



UCCA MOUNTAIN PROJECT

CONTROLLED COPY NO. 102

Subject: Determination of Plane-Strain Fracture Toughness (K_{IC}) and the Threshold Stress Intensity for Stress Corrosion Cracking (K_{ISCC})

Approved by: *M. L. Blaine* 10/4/89
Technical Area Leader Date *Wble*

Approved by: *David W. Stuart* 10/4/89
YMP Quality Assurance Manager Date

Approved by: *John J. Jerich* 10/9/89
YMP Project Leader Date

9005100154 900509
PDR WASTE
WM-11 PDC

**Determination of Plane-Strain Fracture
Toughness (K_{Ic}) and the Threshold Stress Intensity
for Stress Corrosion Cracking (K_{Isc})**

H. S. AHLUWALIA
Science and Engineering Associates
Pleasanton, California 94566

J. C. FARMER
Lawrence Livermore National Laboratory
Livermore, California 94551

Glossary of Terms

a	crack length, in.
a_{cr}	critical crack length, in.
da/dt	crack velocity, in./h
B	thickness, in.
C	compliance, in./lb
E	tensile modulus of elasticity, psi
f(a/w)	mathematical function of a/w
G	potential energy release rate, in.-lb/in. ²
K	stress intensity factor, general, ksi-in. ^{1/2}
K_I	stress intensity factor, opening mode, ksi-in. ^{1/2}
K_{Ic}	plane-strain fracture toughness, ksi-in. ^{1/2}
K_{Isc}	stress-corrosion cracking threshold stress intensity factor, ksi-in. ^{1/2}
P	load, lb
R_{sc}	specimen strength ratio
W	width, in.
ν	Poisson's ratio
V	crack opening displacement, in.
Y	constant which is a dimensionless polynomial function in odd half powers of (a/w) from (a/w) ^{1/2} to (a/w) ^{9/2}
σ_{max}	maximum local stress, ksi
σ_{ys}	yield strength, ksi
σ_{app}	applied stress, ksi
σ_F	fracture stress, ksi
γ	surface energy

Contents

1. Purpose	
2. Scope	
3. Background Theory	
3.1 Griffith's Relationship	
3.2 Orowan/Irwin Relationship	
3.3 Energy Release in Terms of Crack Tip Stresses	
3.4 Effects of Finite Boundaries	
3.5 Specimen Size Requirements	
4. Plane-Strain Fracture Toughness Testing, K_{Ic}	
4.1 Introduction	
4.2 Summary of Test Method	
4.3 Significance	
4.4 Apparatus	
4.4.1 List of Equipment and Materials	
4.4.2 Special Environmental Conditions	
4.4.3 Loading	
4.4.4 Fixtures	
4.4.5 Displacement Gage	
4.4.6 Calibrations	
4.5 Specimen Size, Configurations, and Preparation	
4.5.1 Specimen Size	
4.5.2 Specimen Configurations	
4.5.3 Specimen Preparation	
4.6 General Procedure	
4.6.1 Number of Tests	
4.6.2 Measurement	
4.6.3 Loading Rate	
4.6.4 Test Record	
4.7 Calculation and Interpretation of Results	
4.7.1 Interpretation of Test Record and Calculation of K_{Ic}	
4.7.2 Fracture Appearance	
4.8 Report	
4.9 Accuracy and Bias	
4.9.1 Bias	
4.9.2 Accuracy	
5. Threshold Stress Intensity for Stress Corrosion Cracking, K_{Isc}	
5.1 Introduction to K_{Isc}	
5.2 Summary of Test Method	
5.3 Apparatus	
5.3.1 List of Equipment and Materials	
5.3.2 Special Environmental Conditions	
5.3.3 Loading	
5.3.4 Fixtures	
5.3.5 Displacement Gage	
5.3.6 Test Cell	

5.4 Specimen Size, Configurations, and Preparation
5.4.1 Specimen Size
5.4.2 Specimen Configuration
5.4.3 Specimen Preparation
5.4.4 Fatigue Crack Starter Notch
5.4.5 Fatigue Cracking
5.5 General Procedure
5.5.1 Number of Tests
5.5.2 Crack Measurement
5.5.3 Loading Rate
5.5.4 Calibrations
5.6 Interpretation of Results
5.7 K_I/V Calibration
5.8 Experimental Compliance Calibration
6. Personnel Responsibilities
7. Quality Assurance Records
References
Appendix 1 — Sensitivity Analysis for the Stress Intensity Equation
Appendix 2 — Sensitivity Analysis for the Strength Ratio Equation

1. Purpose

This procedure is part of the proposed electrochemical corrosion testing program for the Yucca Mountain Project (YMP) in Nevada. The procedure establishes the general method to be used in evaluating the stress corrosion behavior of the candidate alloys in terms of the embrittlement index, K_{Ic}/K_{Isc} . This ratio shall be used to rank the six possible candidate alloys on the basis of stress corrosion cracking for fabricating the metal containers to be used in disposing of high-level radioactive waste at a repository in Yucca Mountain, Nevada. The six candidate materials are CDA 102 (OFHC copper), CDA 613 (aluminum bronze), CDA 715 (Cu-³⁰Ni), stainless steels Type 304L and 316L, and Alloy 825 [1]. This procedure is prepared in accordance with procedures of the Quality Assurance Program Plan to permit acquisition of data that might be applicable to the selection criteria being completed under Activities E 20-15 and E 20-19.

2. Scope

This test procedure is divided into three parts. The first part is a brief background theory on plane-strain fracture toughness. The second part covers the determination of plane-strain fracture toughness (K_{Ic}) using fatigue-cracked compact tension specimens. Information concerning the recommendation and requirements for K_{Ic} testing are also discussed. The third part covers the determination of the threshold stress intensity for stress corrosion cracking (K_{Isc}) and discusses the additional requirements for its determination.

3. Background Theory

The fracture mechanics theory has been reviewed extensively [2-4], so Section 3 merely outlines the basic theory of fracture mechanics.

3.1 Griffith's Relationship

The basic theory on which fracture mechanics is founded emanates from the work of Griffith [5] in 1920. His work concerned the calculation of the fracture strength of a brittle solid (glass) that contained a sharp crack. The model (Fig. 1) is that of a through-thickness crack of length $2a$ in an infinite body, lying normal to a uniform applied tensile stress, σ_{app} . Plane-strain conditions are assumed; i.e., a condition of zero strain in the direction of orthogonal to both the crack length and that of the applied stress.

Assuming linear elastic behavior, the energy balance for the fracture stress, σ_F , is

$$\sigma_F = [2E\gamma/\pi(1 - \nu^2)a]^{1/2} \quad (1)$$

where

E = Young's modulus;

ν = Poisson's ratio;

2γ = the work of fracture (γ is often taken as surface energy).

This expression provides a relationship between fracture stress and crack length if the work of fracture (2γ) is known. In a crystalline solid, the total amount of energy that must be supplied to separate two atoms to infinity is known as the work of fracture. This work of fracture is often equated to twice the surface energy (γ) of unit area of a free surface of the appropriate fracture plane of the solid, because the work done has provided enough energy to create two surfaces each of energy γ . The total area under the atomic stress-strain curve represents the work supplied when the plane is fractured; therefore, we can equate this work to 2γ [2].

3.2 Orowan/Irwin Relationship

The relationship in Eq. (1) was later modified by Orowan and Irwin to account for plastic flow at the crack tip before the onset of crack extension. Using elastic relationships for the body as a whole, which can be justified only if the size of the plastic zone is very small, Eq.(1) becomes:

$$\sigma_F = [EG_{Ic}/\pi(1 - \nu^2)a]^{1/2} \quad (2)$$

where G_I is the materials plane strain (Opening Mode I) fracture toughness. In metals, G_I is a measure primarily of the amount of plastic work that must be done before the crack extends. Equation (2) is used to calculate the maximum size of defect that can be tolerated under a given design stress or to estimate the maximum stress that can be applied to a component that contains a crack of known length. The critical strain energy release rate, G_{Ic} , required for crack growth is equal to twice the effective surface energy (γ_{eff}); i.e., $G_{Ic} = 2\gamma_{eff}$. This effective surface energy is predominantly the plastic energy absorption around the crack tip, with only a small part resulting from the surface energy of the crack surfaces. It is also possible to apply stress to the crack in plane shear (Mode II) or antiplane shear (Mode III) where the toughnesses are written G_{IIc} and G_{IIIc} respectively. These modes are illustrated in Fig. 2.

3.3 Energy Release in Terms of Crack Tip Stresses

Most practical situations cannot be modeled by the simple infinite body configuration, so allowance must be made for the presence of free surfaces or combinations of applied stresses. A commonly used method of deriving crack tip stresses is by stress analysis calculation, while a more direct experimental approach uses compliance techniques.

In its simplest form, the tensile stress distribution ahead of a sharp, through-thickness crack of length $2a$ in an infinite body (Fig. 3) is given by:

$$\sigma = \sigma_{app}/(1 - a^2/x^2)^{1/2}, \quad (3)$$

which holds in the region $-x < -a$ and $x > a$.

If we consider Eq. (3) in relation to Fig. 3, we see that near the crack tip, $x \rightarrow a$ and $\sigma \rightarrow \infty$; at large distances, $x \rightarrow \infty$, $a/x \rightarrow 0$, and $\sigma \rightarrow \sigma_{app}$.

If Eq. (3) is now written in terms of the distance ahead of the crack tip, $r = (x - a)$, the local stress very close to the crack tip (i.e., $r \ll a$) becomes:

$$\sigma = K/(2\pi r)^{1/2} \quad (4)$$

where K is defined as the stress intensity factor and has the value $K = \sigma_{app}(\pi a)^{1/2}$ for a central crack of length $2a$. The value K has the units $\text{ksi in.}^{1/2}$ ($\text{MNm}^{-3/2}$).

In the derivation of Griffith's relationship [Eq. (1)], the propagation of a crack is treated thermodynamically by balancing the elastic energy released when a crack extends against the work required to produce two new surfaces. A particularly powerful method of calculating the change in energy, dE , when a crack is extended by an amount, da , makes use of a virtual-work argument. The crack tip stress does work by moving through the displacements of the virtually extended crack, as it approaches zero. Therefore, the virtual work argument produces the following important relationship for the potential energy release rate per unit thickness, G :

$$G = K^2/E \text{ in plane stress} \quad (5)$$

$$G = K^2(1 - \nu^2) / E \text{ in plane strain} \quad (6)$$

Critical values of G (i.e., the fracture toughness) are then related to critical values of K , and these values of K are usually quoted for a material's fracture toughness.

3.4 Effects of Finite Boundaries

The expression for the stress distribution ahead of a sharp crack [Eq. (3)] holds only for an infinite body. If finite surfaces are present, the infinite plate solution is modified by an algebraic, trigonometric, or polynomial function chosen to make the surface forces zero. Often, the calculations of the stress distribution ahead of a crack make use of stress functions that are written as polynomial series rather than single algebraic functions.

For example, in the single-edge-notched (SEN) bend test piece, the stress intensity factor, K , can be derived from the expression:

$$K = PY_1/BW^{1/2}, \quad (7)$$

where

- P = the applied load;
- B = test-piece thickness;
- W = test-piece width;
- Y_1 = dimensionless polynomial function in odd half-powers of (a/w) from $(a/w)^{1/2}$ to $(a/w)^{9/2}$.

3.5 Specimen Size Requirements

The assumed linear elastic stress analysis can be applied only if the extent of in-plane plasticity is small compared with test-piece dimensions. Additionally, the test piece must be sufficiently thick so that most of the deformation will occur under plane-strain conditions [6, 7]. If this is the case, the total fracture instability is coincident with the initiation of plane-strain fracture and the measured toughness is a true material property.

Experimentally, this condition is met if:

$$B \geq 2.5(K_{Ic}/\sigma_y)^2. \quad (8)$$

The crack length, a , is also set by the following consideration. To use the stress-intensity approach, the region of nonlinear behavior (i.e., plastic deformation) must be smaller than the region in which the K description of the stress field is a reasonable approximation. This implies that the plastic zone size must be much smaller than the crack length, a . The rule set by the ASTM standard [8] is that

$$a \text{ (approx)} \geq 2.5(K_{Ic}/\sigma_y)^2 \quad (9)$$

$$0.45 < a/W < 0.55 \text{ (} W = 2B\text{)}. \quad (10)$$

4. Plane-Strain Fracture Toughness Testing, K_{Ic}

4.1 Introduction

This test method describes the determination of plane-strain fracture toughness of fatigue-cracked compact-tension specimens. This procedure shall be used to access the fracture toughness of the candidate materials for fabricating the metal containers to be used in disposing of high-level radioactive waste at a repository in Yucca Mountain, Nevada. Where possible, this procedure is in accordance with ASTM Standard Test Method E 399-83 [8].

4.2 Summary of Test Method

This test method involves testing of notched specimens that have been precracked in fatigue by loading in tension. Load versus displacement across the notch at the specimen edge is recorded autographically. The load corresponding to a 2% apparent increment of crack extension is established by a specific deviation from the linear portion of the record. The K_{Ic} value is calculated from this load by equations that have been established on the basis of elastic stress analysis of various specimens. The validity of the determination of the K_{Ic} value by this test method depends on the establishment of a sharp crack condition at the tip of the fatigue crack in a specimen of adequate size. To establish a suitable crack-tip condition, the stress intensity level at which the fatigue precracking of the specimen is conducted is limited to a relatively low value.

4.3 Significance

The property K_{Ic} determined by this test method characterizes the resistance of a material to fracture in a neutral environment in the presence of a sharp crack under severe tensile constraint, such that the state of stress near the crack front approaches tritensile plane strain, and the crack-tip plastic region is small compared with the crack size and specimen dimensions in the constraint direction. A K_{Ic} value is believed to represent a lower value of fracture toughness.

4.4 Apparatus

4.4.1 List of Equipment and Materials. The equipment and materials listed below are needed for this procedure. Equivalent items may be substituted unless otherwise noted. Purchase of materials is to comply with 033-YMP-QP 4.0, "Procurement Control and Documentation."

Required equipment and materials include: constant extension rate testing machine (CERT), reversing dc potential drop instrument, load cell, displacement gauge, and caliper or micrometer. The identification numbers and calibration records will be identified in the scientific notebook. The six candidate materials to be tested are CDA 102 (OFHC), CDA 613 (aluminum bronze), CDA 715 (Cu-³⁰Ni), stainless steels Type 304L and Type 316L, and Alloy 825. All samples tested must be procured as specified in 033-YMP-QP 4.0 and controlled as specified in 033-YMP-QP 8.0.

4.2.2 Special Environmental Conditions. The tests will be conducted in dry air or in an argon atmosphere. Contact with moisture should be avoided. These tests should be conducted at ambient temperatures.

4.4.3 Loading. Specimens should be loaded in a CERT machine that has provision for recording the applied load to the specimen. A testing machine incorporating a reversing dc potential drop technique also shall be used.

4.4.4 Fixtures. A loading clevis suitable for testing compact specimens is shown in Fig. 4. Both ends of the specimen are held in the clevis and loaded through pins to allow for rotation of the specimen during testing. To provide rolling contact between the loading pins and the clevis holes, these holes are provided with small flats on the loading surfaces. Other clevis designs can be used if it can be demonstrated that they can accomplish the same result as the design shown. Careful attention should be given to achieving as good alignment as possible through careful machining of all auxiliary gripping fixtures.

4.4.5 Displacement gauge. The relative displacement of two precisely located gauge positions spanning the crack starter notch mouth shall be indicated by the displacement gauge output. For the compact specimens, the displacements will essentially be independent of the gauge length up to $1.2W$. A recommended design for a self-supporting, releasable gauge is shown in Fig. 5. The strain gauge bridge arrangement is also shown in Fig. 5.

4.4.5.1 The specimen must be provided with a pair of accurately machined knife edges that support the gauge arms and serve as the displacement reference points. These knife edges can be machined integral with the specimen as shown in Figs. 5 and 6.

4.4.5.2 Each gauge shall be checked for linearity; the resettability of the calibrator at each displacement interval should be within 4×10^{-5} in. ($1 \mu\text{m}$). Readings shall be taken at 10 equally spaced intervals over the working range of the gauge. This calibration procedure should be performed after each run.

4.4.5.3 Other types of gauges can be used as long as they meet the requirements listed below.

4.4.6 Calibrations. All equipment must be calibrated as specified in 033-YMP-QP 12.0. The calibration records will be identified in the scientific notebook.

4.5 Specimen Size, Configurations, and Preparation

4.5.1 Specimen Size

4.5.1.1 For a result to be considered valid according to this method, both the specimen thickness, B , and the crack length, a , should exceed $2.5(K_Q/\sigma_{ys})^2$, where σ_{ys} is the 0.2% offset yield strength of the material for the temperature and loading rate of the test and K_Q is the conditional result used to establish whether a valid K_{Ic} has been measured (Section 3.5) [6, 7].

4.5.1.2 The initial selection of a specimen size from which valid values of K_{Ic} will be obtained might be based on an estimated value of K_{Ic} for the material. It is recommended that the value of K_{Ic} be overestimated, so that a conservatively large specimen will be used for the initial tests. After a valid K_{Ic} result is obtained with the conservative-size initial specimen, the specimen size can be reduced to an appropriate size [a and $B \geq 2.5(K_{Ic}/\sigma_{ys})^2$] for subsequent testing. Alternatively, the ratio of yield strength to Young's modulus can be used for selecting a specimen size that will be adequate for all but the toughest materials (see Table 1).

When it has been established that $2.5(K_{Ic}/\sigma_{ys})^2$ is substantially less than the minimum recommended thickness given in Table 1 (see Section 3.5), then a correspondingly smaller specimen can be used.

4.5.2 Specimen configurations. The general dimensions of the standard compact specimen are shown in Fig. 7. Alternative specimens may have $2 \leq W/B \leq 4$ but with no change in other proportions. It is important to note the crack plane orientation, which is an identification of the plane and direction of a fracture in relation to fracture geometry. This identification is

designated by a hyphenated code with the first letter(s) representing the direction normal to the crack plane and the second letter(s) designating the expected direction of crack propagation (Fig. 8).

4.5.3 Specimen preparation. The dimensional tolerances shown in Fig. 7 are to be followed in specimen preparation.

4.5.3.1 Fatigue crack starter notch. A chevron notch or a straight-through notch are the forms of fatigue crack starter notch used. To facilitate fatigue cracking at low stress intensity levels, the root radius for a straight-through slot terminating in a V-notch should be 0.007 in. (0.18 mm) or less. If a chevron notch is used, the root radius should be 0.010 in. (0.25 mm) or less, and the crack length (total length of crack starter notch plus the fatigue crack) shall be between 0.045 and 0.55 W.

4.5.3.2 Fatigue cracking. The procedure for fatigue cracking shall be similar to that described in ASTM E-399-83 [8].

4.6 General Procedure

4.6.1 Number of tests. A certain amount of data scatter is inevitable in test results. The amount of scatter depends on the uniformity of the test material, the condition of the specimen surface, and the stability of the exposure conditions. All of these factors influence the precision of tests. Therefore, to reduce the likelihood of an incorrect conclusion based on a single nontypical result, it is recommended that at least two tests be conducted for each material under investigation.

4.6.2 Measurement. The thickness (B), crack length (a), and width (W) are the measurements needed to calculate K_{Ic} .

4.6.2.1 Thickness and width measurements. The thickness, B, shall be measured to the nearest 0.001 in. (0.025 mm) or to 0.1%, whichever is larger, at three equally spaced positions along the line of intended crack extension from the fatigue crack tip to the unnotched side of the specimen. The average of the measurements shall be recorded as B. The width, W, shall be measured from the plane of the centerline of the loading holes. The width shall be measured to the nearest 0.001 in. (0.025 mm) or 0.1%, whichever is larger, and the average of three readings near the notch location shall be recorded. A caliper or a micrometer shall be used to make the measurements.

4.6.2.2 Crack length measurement. The crack length, a, shall be measured using a reversing dc electrical potential drop method, first developed by General Electric [9]. The concept is to correlate a change in crack depth to a change in voltage across probe pairs spanning the crack. Historically, drift resulting from thermal EMFs erected at junction points has caused a problem in measuring dc potential. In this approach, the current is reversed at intervals to minimize the problem. The resulting differential potential readings between any two adjacent readings with positive and negative polarity eliminates concern about thermal EMFs. For comparison, the crack also should be measured after fracture with a caliper to the nearest 0.5% at the following three locations: at the center of the crack front, and midway between the center of the crack front and the end of the crack front on each specimen surface.

4.6.3 Loading rate. The specimen will be loaded at such a rate that the rate of increase of stress intensity is within the range 30 to 150 ksi in.^{1/2}/min (0.55 to 2.75 MPa m^{1/2}/s), corresponding to a loading rate for a standard (W/B = 2) 1-in.-thick specimen 4500 to 22,500 lb/min (0.34 to 1.7 kN/s).

4.6.4 Test record. A test record shall be made consisting of an autographic plot of the output of the load-sensing transducer versus the output of the displacement gauge. The initial slope of the linear portion shall be between 0.7 and 1.5. The load from the test record shall be determined with an accuracy of $\pm 1\%$. The test will continue until the specimen can sustain no further increase in load.

4.7 Calculation and Interpretation of Results

4.7.1 Interpretation of test record and calculation of K_{Ic} . A procedure similar to that described in ASTM 399-83 [8] (see Section 9) shall be used to calculate K_{Ic} . Initially, a conditional result, K_Q , shall be calculated to establish whether a valid K_{Ic} has been determined. The procedure is as follows.

4.7.1.1 Draw the secant line, OP_5 (shown in Fig. 9), through the origin of the test record with slope $(P/V)_5 = 0.95(P/V)_0$, where $(P/V)_0$ is the slope of the tangent OA to the initial linear part of the record. The load P_Q is then defined as follows: if the load at every point on the record that precedes P_5 is lower than P_5 , then P_5 is P_Q (Fig. 9, Type I); if, however, there is a maximum load preceding P_5 that exceeds it, then this maximum load is P_Q (Fig. 9, Types II and III).

4.7.1.2 Calculate the ratio P_{max}/P_Q , where P_{max} is the maximum load the specimen can sustain. If this ratio does not exceed 1.10, calculate K_Q . If the ratio exceeds 1.10, the test is not a valid K_{Ic} test because it is then possible that K_Q bears no relation to K_{Ic} .

4.7.1.3 Calculate $2.5(K_Q/\sigma_{ys})^2$, where σ_{ys} is the 0.2% offset yield strength in tension. If this quantity is less than both the specimen thickness and the crack length, then K_Q is equal to K_{Ic} . Otherwise, the test is not a valid K_{Ic} test.

4.7.1.4 If the test fails to meet the requirements in Section 4.7.1.2 or 4.7.1.3 or both, it will be necessary to use a larger specimen to determine K_{Ic} . The dimensions of the larger specimens can be estimated on the basis of K_Q but generally will be at least 1.5 times those of the specimen that failed to yield a valid K_{Ic} value.

4.7.1.5 Calculation of K_Q . For the compact specimen, calculate K_Q in units of $\text{ksi in.}^{1/2}$ ($\text{MPa m}^{1/2}$) from the following expression:

$$K_Q = (P_Q/BW^{1/2}) \cdot f(a/W), \quad (11)$$

where

$$f(a/W) = (2 + a/W)[0.886 + 4.64(a/w) - 13.32(a/w)^2 + 14.72(a/w)^3 - 5.6(a/w)^4]/(1 - a/w)^{3/2} \quad (12)$$

where

- P_Q = load, klb_f (kN);
- B = specimen thickness, in. (cm);
- W = specimen width, in. (cm);
- a = crack length, in. (cm).

To facilitate calculation of K_Q , values of $f(a/W)$ are tabulated for specific values of a/w in Table 2.

The total error or sensitivity to errors in B, W , and P_Q is given by Eq. (13). The derivation is outlined in Appendix A.

$$\Delta K = \left| f(a/w) / W^{1/2} - 1/2 (f(a/w) / W^{3/2}) \right| \Delta W + \left| -P_Q \cdot f(a/w) / (B^2 \cdot W^{1/2}) \right| \Delta B + \left| \Delta P_Q \cdot f(a/w) / (B \cdot W^{1/2}) \right| \quad (13)$$

4.7.1.6 Calculation of R_{sc} . The specimen strength ratio shall be calculated for all specimens (R_{sc} is a dimensionless quantity):

$$R = \frac{2 P_{max} (2W + a)}{B (W - a)^2 \sigma_{ys}} \quad (14)$$

where

P_{max} = maximum load the specimen can sustain;
 σ_{ys} = 0.2% yield strength in tension.

The total error or sensitivity to errors in B, W, and P_{max} is given by Eq. (14). The derivation is outlined in Appendix B.

$$\Delta R = \left| (2 + a)(W - a) - 2(2W + a) / (W - a)^3 \right| \Delta W + \left| 2\Delta P_{max} (2W + a) / B (W - a)^2 \sigma_{ys} \right| + \left| (-2P_{max} (2W + a)) / (B^2 (W - a)^2 \sigma_{ys}) \right| \Delta B \quad (15)$$

4.7.2 Fracture appearance. The fracture appearance of each specimen shall be noted. Common types of fracture appearance are shown in Fig. 10. For fractures of Types a or b, measure the average width, f , of the central flat fracture area, and record the proportion of oblique fracture per unit thickness $(B - f)/B$. Make this measurement at a location midway between the crack tip and the unnotched edge of the specimen. Report fractures of Type c as full oblique fractures.

4.8 Report

All relevant data for determining K_{Ic} should be kept in a bound, legal notebook, as well as in an appropriate data base. The data should be in a tabulated form; a suggested format for a table is given in Fig. 11.

4.9 Accuracy and Bias

4.9.1 Bias. There is no accepted "standard" value for the plane-strain fracture toughness of any material. In the absence of such a true value, any statement concerning bias is not meaningful.

4.9.2 Accuracy. The precision of a K_{Ic} determination is a function of the accuracy and bias of the various measurements of linear dimensions of the specimen and testing fixtures, the precision of the displacement measurements, and the bias of the load measurement as well as the bias of the recording devices used to produce the load displacement record and the precision of the constructions made on this record. It is not possible to make meaningful statements concerning precision and bias for all these measurements.

5. Threshold Stress Intensity for Stress Corrosion Cracking, K_{Isc}

5.1 Introduction to K_{Isc}

The linear fracture mechanics formalism was first applied to the study of stress corrosion crack growth more than 10 years ago by Brown et al. [10] and Johnson et al. [11]. The approach recognizes the presence of early initiation of cracks in a structural component and that structural failure results from the growth of these cracks by stress corrosion cracking. The mechanical driving force for this crack growth is considered to be given by the crack-tip stress intensity factor (K_I) defined by linear elasticity.

As shown in Section 3.3, the stress-intensity factor for opening mode K_I is proportional to the product of the applied stress and the square root of the crack length. At a sufficiently high value of stress intensity, designated K_{Ic} and referred to as fracture toughness, unstable fast fracture ensues. The value of K_{Ic} is not related to stress corrosion behavior; however, if a specimen subjected to a K value less than K_{Ic} undergoes slow crack growth in the presence of a corrosive environment, K will increase until it reaches K_{Ic} and unstable fracture occurs.

Slow stress corrosion crack growth does not occur at all values of K and the minimum initial value at environmental sensitive crack growth occurs is designated K_{Isc} . This latter value has considerable practical significance because it defines the largest crack that can persist in a structure without propagation. Thus, for a surface crack in an infinite plate remotely loaded in tension, the shallowest crack that will propagate as a stress corrosion crack is

$$a_{cr} = 0.2(K_{Isc}/\sigma_y)^2 \quad (16)$$

Cracks shallower than this will be stable.

5.2 Summary of Test Method

The testing technique used to determine K_{Isc} is essentially identical to the procedure used for K_{Ic} fracture testing (ASTM E399-83) [8] except that a slower rate of loading is involved normally, and the specimen is exposed to the environment while being loaded. The slower rate of loading allows for environmentally induced crack initiation and causes time-dependent subcritical propagation. This technique is often referred to as the rising load K_{Isc} testing method [12]. In this technique, stress corrosion characteristics are measured in terms of crack growth rate. The specimen is fixed in a holding device, and the environment is applied to the tip of the machined notch. The test environment should be brought into contact with the specimen before it is stressed. This enhances access of the corrodent to the crack tip to promote earlier initiation of stress corrosion cracking and to decrease the variability in test method. If the specimen has been fatigue precracked, it is deflected, in the presence of the corrodent, to a predetermined K_I value. Crack length using the reversing dc potential drop method is measured, and the crack opening displacement, v , is measured along the line of load application when the load is maintained at the same level for the duration of the test. Once the environment is applied to the specimen, the crack length is monitored as a function of time elapsed from deflection. The overall result of this procedure is to cause the stress intensity factor to decrease as the crack extends under the influence of the corrodent. The slope of the crack length versus time curve at any crack length provides crack growth rate. From the K calibration, the stress intensity level is determined.

The data are plotted as logarithmic crack growth rate or crack velocity versus stress intensity factor. Generally, three stages of crack growth rate can be identified in stress-corrosion results presented in this manner [13] (Fig. 12). Stage I occurs at low stress intensities where crack

growth rate is strongly stress-intensity dependent and the crack may eventually arrest, thus indicating K_{Isc} . Generally, the crack extends at an extremely slow rate, and K_{Isc} is designated at an arbitrarily selected crack velocity. Few explanations for the K dependence of stage I have been offered. One explanation is that in stage I, the crack tip plastic strain rate is increasing rapidly with transport of species into and out of the crack increasing rapidly with increasing crack volume in stage I. Stage II occurs at intermediate stress intensities where crack growth rate is independent of stress intensity. The plateau velocity is characteristic of the alloy-environment combination and is the result of rate-limiting environmental processes such as mass transport of environmental species up the crack to the crack tip. Stage III occurs at stress intensities close to K_{Ic} where crack growth rate again becomes dependent on stress intensity. In stage III, the rate of crack propagation exceeds the plateau velocity as the stress intensity level approaches the critical stress intensity level for mechanical fracture in an inert environment, K_{Ic} .

5.3 Apparatus

5.3.1 List of Equipment and Materials. The equipment and materials listed below are needed for this procedure. Equivalent items may be substituted unless otherwise noted. Purchase of materials is to comply with 033-YMP-QP 4.0, "Procurement Control and Documentation."

Required equipment and materials include: CERT machine, reversing dc potential drop instrument, load cell, displacement gauge, standard calomel electrode, and a caliper or micrometer. The identification numbers and the calibration records will be identified in the scientific notebook. The six candidate materials to be tested are: CDA 102 (OFHC), CDA 613 (aluminum bronze), CDA 715 (Cu-³⁰Ni), stainless steels Type 304L and Type 316L, and Alloy 825. All samples tested must be procured and controlled as specified in 033-YMP-QP 8.0.

5.3.2 Special Environmental Conditions. Electrolytes used for testing will be prepared so as to maintain the same relative concentrations of ions as found in water from Well J-13, if possible. Absolute concentrations may be greater or less than those found in water from J-13 (reference condition). Measurements in other aqueous environments, such as NaCl solutions, will be made if necessary. Tests also will be conducted in a vapor-phase environment containing NO_x species. The environmental variables will include temperature, partial pressure of water, and partial pressure of NO_x species.

5.3.3 Loading. Specimens should be loaded in a CERT machine that has provision for recording the applied load to the specimen. A testing machine incorporating a reversing dc potential drop technique also shall be used.

5.3.4 Fixtures. The method for K_{Ic} testing suggests that (1) the general gripping arrangement for tension testing should be designed to allow rotation as the specimen is loaded and (2) careful attention should be given to achieving as good alignment as possible. These suggestions should be adopted during stress corrosion testing even though the load is constant rather than increasing until fracture of the specimen.

5.3.5 Displacement gauge. The guidelines outlined in Section 4.4.5 should be adopted.

5.3.6 Test cell. The test cell for containing the environment should be constructed of a suitable inert material, such as glass. All auxiliary equipment must be insulated from the specimen with an efficient masking compound to eliminate galvanic and/or crevice corrosion. When necessary, stress-corrosion test cells should be designed so that they are large enough to contain reference and working electrodes. The standard calomel electrode (SCE) shall be the reference electrode. Cells also should provide good visibility of crack growth kinetics if possible. The test environment should be brought into contact with the specimen before it is stressed; this

enhances access of the corrosive to the crack tip to promote earlier initiation of stress corrosion cracking and to decrease the variability in test methods.

5.4 Specimen Size, Configurations, and Preparation

5.4.1 Specimen size. In the method described for K_{Ic} in Section 4.5.1, it was suggested that both the specimen thickness (B) and the crack length (a) exceed $2.5(K_{Ic} / \sigma_{ys})^2$ for the result to be considered valid. However, it is not clear whether the same criteria should be applied during the design of precracked specimens for stress corrosion testing. It is recommended that the dimensions of the plastic zone be kept at a minimum compared with the thickness of the specimen and that the relationship for the validity of K_{Ic} be used as a guide to test the validity of K_{Isc} .

5.4.2 Specimen configuration. The general dimensions of the standard compact tension specimen are shown in Fig. 7.

5.4.3 Specimen preparation. The dimensional tolerances shown in Fig. 7 should be followed in specimen preparation.

5.4.4 Fatigue crack starter notch. The form of the notches described in Section 4.5.3.1 should be adopted for specimens for stress corrosion testing.

5.4.5 Fatigue cracking. No specific procedure for fatigue precracking is recommended; however, the procedure described in ASTM E399-83 [8] should be considered. The K level used for precracking each specimen should not exceed about two-thirds of the intended starting K values for the environmental exposure. This prevents fatigue damage or residual compressive stress at the crack tip, which might alter the stress corrosion cracking behavior, particularly when testing at a K level near the threshold stress intensity for the specimen.

5.5 General Procedure

5.5.1 Number of tests. A certain amount of data scatter is inevitable in corrosion test results. The amount of scatter depends on the uniformity of the test material, the condition of the specimen surface, and the stability of the exposure conditions. All of these factors influence the precision of corrosion tests. Therefore, to reduce the likelihood of an incorrect conclusion based on a single nontypical result, it is recommended that at least two tests be conducted for each material under investigation. If the two test results differ significantly, another test should be conducted.

5.5.2 Crack measurement. To monitor crack propagation rate as a function of decreasing stress intensity, a reversing dc electrical potential drop method, first developed by General Electric [9], shall be used. The concept is to correlate a change in crack depth to a change in voltage across probe pairs spanning the crack. Historically, drift resulting from thermal EMFs erected at junction points has caused a problem in measuring the dc potential. In this approach, the current is reversed at intervals to minimize the problem. The resulting differential potential readings between any two adjacent readings with positive and negative polarity eliminates concern about thermal EMFs. As a backup to the reverse dc measurement technique, the load and crack opening displacement at the load line can be used to measure the crack growth rate. The crack length can be determined from the relationship between the stress intensity expression and compliance characteristics of the specimen. A calibration curve of displacement or load versus crack length should be obtained for the appropriate compact tension specimen. (Details are described in Section 5.8.) Other specimen dimensions should be measured according to Section 4.6.2.

5.5.3 Loading rate. The loading rate for a standard ($W/B = 2$) 1-in.-thick specimen should be between 20 to 5000 lb/min. Once the onset of crack growth has occurred, crack growth rate data can be developed by maintaining the load constant and monitoring the displacement as a function of elapsed time or by monitoring the crack length using the reversing dc technique.

5.5.4 Calibrations. All equipment must be calibrated as specified in 033-YMP-QP 12.0. The calibration records will be identified in the scientific notebook.

5.6 Interpretation of Results

5.6.1 The interpretation of the results to obtain K_{Isc} depends on the method of crack length measurement: i.e., directly, using the reverse dc technique, or indirectly, measuring the displacement and obtaining crack length from a calibration curve.

5.6.1.1 Reverse dc potential drop method. Crack initiation can be determined directly by monitoring the potential signal and noting the corresponding load.

5.6.1.2 Crack growth data are then developed by maintaining the load constant after crack initiation and monitoring the crack length with elapsed time. From the load and the corresponding crack length, the stress intensity factor can be calculated. The data are then plotted as logarithmic crack growth rate versus stress intensity factor, and K_{Isc} is determined (Fig. 12).

5.6.2 The other interpretation of the rising load K_{Isc} testing method follows the procedure proposed originally by McIntyre and Priest [12] and that investigated by Clark and Landes [14].

5.6.2.1 If subcritical crack extension occurs during the rising load test, the load corresponding to crack initiation can be determined from the point of linear deviation on the load displacement record (Fig. 13). From the relationship between the stress intensity expression and compliance characteristics of the specimen [Eq. (17)], the crack length and the stress intensity level associated with the onset of crack growth can be determined.

5.6.2.2 From the calibration curve (Section 5.7), the crack length corresponding to the point of deviation on the load displacement record can be determined. From this crack length and the corresponding displacement value, the stress intensity level associated with the onset of subcritical crack growth can be determined using the K_I/v calibration curve (Section 5.7).

5.6.2.3 It is recommended that a comparison of actual crack length measurements made on broken specimens with the crack length determined from the V/P calibration be made to determine the accuracy of the V/P calibration.

5.6.2.4 As noted in Section 5.5.3, crack growth data can be developed by maintaining the load constant and monitoring the displacement as a function of elapsed time. The results can be converted to crack growth rate by means of the calibration curve (see Section 5.8).

5.6.2.5 To standardize the technique used in establishing the point of deviation on the load displacement record associated with the onset of subcritical crack growth, a 5% secant offset procedure similar to that used for K_{Ic} testing (ASTM E399-83 [8]) should be used.

5.6.2.6 Fracture appearance. The fracture appearance of each specimen should be noted. The suggested method is to take an optical micrograph or a scanning electron micrograph of the fracture surface. The characteristics of stress corrosion cracking are fractures (which might be

transcrystalline or intercrystalline) that show little deformation in otherwise ductile materials and without the formation of easily visible corrosion products. Transgranular cracking is cracking or fracturing that occurs through or across the grains of a metal. The phenomena resemble those of real cleavage fractures. The crack can transverse the whole cross section immediately or can propagate step by step, leaving irregular markings on the fracture surface. Intergranular cracking is cracking or fracturing that occurs between the grains. For intergranular cracking, flat facets of grains are usually observed under the scanning electron microscope.

5.7 K_I/V Calibration

5.7.1 Clark and Landes [14] have described a convenient method of computing K_I for various combinations of crack length and displacement values. The method involves the relationship between the stress-intensity expression and compliance characteristics of the specimen and is outlined as follows.

5.7.2 The stress intensity expression for compact tension specimen is given by:

$$K_I = \frac{Y P a^{1/2}}{B W} \quad (17)$$

where

- a = crack length measured from the centerline of loading;
- P = applied load;
- B = specimen thickness;
- W = specimen width measured from the centerline of loading;
- Y = a constant that is a dimensionless polynomial function in odd half powers of (a/w) from (a/w)^{1/2} to (a/w)^{9/2}.

5.7.3 The appropriate compliance expression for the compact tension specimen is:

$$EB(V_I/P) = C \quad (18)$$

where

- C = compliance constant dependent on a/W;
- E = modulus of elasticity;
- V_I = displacement across the machined slot measured at the centerline of loading.

5.7.4 The compliance expression can be combined with the stress-intensity expression to yield the relationship between K_I , V_I, and a, specifically:

$$\frac{K_I}{V_I} = \frac{YE a^{1/2}}{CW} \quad (19)$$

This expression is then used to compute K_I for various combinations of crack length and displacement values, thus obtaining a calibration curve with K_I/V plotted against crack length ($a - a_n$), which refers to crack length measured beyond the tip of the machined notch. This curve is then used to compute both the stress-intensity factor associated with the initial loading of the specimen (K_{I1}) and the stress intensity at crack arrest ($K_{I_{scc}}$).

5.8 Experimental Compliance Calibration

5.8.1 Compliance is determined experimentally by finding the crack opening displacement caused by a unit of load in a specimen containing a slot (representing a crack), the length of which has been accurately measured. The crack length, a , should be extended in small increments by using a jeweller's saw blade. For each crack length, measurements of force versus crack opening displacement (P vs V) should be made in the tensile machine using a clip gauge. The procedure should be repeated for a sufficient number of crack length values to cover adequately and reliably the range of interest.

5.8.2 Figure 14 (a) shows several P-V curves for different values of crack length. The compliance (V/P) for each is replotted as a function of crack length, a , in Fig. 14 (b). This relationship also can be represented in a dimensionless form, as in Fig. 14 (c), by incorporating the additional terms E and B in the compliance and defining crack length in terms of a/W .

5.8.3 It is convenient to find the equation of the compliance curve by fitting the data shown in Fig. 10 (c) to a general polynomial; for example:

$$\frac{EBV}{P} = C_1 + C_2 (a/W) + C_3 (a/W)^2 + C_4 (a/W)^3 \quad (20)$$

The values of the constants are found by solving the appropriate number of simultaneous equations.

6. Personnel Responsibilities

6.1 The Task Leader whose activities warrant the use of this procedure is responsible for implementing the requirements of this procedure. The Task Leader may delegate this responsibility and authority to a Principal Investigator.

6.2 The individual determining the plane-strain fracture toughness and the threshold stress intensity for stress corrosion cracking is responsible for following the requirements of this procedure, documenting calibrations, and assuring that the latest revision of this document is followed.

6.3 The YMP Quality Assurance Manager (QA Manager) is responsible for monitoring work to ensure proper implementation of this procedure and to ensure its continued effectiveness.

6.4 Copies of this procedure are available from both the Task Leader and the Principal Investigator. Suggestions for revisions or any questions regarding the procedure may be directed to either the Task Leader or the Principal Investigator.

7. Quality Assurance Records

7.1 The documents produced by this procedure are (1) this procedure; (2) the scientific notebook; (3) the data base; and (4) the samples.

7.2 The scientific notebook will identify the calibration status and the calibration procedure (including revisions) used to perform each calibration.

7.3 Determinations of plane-strain fracture toughness and the threshold stress intensity for stress corrosion cracking will be recorded in the scientific notebook in accordance with 033-YMP-QP 3.4, "Scientific Notebooks."

References

1. UCID-21362.
2. J. F. Knott, *Fundamentals of Fracture Mechanics*, Butterworths (London) 1973.
3. *Fracture Toughness Testing and Its Applications*, ASTM STP 381, American Society for Testing and Materials, Philadelphia, PA, 1965.
4. *Developments in Fracture Mechanics Test Methods Standardization*, ASTM STP 632, American Society for Testing and Materials, Philadelphia, PA, 1976.
5. A. A. Griffith, "The Phenomena of Rupture and Flow In Solids," *Phil. Trans.* 221, 163-198 (1921).
6. W. F. Brown, Jr., and J. E. Srawley, *Plane Strain Toughness Testing of High Strength Metallic Materials*, ASTM STP 410, American Society for Testing and Materials, Philadelphia, PA, 1966.
7. J. E. Srawley, M. H. Jones, and W. F. Brown, Jr., "Determination of Plane Strain Fracture Toughness," *Materials Research and Standards*, ASTM 7, 262, American Society for Testing and Materials, Philadelphia, PA, 1967.
8. *Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials*, ASTM E399-83, American Society for Testing and Materials, Philadelphia, PA, pp. 680-701, 1981.
9. W. R. Catlin et al., General Electric Report No. 83 CRD 293, December 1983.
10. B. F. Brown and C. D. Beachem, *Corr Sci.* 5, 747-750 (1965).
11. H. H. Johnson and A. M. Willner, *App. Materials Research*, p. 34 (1965).
12. P. McIntyre and A. H. Priest, *Accelerated Test Technique for the Determination of K_{Isc} in Steels*, British Steel Corporation Report MG/31/72 (1972).
13. R. P. Wei, "The Fracture Mechanics Approach to SCC," in *Stress Corrosion Research*, Hans Arup and R. N. Parkins, Eds., Sijthoff & Noordhoff, p. 65, 1979.
14. W. G. Clark, Jr., and J. D. Landes, "An Evaluation of Rising Load Testing," in *Stress Corrosion — New Approaches*, ASTM STP 610, pp. 108-127, 1976.
15. H. R. Smith and D. E. Piper, "Stress Corrosion Testing with Pre-cracked Specimens," in Part 2 of *Monograph Review of the SCC in High-Strength Steels, Titanium Alloys, and Aluminium Alloys*, Boeing D6-24872, June 1970.

Table 1. Ratio of yield strength to Young's modulus used for selecting specimen size.

Yield strength/Young's modulus (σ_{ys}/E)	Minimum recommended thickness (b) or crack length (a)	
	(in.)	(mm)
0.0050 to 0.0057	3	75
0.0057 to 0.0062	2.5	63
0.0062 to 0.0065	2	50
0.0065 to 0.0068	1.75	44
0.0068 to 0.0071	1.5	38
0.0071 to 0.0075	1.25	32
0.0075 to 0.0080	1	25
0.0080 to 0.0085	0.75	20
0.0085 to 0.0100	0.50	12.5
0.0100 or greater	0.25	6.5

Table 2. Values of $f(a/w)$ for specific values of (a/w) .

Compact specimens			
(a/w)	$f(a/w)$	(a/w)	$f(a/w)$
0.450	8.34	0.500	9.66
0.455	8.46	0.550	9.81
0.460	8.58	0.510	9.96
0.465	8.70	0.515	10.12
0.470	8.83	0.520	10.29
0.475	8.96	0.525	10.45
0.480	9.09	0.530	10.63
0.485	9.23	0.535	10.80
0.490	9.37	0.540	10.98
0.495	9.51	0.545	11.17
—	—	0.550	11.36

Figure 1. Griffith's crack; crack of length $2a$ situated in an infinite body [2].

Figure 2. Modes of crack deformation. Mode I = opening mode: tension stress in y direction (perpendicular to crack surfaces). Mode II = edge-sliding mode: shear stress in x direction (perpendicular to crack tip). Mode III = screw-sliding mode: shear stress in z direction (parallel to crack tip).

Figure 3. Tensile stress distribution ahead of a sharp, through-thickness crack of length $2a$ in an infinite body [2].

Figure 4. Tension testing clevis design [8].

Figure 5. Double-cantilever clip-in displacement gauge showing mounting by means of integral knife edges [8].

Figure 6. Example of integral knife edge design [8].

Figure 7. Compact specimen C(T) standard proportions and tolerances [8]. A surfaces will be perpendicular and parallel as applicable to within $0.002W$ TIR. The intersection of the crack starter notch tips with the two specimen surfaces will be equally distant from the top and bottom edges of the specimen within $0.005W$.

Figure 8. Fracture plane identification [15].

Figure 9. Principal types of load-displacement records [8].

Figure 10. Common types of fracture appearance [8].

Figure 11. Suggested form for reporting test results.

Lab Data Chart for _____

Particulars

0.2% Offset yield strength, σ_{ys} _____
 Young's Modulus _____
 Crack plane orientation _____
 Thickness, B _____
 Width, W _____

Type of test

Plane strain fracture toughness, K_{Ic} []
 Threshold crack initiation for SCC, K_{Isc} []

Test Conditions

Loading rate (ksi \cdot in $^{1/2}$ /min) _____
 Test temperature _____
 Relative humidity _____
 Environment Air [] Solution _____
 Fatigue precracking [] _____

Crack Length

From reversing d.c. measurements _____
 From Caliper measurement _____
 — At center of crack front _____
 — At right of center _____
 — At left of center _____

Calculation of K_{Ic}

P_{max} _____
 P_Q _____
 P_{max}/P_Q _____
 VALID K_{Ic} _____
 R_{sc} _____

Calculation of K_{Isc}

P at crack initiation _____
 K at crack initiation _____
 K_{Isc} from crack growth data _____

Figure 12. Schematic representation of the crack growth kinetics [13].

Figure 13. Schematic of rising load K_{Isc} testing [14].

Figure 14. Curves to develop compliance [15].

Appendix A Sensitivity Analysis for the Stress Intensity Equation

A.1 Sensitivity analysis for the equation used to calculate stress intensity, i.e.:

$$K_Q = (P_Q/BW^{1/2}) \cdot f(a/w). \quad (A1)$$

A.2 Effect of errors in W on errors in K:

Let Eq. (A1) equal g(w):

$$\begin{aligned} K &= g(W), \quad dK = \frac{\partial g(W)}{\partial W} dW \\ DK &= \frac{\partial g(W)}{\partial W} DW \\ g(W) &= \frac{P_Q f(a/w)}{B W^{1/2}} \\ \frac{dg(W)}{dW} &= \frac{f(a/w)W^{1/2} - 1/2W^{-1/2}P_Q f(a/w)}{W^2} \\ &= \frac{f(a/w)}{W^{3/2}} - \frac{1}{2} \frac{f(a/w)}{W^{3/2}} \\ DK &= \left| \frac{f(a/w)}{W^{3/2}} - \frac{1}{2} \frac{f(a/w)}{W^{3/2}} \right| |DW| \end{aligned} \quad (A2)$$

A.3 Effect of errors in B on errors in K:

$$\begin{aligned} \Delta K &= \frac{\partial (P_Q \cdot f(a/w))}{\partial B (B W^{1/2})} \Delta B \\ \Delta K &= \left| \frac{P_Q \cdot f(a/w)}{B^2 W^{1/2}} \right| \end{aligned} \quad (A3)$$

A.4 Effect of errors in P on errors in K:

$$\begin{aligned} \Delta K &= \frac{\partial (P_Q \cdot f(a/w))}{\partial P (B W^{1/2})} \Delta P \\ \Delta K &= \left| \frac{\Delta P_Q \cdot f(a/w)}{B W^{1/2}} \right| \end{aligned} \quad (A4)$$

A.5 Therefore, the total error or sensitivity to errors in B, W, and P is

$$\Delta K = \left| \frac{f(a/w)}{W^{1/2}} - \frac{1}{2} \frac{f(a/w)}{W^{3/2}} \right| |\Delta W| + \left| \frac{(P_Q \cdot f(a/w))}{(B^2 W^{1/2})} \right| \Delta B + \left| \frac{\Delta P_Q \cdot f(a/w)}{B W^{1/2}} \right| \quad (\text{A5})$$

Appendix B

Sensitivity Analysis for the Strength Ratio Equation

B.1 Sensitivity analysis for the equation used to calculate the specimen strength ratio, i.e.:

$$R = \frac{2P_{\max}(2W + a)}{B(W - a)^2 \sigma_{ys}} \quad (B1)$$

B.2 Effect of errors in P_{\max} on errors in R:

$$\begin{aligned} \Delta R &= \frac{\partial (2P_{\max}(2W + a))}{\partial P} \frac{\Delta P}{(B(W - a)^2 \sigma_{ys})} \\ \Delta R &= \frac{2\Delta P_{\max}(2W + a)}{B(W - a)^2 \sigma_{ys}} \end{aligned} \quad (B2)$$

B.3 Effect of errors in B on errors in R:

$$\begin{aligned} \Delta R &= \frac{\partial (2P_{\max}(2W + a))}{\partial B} \frac{\Delta B}{(B(W - a)^2 \sigma_{ys})} \\ \Delta R &= \left| \frac{(-2P_{\max}(2W + a))}{(B^2(W - a)^2 \sigma_{ys})} \Delta B \right| \end{aligned} \quad (B3)$$

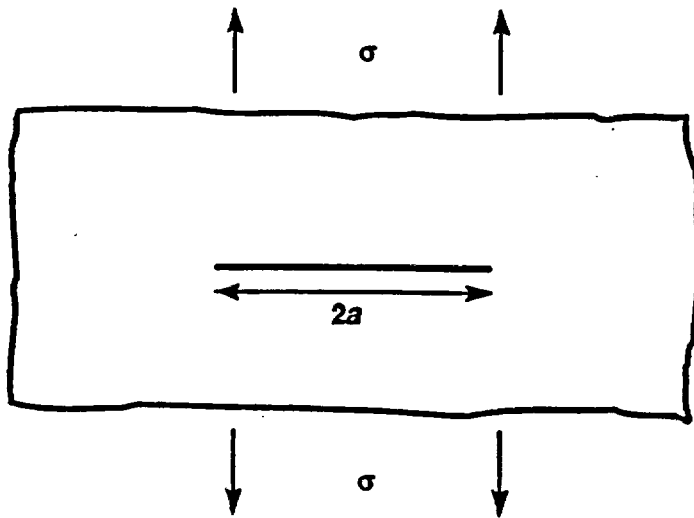
B.4 Effect of errors in W on errors in R:

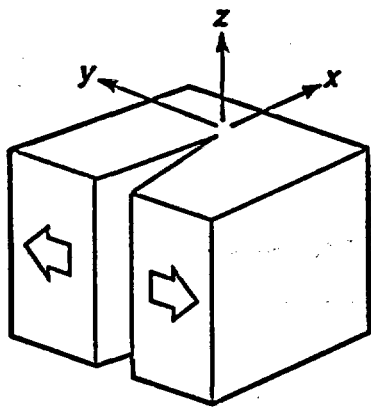
Let Eq. (B1) equal $g(W)$

$$\begin{aligned} R &= g(W), \quad dR = \frac{\partial g(W)}{\partial W} dW \\ \Delta R &= \frac{\partial g(W)}{\partial W} \Delta W \\ \frac{\partial g(W)}{\partial W} &= \frac{f'(2W + a)(W - a)^2(2W + a)}{(W - a)^4} \\ &= \frac{(2 + a)(W - a)^2 - 2(W - a)(2W + a)}{(W - a)^4} = \frac{(2 + a)(W - a) - 2(2W + a)}{(W - a)^3} \\ \Delta R &= \left| \frac{(2 + a)(W - a) - 2(2W + a)}{(W - a)^3} \right| |\Delta W| \end{aligned} \quad (B4)$$

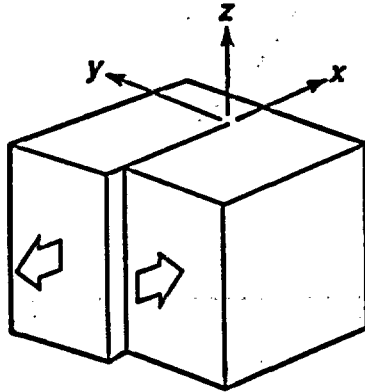
B.5 Therefore, the total error or sensitivity to errors in P_{\max} , B, and W is

$$\Delta R = \left| \frac{(2+a)(W-a) - 2(2W+a)}{(W-a)^3} \right| |\Delta W| + \left| \frac{2\Delta P_{\max}(2W+a)}{B(W-a)^2 \sigma_{ys}} \right| + \left| \frac{(-2P_{\max}(2W+a))}{(B^2(W-a)^2 \sigma_{ys})} \right| \Delta B \quad (B5)$$

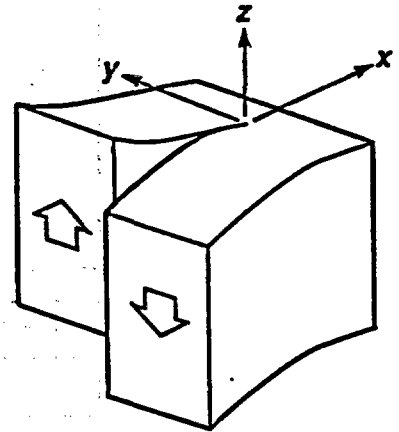




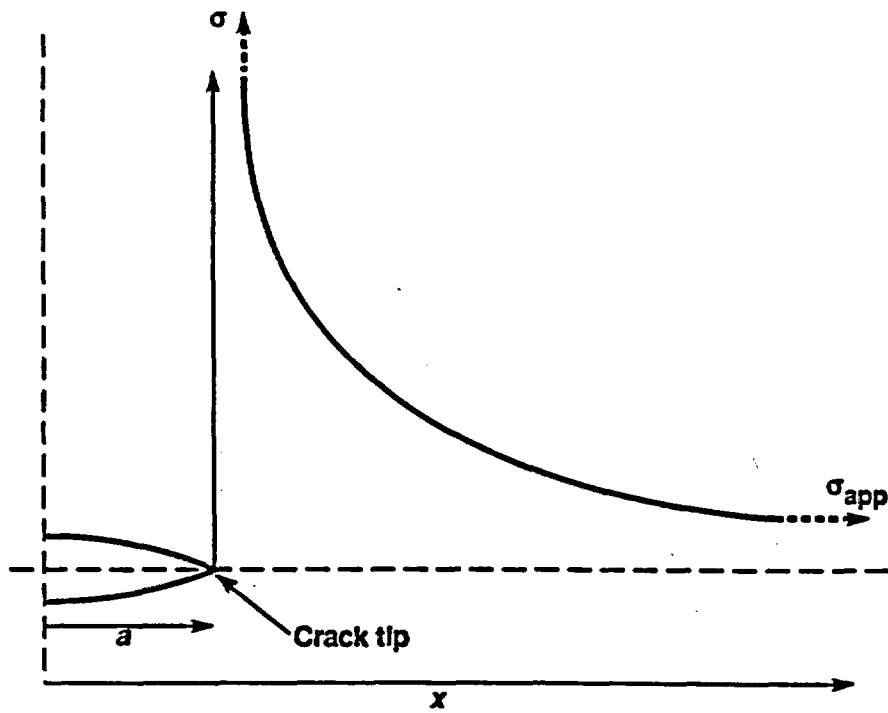
Mode I

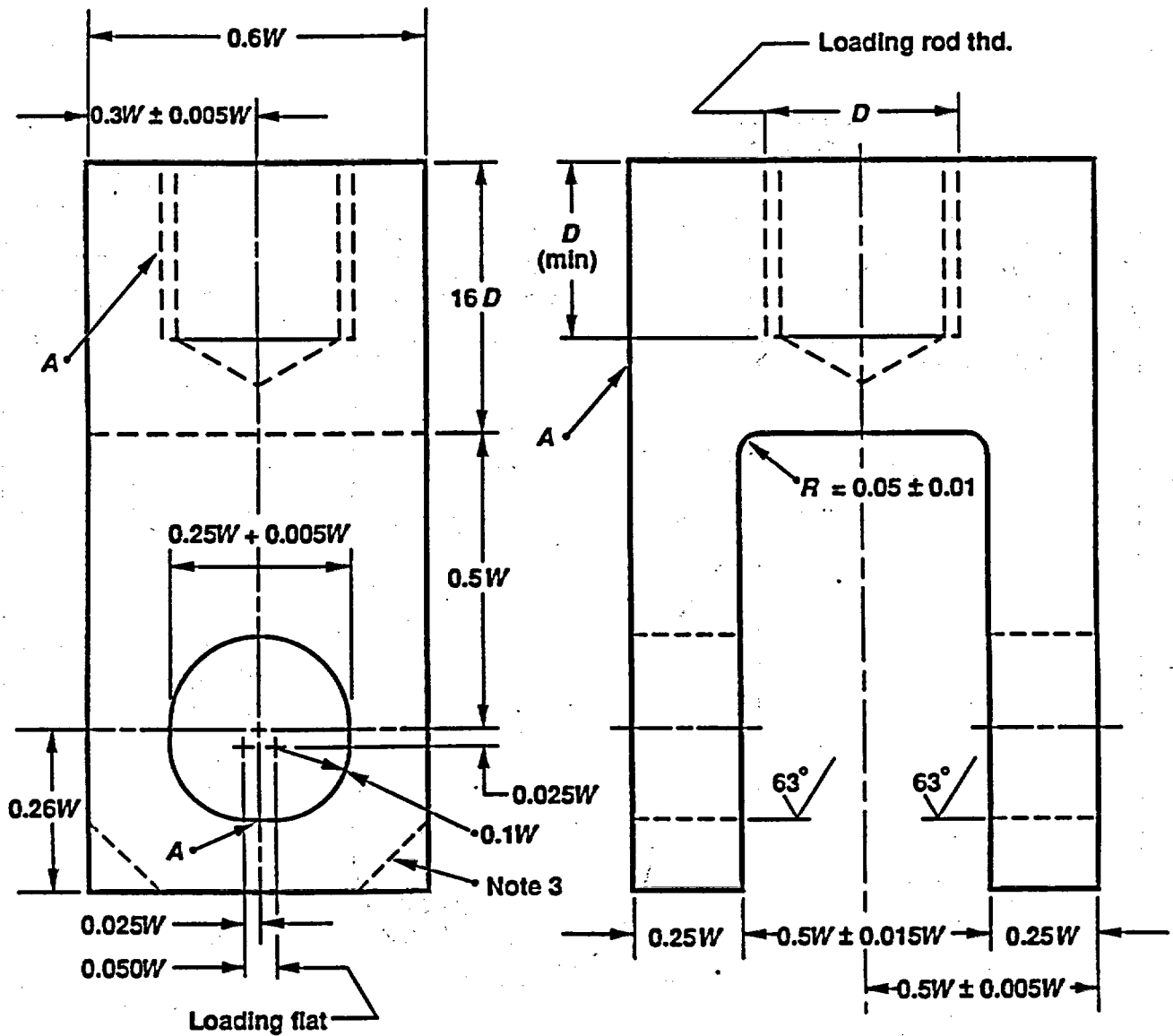


Mode II

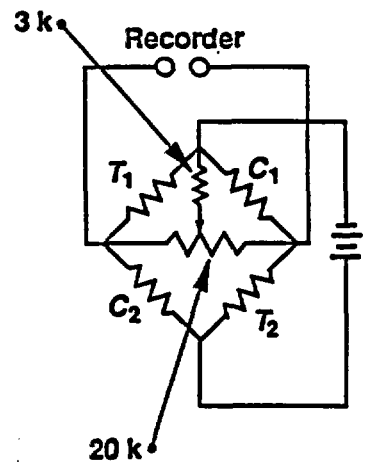
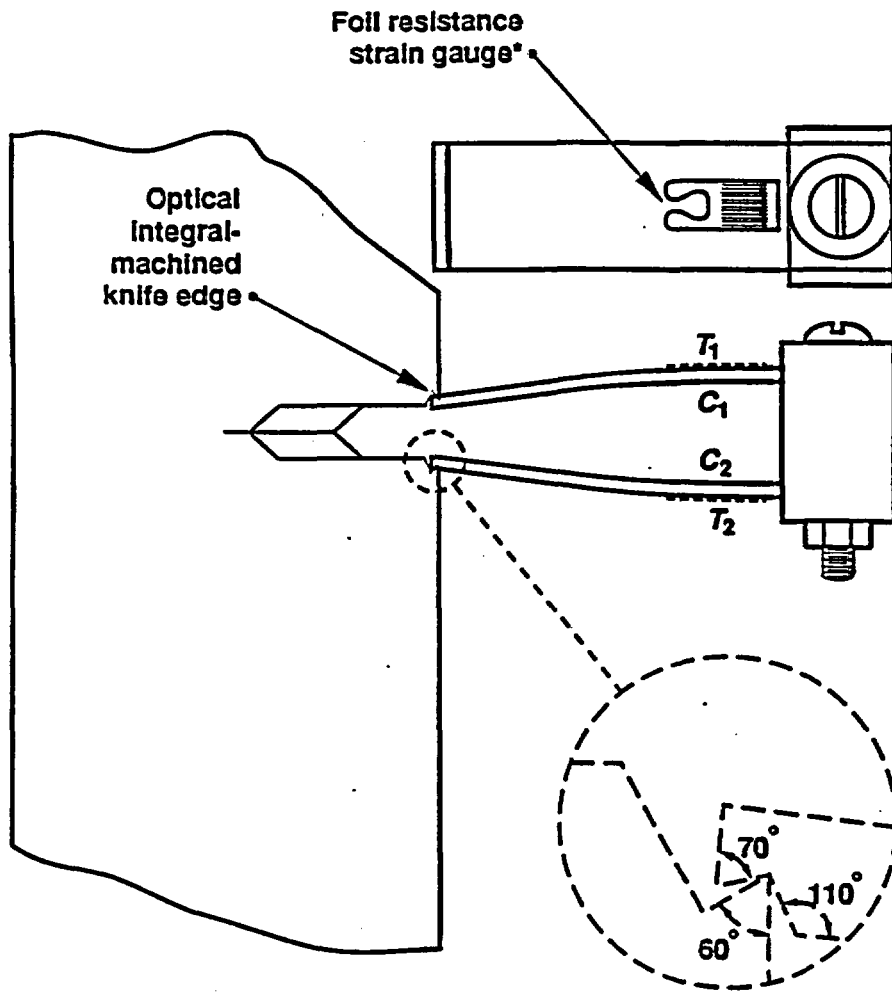


Mode III

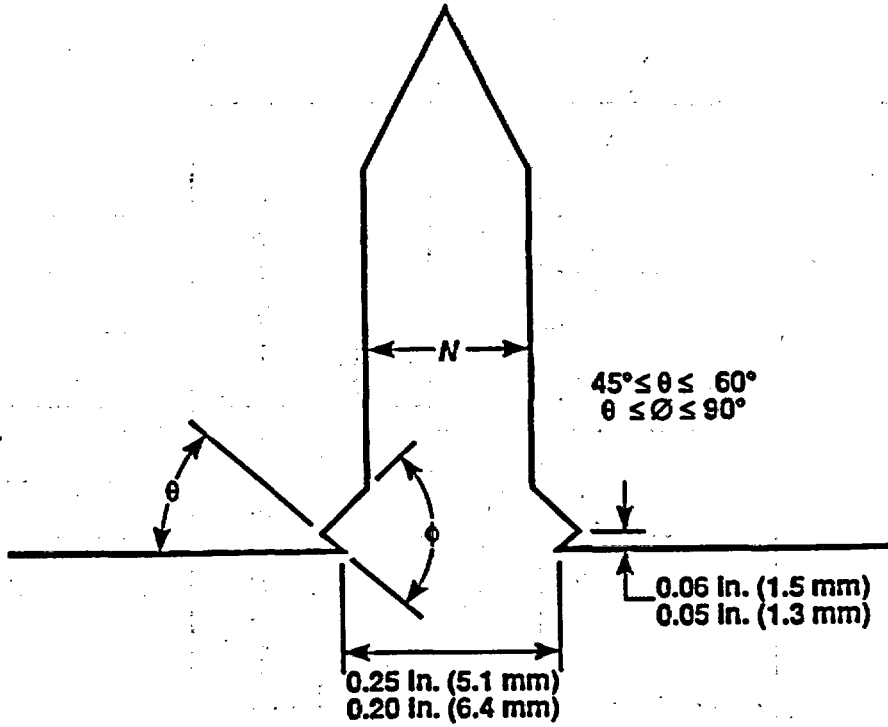


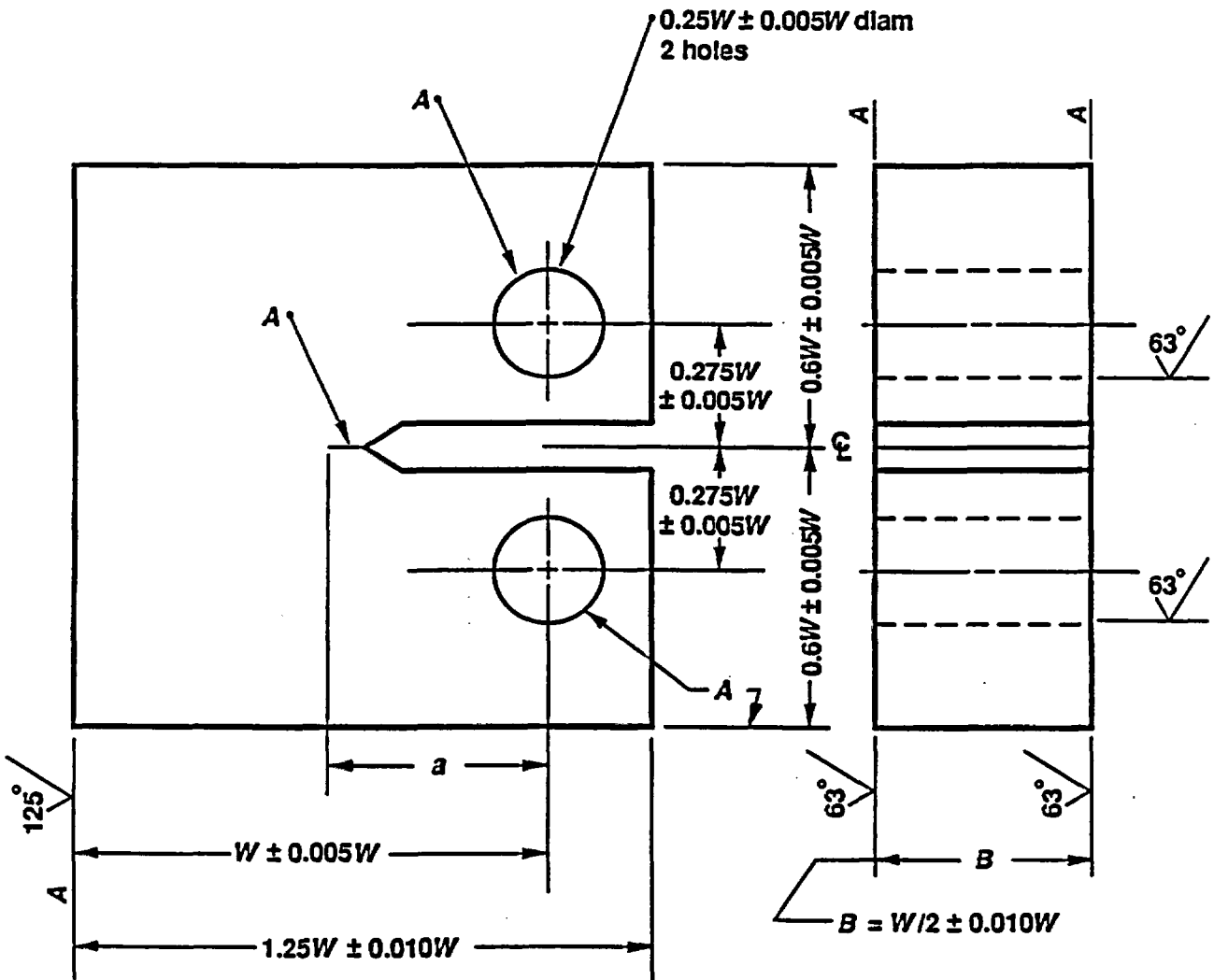


A: Surfaces must be flat, in-line, and perpendicular, as applicable, to within 0.002 in. TIR

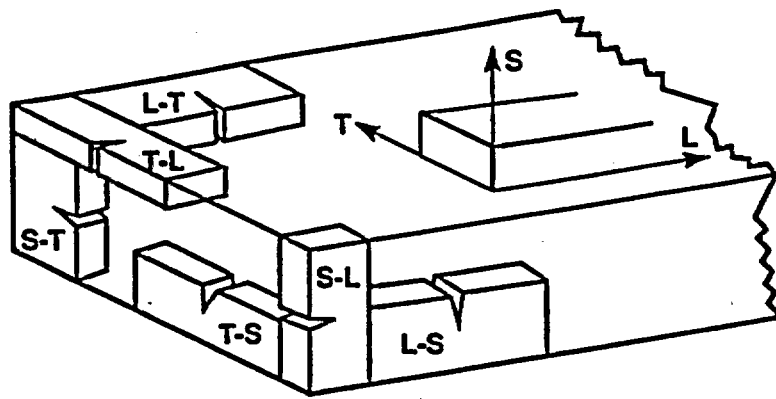


*500-ohm gauges will provide greater sensitivity than 120-ohm gauges

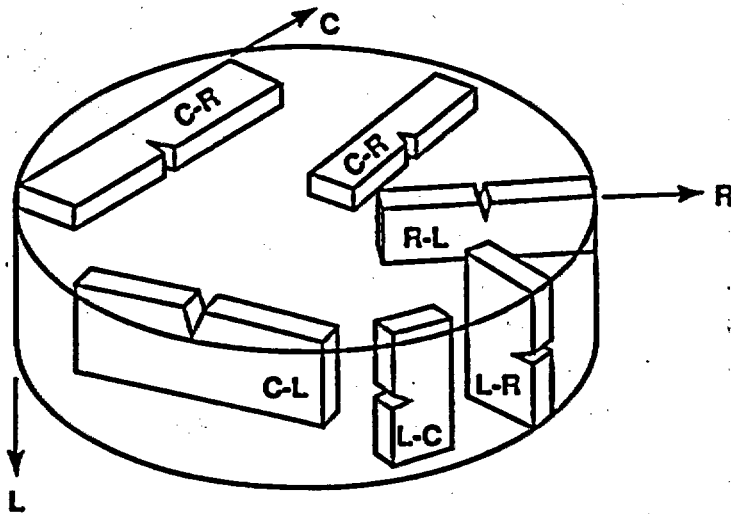




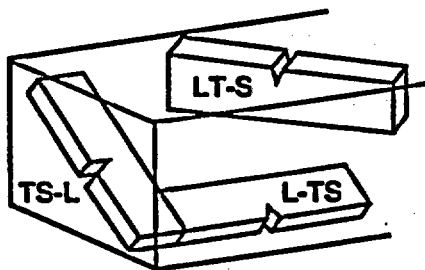
6819-7
 Middleton/Glassley
 QA Procedures
 Acct. 6069-05



(a) Rectangular section



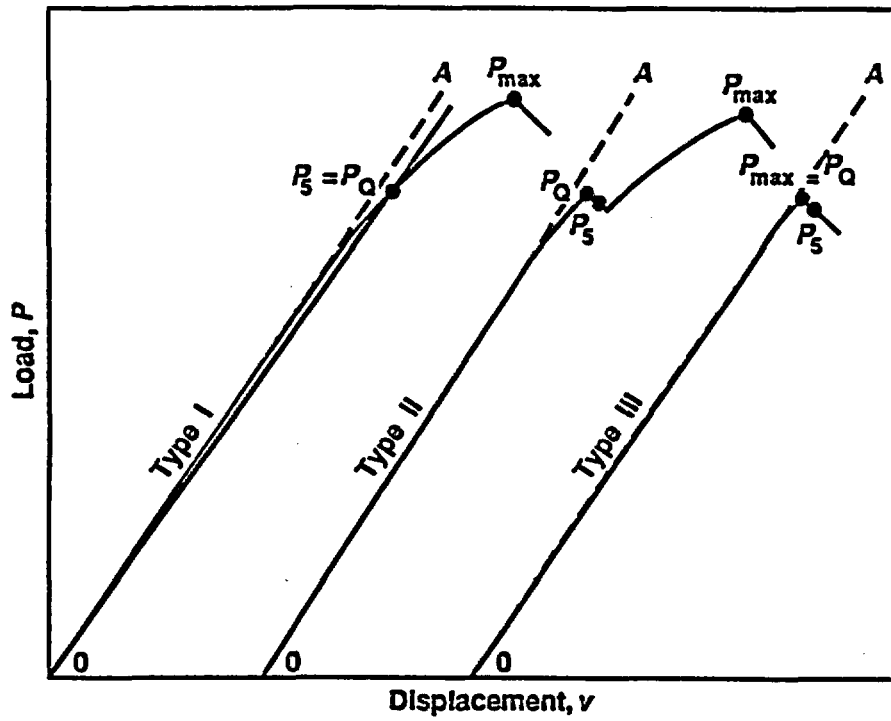
(b) Cylindrical section

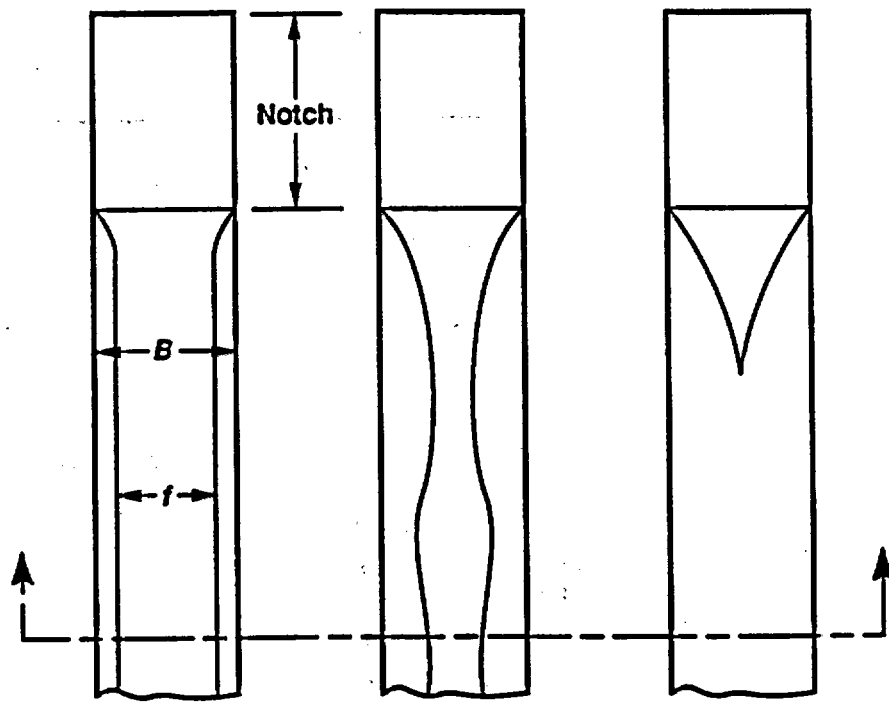


(c) Nonprimary

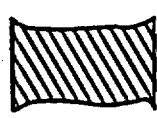
- L = Direction of grain flow
- T = Transverse grain direction
- S = Short transverse grain direction
- C = Chord of cylindrical cross section
- R = Radius of cylindrical cross section

First letter—normal to the fracture plane
 Second letter—direction of crack propagation in fracture plane



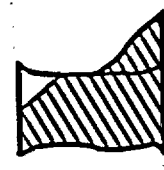


or

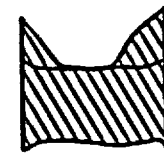


(a)

**Fraction
oblique**

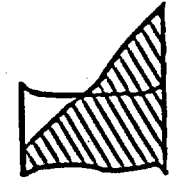


or

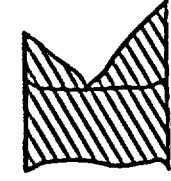


(b)

**Predominant
oblique**



or



(c)

**Full
oblique**

