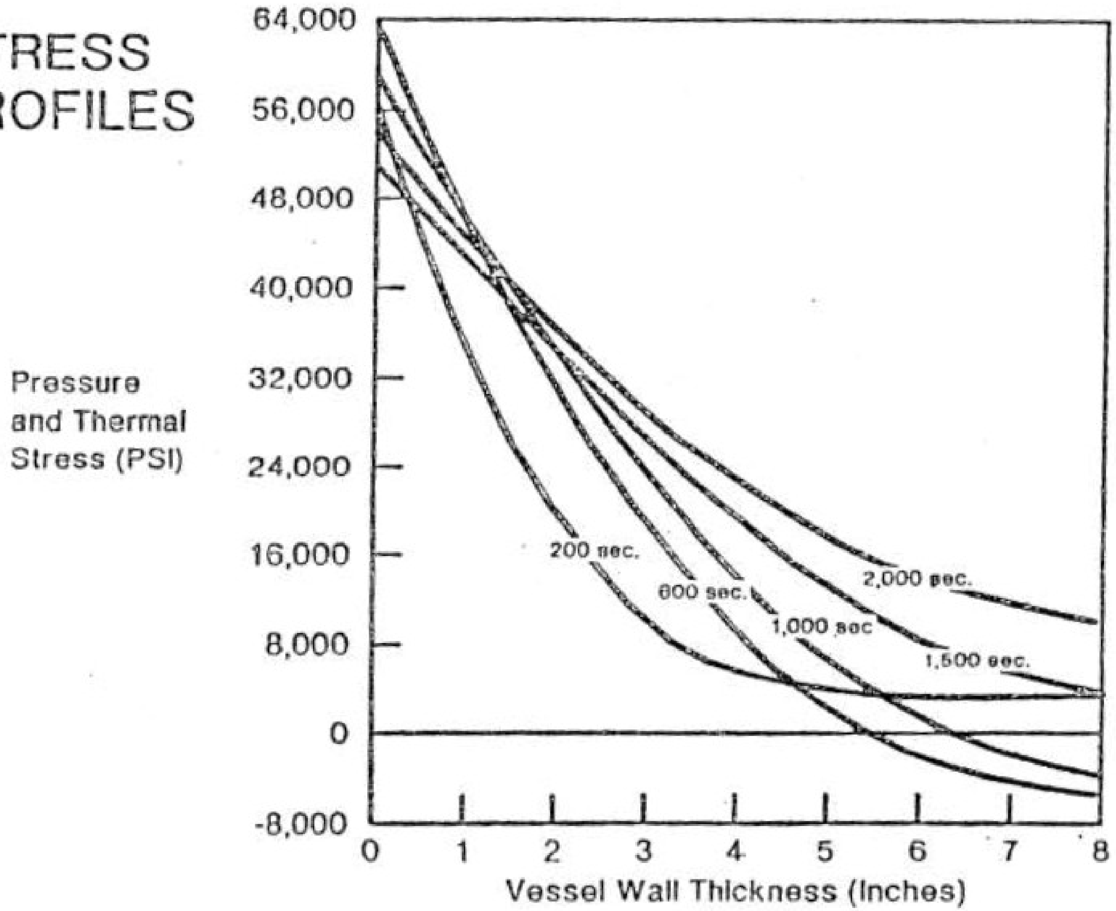
REACTOR VESSEL CRITICAL LOCATIONS



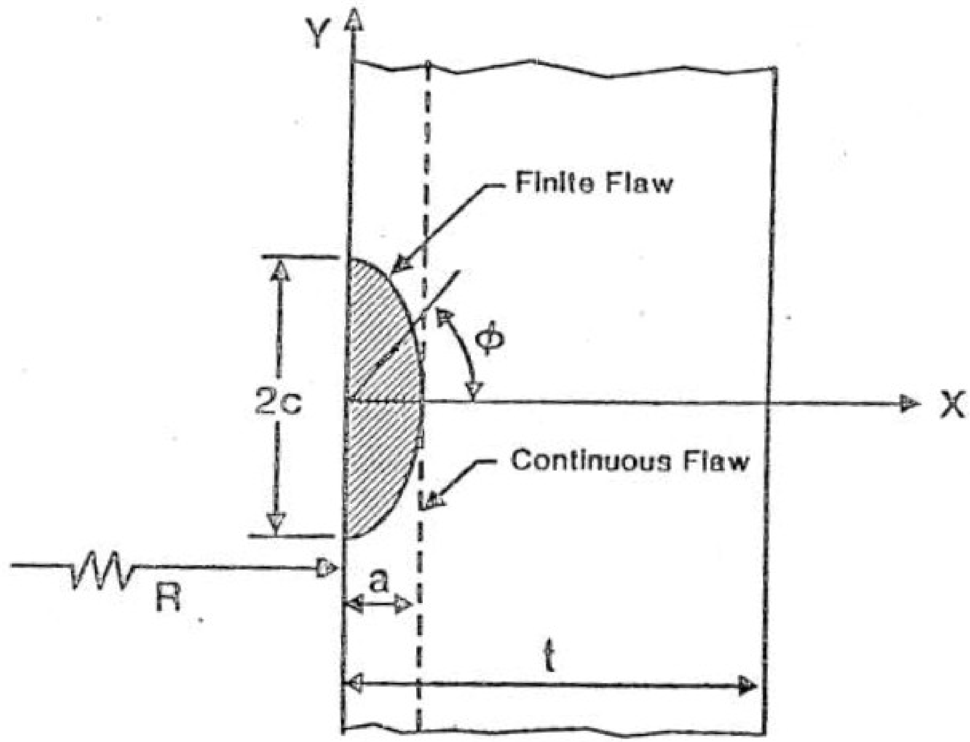
REACTOR COOLANT PRESSURE AND TEMPERATURE TRANSIENTS FOR A REPRESENTATIVE SEVERE THERMAL TRANSIENT



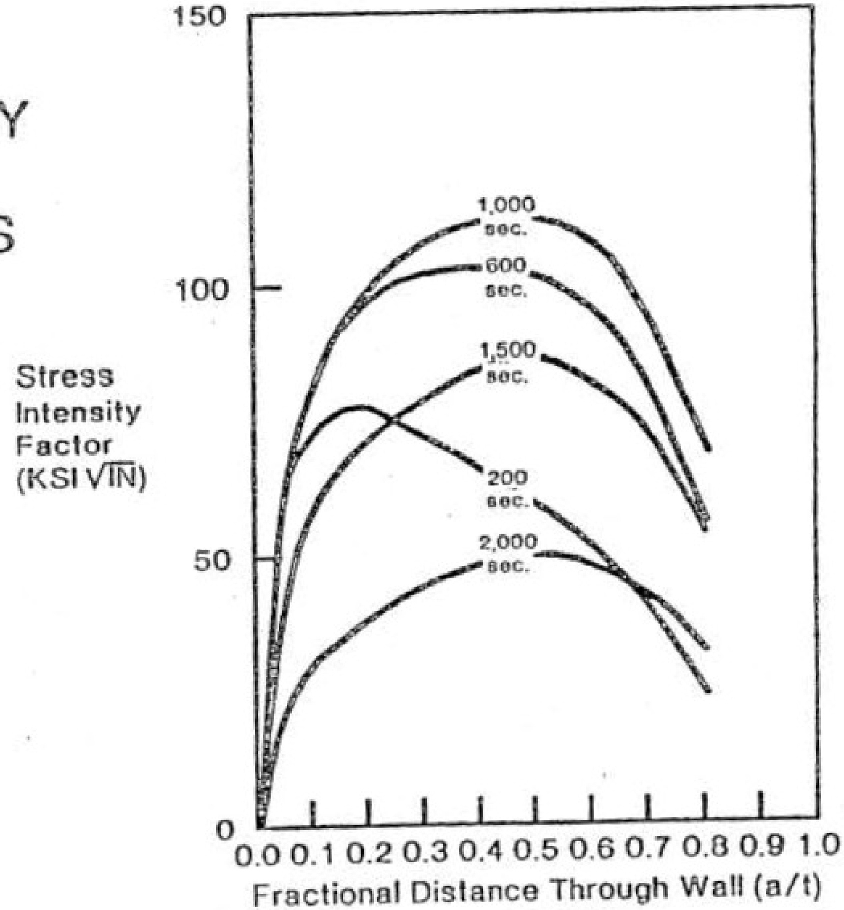
STRESS PROFILES



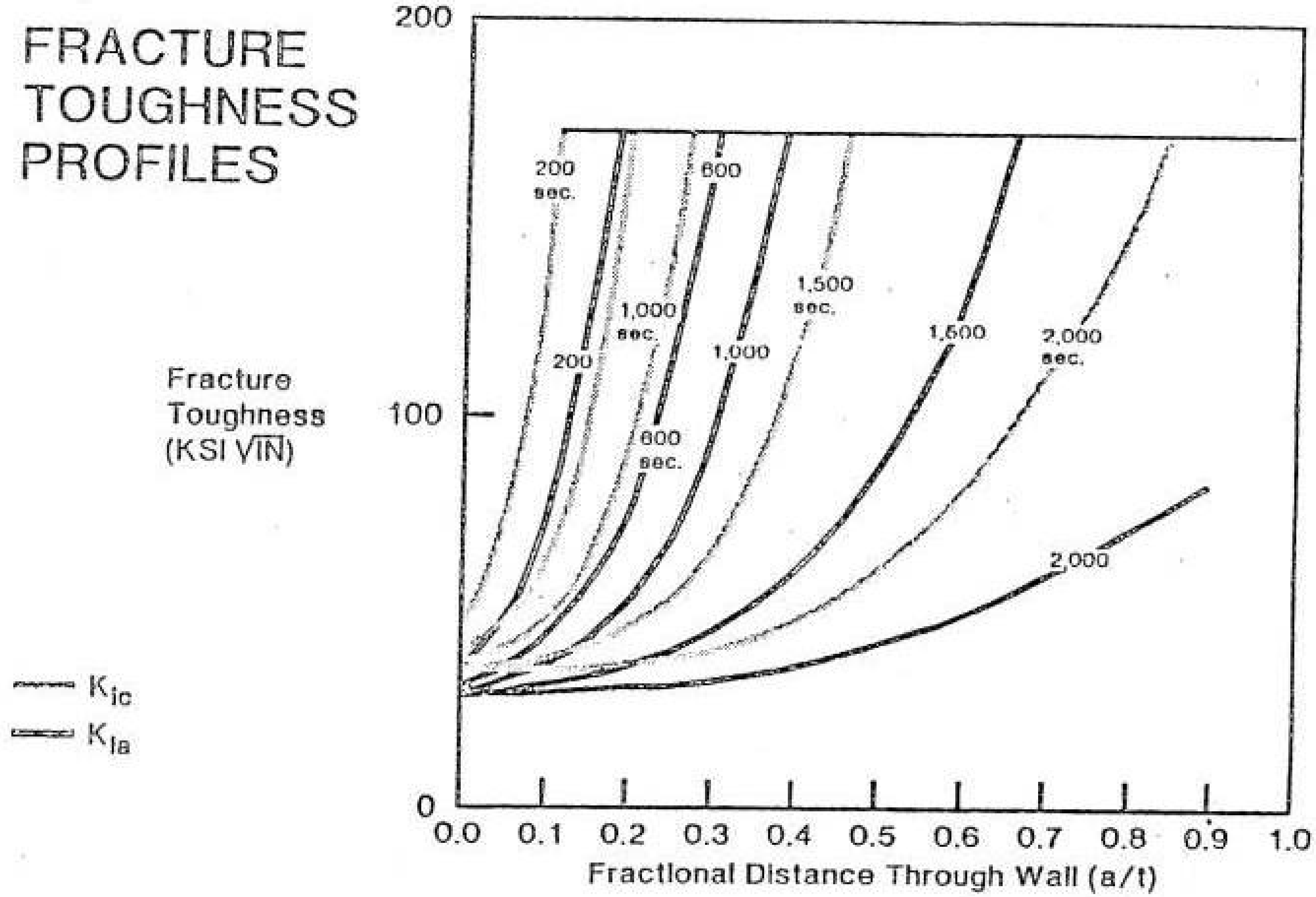
FLAW SHAPES FOR FRACTURE MECHANICS ANALYSIS



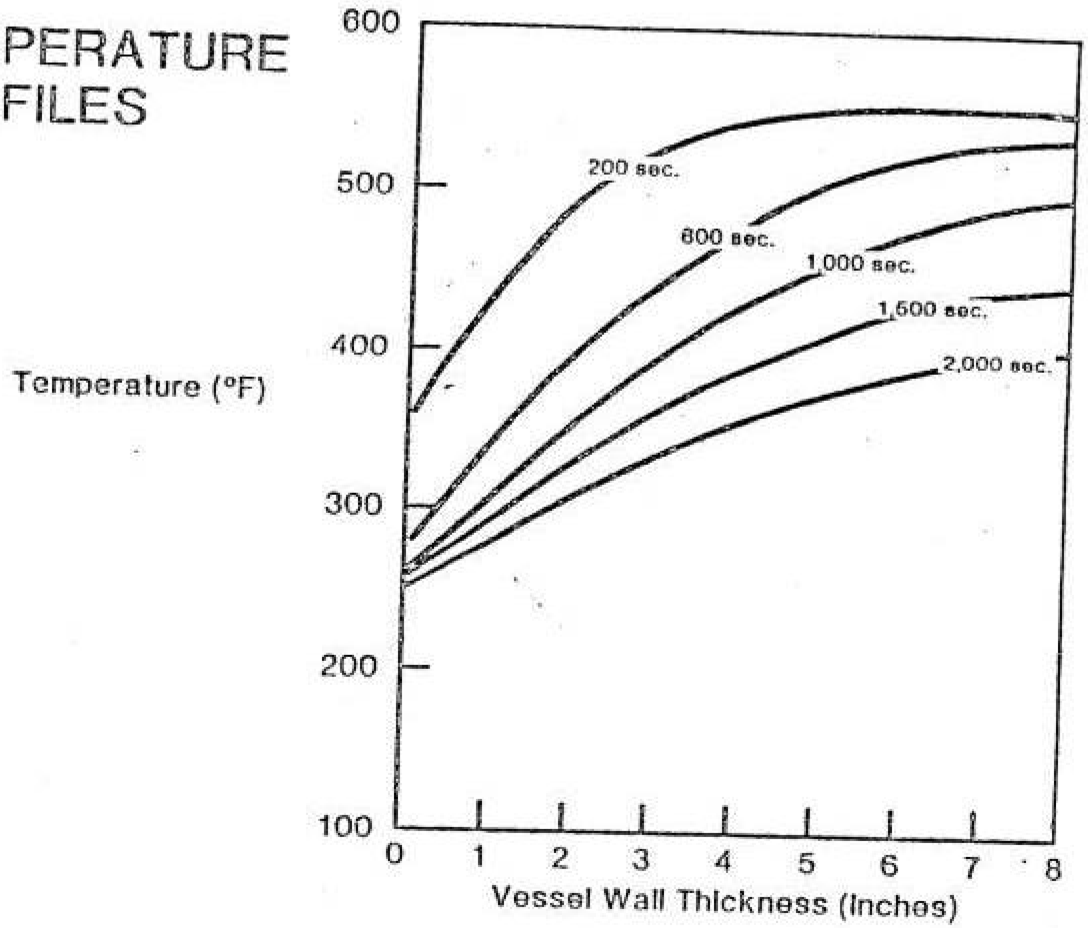
STRESS INTENSITY FACTOR PROFILES



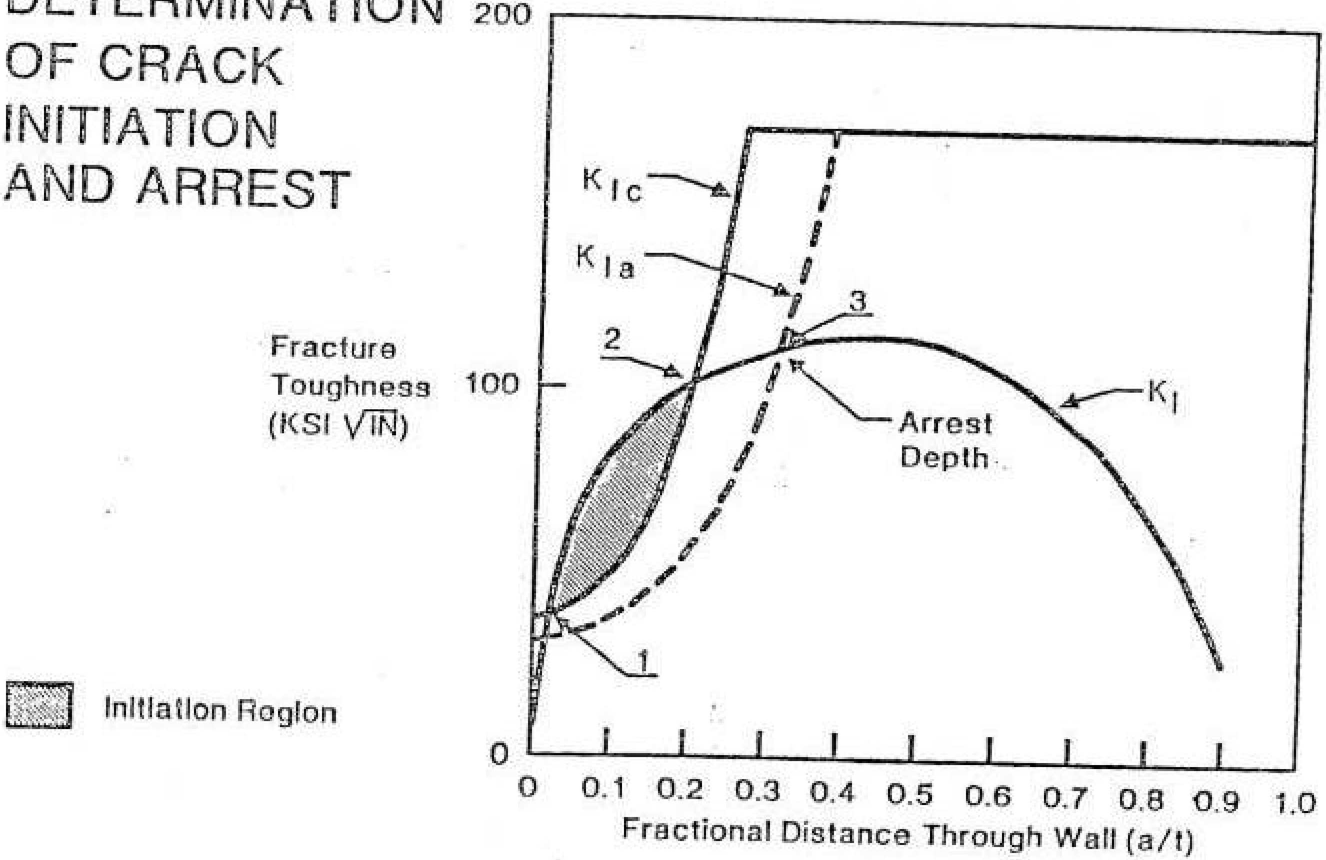
FRACTURE TOUGHNESS PROFILES



TEMPERATURE PROFILES



DETERMINATION OF CRACK INITIATION AND ARREST



Probabilistic Analysis

Each corner of the FM Δ can be given a statistical distribution

1. Applied stresses - Prob of large load excursion
   Prob of reaching N cycles in life

2. Defect - Prob of defect on size, location, orientation

3. Material properties - Prob. on all properties used; K_{Ic}, da/dN vs ΔK, s_{ys},

Rotor example:

P_f = Prob of failure, to be determined
P_q = Prob a_i will grow to $a_f = 0.7$
P_d = Prob a_i will be undetected = 0.0025
P_o = Prob a_i will be in a critical location = 0.1

$$P_f = P_q \times P_d \times P_o = 0.7 \times 0.0025 \times 0.1 = 1.75 \times 10^{-4}$$

Fracture Control Plans

A. Modes of Failure (Barsom & Rolfe)

1. Yielding - plastic deformation
2. Buckling - general instability
3. Subcritical crack growth
4. Unstable crack extension

B. Four elements of a fracture control plan

1. Identification of factors that may lead to fracture
2. Establishment of relative contribution of each
3. Determination of trade-offs in design method to minimize possibility of fracture
4. Recommendation of specific design considerations to ensure safety and reliability of structure

C. Examples of elements

1. Loads, types and magnitude,
   Environment, temperature
   Material properties, low toughness, low K_{Iscc}

2. Investigate various failure causes - high stress, residual stress, toughness, da/dN, temperature

3. Lower stress, eliminate discontinuities, use material with higher K_{Ic}

4. Consider economics, functionality

D. Example Fracture Control Plans

1. Nuclear Pressure Vessels
   (PVRC & ASME Code)

   - Toughness based on K_{IR} for material
   - Test to determine RT_{NDT}
   - Reference flaw size
   - Loading membrane + thermal;
   - Additional factors

2. Steel Highway bridges - AASHTO

- No FM testing, use CVN
- Insure no plane strain fracture in 50 ksi yield steel at - 80 °F
- Need CVN energy ≥ 15 ft-lb at - 80 °F for intermediate load rate
- This corresponds to $K_{Ic} = 50\ ksi\sqrt{in}$ at - 30 °F
- To insure this need dynamic input energy at 15 ft-lb at 40 °F
- For fracture control members require 25 ft-lb to take care of scatter
- Materials other than 50 ksi yield steel have similarly derived conditions

E. Fracture Control by function

1. Design
   a) Stress distribution information
   b) Flaw tolerance regions of largest fracture hazard due to stress
   c) Estimates of stable crack growth for typical periods of service
   d) Recommendations of safe operating conditions for specified intervals between inspections

2. Materials

a) Strength and fracture properties for inert and aggressive environments
b) Recommended heat treatments
c) Recommended welding practices

3. Fabrication

a) Inspection prior to final fabrication
b) Inspection baed on fabrication control
c) Control of residual stress, grain coarsening, grain directions

4. Inspection

a) Same as 3a
b) Same as 3b
c) Direct inspection for defects using appropriate NDE
d) Proof testing
e) Estimates of largest crack-like defect size