FLAW EVALUATION

Presented to:

MIT Course 22.314J
Structural Mechanics in Nuclear Power Technology
December 5, 2006

Presented By:
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(Course 2, 1975, 1982)

INTRODUCTION TO ASME SECTION XI

Nuclear Plants Designed to set of Expected Conditions
- – operation parameters
- – environment
- – plant cycles

- **Plants Constructed to Code Procedures**
- **Process Has Been Very Successful, but…**
  - – some “loadings” missed in design process
  - – Materials selection not optimum
  - – Flaws escaped initial detection
- **ASME B&PV Code Section XI Provides Methods for Evaluation**

INTRODUCTION TO SECTION XI

Key Degradation Found In-Service

- **Initial Flaws Found by Improved Technology**
- **Various Corrosion Mechanisms Surfaced**
  - intergranular stress corrosion cracking (BWRs)
  - primary water stress corrosion cracking (PWRs)
  - Flow accelerated corrosion
  - microbiologically induced corrosion
  - general corrosion/pitting
  - etc.
- **Plant Cycling Exceeded That Considered in Design**

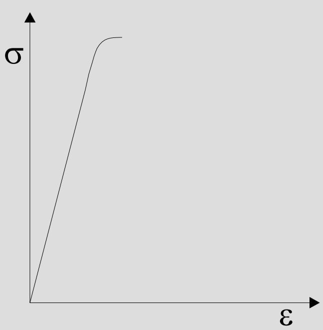
INTRODUCTION TO SECTION XI

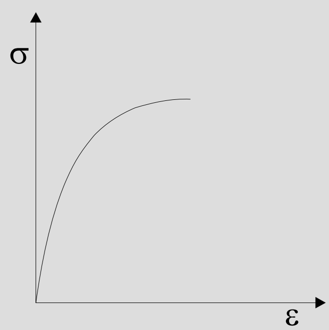
- **Codes for Construction**
  - Use conservative loads
  - Rules for design, analysis, construction/fabrication and initial examination/hydro test
  - Assure adequate initial design
  - Linear indications limited to 3/16 in., no cracks permitted
  - General corrosion allowance, other corrosion phenomena left to Owner
- **Section XI Code for Operating Plants**
  - Addresses Continuing Assessment of Structural Integrity
  - Addresses planar and non-planar flaws
  - Operating plant needs

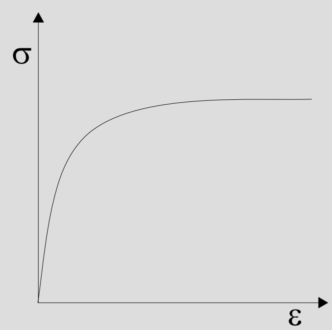
INTRODUCTION TO FRACTURE MECHANICS

Fracture Mechanics

- Linear Elastic Fracture Mechanics (LEFM)
- Elastic-Plastic Fracture Mechanics (EPFM)
- Limit Load (Net Section Plastic Collapse)







LEFM

- Brittle Materials
- High Strength / Low Toughness
- Ferritic Steels at Low Temperature

EPFM

- Semi-Ductile Materials
- Moderate Toughness
- Ferritic Steels at High Temperature
- Stainless Steels and Weldments (SAW and SMAW)

Limit Load

- Very Ductile Materials
- High Toughness
- Stainless Steel Base Metal and GTAW Weldments

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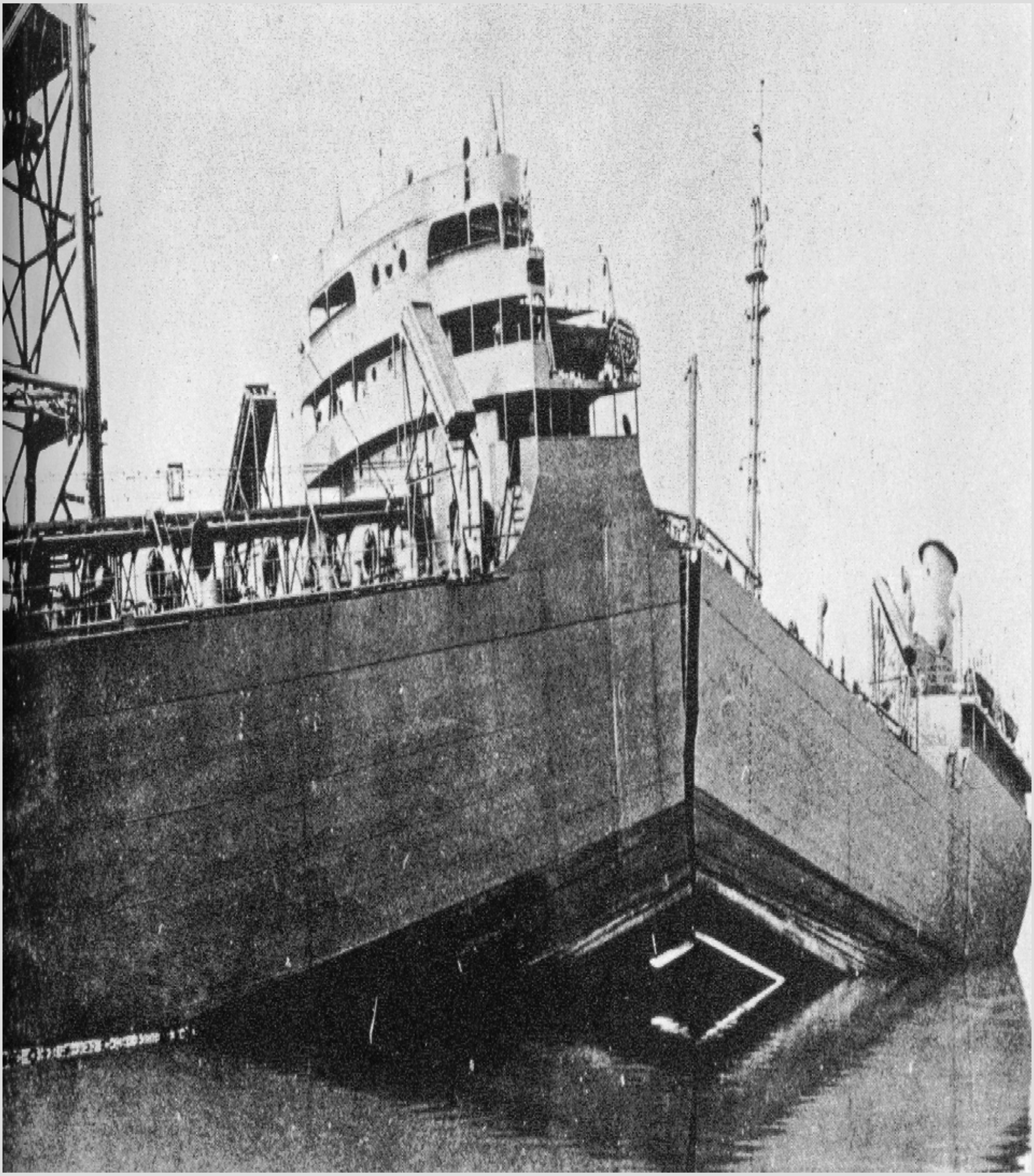
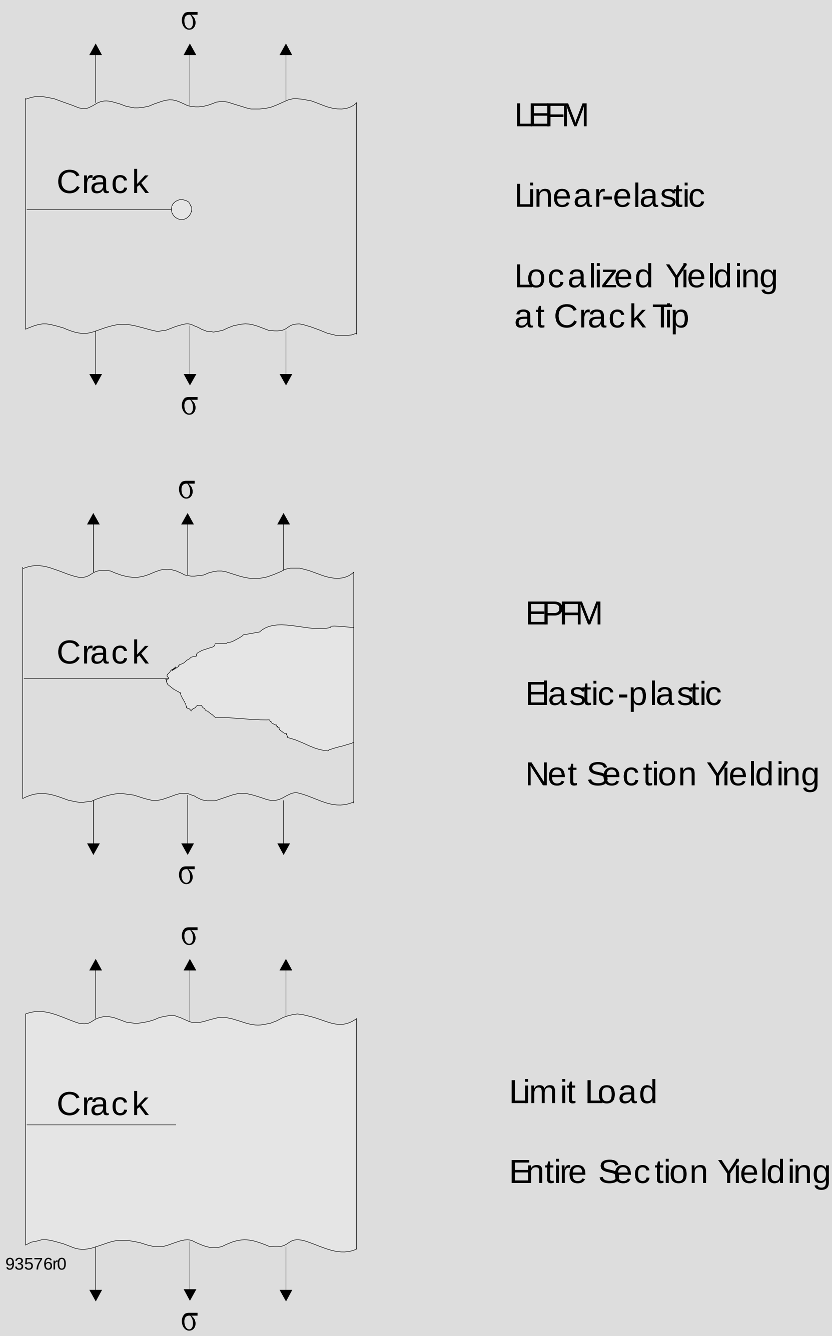
Brittle Failure of Low Toughness Steel in Cold Water

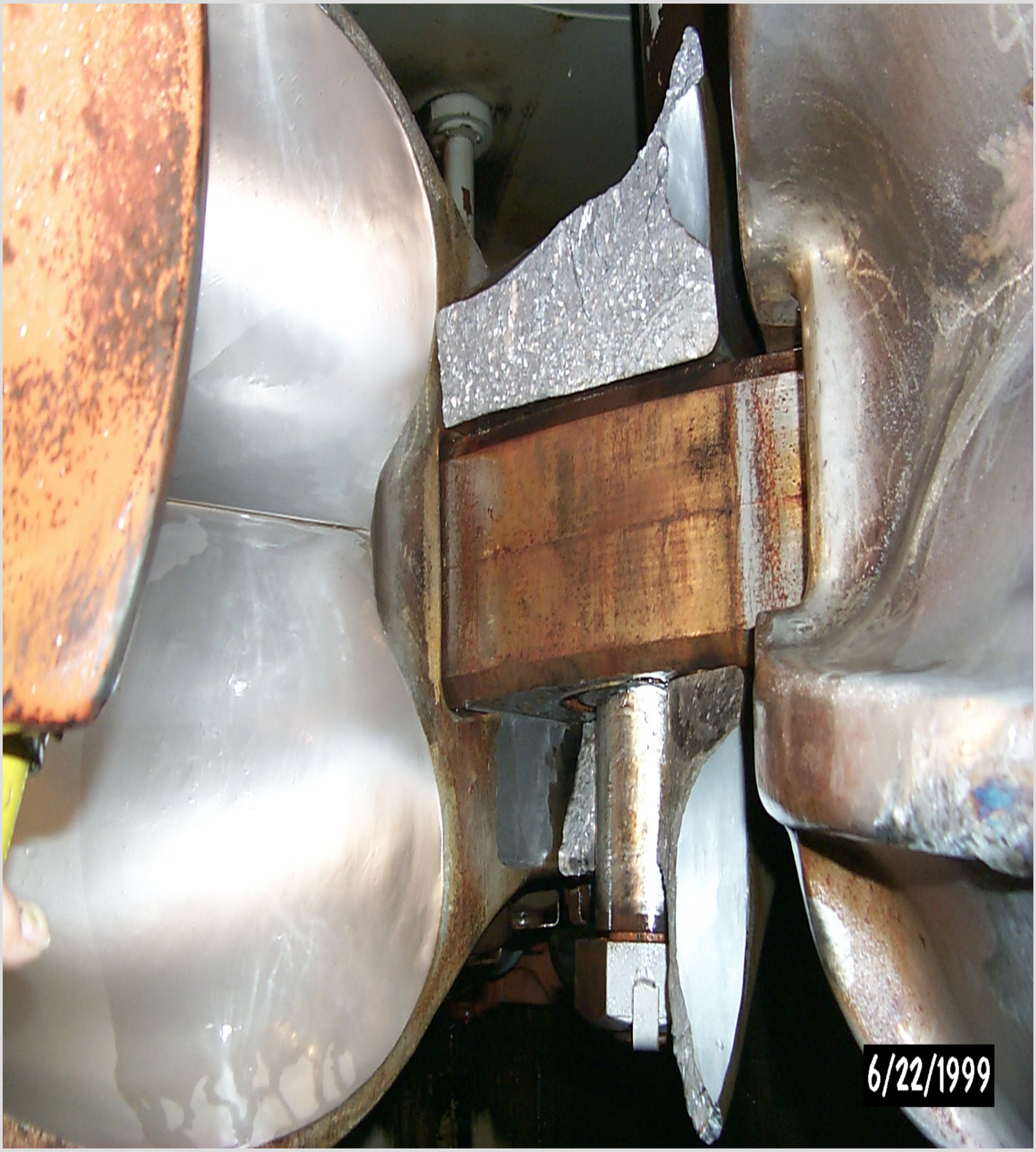


INTRODUCTION TO FRACTURE MECHANICS

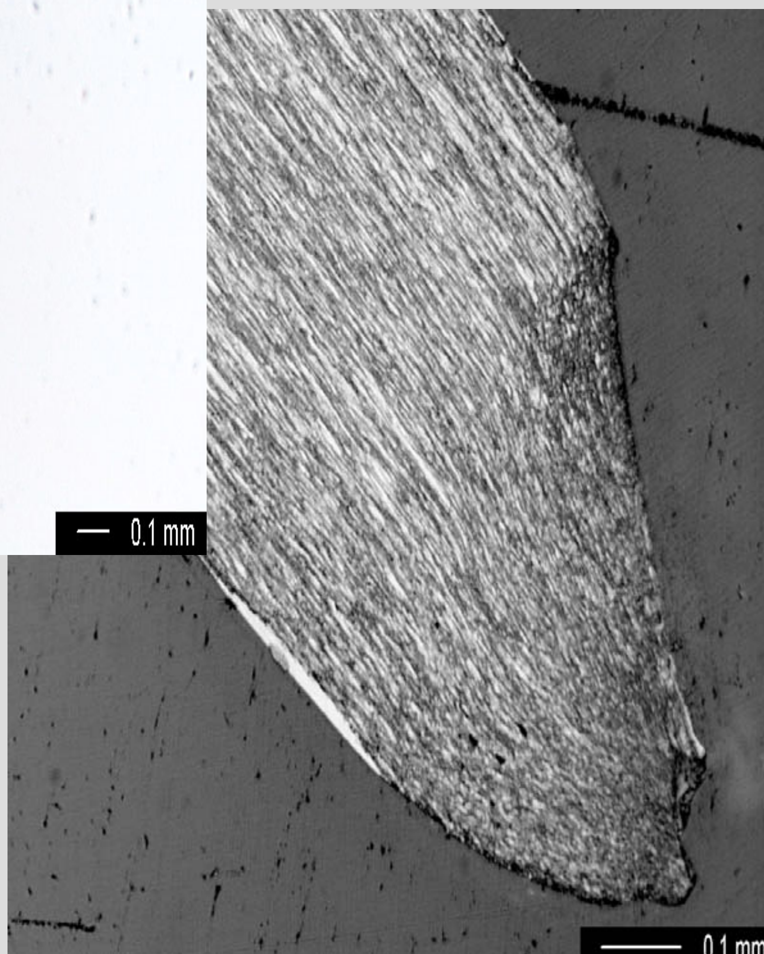


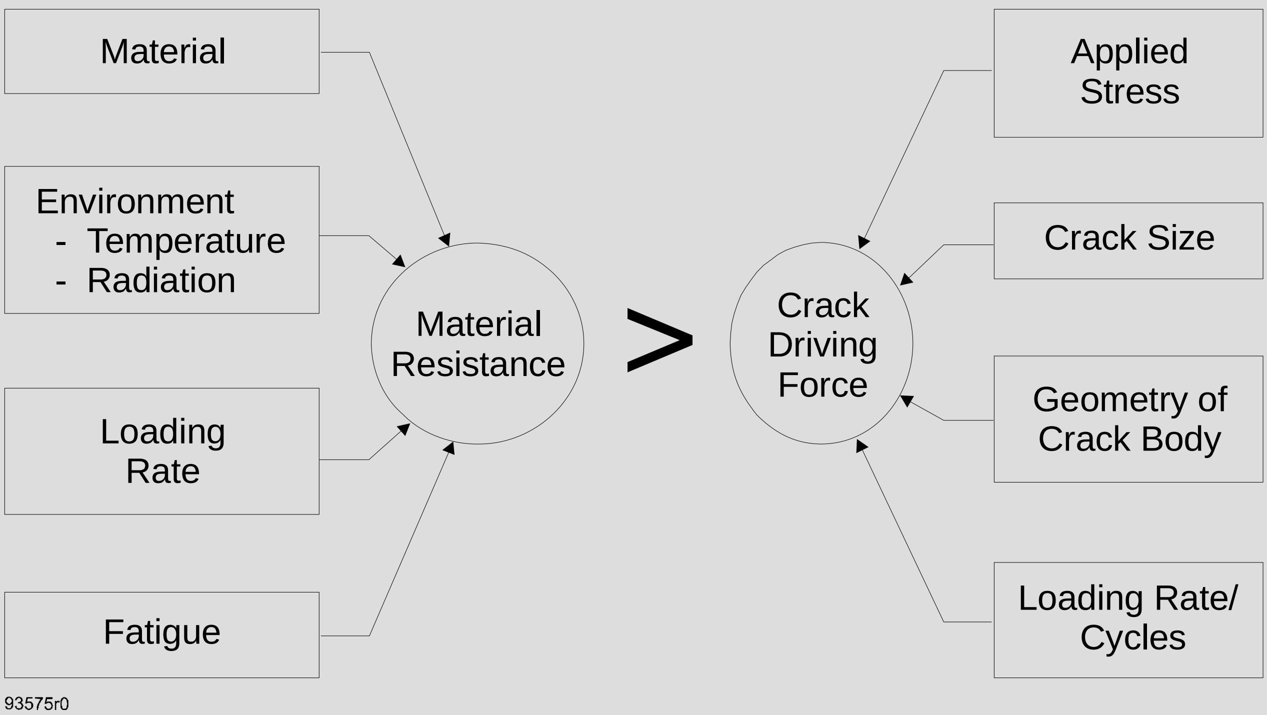
Generalized Categories of Fracture Mechanics for Cracked Bodies

Brittle Fracture



Ductile Fracture





Fundamental Concept in Fracture Mechanics

EVALUATION APPROACH

Elements of Vessel Flaw Evaluation

- **Determine Fracture Toughness (A-4000)**
  - K_{Ic} and K_{Ia} are provided as a function of temperature
  - Upper limit of 200 ksi-√inch
- **Fracture Toughness Affected by Irradiation**

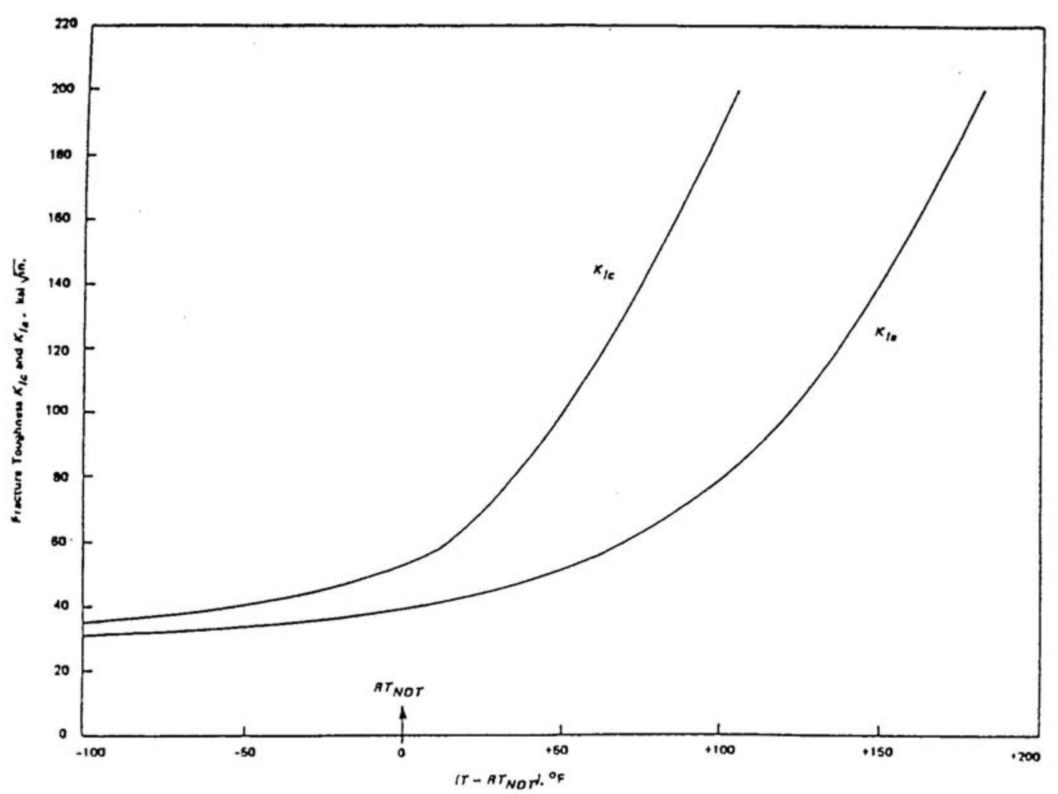
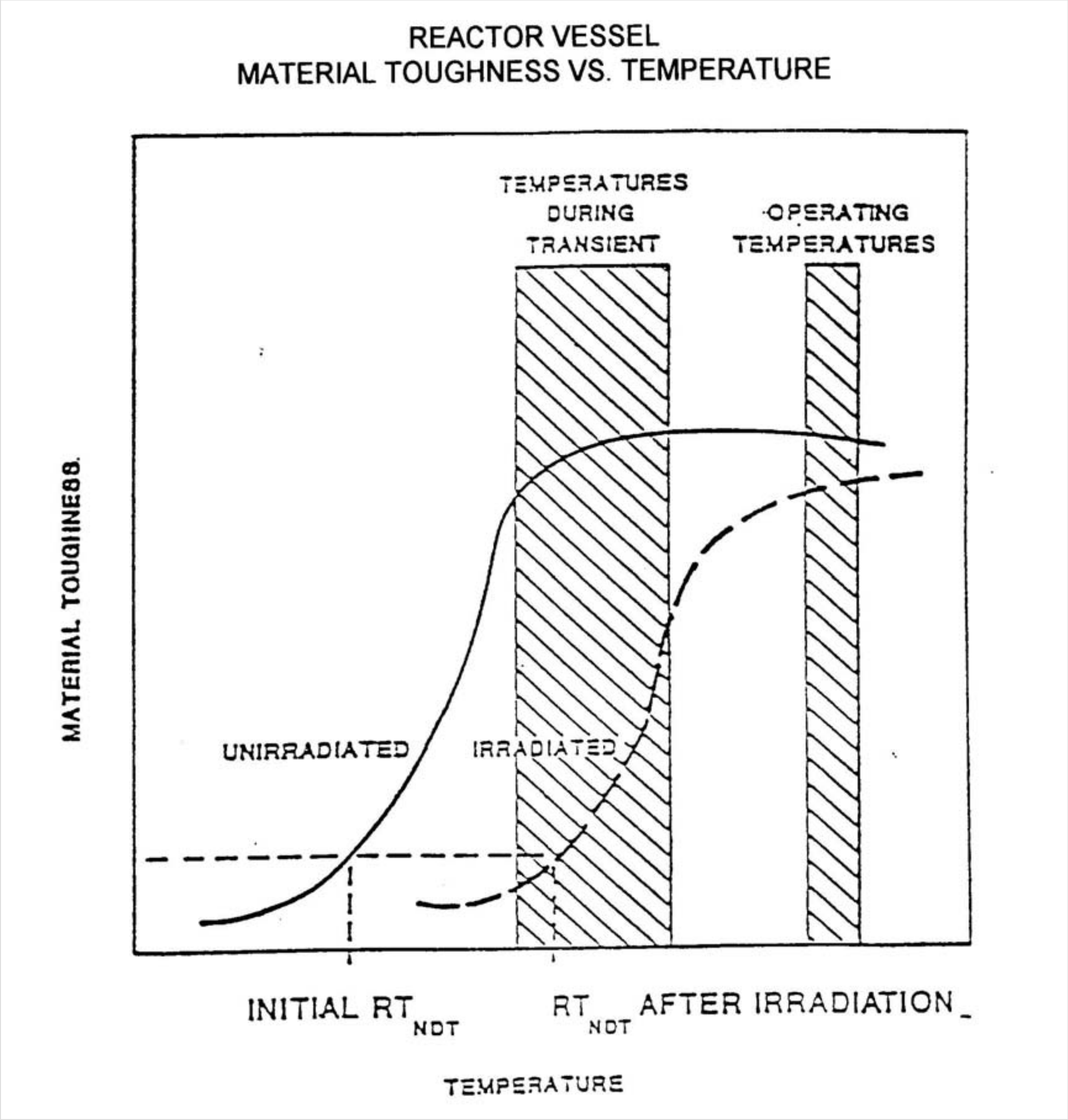


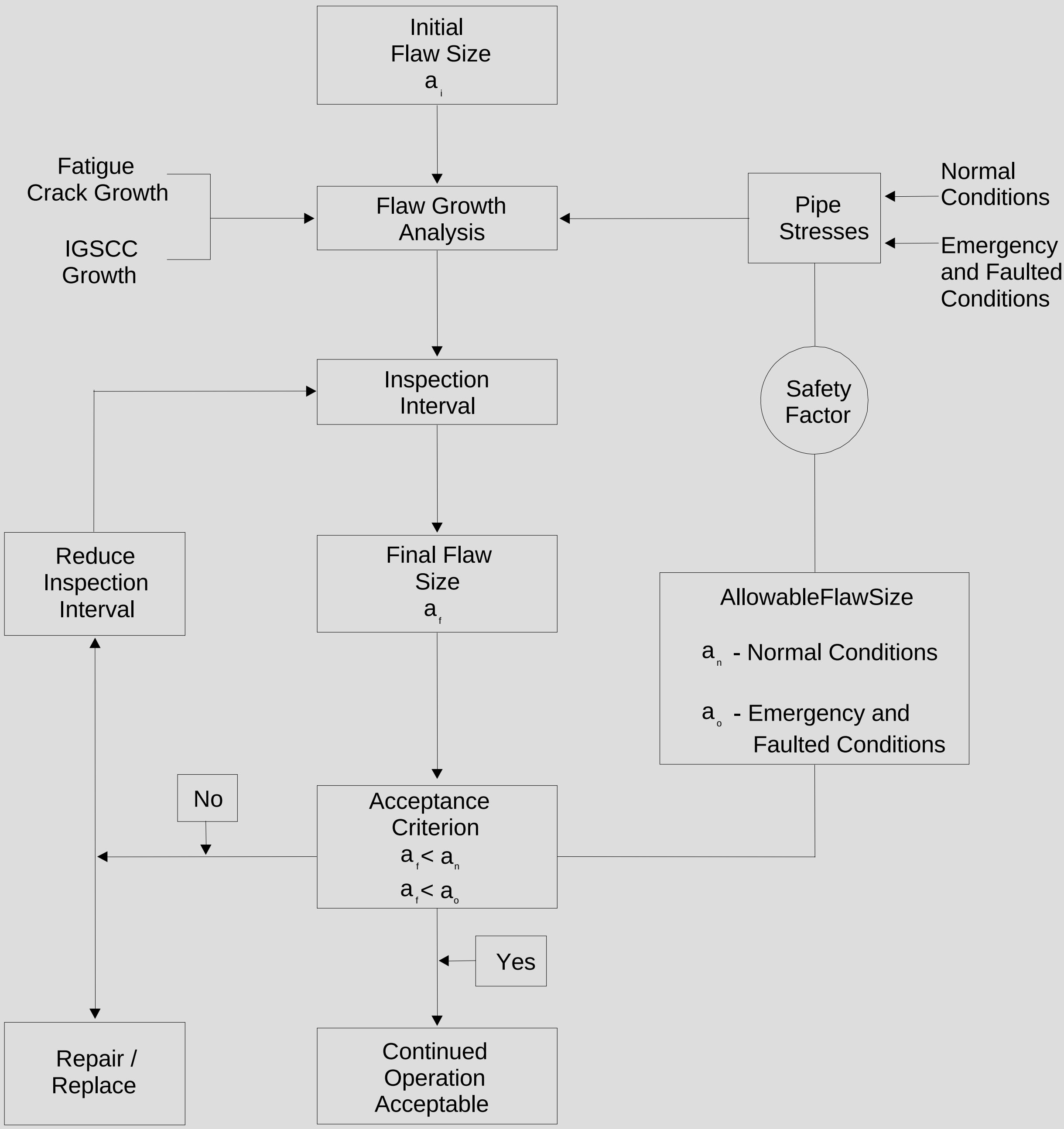
FIG. A-4200-1 LOWER BOUND K_{Ia} AND K_{Ic} TEST DATA FOR SA-533 GRADE B CLASS 1, SA-508 CLASS 2, AND SA-508 CLASS 3 STEELS

EVALUATION APPROACH

Elements of Vessel Flaw Evaluation **(cont'd)**



FLAW EVALUATION (IWB-3610/APPENDIX A)



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Comparison of Fracture Mechanics Analysis Methods

Linear Elastic Fracture Mechanics (LEFM)

Advantages:

1. Many models published
2. Many literature material properties
3. Simple analysis
4. Linear material behavior
5. Linear superposition of load cases is appropriate
6. Applicable to common materials (carbon steels with toughness transition)
7. Broad range of service applicability
8. Easy to develop intuitive understanding of results

Linear Elastic Fracture Mechanics (LEFM) - Continued

Disadvantages:

1. May be very conservative if significant ductility is present
2. May calculate very small allowable flaws
3. Most applicable to linear, brittle materials
4. Material testing may require large specimens for validity
5. Not meaningful where significant plasticity is present (e.g., creep regime)

Limit Load (Net Section Collapse)

Advantages:

1. Applicable to very ductile materials (stainless steel)
2. Very simple – solutions can be derived by hand
3. Linear behavior -- superposition of load cases is appropriate
4. Broad range of service applicability
5. Easy to develop intuitive understanding of results

Disadvantages:

1. Not applicable to irradiated materials
2. ???

Elastic-Plastic Fracture Mechanics (EPFM)

Advantages:

1. Better treatment of ductile materials (high toughness)
2. May demonstrate larger acceptable flaws and/or greater margin of safety
3. Better accounts for plasticity effects, including ductile tearing
4. Material testing may not require large test specimens (ASTM-E-399 vs. ASTM-E-1737)
5. Results can be used to develop "pseudo-elastic" analyses in some high toughness cases
6. Applicable where creep conditions are present

Elastic-Plastic Fracture Mechanics (EPFM) - Continued

Disadvantages:

1. Fewer literature solutions than LEFM
2. Much less literature data on material properties
3. Analysis is much more complex
4. Range of applicability is much more limited
5. Linear superposition is not applicable, and intuition is much more difficult

LEFM -- STRESS INTENSITY FACTOR

- **The basic parameter of linear elastic fracture mechanics is the crack tip stress intensity factor, K_I.**

- **Stress field near crack tip is characterized by K_I as follows:**

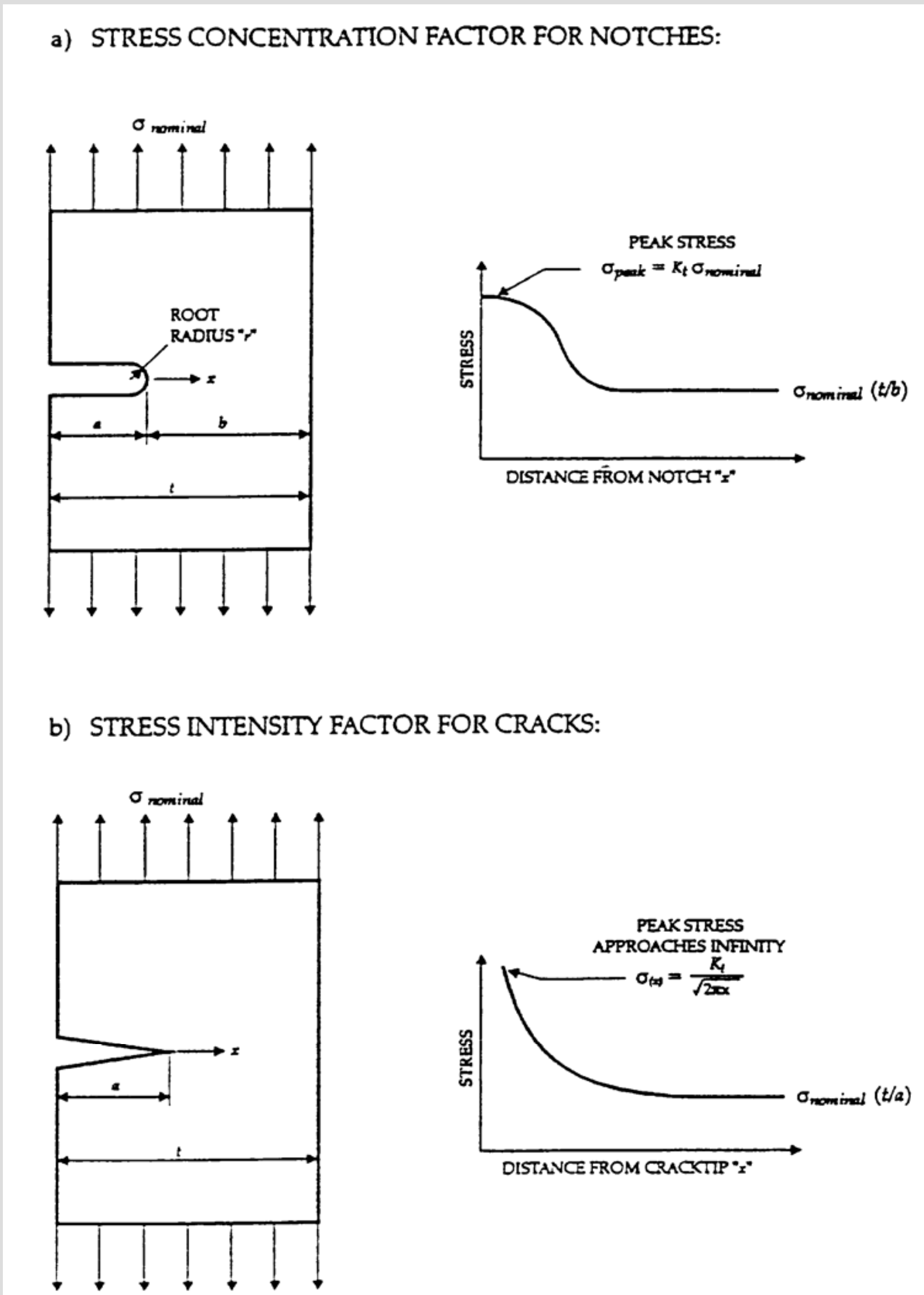
$$\sigma_x = \frac{K_I}{\sqrt{2\pi x}}$$

where: x = the distance from the crack tip

<u>**Fracture Toughness**</u>

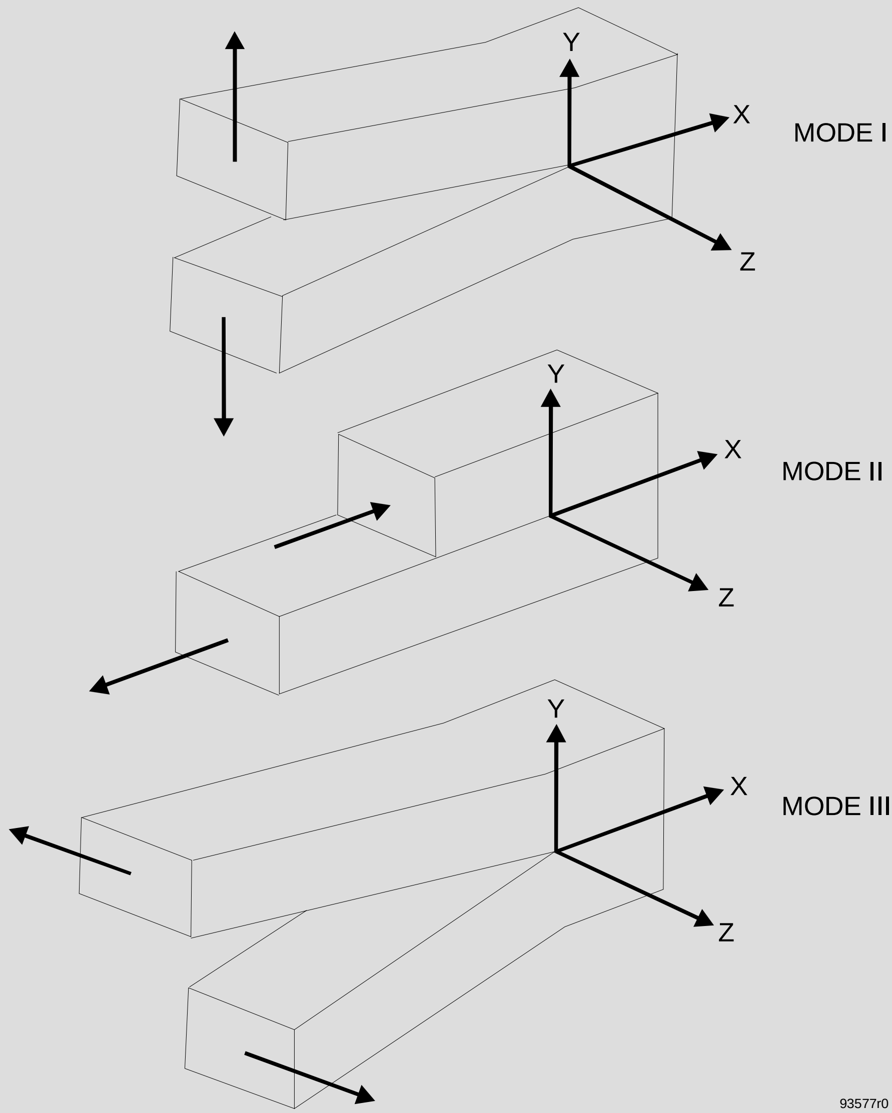
- **K_I parameter characterizes the tendency of crack to propagate unstably under a static load. Critical value of K_I is denoted as K_{Ic} and is called "fracture toughness."**
- **Within certain limits, fracture toughness is a material property, dependent on temperature, environment, etc.**

LEFM -- STRESS INTENSITY FACTOR (cont'd)



Comparison of notch and crack

LEFM -- STRESS INTENSITY FACTOR (cont'd)



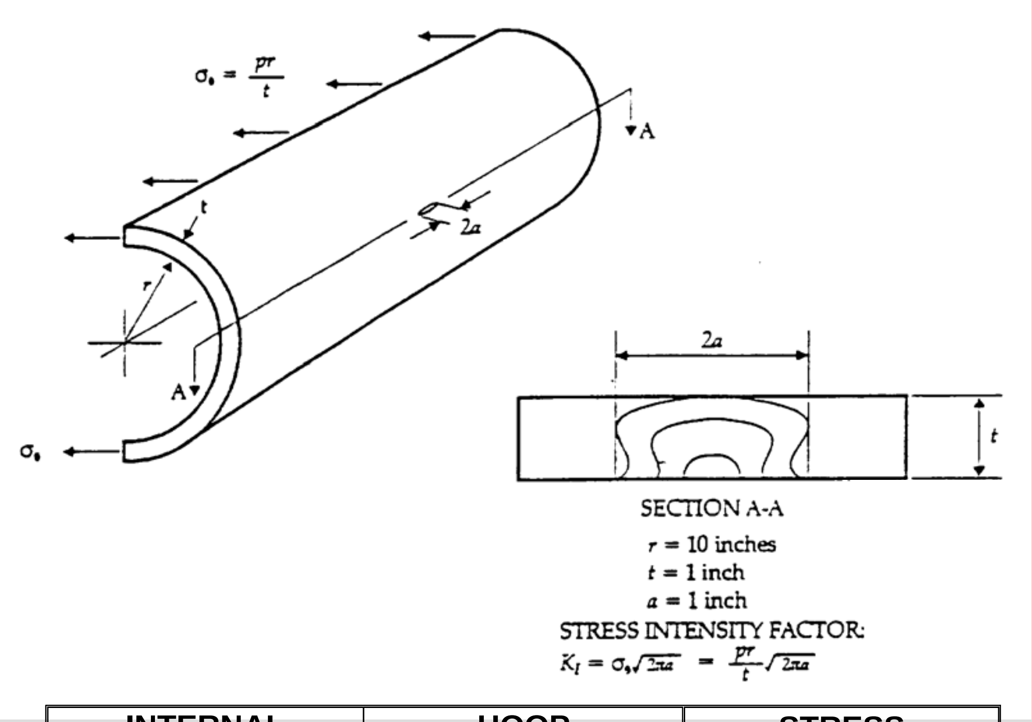
Three Basic Modes of Crack Surface Displacements

LEFM EXAMPLE

- The problem presented in Figure 8 illustrates application of K_{Ic} concept to evaluation of the burst pressure of the pipe.
- At 40°F $K_{Ic} = 50\ ksi\sqrt{in}$, and the corresponding burst pressure ~3,000 psi. Corresponding nominal hoop stress is 30,000 psi, which is less than ultimate tensile strength of 80,000 psi.
- At 200°F $K_{Ic} = 200\ ksi\sqrt{in}$ and the corresponding burst pressure would be greater than 10,000 psi. The pipe will actually burst at the 8,000 psi level predicted by the ultimate tensile strength.

This problem demonstrates how the presence of the crack may or may not have a significant effect on the structural capacity of a component.

LEFM EXAMPLE (cont'd)



INTERNAL PRESSURE ρ (psi)	HOOP STRESS σ_s (psi)	STRESS INTENSITY FACTOR K_I (psi-in$^{.5}$)
1,000	10,000	17.725
2,000	20,000	35,450
3,000	30,000	53,175
4,000	40,000	70,900
5,000	50,000	88,625
6,000	60,000	106,350
7,000	70,000	124,075
8,000	80,000	141,800
9,000	90,000	159,525
10,000	100,000	177,250

LEFM – FATIGUE CRACK PROPAGATION

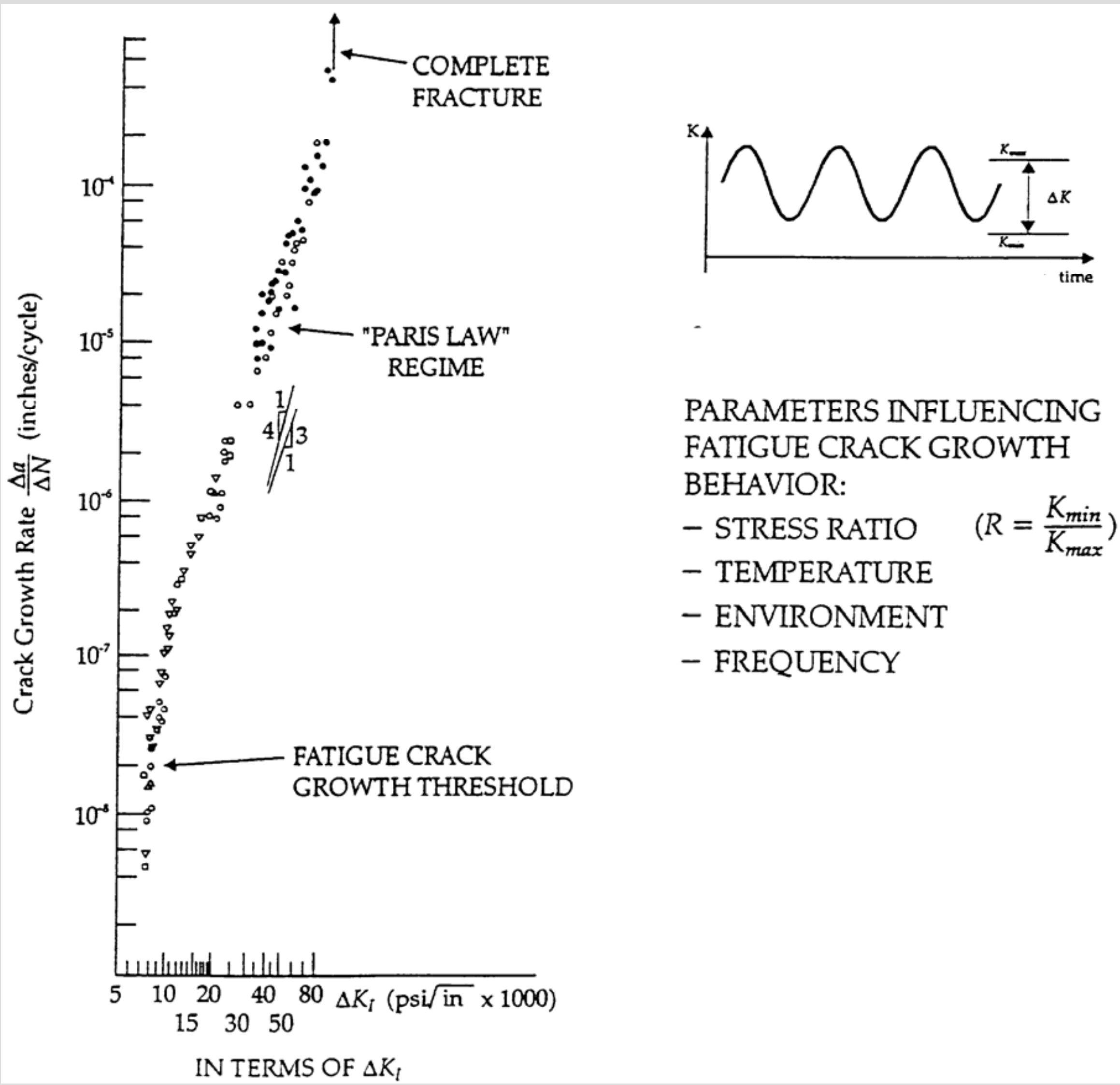
- Stress intensity factor K_I also characterizes the rate of crack propagation due to fatigue cycling
- Range of K_I (ΔK) is the controlling parameter

- Below certain ΔK there is basically no growth. This ΔK value is called fatigue crack growth threshold
- Over a long portion of the curve, there is a straight line log-log relationship, known as Paris Law:

$$\frac{da}{dn} = C \cdot (\Delta K_I)^n$$

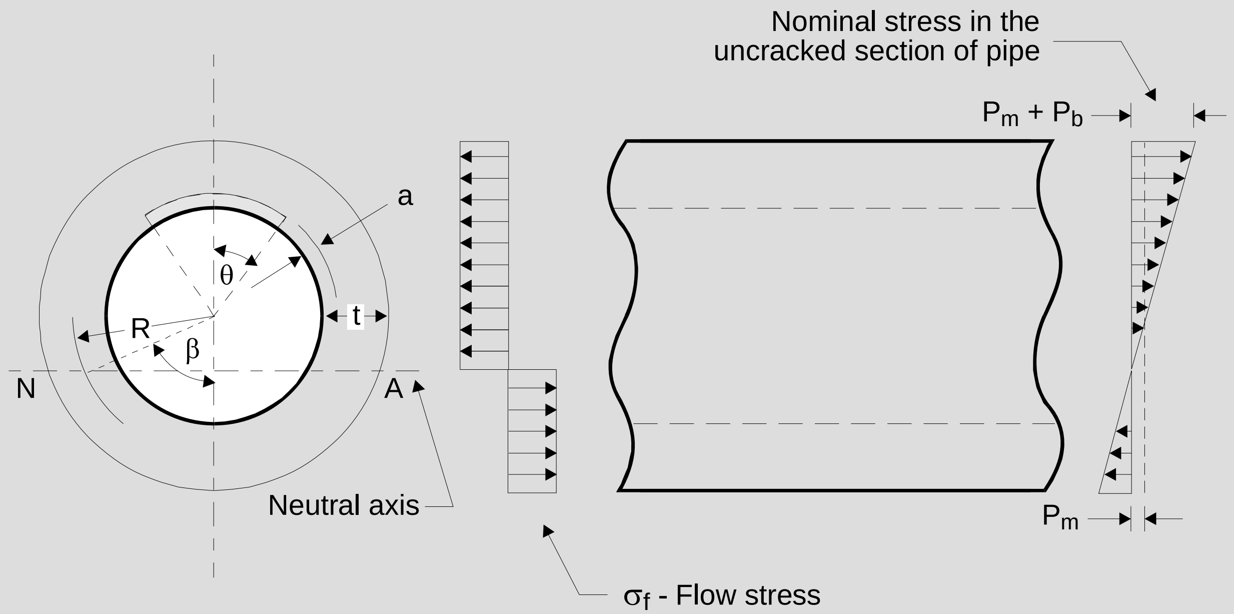
- At very high crack growth rates (10^{-4} in/cycle) the curve turns vertical—that is final fracture.
- Crack growth curve depends on mean stress effects, environment effects, and load cycle frequency.

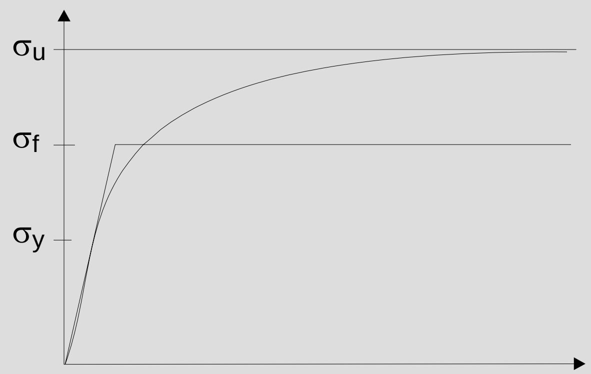
LEFM – FATIGUE CRACK PROPAGATION (cont'd)



Fatigue Crack Growth Data: Pressure Vessel Steels

LIMIT LOAD ANALYSIS (NET SECTION PLASTIC COLLAPSE)





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Limit Load (Net section plastic collapse)

Structural Integrity Associates, Inc.

LIMIT LOAD ANALYSIS (NET SECTION PLASTIC COLLAPSE)

For $\theta + \beta \le \pi$

$$\beta = \frac{\left(\pi - \frac{a}{t}\theta\right) - \left(\frac{P_m}{\sigma_f}\right)\pi}{2}$$

$$P_b = \frac{2\sigma_f}{\pi}\left(2\sin\beta - \left(\frac{a}{t}\right)\sin\theta\right)$$

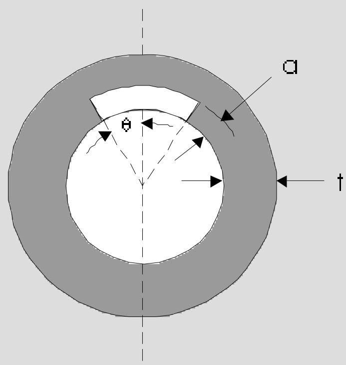
For $\theta + \beta > \pi$

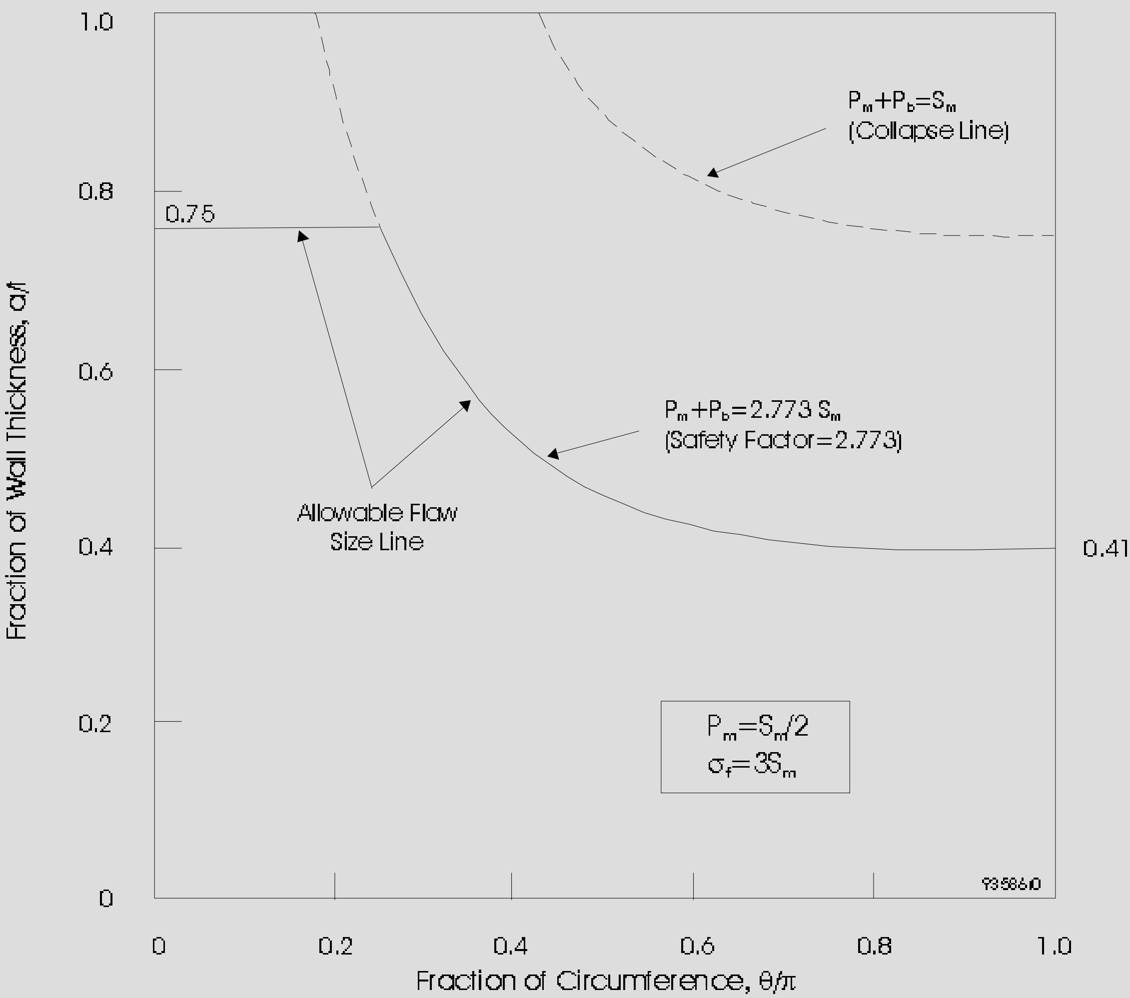
$$\beta = \frac{\pi\left(1 - \frac{a}{t} - \frac{P_m}{\sigma_f}\right)}{2 - \frac{a}{t}}$$

$$P_b = \frac{2\sigma_f}{\pi}\left(2 - \frac{a}{t}\right)\sin\beta$$

Limit Load for a Circumferentially Flawed Pipe

LIMIT LOAD ANALYSIS (NET SECTION PLASTIC COLLAPSE)





Elastic-Plastic Fracture Mechanics

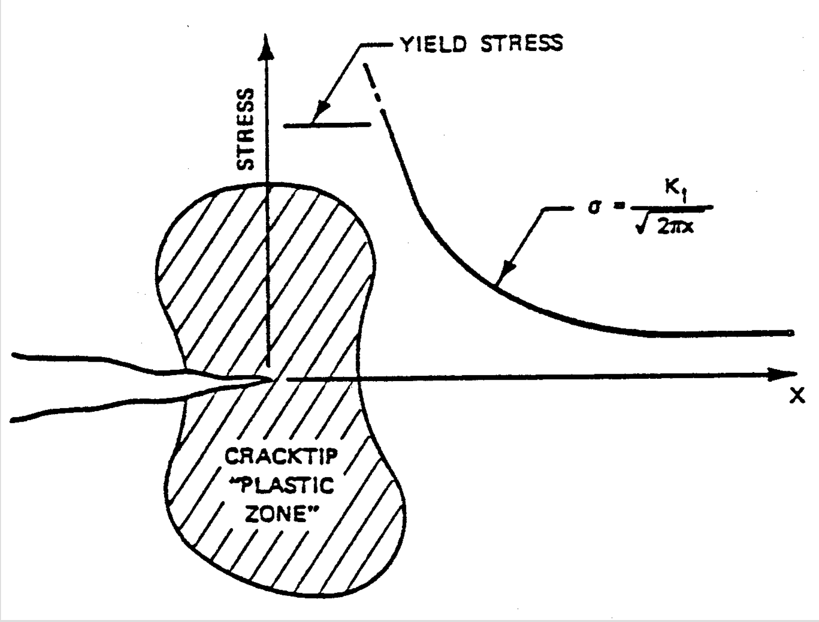


Figure 17. Elastic-Plastic Fracture Mechanics - The J-Integral

- ***J_I* is a Path Independent Integral Which Characterizes Peak Strains in the Crack Tip Plastic Zone in a Manner Similar to Which *K_I* Characterizes Peak Stress in Linear Elastic Cases**
- **For Linear Elastic Cases:**

$$J_I = \frac{K_1^2}{E}\left(1-\nu^2\right)$$

- **For Large Plastic Zones (Ductile Materials) *J_I* Permits Extension of Fracture Mechanics Concepts**

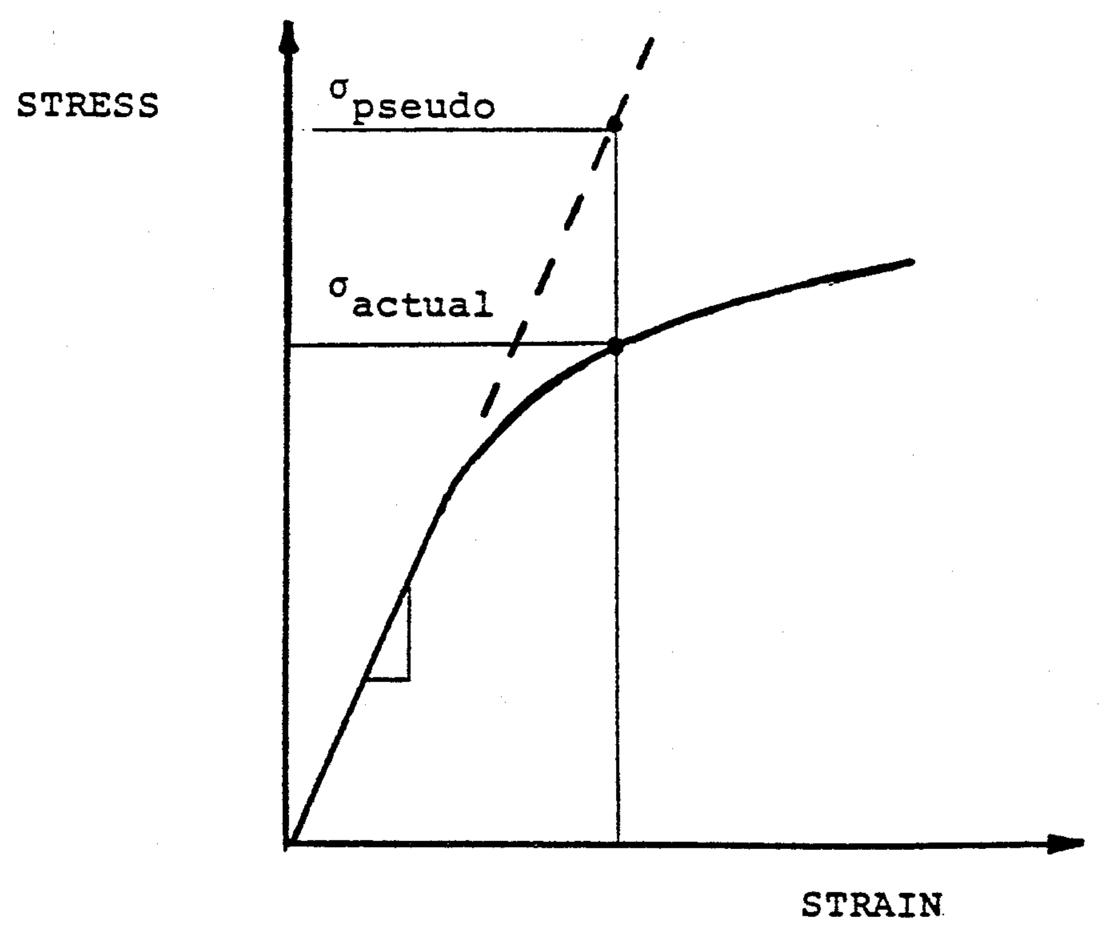
THE J-INTEGRAL (Cont'd)

For Moderate Amounts of Yielding

$$\left(\varepsilon < 3 \text{ x } \varepsilon_{yield}\right):$$

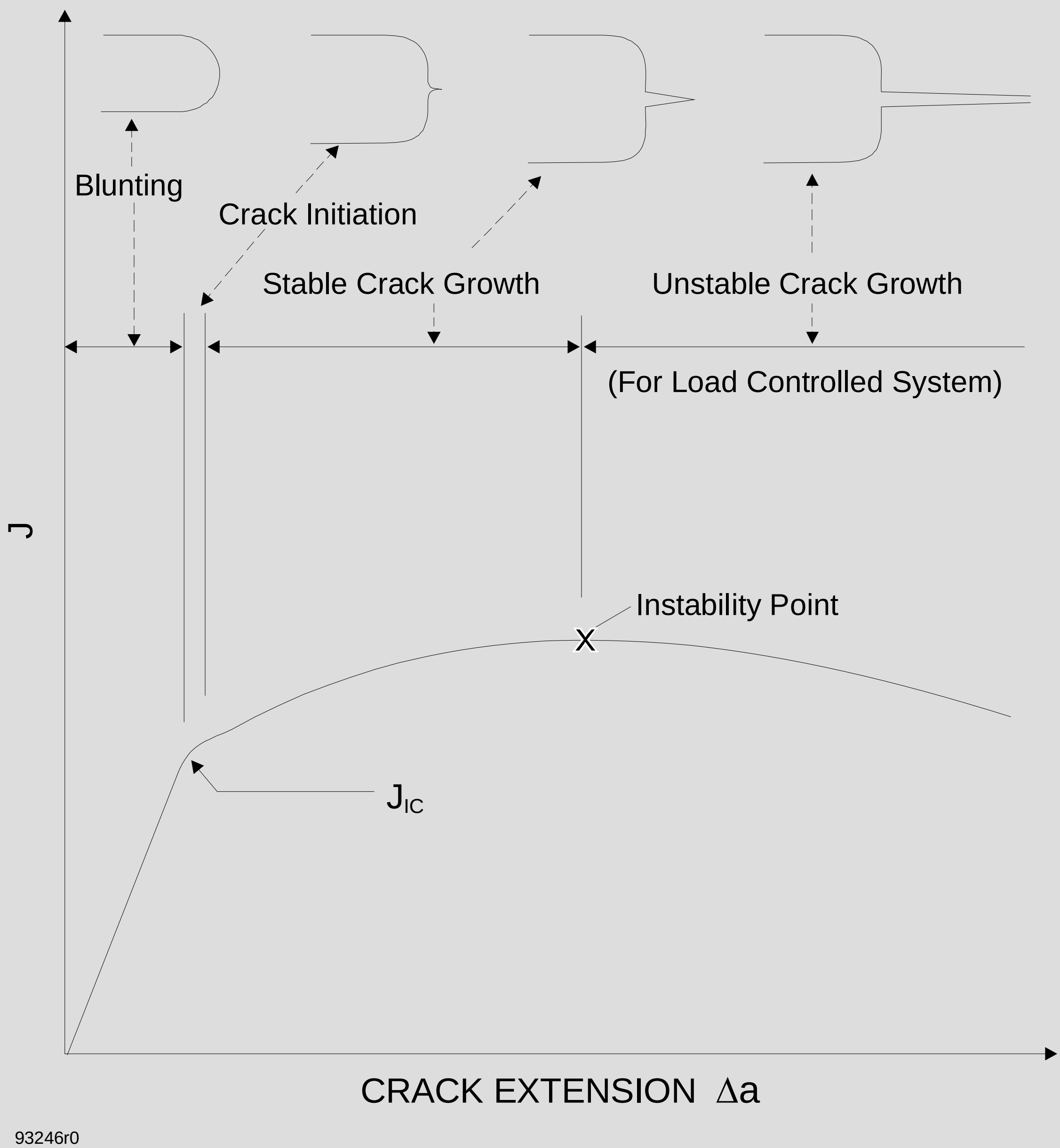
$$K_{pseudo} = \sigma_{pseudo}\sqrt{\pi a}$$

$$J_{pseudo} = \frac{\left(K_{pseudo}\right)^2}{E}\left(1-\nu^2\right) = J_{actual}$$



Pseudo-Elastic Approach to EPFM

TEARING INSTABILITY ANALYSIS



Typical Crack Growth Behavior of Ductile Materials

TEARING INSTABILITY CONCEPT

For Equilibrium:

$$J_{Applied} = J_{Material} \Rightarrow \text{(No Crack Propagation)}$$

For Stability:

$$J_{Applied} > J_{Material} \Rightarrow \text{Crack Propagation}$$

$$\frac{dJ_{Applied}}{da} \leq \frac{dJ_{Material}}{da} \Rightarrow \text{Stability}$$

$$\frac{dJ_{Applied}}{da} \geq \frac{dJ_{Material}}{da} \Rightarrow \text{Instability}$$

For Convenience, Define:

$$T = \frac{dJ}{da}\frac{E}{\sigma_o^2}$$

General Fracture Mechanics Procedure

1. Characterize Flaw: Flaw Location and Shape
   a. NDE of Actual Flaw
   b. Hypothetical Flaw
2. Define Analysis Objective:
   a. Remaining life?
   b. Evaluate failure?
   c. Margin to allowable?
3. Determine Component Geometry
4. Determine Loading Conditions
5. Determine Material Properties (from literature or testing)
   a. Flaw Resistance (e.g., toughness)
   b. Stress-Strain Behavior (e.g., linear, Young's modulus)
   c. Direction Effects (if any)

General Fracture Mechanics Procedure (continued)

6. Select Appropriate Flaw Model (from literature or derived)
7. Calculate Applied Parameter (e.g., $K_{I\ applied}$):

   $K_{I\ applied} = \sigma$ applied x $\sqrt{(\pi a/Q)}$

   Where

   a = flaw depth

   Q = geometry factor
8. Compare Applied to Material Resistance (e.g., K_{Ic})

   -Include Margins

   -If applied < material resistance, then there is remaining life.
9. Is there an active crack growth mechanism (fatigue, IGSCC, etc.)?
10. If yes, perform crack growth calculation to end of period, and re-do analysis.

Example: Weld Overlay Repair of BWR Austenitic and Dissimilar Metal Welds

Background

- Intergranular stress corrosion cracking (IGSCC) has been a major issue for the BWR industry for the past three decades and has had significant impact on resources and plant availability
- IGSCC is caused by the combination of susceptible material, high tensile stress and oxygenated environment.
- Elimination of one or more of the above contributing factors significantly mitigates and may eliminate IGSCC.
- Hydrogen water chemistry and/or noble metal chemistry improve environment
- Stress improvement (MSIP or IHSI) mitigates high tensile residual stresses.
- Weld overlay repairs have been applied at many plants

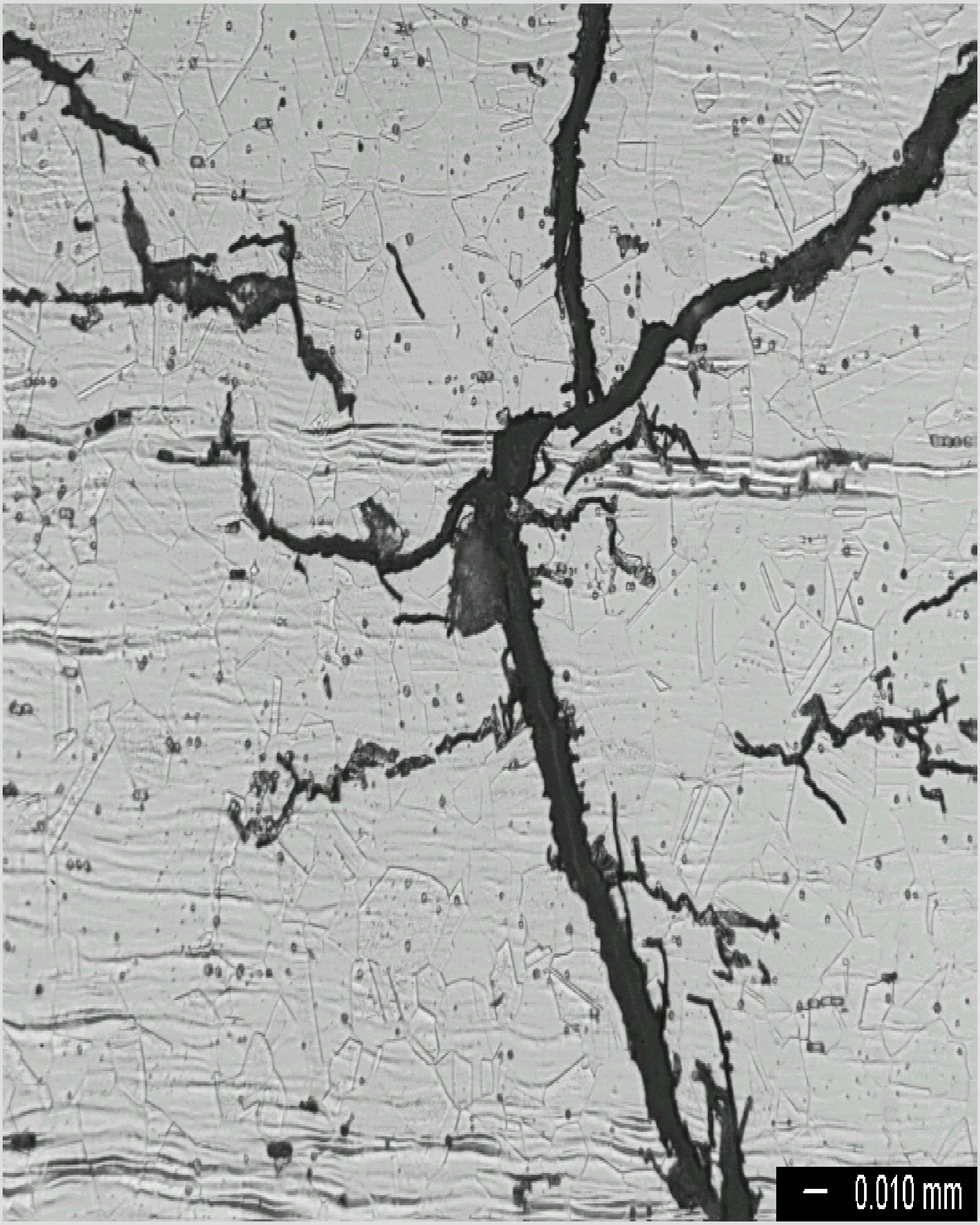
BWR Components Affected by IGSCC

- **Piping welds (usually sensitized stainless steel)**

- **Nozzle-to-pipe or nozzle to safe end welds (especially where Alloy 182 weld material is present)**

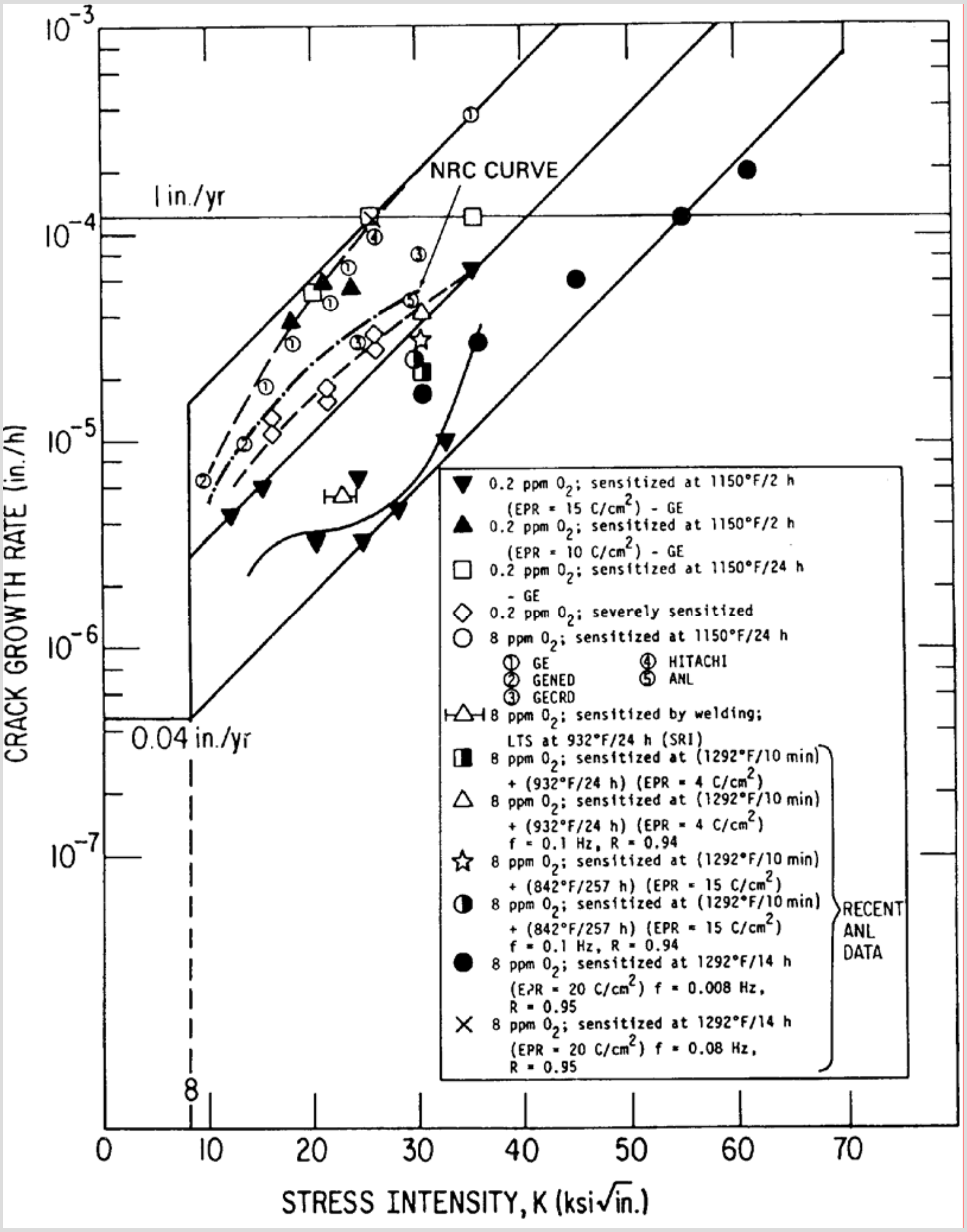
- **BWR Internals**
  - Core shroud
  - Jet pump assemblies
  - Core spray piping and sparger
  - Core shroud support structure
  - Top guide
  - Steam dryers
  - Shroud head bolts

SCC OF STAINLESS STEEL



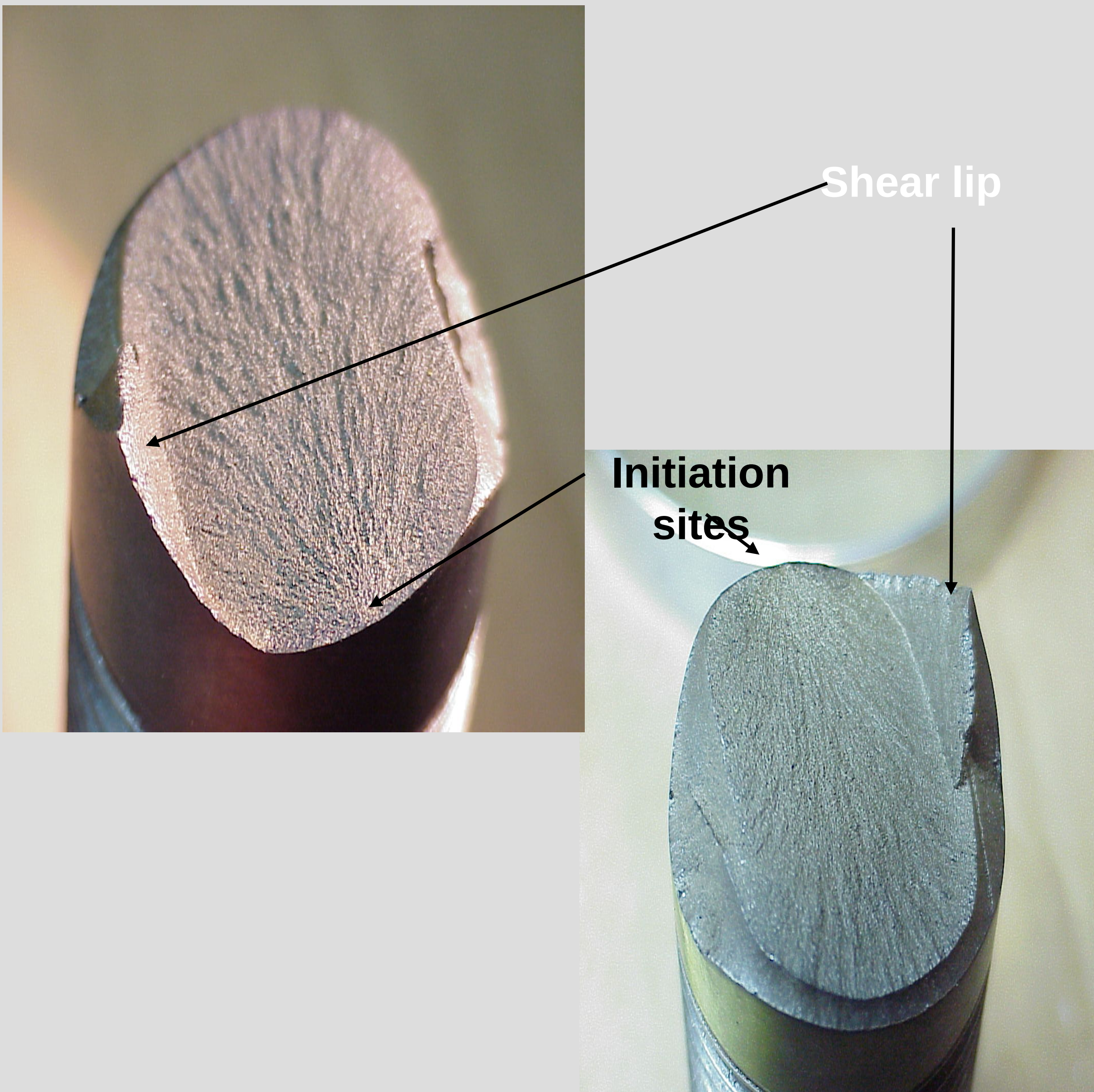
SCC OF STAINLESS STEEL

FRACTURE MECHANICS APPROACH TO STRESS CORROSION CRACKING (Cont'd)

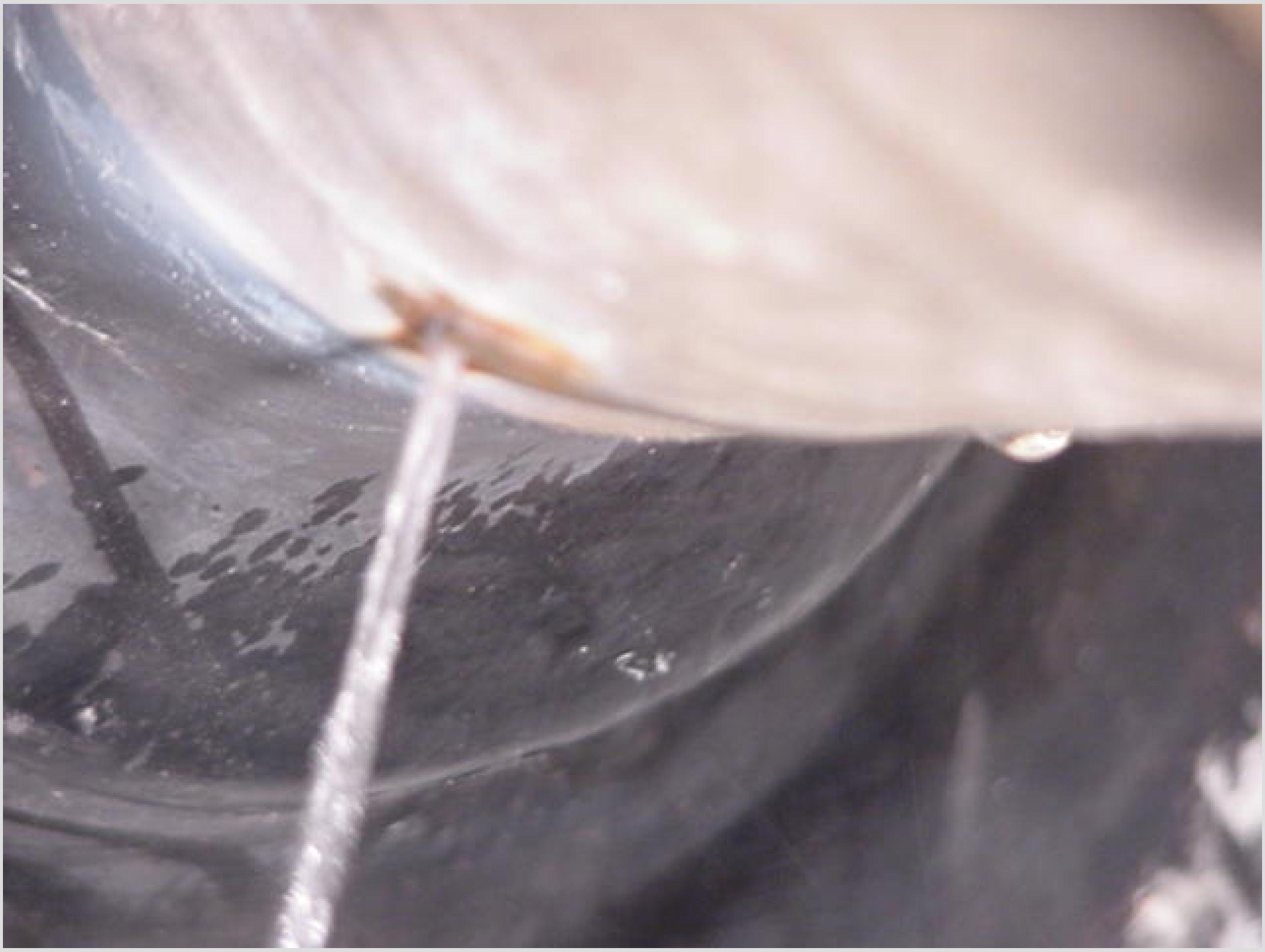


Stress Corrosion Crack Growth Data for Sensitized Stainless Steel in Boiling Water Reactor Environment (from NUREG-0313, Rev. 2)

SCC + Overload (Shear Lip)



Leak from Nozzle End Cap



CRD RETURN NOZZLE

- CRD CAP REPLACED IN 1977
- MATERIAL INSTALLED DURING REPLACEMENT (INCONEL) IS SUBJECT TO STRESS CORROSION CRACKING (SCC)
- WELD REPAIR PERFORMED DURING INSTALLATION
- LEAK FOUND DURING DRYWELL WALKDOWNS
- CRACK WAS APPROX. 2” LONG IN AREA OF PREVIOUS WELD REPAIR

Flaw Evaluation and Repair Design Bases

- Flaw evaluation and repair design are based upon fracture mechanics analyses.
- Because of high ductility of overlay weld material, net section collapse methods apply to design.
- Evaluations are based on the use of an appropriate crack growth law, weld residual and applied stresses and fracture mechanics modeling
- Weld overlay repairs are considered as permanent (life of the component) repairs with periodic inspections

Weld Overlay Repairs

- **Weld overlays are used to repair IGSCC flaws**
  - Proven process used successfully in the nuclear power industry
  - Repair is performed remotely thereby reducing man-rem exposure
  - The process is very familiar to the NRC
- **Weld overlays are applied by deposition of weld metal on component outside surface restoring ASME Code safety margins**
- **For repairs to dissimilar metal welds such as nozzle to safe end welds, ambient temperature temper bead welding minimizes thermal effects on nozzle material and eliminating the need for PWHT**

Special Problems with Dissimilar Metal Welds

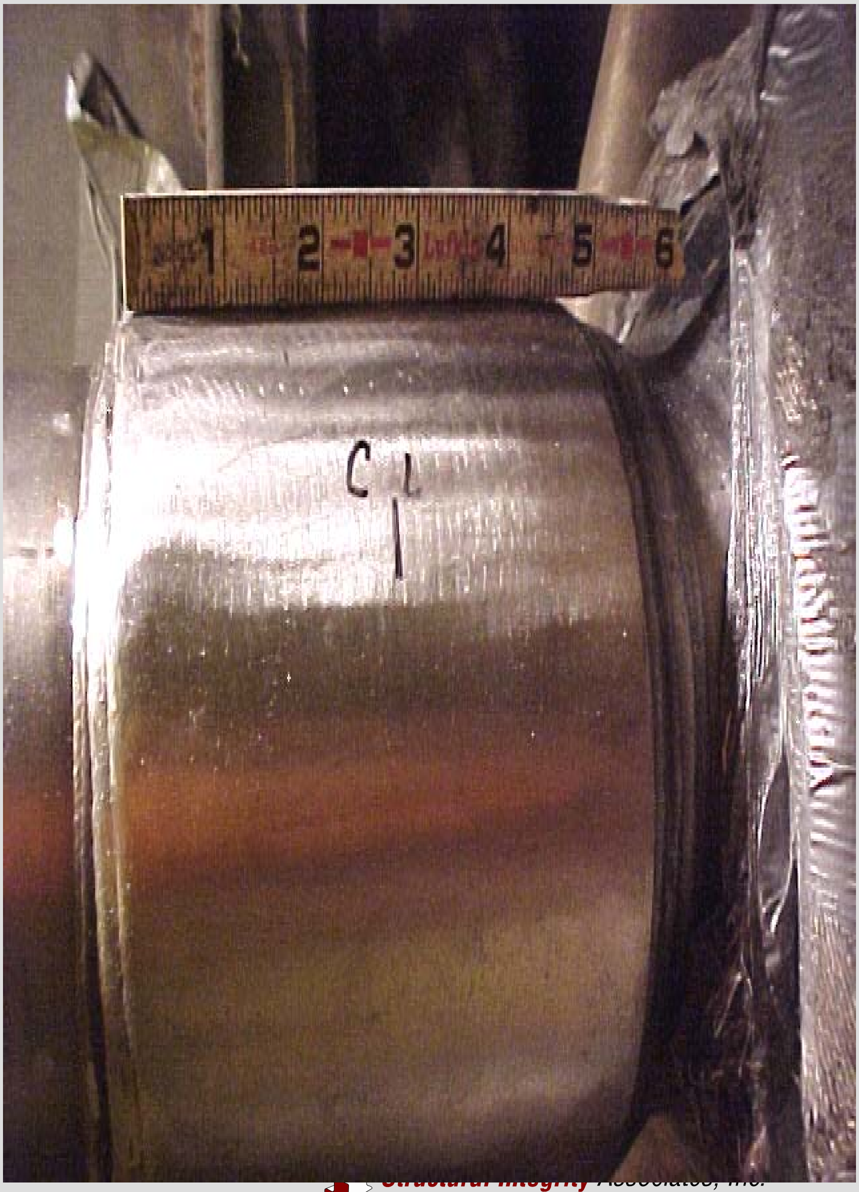
- **Nickel-based weld overlay material (e.g., Alloy 52) is required**
  - Stainless weld material applied over nickel based base or weld material cracks
  - Alloy 52 weld material is very resistant to IGSCC, due to very high chromium content, but may be more difficult to obtain
  - Some welding problems may occur. Use of modified Alloy 52 may minimize these

- **Alloy 52 is fully austenitic, but not a stainless steel**

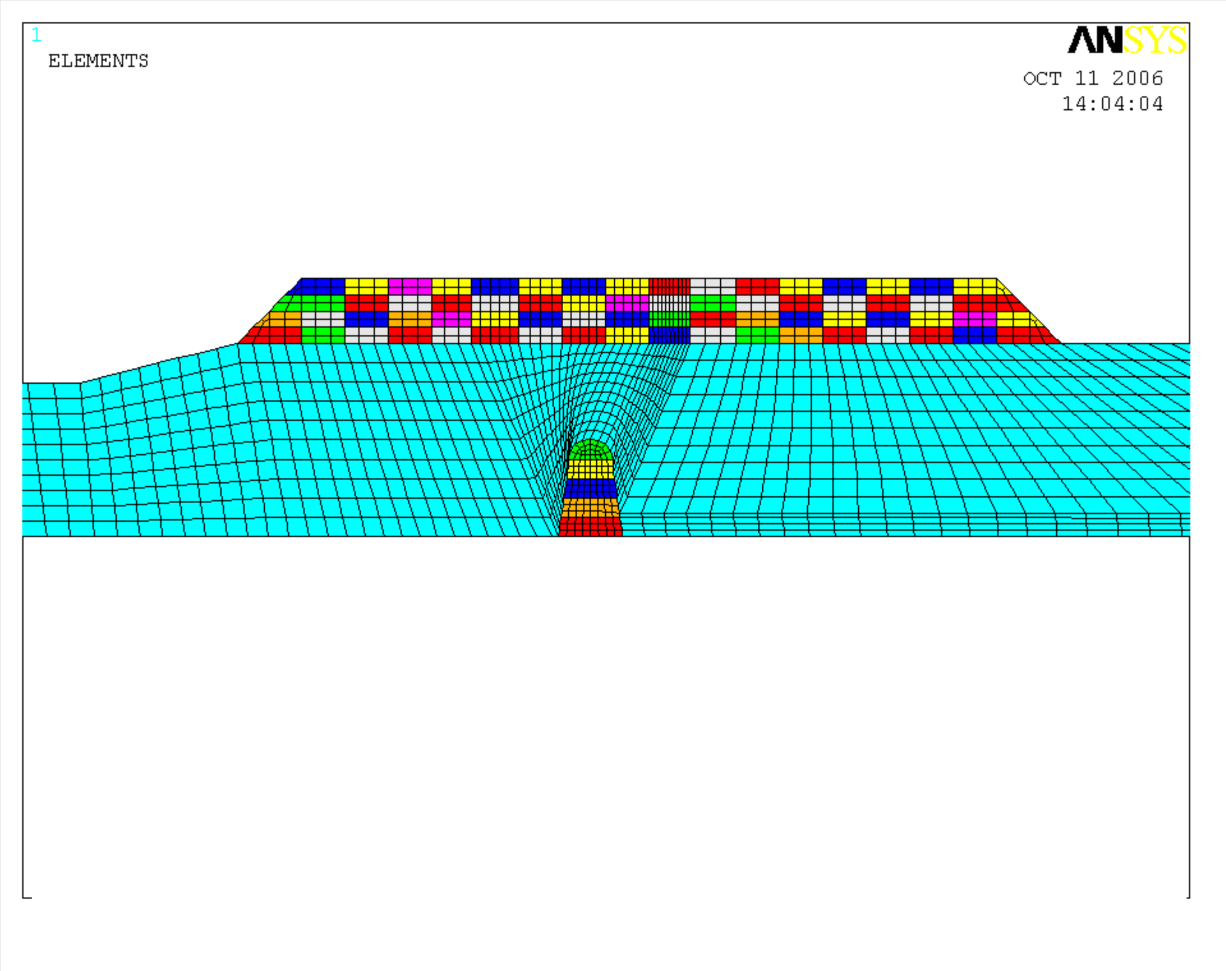
- **N-638 requires a 48 hour hold time after welding**
  - Detect hypothetical delayed cracking

CRD WELD OVERLAY

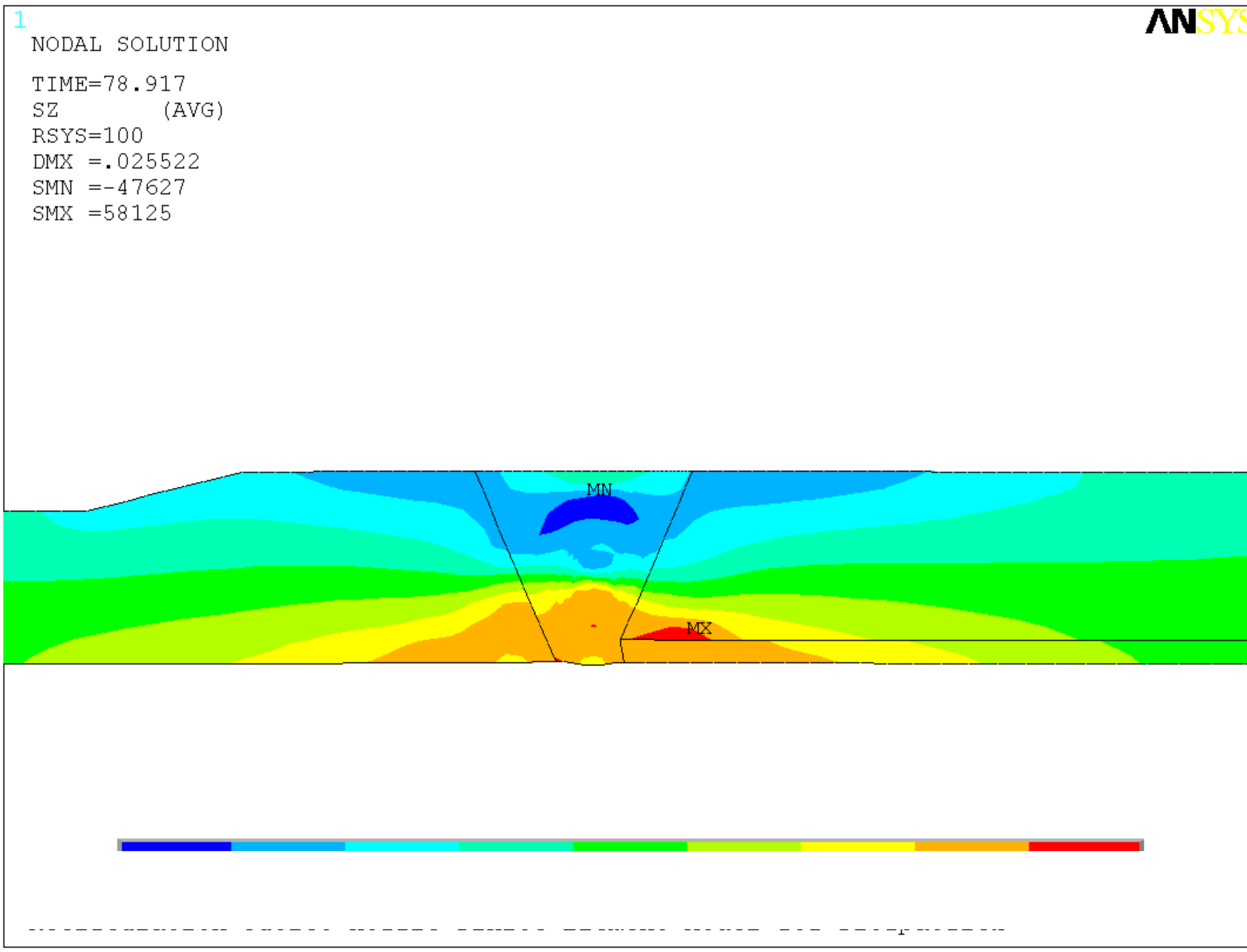
- ADDITIONAL 164 HOURS OFF LINE
- $350K IN DIRECT COSTS
- 13 PERSON REM



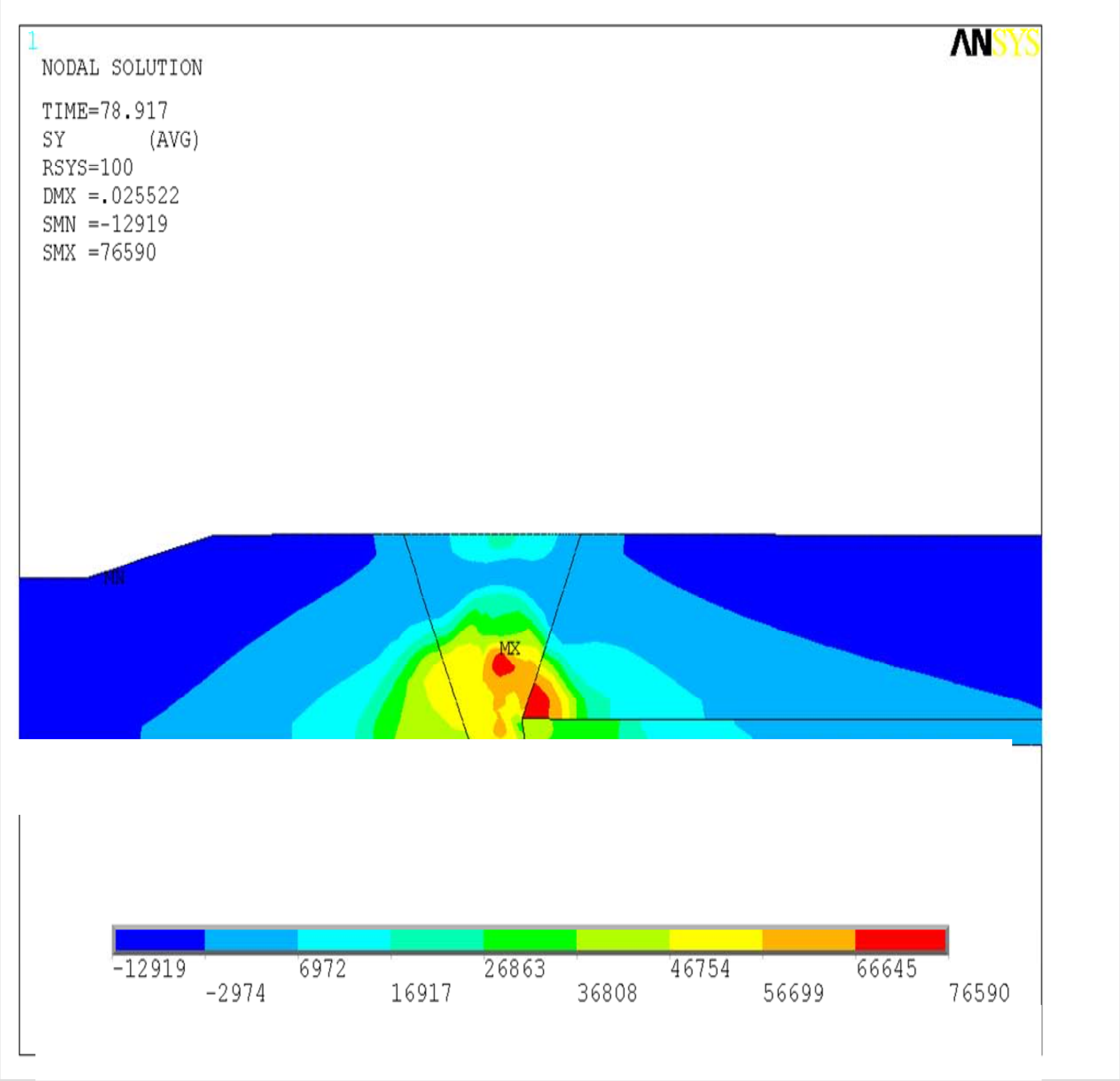
Thermal Model of Repair Welding



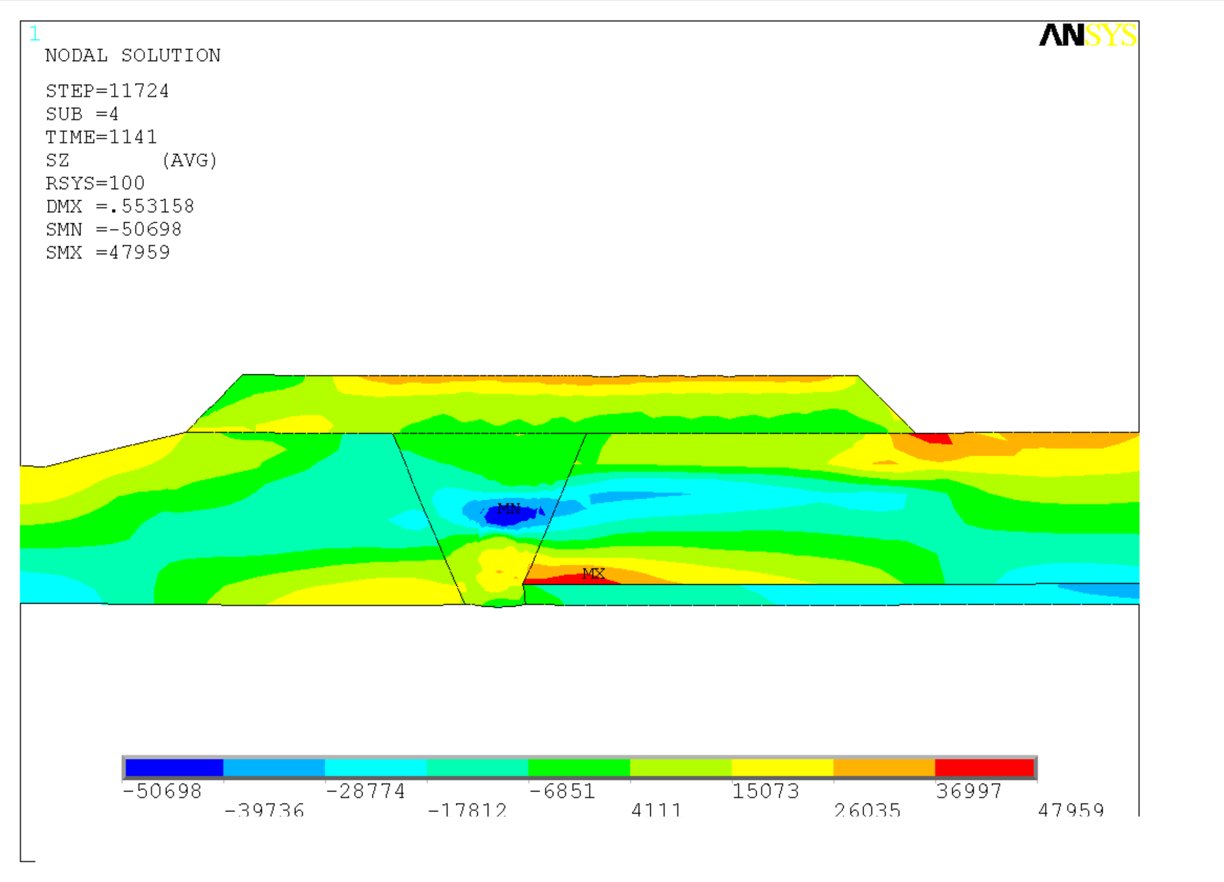
Axial stress before repair



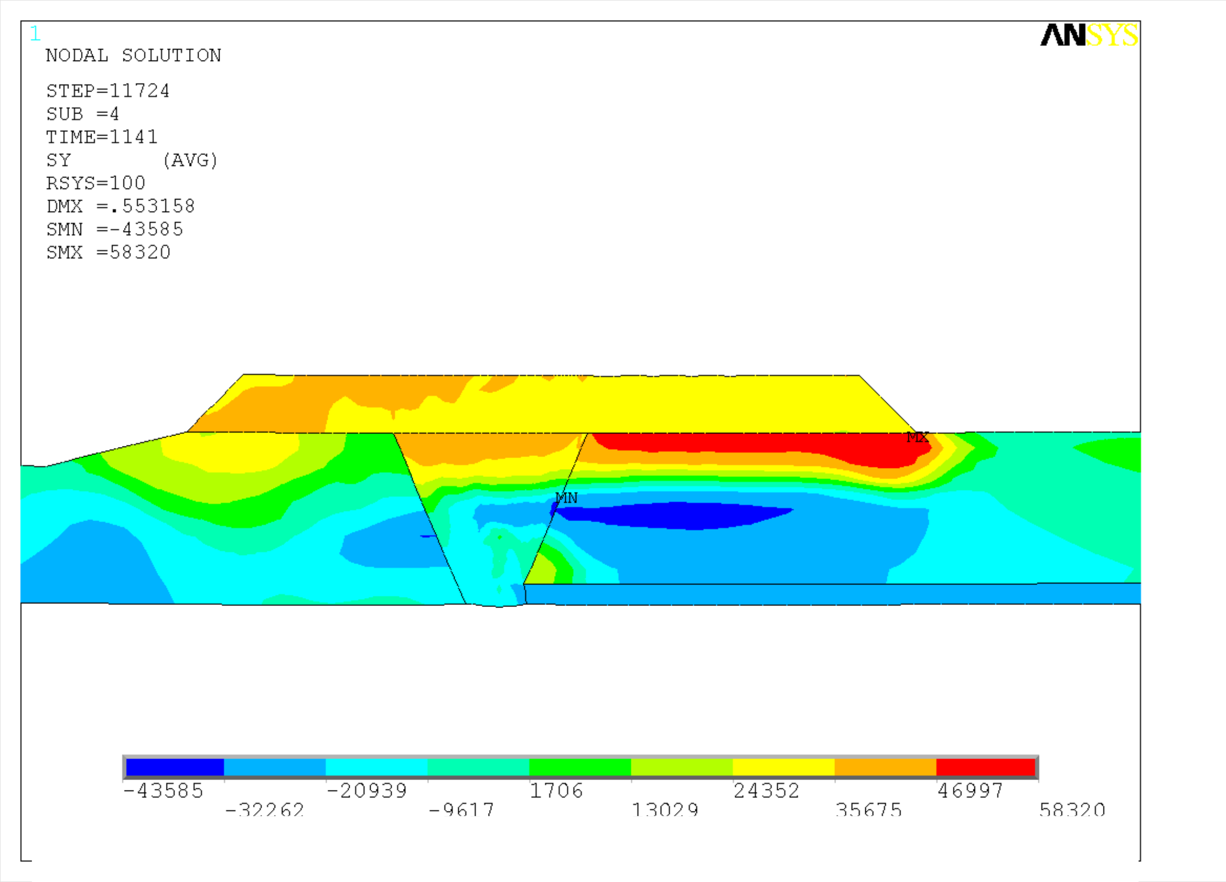
Hoop stress before repair



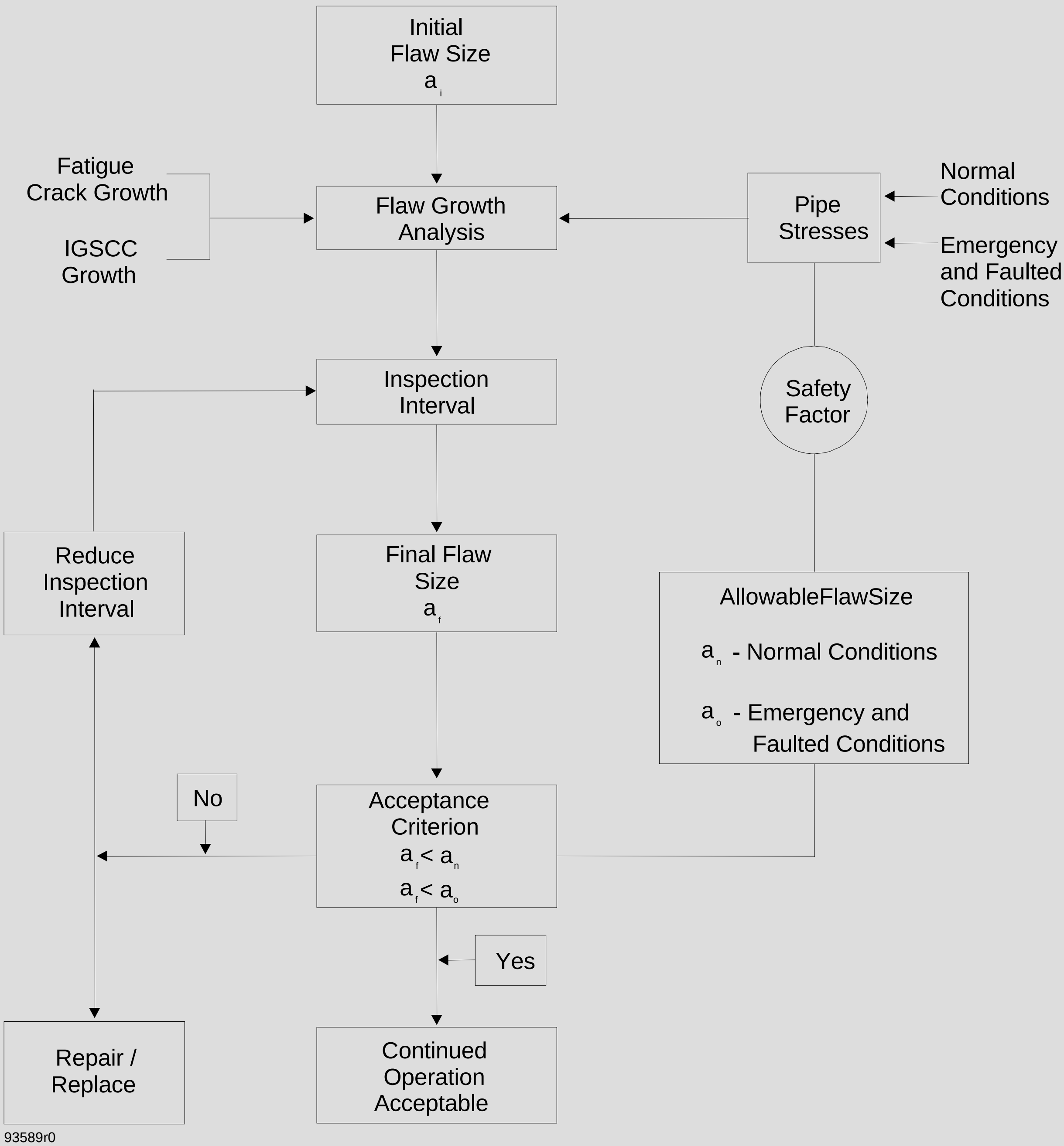
Axial stress after repair



Hoop stress after repair



FLAW EVALUATION (IWB-3610/APPENDIX A)



Section XI Flaw Evaluation

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